Final UNRBA Falls Lake Modeling Report

Prepared for
Upper Neuse River Basin Association, NC

November 2024

Prepared by

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List of Acronyms and Abbreviations

CAAE	North Carolina State University Center for Applied Aquatic Ecology
CASTNET	Clean Air Status and Trends Network
Chla	Chlorophyll-a
DEQ	NC Department of Environmental Quality
DO	Dissolved Oxygen
DOT	North Carolina Department of Transportation
DWR	North Carolina Division of Water Resources
EFDC	Environmental Fluid Dynamics Code
EMC	Environmental Management Commission
EPA	Environmental Protection Agency
FWS	US Fish and Wildlife Service
LOESS	Locally Estimated Scatterplot Smoothing
µg/L	micrograms per liter
MRSW	Modeling and Regulatory Support Workgroup
NADP	National Atmospheric Deposition Program
NC	North Carolina
NCDC	National Climatic Data Center
NCDA&CS	North Carolina Agriculture and Consumer Services
NHD	National Hydrography Dataset
NOAA	National Oceanic and Atmospheric Administration
OHHABS	Center for Disease Control One Health Harmful Algal Bloom System
pBias	Percent Bias
PFC	Path Forward Committee
QAPP	Quality Assurance Project Plan
RMSE	Root Mean Square Error
RSR	Ratio of RMSE to Standard Deviation
SecchiD	Secchi depth

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SME	Subject matter expert
SOD	Sediment Oxygen Demand
TAW	Technical Advisors Workgroup
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TSS	Total Suspended Sediment
UNC	University of North Carolina at Chapel Hill
UNRBA	Upper Neuse River Basin Association
US	United States
USACE	United States Army Corps of Engineers
USFS	United States Forest Service
USGS	United States Geological Survey
WARMF	Watershed Analysis Risk Management Framework
WQ	Water Quality
WRC	North Carolina Wildlife Resources Commission

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Executive Summary

Purpose of Report

The objectives of this report are two-fold: 1) to document that models were developed following the approved UNRBA Modeling Quality Assurance Project Plan (QAPP) and 2) to provide modeling results to guide the Upper Neuse River Basin Association's (UNRBA's) development of recommendations for a revised Falls Lake Nutrient Management Strategy and updated Falls Lake Rules. The current Falls Lake Rules require that models used to re-examine the nutrient load reduction requirements are developed according to a state-approved modeling QAPP.

More detailed descriptions of the development of the models can be found in the extensive and detailed appendices. Readers should reference these appendices when seeking additional information.

Introduction and Background

The Falls Lake project was authorized by Congress as part of the Flood Control Act in 1965. The reservoir began filling in January 1983. The designated uses of Falls Lake include drinking water supply, recreation, aquatic life, and wildlife. Design and construction of the impoundment were conducted by the USACE, which continues to manage the reservoir today.

Pre-impoundment studies predicted that Falls Lake would be highly eutrophic, especially in the upper end (Figure ES-1) of the lake (DNER 1973, USACE 1974, NCDEM 1983). These studies predicted that dissolved oxygen would be depleted in deeper portions of the lake during thermally stratified conditions. Despite the predicted high chlorophyll-a concentrations and low dissolved oxygen concentrations in deep waters, each study indicated that the uses of Falls Lake would be met. Water quality conditions in the lake today are much better than predicted based on monitoring by the NC Division of Water Resources (DWR).

Water quality conditions in the lake today are much better than predicted based on monitoring by the NC Division of Water Resources (DWR).

In 2008, the NC Department of Environmental Quality (DEQ) placed Falls Lake on the 303(d) list for non-attainment of the State's chlorophyll-a standard (40 micrograms per liter [µg/L]). Chlorophyll-a is a measure of the amount of green pigment in water and is used as an indicator of algal productivity. While algae are an essential component of healthy aquatic ecosystems, high concentrations of algae can cause problems for water users (e.g., drinking water supply utilities, recreators) and impact the designated uses of the water body.

Eutrophication is the progressive increase in nutrient concentrations (nitrogen and phosphorus) that can result in harmful algal blooms, fish kills, and other designated use impairments. A healthy waterbody is one in which the nutrient inputs are in balance with the aquatic biological ecosystem. Even a healthy waterbody may be at risk for progressive eutrophication under changing conditions. Most piedmont reservoirs in NC are characterized as eutrophic; however, this designation is not, by itself, a determination of progressive or stable trophic condition. For Falls Lake, the UNRBA primary goal is to develop a revised nutrient management strategy that continues to protect the designated uses of the lake and mitigate long-

The UNRBA's primary goal for Falls Lake is to develop a revised nutrient management strategy that continues to protect the designated uses of the lake and mitigate long-term risks.

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term risks. It is important to note that the sum total of the UNRBA's scientific evaluation of Falls Lake, including evaluation of the long-term monitoring record, indicates that the trophic condition of the lake is stable at this time.

In 2010, the Environmental Management Commission (EMC) passed the Falls Lake Nutrient Management Strategy (the "Strategy" or the "Rules"). 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 lake (below Highway 50). The goal of Stage II is to comply with the chlorophyll-a standard everywhere in the lake. The current Strategy dictates load reduction requirements for local governments and other entities, which were based on a lake nutrient response model developed by the DWR (2009). This Strategy requires very large reductions in nutrient loading to the lake.

Adoption of the strategy resulted in Falls Lake being moved from the 303(d) list of impaired waters needing a total maximum daily load or management strategy (Category 5) to a 4B designation on the NC Integrated Waters Report. The 4B designation indicates that a waterbody is not meeting a water quality standard, but a plan is in place to address non-attainment. The Categorization document does not describe the assessment procedures to move a waterbody into compliance status with a management strategy (Category 1B). This report assumes the delisting requirements for a Category 5 waterbody would be followed to move Falls Lake into the 1B category.

The modeling developed by the State, used as the basis of the rules, was developed on a compressed schedule with limited data, and there is a lot of uncertainty in the required load reduction targets. For this reason, the rules allow for a "reexamination" of the required nutrient load reductions.

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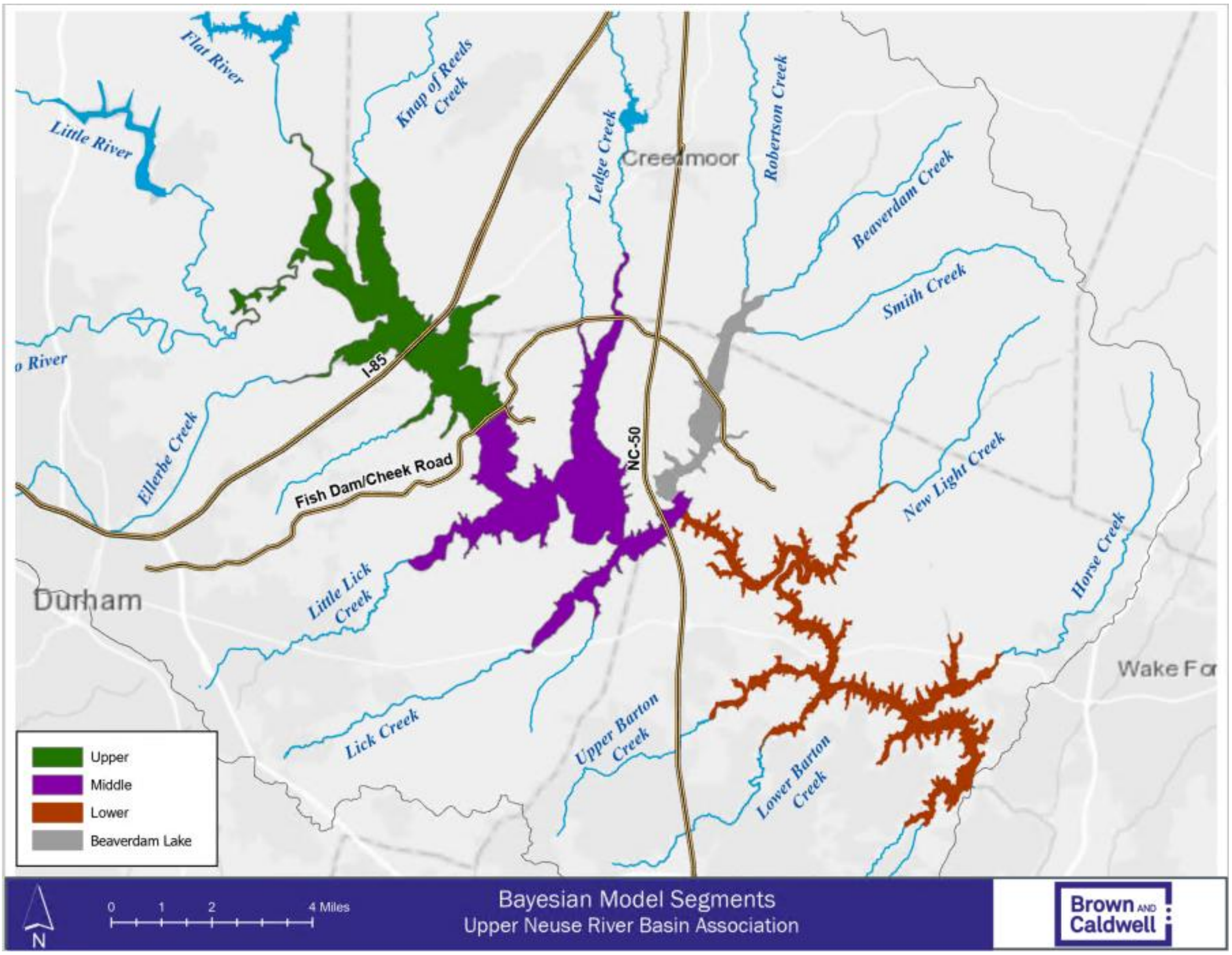

Figure ES-1. Segmentation of Falls Lake at Fish Dam/Cheek Road and near Highway 50

Based on the State's fiscal analysis (DWQ 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). Implementation costs for Stage II are expected to approach $1 billion for regulated entities. The UNRBA began planning for a reexamination of the required nutrient load reductions for Stage II in 2011 in accordance with the procedures and requirements outlined in the Rules (15A NCAC 02B.0275 Section (5)(f)). This section of the rules is generally referred to as the "adaptative management" provision because it includes an opportunity to revise the strategy based on updated water quality information. While the UNRBA supports its members in the implementation of Stage I of the management strategy, the large reduction goals required for Stage II are infeasible and beyond the limits of technology. This conclusion is supported based on a technical review of the Stage II provisions (see Section 3 of Framework for Reexamination of Stage II). This has been confirmed by the modeling effort and other evaluations developed during reexamination.

The UNRBA developed a plan for conducting the reexamination in 2013 (Cardno ENTRIX 2013). This plan included a minimum of four years of water quality monitoring in the watershed and the lake. The UNRBA began collecting water quality data in 2014. The main purpose for collecting water quality data was to support the development of revised and new watershed and lake simulation models which provide critical

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hydrological and water quality information to support the reexamination. The 2019 comprehensive monitoring report and access to the UNRBA data are available at https://unrba.org/resource-library.

In 2016, the UNRBA initiated the Modeling and Regulatory Support project as part of the reexamination of the Strategy. The UNRBA modeling contractors worked with the Path Forward Committee (PFC) and other stakeholders to select the modeling packages for the reexamination. The selection process was approved by the UNRBA PFC in December 2016. Documentation of this process is available in the Evaluation and Selection of Model Packages for the UNRBA Modeling and Regulatory Support Project.

The UNRBA selected different types of models to support the reexamination. The watershed model was developed using the Watershed Analysis Risk Management Framework (WARMF) as described in the UNRBA Watershed Modeling Report (BC and Systech Water Resources 2023). This model predicts the mass of nutrient loading to the lake from various sources in the watershed. These loads serve as input to the lake nutrient response models which predict the growth of algae in response to nutrient loads. Because the prediction of algal growth in the lake informs the revised nutrient management strategy, the UNRBA decided to develop multiple lake nutrient response models including the WARMF Lake, the Environmental Fluid Dynamics Code model (EFDC), and a statistical/Bayesian lake model. Having multiple models reduces the reliance on a single model and provides corroboration for the results. EFDC and WARMF Lake simulate the physical, chemical, and biological processes in the lake (e.g., settling of sediment and algae, growth and decay of algae, nutrient uptake rates). Both models have been calibrated to simulate water quality observations collected in Falls Lake for the UNRBA study period (2014 to 2018). The statistical/Bayesian lake model links inputs to the lake to water quality conditions in Falls Lake as well as satisfaction with designated uses by the users of Falls Lake.

Model Frameworks and Applications

To provide an expanded and more complete understanding of the watershed and the lake as an integrated system, the UNRBA developed one watershed and three lake models to support the reexamination. The models focus on hydrology, nutrients, algae growth, chlorophyll-a, and total organic carbon and are used to evaluate potential nutrient management strategies and impacts to water quality in Falls Lake.

To provide an expanded and more complete understanding of the watershed and the lake as an integrated system, the UNRBA developed one watershed and three lake models to support the reexamination.

Two mechanistic model frameworks (WARMF and EFDC) were selected for the UNRBA Falls Lake study. Both are EPA-approved and peer-reviewed water quality modeling tools that have been successfully applied for numerous nutrient allocation studies nationwide. Both modeling frameworks were previously used by DWR for this lake and watershed, but the watershed and lake models were not linked for development of the Falls Lake Rules. Rather, DWR used only the EFDC model to establish the required nutrient load reductions. DWR's loading was calculated based on the data available from the lake's main tributaries. The UNRBA linked the watershed model to both lake models to better understand how watershed nutrient loads and processes affect lake water quality. This linkage was essential to evaluate different watershed management actions and their impact on lake water quality. This scenario-based approach provided a comprehensive consideration of a broad range of watershed conditions and the resultant lake response. The UNRBA also developed a statistical/Bayesian lake model using empirical, probabilistic, and Bayesian techniques. This model links flow and nutrient loading to Falls Lake to lake water quality and user satisfaction with designated uses. The statistical/Bayesian lake model was developed "from scratch" and does not rely on an existing model framework like the other two models. The model is based on the data itself and as such is

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not a mechanistic (process-based) model like EFDC or WARMF-Lake. The software used to run the model and perform the computations is Netica (https://www.norsys.com/netica.html).

This multi-model approach provides the following benefits (for more information, see Section 10

- Avoids reliance on a single model and uses three independent lake models to inform decision making
- Improves the ability to answer a range of questions raised by stakeholders that a single model would not be capable of

Development and calibration of the watershed and lake models is guided by the UNRBA Modeling QAPP approved by DWR in April 2018. The Modeling and Regulatory Support Workgroup (MRSW) oversaw development of the WARMF watershed and lake model and the EFDC lake model. This workgroup is comprised of UNRBA members as well as DWR modeling group staff, US Forest Service researchers, NC Collaboratory researchers, representatives of agriculture, environmental advocacy groups, and state agencies including the NC Departments of Transportation (DOT) and Agriculture and Consumer Services (NCDA&CS). The Technical Advisors Workgroup (TAW) oversaw development of the UNRBA statistical/Bayesian lake model. This workgroup is comprised of UNRBA members with specific representation by organizations that manage the uses of Falls Lake (e.g., City of Raleigh water utility managers, Wake County Parks and Recreation) or represent a large user group (Triangle Fly Fishers). Both the MRSW and TAW report to the PFC at open meetings which are also attended by each of the organizations listed above.

To provide structure for making decisions throughout the reexamination process, the UNRBA developed the UNRBA Decision Framework. Status reports and decisions made by the MRSW, PFC, and TAW are available on the UNRBA meetings website. Workgroup discussions and decisions are noted throughout this report.

Like many mechanistic lake water quality models, the underlying EFDC and WARMF Lake model frameworks were developed to simulate only three groups of algae: cyanobacteria (i.e., blue-green algae), diatoms, and green/other algae. These models simulate the growth of algae based on water temperature and the availability of nutrients and light using a series of kinetic equations. Based on algae data collected monthly by DWR at three locations in Falls Lake, other algal groups often dominate the system. The modeling team considered modifications to the models to simulate more than three algal groups, but insufficient information was available in the literature to populate the numerous values required by the models. The decision was made with the subject matter experts, DWR, and the MRSW to continue the modeling with three algal groups simulated by both EFDC and WARMF Lake. Model modification was not practical or technically supportable.

The UNRBA Modeling QAPP listed several goals for this project. Table ES-1 lists the project goals and applicable model. Analysis of historic water quality monitoring data as a separate "model" of the system is also included. Similarly, information from the TAW provides a critical understanding of how water quality affects the management of Falls Lake in relation to its uses.

Table ES-1. Project Goals from the UNRBA Modeling QAPP and Appliable Model

Project Goal	Applicable Model or Input
Estimating nutrient, carbon, sediment, and chlorophyll-a loading to Falls Lake	WARMF Watershed Data Analysis of Historic Record
Evaluating the impacts of management strategies on water quality	WARMF Lake EFDC
Revising the lake response and watershed models using data that was not available at the time DWR conducted their modeling to develop the Falls Lake Nutrient Management Strategy;	WARMF Watershed EFDC

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Table ES-1. Project Goals from the UNRBA Modeling QAPP and Appliable Model	
Project Goal	**Applicable Model or Input**
Understanding how changes in lake water quality affect the designated uses of the lake;	Information from the Technical Advisors Workgroup Statistical/Bayesian
Evaluating management strategies in the lake and watershed to determine the impacts to lake water quality and designated uses;	WARMF Watershed WARMF Lake EFDC Statistical/Bayesian
Examining alternative chlorophyll-a criteria that include duration, frequency, spatial, and temporal components consistent with the chlorophyll-a criteria approved by EPA for states with more recent standards (North Carolina's standard was developed in the 1970s).	Data Analysis of Historic Record Statistical/Bayesian

Falls Lake Model Configurations

Models divide a waterbody into discrete grid cells or segment(s) to perform model calculations. Some models like EFDC are highly refined and divide the lake into hundreds of grid cells for which calculations are made on the scale of several seconds to a couple of minutes. Other models like WARMF Lake are more-simplified representations that define several lake segments and perform their calculations on hourly to daily time steps. Empirical models like the UNRBA statistical/Bayesian model tend to use longer time frames, like annual, seasonal, or monthly conditions, and may evaluate individual stations or groups of stations within segments. The UNRBA selected a multi-pronged modeling approach to avoid reliance on a single model and to develop a range of tools for planning and decision making.

The UNRBA selected a multi-pronged modeling approach to avoid reliance on a single model and to develop a range of tools for planning and decision making.

The Falls Lake EFDC model developed by Dynamic Solutions, LLC simulates 10 vertical water column layers, 2 sediment layers, and 862 grid cells with a time step a few seconds to a couple of minutes. The MRSW approved the EFDC model configuration on August 4, 2020. The Falls Lake WARMF model developed by Systech Water Resources, Inc. divides the main stem of the lake into six segments with the seven lake arms simulated separately. The Falls Lake WARMF model operates on a 6-hour time step and is directly linked to the Falls Lake WARMF watershed model. The WARMF watershed model also provides watershed inputs to the EFDC lake model. The MRSW approved the WARMF Lake model configuration on November 3, 2020.

The UNRBA statistical/Bayesian model evaluates three lake segments: upstream of Fish Dam/Cheek Road, between Fish Dam/Cheek Road, and downstream of Highway 50. Not all datasets are available for all three segments across the period of record. The TAW approved the initial UNRBA statistical/Bayesian model segmentation on July 12, 2022, during their discussion of available datasets but acknowledged that not all data were available for each of the three segments. As part of his UNRBA contract, UNRBA subject matter expert Dr. Marty Lebo evaluated water quality data from Falls Lake. Based on his analysis, moving the upper segment boundary to Fish Dam/Cheek Road would be most consistent with the morphologic, lake sediment depth, and lake water quality data. Moving this boundary from Interstate 85 to Fish Dam/Cheek Road also resolved the issue with missing data upstream of Interstate 85. This modification to the segment boundaries was approved by the PFC at their November 2023 PFC meeting.

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Configuration of the lake models relied heavily on the bathymetric mapping conducted by the UNRBA during its monitoring program. Development of this data set is described in the UNRBA 2019 Monitoring Report, and the map is shown in Figure 3-1 of this report.

Summary of Data Sources and Model Inputs

Many organizations including the UNRBA, NC Collaboratory, US Geologic Survey (USGS), DWR, NC Wildlife Resources Commission (WRC), NC State University Center for Applied Aquatic Ecology (CAAE), Cities of Durham and Raleigh, US Army Corps of Engineers (USACE), US Forest Service (USFS), and Region 4 of the Environmental Protection Agency (EPA) have conducted studies on Falls Lake or its watershed that informed development of the three UNRBA lake models. Nearly 40 distinct monitoring programs or research studies conducted on Falls Lake, or its watershed, were used to support model development. Nearly 30 water quality monitoring stations are located on Falls Lake where nutrient species, algal cell counts and biovolume (three stations), chlorophyll-a concentrations, and total organic carbon concentrations are measured at frequent intervals (usually monthly). These data have been supplemented with regional and national datasets including the Center for Disease Control One Health Harmful Algal Bloom System (OHHABS) and the National Atmospheric Deposition Program (NADP) to fill data gaps. The amount of data available and the number of researchers involved in this study is extraordinary.

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For both WARMF Lake and EFDC, streamflow and pollutant loading from the watershed were obtained from the WARMF watershed model. Development, calibration, model performance, model review, and results of scenario analyses for the watershed model are described in the UNRBA Watershed Model Report. Watershed changes impacting nutrient loading and their effect on lake water quality is the primary focus of the modeling effort. Linking the watershed and lake models is critical both to model development and use of the models in the evaluation of management alternatives.

Linking the watershed and lake models is critical both to model development and use of the models in the evaluation of management alternatives.

Once the NC Collaboratory was formed, the UNRBA worked closely with the staff and researchers to ensure their research studies provided additional information to supplement the UNRBA monitoring efforts and provide new information to support modeling. The NC Collaboratory funded studies on water movement and circulation, nitrification and denitrification rates, algal toxin evaluations, and several others. Previous studies conducted by the UNRBA included a Falls Lake bathymetry, sediment depth and sediment quality, light extinction, constriction point water movement and water quality, and model evaluations. The UNRBA studies are summarized in the UNRBA 2019 Monitoring Report. The NC Collaboratory reports are available at https://nutrients.web.unc.edu/resources/. Coordination between the UNRBA and NC Collaboratory helped ensure efforts were not duplicated.

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The UNRBA models were developed with significant input from the NC Collaboratory researchers and modeling staff at DWR. Researchers funded by the NC Collaboratory have been studying nutrient-related processes in Falls Lake since 2019. Some of these researchers also provided "third-party" and subject matter expert review of the lake and watershed models. The UNRBA began presenting our coordination with the NC Collaboratory-funded "third-party" subject matter expert reviewers to the Board, PFC, and MRSW in September 2019. The Association routinely presented the plan to incorporate the "third-party" review into the model development process rather than receive feedback after the models had been calibrated, scenarios evaluated, and reports written. When the "third-party" review occurs after these steps have been completed, there is often little time or budget remaining to make changes to the models.

The UNRBA models were developed with significant input from the NC Collaboratory researchers and modeling staff at DWR.

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

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

The results of the NC Collaboratory research studies have been incorporated into the development of the three lake models developed by the UNRBA. For example, researchers found that denitrification in the lake arms reduces nitrogen before reaching the main part of the lake. They also measured rates of nitrogen fixation by blue-green algae where the algae can "import" nitrogen from the atmosphere to support their growth. The researchers found that rates of nitrogen fixation in Falls Lake are currently low. Organizations that would like to conduct their own review can request the necessary files and model executables from the UNRBA Executive Director, Forrest Westall, at forrest.westall@unrba.org.

In addition to data regarding the physical, chemical, and biological characteristics of Falls Lake, the UNRBA compiled available information regarding the designated uses (aquatic life, recreation, and drinking water supply). The UNRBA TAW was formed by the PFC at the January 2021 PFC meeting to assist with data compilation, provide contacts to gather additional data, and discuss how their organizations apply data collected in Falls Lake to their decision making regarding designated uses. The TAW is comprised of PFC and MRSW members representing cities, counties, and utilities in the UNRBA. The TAW worked with the statistical modeling team to structure the statistical/Bayesian model and determine the model outputs most useful to the managers of the lake's designated uses. The TAW discussed what information the statistical model could provide that would be most useful to their organizations.

Additional contacts provided by the TAW included representatives from the DEQ, WRC, Triangle Fly Fishers, state and local parks and recreation departments, USACE, US Fish and Wildlife Service (FWS), water supply facility operators and laboratories, local water-based recreational businesses, watershed organizations and

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river keepers, and the NC Department of Public Health. These contacts were asked similar questions as the TAW about available data, information, and decision making regarding the designated uses of Falls Lake. Not all contacts were available for discussion. Table ES-2 provides examples of input received from these organizations regarding the designated uses of Falls Lake.

Table ES-2. Example Input from Representatives of Local Organizations Regarding the Designated Uses of Falls Lake

Organization	Input
Recreation (Fishing, Swimming, Etc.)	
NC State Parks	No known record keeping of complaints; most complaints relate to "too crowded" or negative personal interactions, or trash/facility needs; more related to guest experience than water quality concerns. State Parks data indicates that visitation to Falls Lake increased from 1 million in 2020 to nearly 1.5 million in 2021.
Wake County	Wake County manages some of the recreational areas on Falls Lake including swim beaches. The County has a response plan that includes coordination with DEQ, signage, etc. if DEQ confirms toxin exposure has led to an adverse event. Algal toxin levels have never resulted in a beach closure at Falls Lake.
Triangle Fly Fishers	Triangle Fly Fishers are frequently on Falls Lake and have extensive knowledge of fish species, fish movement, and trends on Falls Lake. Triangle Fly Fishers does not track algal toxin data in Falls Lake because toxins are consistently low. The group is not concerned about environmental or consumptive exposure to algal toxins on Falls Lake. If a fish kill was noticed, they would notify their members and DWR, but the group has not seen fish kills on Falls Lake.
City of Durham	Food web accumulation is a potential exposure pathway to subsistence fishers. Currently there is no data from Falls Lake to include in the model (potential future study).
Center for Disease Control (CDC)	The CDC launched a national database in 2016 called the OHHABS. The database includes voluntary reporting by States of toxic bloom events. The amount of information included for each event varies but may include environmental conditions, water quality and algae monitoring data, human health effects, and animal effects. OHHABS was used for comparison to Falls Lake algal toxin data and to provide a reference for algal toxin levels that cause human or animal adverse effects. Toxin levels in Falls Lake are relatively low compared to those in the OHHABS data and adverse effects from algal toxins in Falls Lake have not been documented by the State.
Aquatic Life	
NC Wildlife Resources Commission (WRC)	Staff noted the quality of fisheries in Falls Lake is generally above average for the Piedmont and not highly variable. Crappie fluctuates more than largemouth bass, but this is probably more a natural, ecological cycle than a response to specific lake conditions. Noted if we want to see problems, we would probably have to expand our fisheries data beyond Falls Lake. Noted fisheries benefit from being eutrophic (more food) to a degree. There is a "sweet spot" level of eutrophication to provide a great fishery without detrimental impacts to the fishery or other uses. The 2015 WRC Overview of the Falls Lake Largemouth Bass Fishery (2007–2015) states that "Falls Lake supports an excellent Largemouth Bass fishery and is being appropriately regulated" and "survey results indicate that the abundance of Largemouth Bass and the size structure of the fishery has been relatively stable."
NCDEQ	NCDEQ maintains a statewide database of reported fish kills. DEQ provided reported events for Falls Lake, and this information was used to assess nutrient-related impacts to the aquatic life designated use. Falls Lake records extend back to 1986. Nutrient or algae-related fish kills have not been reported since 1988 relatively soon after the lake was filled. Recreational use of the lake has increased over time, allowing for more potential observers if a fish kill occurred. NCDEQ created a phone application in 2018 for users to report fish kills making it easier to report events.
Triangle Fly Fishers	Triangle Fly Fishers are frequently on Falls Lake. If a fish kill was noticed, they would notify their members and DWR, but the group has not seen fish kills on Falls Lake.
Dr. Nathan Hall	In 2021, EPA issued proposed models to calculate site-specific chlorophyll-a standards based on the relationship between phytoplankton (algae) and zooplankton (small organisms that eat algae and are in turn eaten by small fish). Hall and Piehler (2021) evaluated this relationship for Falls Lake and other southeastern reservoirs. He found the approach was not appropriate for Falls Lake and that chlorophyll-a in Falls Lake is about half the average of other southeast reservoirs.

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Table ES-2. Example Input from Representatives of Local Organizations Regarding the Designated Uses of Falls Lake	
Organization	**Input**
Drinking Water Supply	
City of Raleigh	The City of Raleigh has monitored water quality in Falls Lake for the past two decades. Over this period, the type and timing of algal blooms has become more stable. Drought/flood cycle tends to increase total organic carbon in the lake. Staff are hopeful that research studies will increase the knowledge about how the lake bottom serves as a nutrient and sediment trap and whether dam releases stir up these materials. Noted manganese is the most difficult and expensive to treat. Concentrations above 0.45 mg/L trigger additional monitoring and may require additional treatment. Manganese concentrations can become high in Falls Lake when bottom material is stirred up. City of Raleigh drinking water staff track algal toxin levels. Monitoring to date has not shown a concern in Falls Lake. Results show consistently low levels. Diatoms can clog filters at the drinking water plant. The City has two terminal ponds between Falls Lake and the treatment plant that are used for treatment of diatoms when needed. The City noted that they have had only one issue several years ago that required treatment in the terminal ponds. The City does not have issues with taste and odor or disinfection byproducts at Falls Lake. In 2023, the American Water Works Association ranked the City of Raleigh 3rd in its international "'Best of the Best' Water Taste Test"

Simulation of Internal Nutrient Loading from Lake Sediments

Large waterbodies like lakes can accumulate nutrient-rich organics and sediments on the lake bottom that have the potential to release nitrogen and phosphorus into the water column. The level of impact is site-specific, and Falls Lake has its own unique nutrient balance characteristics. The importance and quantification of sediment flux was identified, evaluated, and assessed throughout the monitoring and modeling process. This comprehensive assessment has established that the process of sediment nutrient cycling is an important factor in making regulatory decisions and evaluating long-term changes in the nutrient balance of this reservoir.

The UNRBA identified the critical importance of these releases on the nutrient balance of Falls Lake and developed special studies to better understand these processes. Along with the bathymetric survey of Falls Lake, the UNRBA conducted a sediment depth survey and sediment quality survey of the lake. Sediment cores were extracted, analyzed, and modeled by Dr. Marc Alperin (2018). This study provided important information about the porewater (water contained between the spaces of the sediment particles) concentrations and sediment quality in Falls Lake. Several additional studies have been conducted on Falls Lake to estimate sediment-nutrient release rates at different locations (4.3). These studies provide a basis of comparison to ensure the simulated nutrient releases from lake sediments by the Falls Lake models are reasonable. Because these studies reflect specific locations and times, the study results should not be considered a measured or known value representative of the entire lake. Together the studies represent the relative magnitude of this source and potential changes in response to management actions.

Based on the available studies, estimates of ammonia releases from Falls Lake sediments range from 200,000 to 500,000 pounds of nitrogen per year. This amount is roughly 12 to 30 percent of the total nitrogen load delivered to Falls Lake from the watershed or deposited from the atmosphere (1.65 million pounds of total nitrogen per year on average during the study period, 2014 to 2018. The studies indicate that ammonia releases from lake sediments are higher in the deeper areas of the lake where sediment and organic material accumulate. Estimates of phosphate releases from the lake sediments range from 10,000 to 50,000 pounds of phosphorus per year. This amount is roughly 5 to 27 percent of the delivered load from the watershed during the study period (183,000 pounds of total phosphorus per year on average, 2014-2018. The significant variation in ranges of estimated nutrient release rates from Falls Lake sediments indicate a great deal of uncertainty relative to specific release rates, particularly for phosphate where releases are controlled by the chemical characteristics and conditions at the sediment-water interface. However, the studies show that nutrient release rates in Falls Lake are an extremely important

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factor in evaluating lake response to management actions. Nutrient release rates from lake sediments will remain an important consideration in making management decisions.

The relative importance of this source of nutrients compared to the watershed also depends on hydrologic condition. During dry periods, stream flows and nutrient loading from the watershed are relatively low. This condition increases the significance of sediment-nutrient releases in three ways. First, the amount of loading from the watershed is lower, but the amount released from the sediment is less variable. Second, less stream flow to the lake results in longer residence times, meaning the water "sits" in the lake longer with greater exposure to sediment releases. Third, longer residence times in the warm summer months will more strongly stratify the water in the lake into separate layers. Stratification prevents mixing of the layers, and the bottom water is more likely to have low dissolved oxygen concentrations. Based on the NC Collaboratory research (Smiley et al. 2023), ammonia and phosphate releases are generally higher when oxygen levels are very low.

Smiley et al. (2023) also found that releases of ammonia from Falls Lake sediments are largely mitigated by denitrification, a biological process that removes nitrogen from the system as nitrogen gas. NC Collaboratory researchers estimate the amount of denitrification as equivalent to the amount of ammonia released from the lake sediments. Phosphorus releases tend to occur in the deeper parts of the lake during warm stratified conditions. These releases are usually "trapped" near the lake bottom but can be moved to the surface layers when the lake de-stratifies and "turns over." Destratification occurs in the fall months, and higher concentrations of total phosphorus are sometimes observed in the upper layers of Falls Lake in the fall.

Additional information regarding simulation of nutrient releases from sediments is available in Appendix A for the EFDC model and Appendix B for WARMF.

EFDC and WARMF Lake Calibration and Validation

Both EFDC and WARMF Lake use model coefficients to simulate the physical, chemical, and biological processes. The values of these coefficients were adjusted during the model calibration process to result in the best fit between simulated and observed values for the calibration period (2015 to 2016). Often improving the model fit for one parameter and/or location will have a detrimental impact on another parameter or location. A separate validation period (2017 to 2018) was used to test the models to ensure they were not calibrated so specifically to one period that they would not be representative if used to simulate another period or set of conditions.

Model calibration is an iterative process where changing one coefficient may have the desired effect on one parameter (improved fit to observed data) while potentially having a worsening effect on another parameter. Decisions on whether or not to continue model calibration depend on resource constraints, project schedules, and model limitations in terms of simulating site-specific processes not well accounted for in the model framework. The UNRBA worked with the subject matter experts, "third-party" reviewers, and DWR modeling staff as the models were developed and calibrated to test variations in model coefficients, evaluate modeling results with respect to different types of available data, and determine when calibration was sufficient for the purposes of the project (i.e., understand how lake water quality would change in response to changing nutrient loads). To guide this process, the UNRBA developed, and DWR approved, the UNRBA Modeling Quality Assurance Project Plan (QAPP).

DWR modeling staff and "third-party" model reviewers provided review and input during model development and calibration. "Third-party," subject matter expert, and DWR input was used to guide calibration decisions. All critical decisions were also reviewed and confirmed by the MRSW. The availability of four years of monitoring data including special studies on Falls Lake was critical for this process. This information provided a level of model calibration guidance not normally available for development of models.

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The performance of each lake water quality model was evaluated by a combination of visual inspection of figures comparing simulated values to observations as well as model performance statistics described in the QAPP. Performance statistics, full-page time series comparisons, and scatter plots comparing simulated to observed values are provided in Appendix A for the EFDC model and Appendix B for the WARMF Lake model. The statistical model summarizes and relates observed water quality in Falls Lake for several parameters. It is a different type of model that is not calibrated like WARMF Lake or EFDC.

Several discussions with the MRSW, subject matter experts, and DWR modeling staff in 2022 were held to discuss ways to improve the performance of both models. These discussions resulted in several rounds of model testing of various model coefficients with a focus on calibrating the models to chlorophyll-a concentrations observed in Falls Lake. Based on these discussions and input from the subject matter experts and DWR modeling staff, the MRSW approved the calibration of the EFDC and WARMF Lake models in January 2023. Best professional judgement is an important component of determining when to stop the calibration process. The additional testing performed showed that continued calibration efforts would not yield overall improvements to the model calibration. Based on model performance statistics, visual comparisons of simulated and observed data, and input from the reviewers of the modeling effort, the performance of both models was deemed acceptable for assessing regulatory and management decisions for Falls Lake.

Probability Distributions of the Falls Lake Statistical Bayesian Model

The Falls Lake Statistical Bayesian model is developed using the historic record of water quality data and observed conditions. It provides an interactive summary of all observed data and the probabilistic relationships among variables. Rather than adjust model coefficients, like EFDC or WARMF, to fit the observations, the observations are used to generate probability distributions that indicate how frequently something has occurred.

When the full record is evaluated with the model, this is the “default condition” or “default scenario.” For example, the default condition evaluates all data collected in the warm and cool seasons. If the user wants to see how the probability distributions change if warm season is selected, this would be a scenario.

Each of the three lake segments has a unique set of probability distributions. The categories for each variable (e.g., low, medium, high) are based on all the data collected in Falls Lake. The models for each segment use the same categories (also called bins) but focus on data and conditions for that segment. The upper lake has higher probabilities of high nutrient and high chlorophyll-a concentrations. The lower lake has higher probabilities of low nutrient and low chlorophyll-a concentrations. The distributions of the data and the conditions under which they were collected affect how responsive the outputs are to scenarios. For example, in the upper lake, chlorophyll-a concentrations are generally high, and high concentrations of chlorophyll-a have been observed across the range of seasons, nutrient loads, and precipitation regimes. Changing these model inputs does not have a significant impact on the probability distributions for chlorophyll-a because they are typically high regardless of the other conditions. In the lower lake, the impact of changing conditions has even less effect on chlorophyll-a because concentrations have been consistently low regardless of other conditions.

Sensitivity Analyses

Following calibration of the EFDC and WARMF Lake models, sensitivity analyses were conducted on a subset of model coefficients to evaluate how changing these would affect simulated water quality in Falls Lake. The purpose of the sensitivity analysis is to gain a better understanding of how changing a model input coefficient affects modeling results. The sensitivity analysis provides useful information regarding the relative importance of the physical, chemical, and biological processes represented in the model and identifies the most influential parameters for improving model accuracy. This information can also provide

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future insight to help identify research studies that would improve future modeling efforts under an adaptive management framework.

The modeling team worked with the MRSW, "third-party" model reviewers, and DWR modelers to determine the parameters and ranges to evaluate for the sensitivity analyses. The regulatory driver for the project is chlorophyll-a, so this output parameter in Falls Lake is the focus of the sensitivity analyses. Total organic carbon, total nitrogen, and total phosphorus were also evaluated for change as described in the model-specific appendices. Because the focus of the reexamination is the impact of nutrient levels on algal production and chlorophyll-a, the sensitivity analyses focused on lake model parameters addressing algal kinetics and impacts on nutrient release rates from the lake sediments.

Sensitivity analyses were performed with the calibrated and validated Falls Lake EFDC water quality model for four model input coefficients including the carbon to chlorophyll-a ratios assigned to each algal group, the maximum algae growth rate for each group, algae settling velocity for each group, and the diffusion coefficient in pore water of the lake sediments. For the EFDC model, simulated chlorophyll-a, total organic carbon, total nitrogen, and total phosphorus were all most sensitive to the maximum algal growth rate. Simulated chlorophyll-a, total organic carbon, and total nitrogen were the least sensitive to the diffusion coefficient in the pore water of the lake sediments. Total phosphorus was least sensitive to changes in the algae settling velocity.

For the WARMF Lake model, sensitivity analyses were conducted on algal growth, sediment bed diffusion, nitrification, and organic material decay rates. Total nitrogen and total organic carbon were most sensitive to increases in bed diffusion rates (this simpler model does not include as many model coefficients associated with sediment diagenesis compared to EFDC). These parameters were also sensitive to organic matter decay rate. Chlorophyll-a was sometimes sensitive to the bed diffusion rate, but generally concentrations were similar across the analyses. The algal growth rates sometimes shifted the timing of the peak chlorophyll-a concentration but usually had little effect on simulated values. Total phosphorus was usually not sensitive to these parameters.

One product of the statistical/Bayesian model is a sensitivity analysis. This analysis summarizes how much the variability in the expected value of one variable is reduced given knowledge of each of the other variables in the model, individually. The output is expressed as a percent reduction in variability. A higher percent reduction means the variable is more sensitive and there is a stronger relationship. Given the complexity of the system (hydrologic, seasonal, algal species shifts, changes in nutrient loading patterns, changes in nutrient availability), the sensitivities among the variables were relatively low. No variable in any segment caused even a 10 percent reduction in variability for any other variable. Such results support conclusions that (1) knowledge of one variable does not result in high certainty of the values of any other variables; and (2) a change in the value of one variable has not predictably changed values of other variables.

Sensitivity analyses are further described in Section 7 for the three models with additional details provided in Appendix A for the EFDC model, Appendix B for WARMF Lake, and Appendix C for the statistical/Bayesian model.

Scenario Analysis

The primary purpose of the UNRBA modeling tools is to evaluate the effects of potential watershed nutrient management actions on lake water quality. This evaluation guided development of the UNRBA's recommendations for a revised nutrient management strategy. This evaluation is not a component of calibration or validation which occurred previously in model development.

Scenarios allow the model user to change conditions in the model and evaluate the effects. Changing conditions may be related to changing rainfall patterns, land uses, rates of atmospheric deposition, etc. The UNRBA formed a Scenario Screening Workgroup to prioritize and select scenarios to evaluate with each

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model. This workgroup included UNRBA members as well as representatives from DWR, agriculture, DOT, and environmental advocacy groups. The MRSW and PFC also provided review of and input on the scenarios considered. The scenarios evaluated by the UNRBA provide important information for understanding the system and making regulatory decisions. The model selected for each scenario was determined based on the particular aspects of the models.

The calibrated EFDC water quality model was applied to understand how lake water quality would change if study-period watershed loading (2014 to 2018) persisted into the future or changed over time. The UNRBA EFDC model was selected for these scenarios because it includes the sediment diagenesis model that simulates how nutrient releases from lake sediments can change over time. As noted, sediment release is a critical factor in determining nutrient balance and potential changes in lake water quality relative to a specific management scenario. Another set of EFDC model scenarios was developed to determine the combination of nitrogen and phosphorus load reductions that would be needed to meet the chlorophyll-a standard at DWR monitoring station NEU013B near Fish Dam/Cheek Road where observed concentrations are typically highest. DWR did a similar evaluation at this station which they referred to as the "compliance point" in their lake modeling report (DWR 2009).

The calibrated WARMF Lake model was used to evaluate scenarios dealing with changes in the watershed because the WARMF watershed and lake models are directly linked. These scenarios include the following:

- Instantly converting all land to forests, eliminating discharges from onsite and centralized wastewater treatment systems, and eliminating nutrient application to land surfaces. This hypothetical scenario provides an estimate of the lowest possible anthropogenic nutrient load to Falls Lake for this watershed given its current conditions. Hydrologic and chemical properties of the soils in the watershed were not altered for this analysis, nor were characteristics of streams. Rates of atmospheric deposition were not revised under this scenario. Therefore, this is not representative of prehistoric conditions.
- Increasing or decreasing the amount of atmospheric deposition of nutrients and total organic carbon by 25 percent
- Increasing or decreasing the amount of rainfall by 20 percent
- Simulating the lake spillway at normal pool elevation (251.5 feet above mean sea level).

Table ES-3 and Table ES-4 summarize the impacts of each scenario on simulated chlorophyll-a percent exceedances for the EFDC and WARMF Lake models, respectively. Impacts on total nitrogen, total phosphorus, and total organic carbon are provided in the sections below or in model-specific appendices.

Table ES-3. Scenarios Evaluated with the Falls Lake EFDC Model and Simulated Changes to Chlorophyll-a
Simulation of Long-Term Impacts Using Study-Period Watershed Loads
One of the scenarios selected for evaluation with the EFDC model included running long-term simulations using the study-period watershed loads (2014 to 2018) to the lake. These long-term simulations were run for 25 and 50 years. As described in the UNRBA Watershed Model Report, significant reductions in delivered loading to Falls Lake have occurred since the baseline period. The purpose of this model scenario was to see if chlorophyll-a concentrations would decrease over time due to reduced nutrient releases from the sediments. It was assumed that the reduced loading from the watershed over the past decade would eventually reduce lake cycling of nutrients and reduce algal growth and chlorophyll-a concentrations. *Scenario Conclusion: Chlorophyll-a concentrations were not significantly affected even after 50 years, supporting the finding that chlorophyll-a concentrations in Falls Lake are stable and that sufficient nutrients to sustain chlorophyll-a levels are present even with the reductions documented from the baseline year.*
Simulation of Nutrient Load Reduction Curves
The EFDC model was selected to evaluate combinations of total nitrogen and total phosphorus load reductions from all tributaries to Falls Lake and the effect on the percent of time the chlorophyll-a standard (40 µg/L) would be exceeded. Combinations of nutrient load reductions were evaluated to determine the level of load reduction needed from 2015-2016 levels to achieve the chlorophyll-a standard everywhere in the lake at least 90 percent of the time. Note that meeting the chlorophyll-a standard at least 90 percent of the time (exceeding 10 percent of the time) would not necessarily result in attainment of DWR's standard for chlorophyll-a based on NC's current Clean Water Act Section 303(d) assessment methodology. Models are not used

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Table ES-3. Scenarios Evaluated with the Falls Lake EFDC Model and Simulated Changes to Chlorophyll-a

for assessment, but rather to predict future changes and likely outcomes. Assessment requires collection of data. Assessment methods are summarized in Section 1.3.

This evaluation showed that attaining the chlorophyll-a standard of 40 µg/L in the upper, shallow part of the lake would require a 50 percent reduction in total nitrogen load delivered to Falls Lake beyond the reductions already achieved; i.e., an additional 50 percent reduction in total nitrogen loading relative to the UNRBA study period (2014 to 2018).

Conclusion: Based on analyses presented in the UNRBA Watershed Modeling Report (BC and Systech Water Resources 2023), achieving a 50 percent reduction in total nitrogen loading to Falls Lake is not feasible. Even meeting this load reduction requirement would likely not result in attainment of DWR's standard for chlorophyll-a based on the current 303(d) assessment methodology.

Simulation of 20 Percent Increase in Nutrient Loads Delivered to Falls Lake

The EFDC model was also used to simulate the impacts of increased nutrient loading from the tributaries by 20 percent. This simulated increase was used to understand the potential impacts of further land use changes and increased nutrient loading to Falls Lake.

Near Fish Dam/Cheek Road, a 20 percent increase in total nitrogen and total phosphorus delivered to Falls Lake increased the percent of time the chlorophyll-a standard was exceeded from 40 percent (for the calibrated model) to 45 percent. Near the dam, the 20 percent increase in nutrient load did not affect simulated chlorophyll-a concentrations.

Conclusion: This load-increase scenario further supports the stability of chlorophyll-a concentrations in Falls Lake, particularly near the dam where most of the nutrient processing has already occurred in upstream portions of the lake. Historically, water quality near the dam has been stable even under higher nutrient loading conditions.

Table ES-4. Scenarios Evaluated with the Falls Lake WARMF Lake Model and Simulated Changes to Chlorophyll-a

Simulation of Land Conversion to Forests and Removal of Nutrient Application and Wastewater-Related Discharges ("All Forest")

This scenario establishes the lowest potential loading to Falls Lake and the resulting lake water quality if conditions on the ground were changed instantaneously (assuming atmospheric deposition rates remain at current levels). This "all forest" scenario is further described in the UNRBA Watershed Modeling Report (BC and Systech Water Resources 2023).

While the "all forest" scenario resulted in lower chlorophyll-a concentrations than the calibrated model, these levels still exceed the 40 µg/L chlorophyll-a standard near Interstate 85 approximately 31 percent of the time.

Conclusion: Not even this hypothetical scenario can meet the chlorophyll-a standard everywhere, all the time in Falls Lake. Converting the entire watershed to a forest condition is the lowest nutrient loading condition within the watershed. While this is a hypothetical scenario, modeling this condition illustrates that there is not a watershed-based management approach that can achieve the chlorophyll-a standard in Falls Lake as currently applied.

Implications: These results are not presented to imply that forests are bad for water quality. On the contrary, forests are the best possible land use for watershed health. If the Falls Lake dam were not present, this scenario would attain the chlorophyll-a standard. Current watershed conditions would also likely achieve the chlorophyll-a standard if the dam were not present. However, the Falls Lake reservoir provides irreplaceable benefits to society. Expecting water quality in the reservoir, even under an "all forest" condition, to mimic the water quality of an undisturbed system without a dam, is not realistic.

Simulation of Changes to Rates of Atmospheric Deposition

Another scenario that was previously evaluated with the UNRBA WARMF watershed model (BC and Systech Water Resources 2023) either increased or decreased rates of atmospheric deposition by 25 percent for total nitrogen, total phosphorus, and total organic carbon. This amount is similar to the reduction in total nitrogen deposition that has occurred since 2006 in the watershed.

Conclusion: There is little discernable difference in simulated chlorophyll-a concentrations when rates of atmospheric deposition are increased or decreased by 25 percent. As discussed in the UNRBA Watershed Modeling Report, these scenarios do not significantly impact nutrient loading to Falls Lake (up to a 5 percent change in delivered loads of total nitrogen).

Simulation of Changes to Rainfall

Watershed modeling demonstrates that precipitation is the determining factor for the amount of nutrient loading delivered to Falls Lake (BC and Systech Water Resources 2023). Two precipitation scenarios were developed for the WARMF watershed model and Falls Lake model. One modeling scenario decreased precipitation amount by 20 percent to represent rainfall amounts that occurred during the DWR baseline modeling period for the Falls Lake Rules and the monitoring studies conducted by the US Forest Service in the Falls Lake watershed. One modeling scenario increased precipitation amount by 20 percent to represent larger, more frequent storm events.

During certain times of the modeling period, the 20 percent less precipitation scenario results in higher concentrations of chlorophyll-a than the calibrated model or the 20 percent more precipitation scenario. This increase in simulated chlorophyll-a concentration is likely because less rainfall results in stagnation of the lake water allowing more time for algae to grow. This lower rainfall scenario results in 35 percent less total nitrogen load delivered to Falls Lake and 42 percent less total phosphorus load delivered to Falls Lake. On the other hand, a 20 percent increase in rainfall increases delivered total nitrogen and total phosphorus loads by 36 percent and 60 percent, respectively, but these load increases do not translate to increases in

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Table ES-4. Scenarios Evaluated with the Falls Lake WARMF Lake Model and Simulated Changes to Chlorophyll-a
simulated chlorophyll-a concentrations. While the nutrient loads increase under the higher precipitation scenario, stream flows also increase and water moves through the lake more quickly, reducing the potential for algal growth. *Conclusion: These precipitation scenarios illustrate that delivered nutrient loading is not the single determining factor for algae growth and chlorophyll-a concentrations in Falls Lake.* Hydrologic conditions are also important. This scenario further confirms that algal levels are relatively stable in the lake and that sufficient nutrients are available to sustain current algal levels, despite substantial reductions or increases in loading to the lake.
Simulation of Changes to Falls Lake Operations
One WARMF Lake model scenario was designed to address a question frequently asked by stakeholders regarding the impact of USACE lake operations on nutrient cycling, algal growth, and chlorophyll-a concentrations in Falls Lake. A scenario was evaluated that simulates an open outflow structure (weir) at the normal pool elevation (251.5 feet above mean sea level). Under current operations, following a large rain event, the USACE stores water in the lake to minimize downstream flooding. The USACE closes the flow release gates to store the water, and the lake water level rises. Once the risk of downstream flooding has passed, the USACE releases water from Falls Lake. These releases continue until the target elevation is met. If a large event has not occurred, the USACE balances releases with inflows to maintain normal pool. Because large rain events are relatively infrequent, the USACE is usually able to maintain normal pool except during drought periods. Therefore, most of the time, the water level is 251.5 feet. Conclusion: Under this scenario, an open weir is simulated at normal pool. This simulation removes the operation of the lake through flow release gates. Because the USACE already targets normal pool elevation in their operation of Falls Lake and large rain events occur infrequently, this scenario did not significantly affect simulated water quality in Falls Lake. Maximum values of chlorophyll-a simulated for this change to lake operations either increased, decreased, or shifted in time depending on when and where the simulation is compared to the calibrated model. *However, the percentage of simulated chlorophyll-a concentrations exceeding the standard was similar for the current and modified lake operations simulated by this scenario. Operations by the USACE to limit flooding downstream do not dictate whether or not Falls Lake would be compliant with the chlorophyll-a standard.*

Scenarios for the statistical/Bayesian model were evaluated to determine if changing one or more system inputs would significantly change the model outputs for either regulatory variables (dissolved oxygen, pH, chlorophyll-a regulatory) or use-related variables (manganese, TOC, and algal toxin levels). The "default scenario" is based on all data collected in a lake segment, without selecting a specific condition, like season. A scenario is created when one or more inputs are selected like warm or cool season, very low or very high nutrient loads, or low to high precipitation. Selecting specific inputs can change the probability distribution of one or more output variables.

Table ES-4 summarizes the scenarios that most impact each of the output variables compared to the default scenario. An increase in the probability, expressed as a percent, means that for the historic record, the scenario was more likely to generate an outcome than the default. A lower percent probability means that condition was less likely to generate an outcome. Because of the variability in the historic record with nearly every outcome observed under nearly every condition, the model scenarios do not have a strong impact on the probabilities. Scenarios can also have a different impact on the upper versus lower lake.

Table ES-2. Scenarios Evaluated with the Falls Lake Statistical/Bayesian Model that Have the Greatest Impact on Model Output Variables within the Photic Zone

Output Variable	Scenario	Upper Lake Probability (%)	Middle Lake Probability (%)	Lower Lake Probability (%)
Dissolved oxygen (DO) concentrations less than the instantaneous standard (4 mg/L)	Default scenario	14.8	9.0	8.8
	Warm season, dry	25.5	16.5	16.5
	Warm season, dry, very high nutrient loads	25.5	16.5	17.0
pH below 6, pH above 9	Default scenario	3.1, 1.2	<1, <1	<1, <1
	Warm season, dry	<1, 8.2	<1, <1	<1, <1
	Warm season, wet	1.7, <1	<1, <1	<1, <1

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Table ES-2. Scenarios Evaluated with the Falls Lake Statistical/Bayesian Model that Have the Greatest Impact on Model Output Variables within the Photic Zone

Output Variable	Scenario	Upper Lake Probability (%)	Middle Lake Probability (%)	Lower Lake Probability (%)
Chlorophyll-a greater than the standard (40 µg/L)	Default scenario	44.6	16.6	8.6
	Warm season, dry	50.6	18.4	10.1
	Warm season, dry, very high nutrient loads	50.7	18.4	10.7
Manganese greater than the City of Raleigh's threshold for additional monitoring (0.45 mg/L)	Default scenario	30.7	4.18	5.81
	Warm season	51.5	8.14	10.3
	Warm season, dry	53.4	21	10.6
Total Organic Carbon Greater than 8 mg/L	Default scenario	58.0	41.5	22.1
	Warm season, dry	45.4	22.9	11.8
	Warm season, wet	75.0	57.5	27.8
Algal Toxin Levels Above Drinking Water or Recreational Use Thresholds	There have been no observations of algal toxin concentrations greater than the drinking water or recreational use health guidelines. The observations have been collected across decades, by multiple organizations, under varying seasons, precipitation conditions, and nutrient loading. Therefore, none of the model scenarios result in even a small probability of exceeding algal toxin thresholds.			

Model scenarios are further described in Appendix A for the EFDC model, Appendix B for WARMF Lake, and Appendix C for the statistical/Bayesian model.

Key Findings

The UNRBA has invested over ten years and ten million dollars in a comprehensive and extensive study and evaluation of Falls Lake. Several other organizations have studied Falls Lake with some data extending back to the 1980s. The UNRBA effort also has looked at these studies. The data collection efforts over the entire period encompass not only water quality data but water level and movement; lake sediment depth, quality, and nutrient releases; physical, chemical, and biological processes; light availability; algal types; and algal toxins. Additional data sets relate to satisfaction with the designated uses of Falls Lake including aquatic life, recreation, and drinking water supply. Several of these studies were summarized previously in the UNRBA 2019 Monitoring Report. Compared to similar studies and modeling efforts, the amount of data, level of information available, and number of researchers involved in this study are extraordinary.

The calibrated UNRBA lake water quality models, long-term lake monitoring data, and research studies show that concentrations of nutrients in Falls Lake were relatively low for the UNRBA study period (2014 to 2018). While water quality in the upper part of the lake (upstream of Fish Dam/Cheek Road) has been highly variable over time, it has stabilized in the past decade based on water quality measurements. Water quality in the lower part of the lake (downstream of Highway 50 to the dam) has been stable since the lake was filled. The algae in Falls Lake are resilient, and chlorophyll-a can reach high concentrations even when nutrient concentrations and nutrient loading remain low. Species shifts are evident in the DEQ algae data collected in Falls Lake. These shifts and inconsistent patterns between algal biovolume measurements and chlorophyll-a concentrations complicate model calibration because the models are designed to predict more chlorophyll-a when more algae are present. In reality, algal species can modify the amount of chlorophyll-a they produce in response to environmental stressors. It is difficult to simulate rapidly changing algal patterns and species shifts and not possible to simulate varying chlorophyll-a production rates within a simulated algal group. Chlorophyll-a values alone do not definitively define overall water quality trophic condition.

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Lake modeling scenarios including long-term evaluations further validate the information from the monitoring data, research studies, and calibrated Falls Lake models:

- Water quality in Falls Lake, including chlorophyll-a, has stabilized in the past decade.
- Recent nutrient inputs (2014 to 2018) have significantly declined due to improvements at wastewater treatment plants and reductions in agricultural production, nutrient application to crops, and atmospheric deposition of nitrogen. Based on long-term simulations at these reduced nutrient input levels (2014 to 2018), nutrient releases from Falls Lake sediments are stable and in balance with inputs from the watershed.
- Most of the nutrients delivered to Falls Lake from the watershed are not readily available to support algae. In the study period, approximately 90 percent of the total nitrogen load is in organic form. Decay processes are relatively slow but provide a long-term source of available nutrients as decay occurs. Most (60 percent) of the total phosphorus concentrations range from 0.03 mg/L to 0.08 mg/L over the period of record. Most of the total phosphorus in Falls Lake is either bound to sediment or in organic matter. DWR stopped monitoring Falls Lake for dissolved phosphorus many years ago due to detection issues.
- Increasing nutrient loading by 20 percent relative to the study period (2014 to 2018) does not significantly change chlorophyll-a concentrations especially near the dam where the historic record shows relatively low and stable concentrations, even in the 1980s when nutrient loading to the lake was highest.
- Decreasing nutrient loads by even 50 percent in addition to the load reductions already achieved will not result in Falls Lake attaining the water quality standard for chlorophyll-a as currently applied.
- The statistical/Bayesian model does not support a conclusion that chlorophyll-a concentrations vary predictably or significantly with changes in nutrient loading to Falls Lake. High nutrient loading typically occurs in response to high rainfall events that deliver high stream flows to Falls Lake. These higher flows move water through the lake quickly and reduce the amount of time for algae to grow. There are competing processes when nutrient loading and hydrologic condition are evaluated.
- The chlorophyll-a standard cannot be met as currently applied in Falls Lake.

The information developed during this evaluation process shows a reservoir that has been eutrophic since it was constructed but is meeting its designated uses. This finding is consistent with projections of tropic status that were made as part of the environmental impact assessment conducted prior to reservoir construction. While water quality and chlorophyll-a concentrations are stable, the evaluation shows a lake that is likely subject to increases in nutrient loading due to changing weather patterns and ongoing development in the watershed. Therefore, ongoing management is needed. This includes investment in water improvement projects in the watershed that address existing land use (land under active human management), land conservation, and continued implementation of the new development rule. These actions are essential components of an effective, ongoing strategy. Actions to improve watershed health and address current nutrient loading will provide protection of this important water resource.

To summarize the findings of the modeling effort and address future challenges to ensure protection of the uses of Falls Lake, the UNRBA has developed a set of recommendations for a revised nutrient management strategy called Concepts and Principles for the UNRBA Recommendations for a Revised Falls Lake Nutrient Management Strategy. The UNRBA Board of Directors unanimously approved this document and a focused set of revised consensus principles (Consensus Principles II) on September 20, 2023. The UNRBA hopes to work collaboratively with DWR as the Falls Lake rules are readopted using these two documents and the results of the modeling to guide the process. The scientific understanding of the watershed and the lake have been greatly improved by the UNRBA, its members, and the researchers at the NC Collaboratory and other organizations.

The successful completion of the UNRBA modeling efforts and development of the guiding documents for the revised rules would not have been successful without direct input from the organizations and

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stakeholders operating in the watershed. The UNRBA sincerely thanks everyone who has participated in this project as a provider of data and information, reviewer of models and reporting, facilitator of external discussions, and active participant in discussing the challenges and path forward for this unique system. The next phase of work will include additional opportunities for discussion and feedback as the State moves through its rules readoption process. The UNRBA is hopeful the process will remain open and collaborative, engaging a broad range of stakeholders to identify issues and concerns as rule language is drafted.

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Section 1

Introduction and Background

1.1 Purpose of Report

The objectives of this report are two-fold: first, to document that models developed following the approved QAPP for review under the rules and second to provide modeling results, like the scenarios, to guide the UNRBA's development of recommendations for a revised Falls Lake Nutrient Management Strategy.

This report provides a summary of the UNRBA lake modeling efforts. It documents the extensive modeling effort conducted by the UNRBA to support its recommendations for a revised Falls Lake Nutrient Management Strategy and updated Falls Lake Rules.

One purpose of this report is to document that the UNRBA lake models were developed according to the UNRBA Lake Modeling Quality Assurance Project Plan (QAPP). The Falls Lake Rules require that models used to re-examine the nutrient load reduction requirements are developed according to a state-approved modeling QAPP. Another purpose is to document application of the models to guide the UNRBA's development of recommendations for revised Falls Lake Rules.

This report is supported by more extensive and detailed appendices that discuss development of the specific models. Readers should reference these appendices when seeking more detailed descriptions of the development of the models.

1.2 Creation of Falls Lake

The Falls Lake project was authorized by Congress as part of the Flood Control Act in 1965, and the reservoir began filling in January 1983. The designated uses of Falls Lake include drinking water supply, recreation, fishing, aquatic life, and wildlife. Design and construction of the impoundment were conducted by the USACE, which continues to manage the reservoir today.

1.3 Listing for Non-Attainment of the Chlorophyll-a Standard

In 2008, the NC Department of Environmental Quality (DEQ) placed Falls Lake on the 303(d) list for non-attainment of the State's chlorophyll-a criterion (40 µg/L). Chlorophyll-a is a measure of the amount of green pigment in the water and is used as an indicator of algal productivity. While algae are an essential component of healthy aquatic ecosystems, high concentrations of algae can cause problems for water users and impact the designated uses of the water body (e.g., drinking water supply, recreation, and aquatic life). North Carolina established its chlorophyll-a standard in the 1970s under its delegated authority under Section 303(d) of the Federal Clean Water Act. Authorized states and tribes can establish their own water quality standards and assessment methodologies. Waters that do not meet a standard are placed on the 303(d) list. The state or tribe must develop a plan for the waterbody to meet the water quality standard before it can be removed from the 303(d) list. NC's instantaneous chlorophyll-a standard applies to all locations in all waterbodies unless a site-specific standard is developed and approved by the State.

NC's 303(d) assessment methodology in place in 2008 was used to place Falls Lake on the 303(d) list: https://www.deq.nc.gov/water-quality/planning/tmdl/303d/2008-methods-20100505/download. At that time, an assessment unit could be listed as not meeting the standard if greater than 10 percent of samples were greater than 40 µg/L and a minimum of 10 samples were collected. This assessment methodology

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was also applied in 2010 and 2012. In 2014, the assessment methodology was changed to include 90 percent confidence in the assessment: https://www.deq.nc.gov/energy-mineral-and-land-resources/land-quality/violations/2014/2014-303-d-lm-emc-approved-updated1-13-14/download. The 2014 assessment methodology was also used in 2016.

In 2018, the procedure was amended again, requiring a minimum of 9 samples and greater than 10 percent exceedance with greater than or equal to 90 percent confidence. If the 90 percent confidence threshold could not be met, but there were at least four excursions in newer data not previously assessed, then the assessment unit could be listed as not meeting the water quality standard and added to the 303(d). It was in 2018 that NC also added additional requirements for an assessment unit to be delisted:

> "For delisting waters, if the 2018 assessment results in greater than 10% exceedance rate with less than 90% statistical confidence and the water was on the 2016 303(d) list, the water will be delisted if there are less than 2 excursions of the criterion in newer data that have not been previously assessed. If the 2018 assessment results in less than 10% exceedance rate and the water was on the 2016 303(d) list, the water will be delisted if there is greater than 40% statistical confidence that there is less than a 10% exceedance of the criterion or if there are less than 3 excursions of the criterion in newer data that have not been previously assessed."

The 2018 method also applied in 2020 and 2022 and will be applied in 2024 with the year "2016" being replaced with the prior assessment period (i.e., 2022 303(d) list for 2024 assessment). The delisting methodology does not consider the number of samples of samples collected --- the only 1 or 2 exceedances of the criteria applies regardless of the number of samples collected, be it 10 or 100. Thus, waterbodies with extensive monitoring like Falls Lake, are unlikely to ever be deemed in attainment for a parameter like chlorophyll-a.

Adoption of the 2011 Falls Lake Nutrient Management Strategy resulted in Falls Lake being moved from the 303(d) list of impaired waters needing a total maximum daily load or management strategy (Category 5) to a 4B designation on the NC Integrated Waters Report. The 4B designation indicates that a waterbody is not meeting a standard, but a plan is in place to address non-attainment. Neither the categorization document nor the assessment document describes the assessment procedures to move a waterbody into compliance status with a management strategy (Category 1B). This report assumes the delisting requirements for a Category 5 waterbody would be followed to move Falls Lake from the 4B to the 1B category.

Pre-impoundment studies predicted that Falls Lake would be highly eutrophic, especially in the upper end of the lake (DNER 1973, USACE 1974, NCDEM 1983). These studies predicted that dissolved oxygen would be depleted in deeper portions of the lake during thermally stratified conditions. Despite the predicted high chlorophyll-a concentrations and the low dissolved oxygen concentrations in deep waters, each study indicated that the uses of Falls Lake would be met. Conditions in the lake today based on monitoring by the NC Division of Water Resources are much better than predicted. For example, the earlier studies predicted summer average chlorophyll-a concentrations of 110 µg/L while data collected from August 2014 to October 2018 show a summer average concentration of 41 µg/L in the upper part of the lake. These data are summarized in the UNRBA 2019 Monitoring Report.

Eutrophication is the progressive increase in nutrient concentrations (nitrogen and phosphorus) that can result in harmful algal blooms, fish kills, and other designated use impairments. A healthy waterbody is one in which the nutrient inputs are in balance with the aquatic biological ecosystem. Even a healthy waterbody may be at risk for progressive eutrophication under changing conditions. Most piedmont reservoirs in NC are characterized as eutrophic, however, this designation is not, by itself, a determination of progressive or stable trophic condition. For Falls Lake, the Upper Neuse River Basin Association's (UNRBA) primary goal is to develop a revised nutrient management strategy that continues to protect the designated uses of the lake and mitigate long-term risks. It is important to note that the sum total of the UNRBA's scientific evaluation of

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Falls Lake, including evaluation of the long-term monitoring record, indicates that the trophic condition of the lake is stable at this time.

1.4 The Falls Lake Nutrient Management Strategy

In 2010, the Environmental Management Commission (EMC) passed the Falls Lake Nutrient Management Strategy (the "Strategy" or the "Rules"). 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 lake (below Highway 50). The goal of Stage II is to comply with the chlorophyll-a standard everywhere in the lake. The current Strategy dictates load reduction requirements for local governments and other entities, which were based on a lake nutrient response model developed by the NC Division of Water Resources (DWR 2009). This Strategy requires very large reductions in nutrient loading to the lake.

Based on the State's fiscal analysis (DWQ 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). Implementation costs for Stage II are expected to approach and potentially exceed $1 billion for regulated entities. The reduction goals for Stage II are infeasible and beyond the limits of technology (Cardno ENTRIX 2013). For these reasons, the Upper Neuse River Basin Association (UNRBA) began planning for a reexamination of the required nutrient load reductions in 2011 in accordance with the procedures and requirements outlined in the Rules (15A NCAC 02B.0275 Section (5)(f)). This section of the rules is generally referred to as the adaptative management provision because it includes an opportunity to revise the strategy based on updated water quality information. The UNRBA supports its members in the implementation of Stage I of the management strategy, however, the large reduction goals required for Stage II are infeasible and beyond the limits of technology. This conclusion is supported based on a technical review of the Stage II provisions (see Section 3 of Framework for Reexamination of Stage II). This has been confirmed by the modeling effort and other evaluations developed during reexamination.

1.5 UNRBA Reexamination of Stage II of the Strategy

In 2016, the UNRBA initiated a Modeling and Regulatory Support project as part of the reexamination of the Falls Lake Nutrient Management Strategy. The Falls Lake Nutrient Management Strategy developed by DWR and approved by the EMC requires extremely large reductions in nutrient loading to the lake. The modeling developed by the State, used as the basis of the rules, was developed on a compressed schedule with limited data, and there is a lot of uncertainty in the required loading targets. For this reason, the rules allow for a "reexamination" of the required nutrient load reductions.

The UNRBA developed a plan for conducting the reexamination in 2013 (Cardno ENTRIX 2013). This plan included a minimum of four years of water quality monitoring in the watershed and the lake. The UNRBA began collecting water quality data in 2014. The main purpose for collecting water quality data was to support the development of revised and new watershed and lake simulation models which provide critical hydrological and water quality information to support the reexamination. The 2019 comprehensive monitoring report and access to the UNRBA data are available at https://unrba.org/resource-library.

The UNRBA followed a model selection process and selected different types of models to support the reexamination. The watershed model was developed using the Watershed Analysis Risk Management Framework (WARMF). This model predicts the mass of nutrient loading to the lake from various sources in the watershed. These loads serve as input to the lake nutrient response models which predict the growth of algae in response to nutrient loads. Because the prediction of algal growth in the lake informs the revised nutrient management strategy, the UNRBA decided to develop multiple lake nutrient response models including WARMF Lake, the Environmental Fluid Dynamics Code model (EFDC), and a statistical/Bayesian lake model. Having multiple models reduces the reliance on a single model and provides corroboration for

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the results. These model frameworks are described in Section 2. The multi-modeling approach for this project is described in the Conceptual Modeling Plan and illustrated in Figure 1-1.

Each of the three lake models vary in complexity and approach. Their configuration in terms of spatial and temporal resolution is described in Section 3. Appendix A, Appendix B, and Appendix C provide additional details on model development and performance for EFDC, WARMF Lake, and the statistical/Bayesian model, respectively.

The UNRBA study period, 2014 to 2018, corresponds to the four years of the full UNRBA Monitoring Program (August 2014 to October 2018). Because 2014 monitoring did not begin until August, 2014 is used to initialize the models and establish reasonable water level and water quality conditions in the lake before the models are calibrated. Therefore, performance statistics and visual comparisons are provided only for the calibration period (2015 to 2016) and validation period (2017 to 2018).

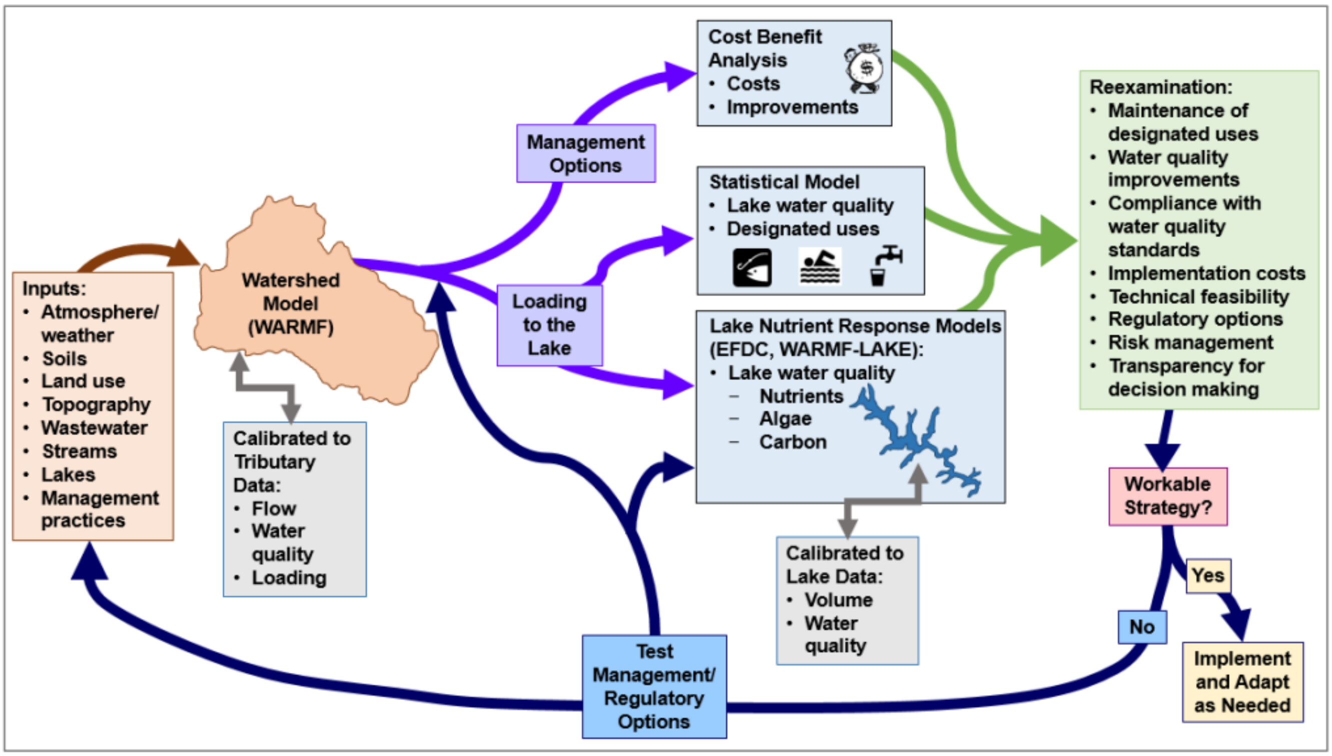

Figure 1-1. Illustration of the UNRBA Conceptual Modeling Framework

In 2016, the NC legislature formed and funded the NC Collaboratory. One of the charges of the NC Collaboratory is to study nutrient management in NC reservoirs with a focus on Jordan Lake and Falls Lake. Research on Falls Lake and the watershed began in 2019 after the Jordan Lake studies were completed. The UNRBA shared its data with the NC Collaboratory, and the two organizations identified additional studies that would be beneficial to the UNRBA modeling and the NC Collaboratory's charge. The NC Collaboratory research reports on Falls Lake are available at https://nutrients.web.unc.edu/resources/. The NC Collaboratory also funded "third-party" review of the UNRBA models. Given the importance of the models on the development of a revised nutrient management strategy and the level of scrutiny from interested parties, having this level of specialized input from the researchers and the reviewers has been invaluable.

Many organizations including the UNRBA, NC Collaboratory, US Geologic Survey (USGS), DWR, NC Wildlife Resources Commission (WRC), NC State University Center for Applied Aquatic Ecology (CAAE), Cities of Durham and Raleigh, US Army Corps of Engineers (USACE), US Forest Service (USFS), and US Environmental Protection

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Agency (EPA) have conducted studies on Falls Lake or its tributaries that informed development of the three UNRBA lake models. The UNRBA has invested over $10 million in the monitoring and modeling studies of Falls Lake and its watershed. Section 4 of the main lake modeling report summarizes the extensive data sets used to develop these models.

During development of the WARMF Lake and EFDC models for Falls Lake, the modeling team, the UNRBA management team, modeling staff from the DWR, the “third-party” reviewers funded by the NC Collaboratory, and other interested subject matter experts met several times to review the lake model calibrations. Discussions focused on chlorophyll-a concentrations, algal group data collected by DWR, and sediment nutrient release studies conducted on Falls Lake. In response to this input, the UNRBA provided additional funds to further test the models, improve calibration in reference to these studies, and document these efforts. Additional documentation of these efforts is included in Appendix A and Appendix D.

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

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

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

This report summarizes the development of the three models for Falls Lake. Model-specific appendices provide more technical information on the development and calibration of each model.

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Section 2

Overview of Model Frameworks and Application

To provide an expanded and more complete understanding of the watershed and the lake as an integrated system, the UNRBA developed one watershed model and lake models to support the reexamination of Stage II of the Falls Lake Nutrient Management Strategy. The models focus on hydrology, nutrients, algae growth, chlorophyll-a, and total organic carbon and are used to evaluate potential management strategies and impacts to water quality in Falls Lake.

Like many mechanistic (process-based) lake water quality models, the underlying EFDC and WARMF Lake model frameworks were developed to simulate only three groups of algae: cyanobacteria (i.e., blue-green algae), diatoms, and green/other algae. These models simulate the growth of algae based on the water temperature and the availability of nutrients and light using a series of kinetic equations. Based on algae data collected by DWR at three locations in Falls Lake, other algal groups often dominate the system. The modeling team considered modifications to the models to simulate more than three algal groups, but insufficient information was available in the literature to populate the numerous values required by the models, so the decision was made with the subject matter experts, DWR, and the UNRBA Modeling and Regulatory Support Workgroup (MRSW) to continue the modeling with three algal groups. Model modification was not practical or technically supportable.

The models simulate the amount of nutrients and carbon stored in the algae. The carbon is converted to chlorophyll-a using a ratio assigned to each algal group. This simulated concentration of chlorophyll-a is then compared to water quality observations. During model calibration, kinetic constants and algal preferences for light and nutrients are adjusted to better match chlorophyll-a observations. After model calibration, changes in simulated chlorophyll-a can be compared across model scenarios to understand the impacts of system changes. While the carbon to chlorophyll-a ratios can be set differently for each simulated algal group, the ratio cannot be adjusted within an algal group to reflect varying environmental conditions or dominance of different algal species within a group. While this is a limitation, it is standard practice for these types of models.

Appendix D to the main report documents the discussions held with the subject matter experts and DWR modeling staff. The analyses regarding the dominant groups of algae in Falls Lake and the decision to use the "green/other" group to simulate algae that are neither diatoms nor cyanobacteria is included as well.

The UNRBA modeling contractors worked with the MRSW to select the modeling packages for the reexamination. Selection of the modeling packages was approved by the UNRBA Path Forward Committee (PFC) in December 2016. Documentation of this process is available in the Evaluation and Selection of Model Packages for the UNRBA Modeling and Regulatory Support Project.

Two mechanistic model frameworks were selected for the UNRBA Falls Lake study: the WARMF watershed and lake model and the EFDC lake model. Both are EPA-approved and peer-reviewed water quality modeling tools that have been successfully applied for numerous nutrient allocation studies nationwide. Both modeling frameworks were previously used by DWR for this lake and watershed, but the watershed and lake models were not linked for development of the Falls Lake Rules. Rather, DWR used the EFDC model to establish the Falls Lake Nutrient Management Strategy and required load reductions. DWR's loading was

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calculated based on the data available from the lake's main tributaries. The two models are linked in the UNRBA application to better understand how watershed nutrient loads and processes affect lake water quality. This linkage was essential to evaluate different watershed management actions and their impact on lake water quality. This scenario-based approach provided a comprehensive consideration of a broad range of watershed conditions and the resultant lake response. The UNRBA also developed a statistical/Bayesian lake model using empirical, probabilistic, and Bayesian techniques. This model links flow and nutrient loading to Falls Lake to lake water quality and user satisfaction with designated uses. This multi-model approach provides the following benefits; for more information, see Section 10

- Avoids reliance on a single model and uses three independent lake models to inform decision making
- Improves the ability to answer a range of questions raised by stakeholders that a single model would not be capable of

Development and calibration of the watershed and lake models is guided by the UNRBA Modeling Quality Assurance Project Plan (QAPP). The QAPP was approved by DWR in April 2018. The MRSW oversaw development of the WARMF watershed and lake model and the EFDC lake model. This workgroup is comprised of UNRBA members as well as DWR modeling group staff, US Forest Service researchers, NC Collaboratory researchers, representatives of agriculture, environmental advocacy groups, and state agencies including the NC Departments of Transportation (DOT), and Agriculture and Consumer Services (NCDA&CS). The Technical Advisors Workgroup (TAW) oversaw development of the UNRBA statistical/Bayesian lake model. This workgroup is comprised of UNRBA members with specific representation by organizations that manage the uses of Falls Lake (e.g., City of Raleigh water utility managers, Wake County Parks and Recreation) or represent a large user group (Triangle Fly Fishers). Both workgroups report to the PFC at open meetings which are also attended by each of the organizations listed above. To provide structure for making decisions throughout the reexamination process, the UNRBA developed the UNRBA Decision Framework. Status reports and decisions made by the MRSW, PFC, and TAW are available on the UNRBA meetings website; workgroup discussions and decisions are noted throughout this report.

The UNRBA Modeling QAPP listed several goals for this project. Table 2-1 lists the project goals and applicable model. Analysis of historic water quality monitoring data as a separate "model" of the system is also included. Similarly, information from the TAW provides a critical understanding of how water quality affects the management of Falls Lake in relation to its uses.

Table 2-1. Project Goals from the UNRBA Modeling QAPP and Appliable Model

Project Goal	Applicable Model or Input
Estimating nutrient, carbon, sediment, and chlorophyll-a loading to Falls Lake	WARMF Watershed Data Analysis of Historic Record
Evaluating the impacts of management strategies on water quality	WARMF Lake EFDC
Revising the lake response and watershed models using data that was not available at the time DWR conducted their modeling to develop the Falls Lake Nutrient Management Strategy;	WARMF Watershed EFDC
Understanding how changes in lake water quality affect the designated uses of the lake;	Information from the Technical Advisors Workgroup Statistical/Bayesian
Evaluating management strategies in the lake and watershed to determine the impacts to lake water quality and designated uses;	WARMF Watershed WARMF Lake EFDC Statistical/Bayesian

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Table 2-1. Project Goals from the UNRBA Modeling QAPP and Appliable Model	
Project Goal	**Applicable Model or Input**
Examining alternative chlorophyll-a criteria that include duration, frequency, spatial, and temporal components consistent with the chlorophyll-a criteria approved by EPA for states with more recent standards (North Carolina's standard was developed in the 1970s).	Data Analysis of Historic Record Statistical/Bayesian

The watershed (WARMF) and lake (WARMF, EFDC, and statistical) model frameworks developed for this project were used to evaluate various management approaches to improving and protecting water quality conditions in the lake, including a range of selected pollutant load reduction scenarios. The watershed model provides insight about the relative sources of loading to Falls Lake and the importance of hydrologic conditions on loading. The lake models and data collected in Falls Lake show the resilience of the lake in maintaining a balanced water quality and biologic regime. The scientific understanding of the watershed and the lake have been greatly improved by the UNRBA, its members, and the researchers at the NC Collaboratory.

Additional information about the application of the watershed and three lake models to the project goals is provided in Section 10.3.

2.1 EFDC

The EFDC model was selected as the complex, process-based lake nutrient response model to be used for this study. EFDC was used to develop a hydrodynamic, sediment transport, water quality, and sediment diagenesis model of Falls Lake. EFDC is a peer-reviewed and EPA-approved surface water model that has been applied for hundreds of TMDL and water quality management studies nationwide and worldwide. EFDC_Explorer (Craig 2012) was used to facilitate processing of data for model setup and extraction of model results for visualization of time series plots, vertical profiles, longitudinal transects, animated maps, calculation of output variables, and calculation of model performance statistics. EFDC was developed using output from the WARMF watershed model. Additional information about the EFDC model framework is provided in Appendix A.

2.2 WARMF Lake

WARMF was selected as the modeling tool for development of both a watershed and lake model for Falls Lake. WARMF is an EPA-approved and peer-reviewed model that has been used nationwide for water quality assessment and Total Maximum Daily Load (TMDL) development. The representations of watershed processes within WARMF are comprehensive and based on fundamental principles of physics and chemistry. It is a continuous, lumped parameter, watershed–scale model that simulates hydrology and the movement and transformation of sediment, nutrients, and other constituents on pervious and impervious surfaces, in soil profiles, and within streams and impoundments. The WARMF watershed model was developed and calibrated to focus on the simulation of streamflow, temperature, chlorophyll-a, sediment, nutrient, and carbon. WARMF watershed simulation results were used as inputs to both WARMF Lake and EFDC.

The WARMF Lake model is included as part of the complete WARMF model application and is internally linked to the WARMF watershed model. The WARMF Lake model is a moderately complex, pseudo-2D mechanistic model that simulates vertical stratification and allows for subdivision of the lake body into multiple linked segments. The model performs a mass balance and simulates chemical/physical processes within each vertical layer of a lake segment. WARMF Lake was used to simulate water quality in Falls Lake as well as in seven smaller impoundments in the watershed. Additional information about the WARMF model framework is provided in Appendix B.

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2.3 Statistical/Bayesian

The statistical/Bayesian model for Falls Lake was designed to incorporate many types of data, information, and expert knowledge into a structured decision-making tool. It was developed "from scratch" and does not rely on an existing model framework like the other two models. The model is based on the data itself and as such is not a mechanistic (process-based) model like EFDC or WARMF-Lake. The project-specific tool has been constructed using the open-source R programming language and Netica software (https://www.norsys.com/netica.html).

Figure 2-1 illustrates the structure of tool in terms of inputs and drivers on the left, in-lake processes and water quality in the middle, and outputs on the right. Additional information about the statistical/Bayesian model for Falls Lake is provided in Appendix C.

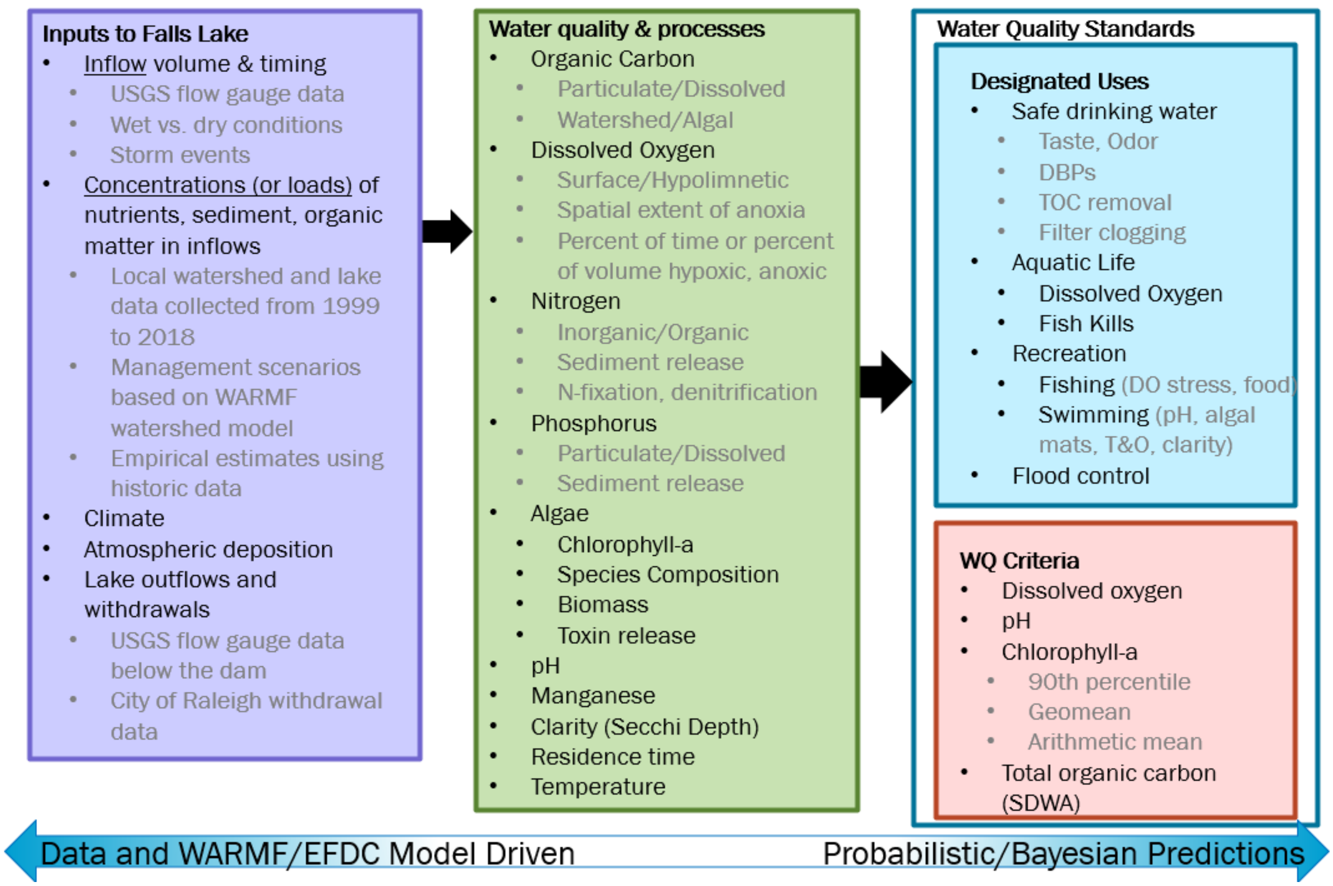

Figure 2-1. Structure for the Falls Lake Statistical/Bayesian Model

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Section 3

Falls Lake Model Configurations

Models divide a waterbody into discrete grid cells or segment(s) to perform model calculations. Some models like EFDC are highly refined and divide the lake into hundreds of grid cells for which calculations are made on the scale of several seconds to a couple of minutes. Other models like WARMF Lake are more-simplified representations that define several lake segments and perform their calculations on hourly to daily time steps. Empirical models like the UNRBA statistical/Bayesian model tend to use longer time frames, like annual or seasonal conditions, and may evaluate individual stations or groups of stations within segments. The UNRBA selected a multi-pronged modeling approach to avoid reliance on a single model and to develop a range of tools for planning and decision making.

The Falls Lake EFDC model developed by Dynamic Solutions, LLC. simulates ten 10 vertical water column layers, two sediment layers, and 862 grid cells with a time step a few seconds to a couple of minutes. The MRSW approved the EFDC model configuration on August 4, 2020.

The Falls Lake WARMF model developed by Systech Water Resources, LLC divides the main stem of the lake into six segments with the seven lake arms simulated separately. The Falls Lake WARMF model operates on a 6-hour time step and is directly linked to the Falls Lake WARMF watershed model. The watershed model also provides input to the EFDC model on a 6-hour time step. However, the lake calculations for EFDC occur much more frequently. The MRSW approved the WARMF Lake model configuration on November 3, 2020.

The UNRBA statistical/Bayesian model evaluates three lake segments: upstream of Fish Dam/Cheek Road, between Fish Dam/Cheek Road and downstream of Highway 50, and downstream of Highway 50. Not all datasets are available for all three segments across the period of record. The TAW approved the UNRBA statistical/Bayesian model segmentation on July 12, 2022, during their discussion of available datasets. The TAW acknowledged not all data were available for each of the three segments. The TAW discussed that combining the upper segment upstream of Interstate 85 and the middle segment between Interstate 85 and Highway 50 may be needed for some components of the model. As part of his UNRBA contract, UNRBA subject matter expert Dr. Marty Lebo evaluated water quality data from Falls Lake. Based on his analysis, moving the upper segment boundary to Fish Dam/Cheek Road would be most consistent with the morphologic, lake sediment depth, and lake water quality data. Moving this boundary from Interstate 85 to Fish Dam/Cheek Road also resolved the issue with missing data upstream of Interstate 85. This modification to the segment boundaries was approved by the Path Forward Committee at their November 2023 PFC meeting.

Configuration of the lake models relied heavily on the bathymetric mapping conducted by the UNRBA during its monitoring program. Development of this data set is described in the UNRBA 2019 Monitoring Report, and the map is shown in Figure 3-1 of this report. The spatial resolution, simulation period, and time steps for each model are described below.

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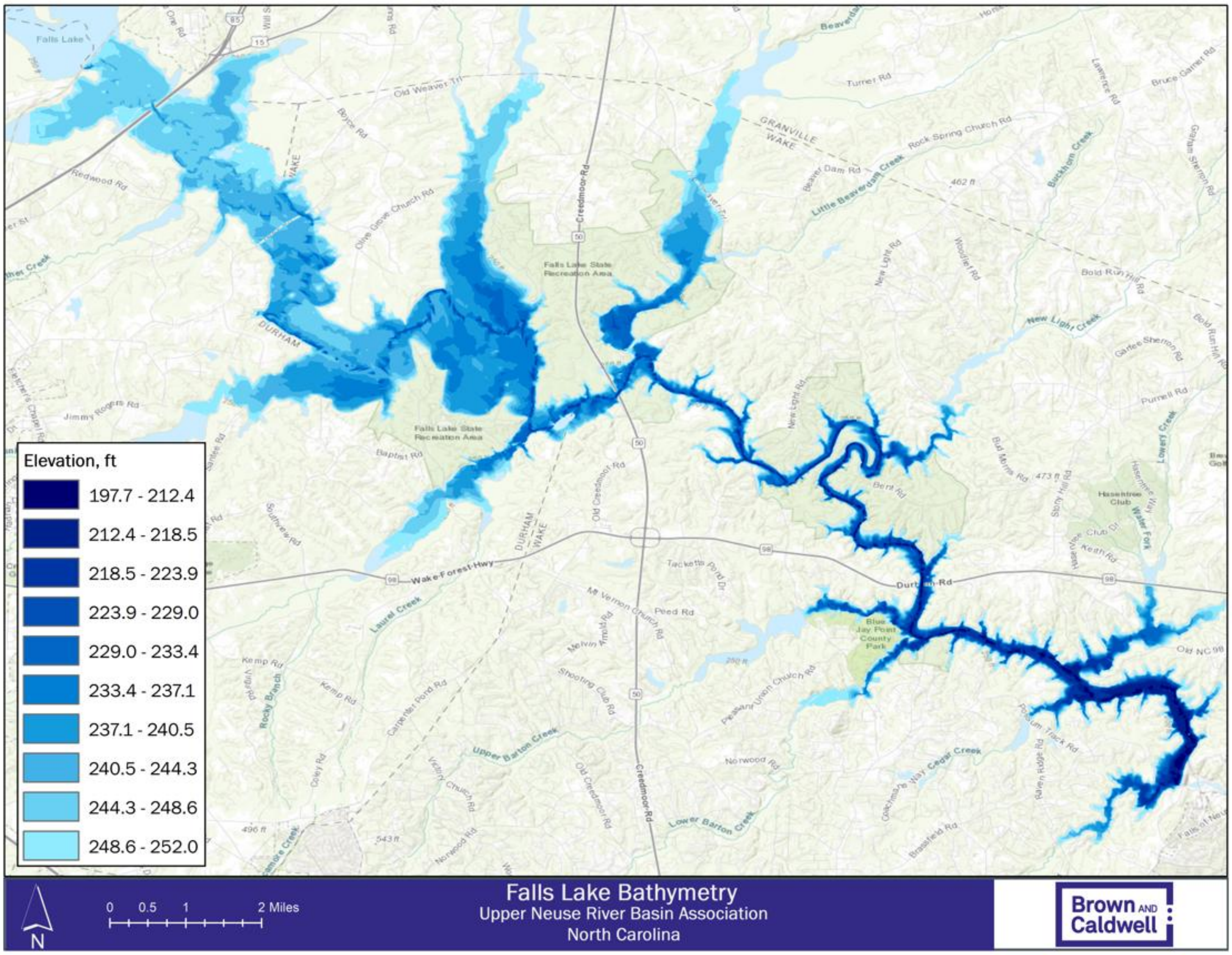

Figure 3-1. Falls Lake Bathymetry Data Developed by UNRBA

3.1 UNRBA Falls Lake EFDC

The EFDC model was selected by the UNRBA as the hydrodynamic/water quality modeling tool for Falls Lake. This model is a complex tool that performs calculations on the scale of several seconds to a couple of minutes. The UNRBA Falls Lake EFDC model was developed to correspond with the UNRBA monitoring period (2015 to 2018) with 2014 serving as the initialization year. Simulated inputs to the lake from the watershed (stream flows and sediment, nutrients, etc.) are provided by the UNRBA WARMF watershed model for 2014 to 2018.

EFDC requires development of a model grid to perform the calculations for the lake model. A Sigma-Zed grid with 862 horizontal grid cells was developed to represent Falls Lake. Each horizontal grid cell is further separated (discretized) into a number of vertical layers that represent the water column. The Sigma-Zed grid allows for the number of layers to vary over the model domain and maintains a uniform thickness for each layer. The number of layers assigned to each cell remains constant throughout the simulation, though the thickness of each layer varies in time to accommodate the time varying water depths. This grid is more computationally efficient than the standard EFDC Sigma grid (in which the number of layers stays the same over the model domain, but the thickness varies with depth). Each cell in the Sigma-Zed Falls Lake grid has

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two sediment layers, and up to ten water column layers. The following data were used in development of the model grid and bathymetry interpolation:

- Shoreline and road shape files including numerous bridges and causeways in the Falls Lake system downloaded from National Hydrography Dataset (NHD) and Census Tiger Roads
- Bathymetry data (Falls_Lake_2017_ASCII_HF_DTM_10_ft_Grid.txt) resulting from the UNRBA bathymetric survey of Falls Lake.

The model grid was designed to follow the lake shoreline and represent causeway flow restrictions. The grid is comprised of 862 horizontal cells as shown in Figure 3-2. Spatial resolution of the model grid was chosen based on the following two primary considerations:

- The model grid reasonably captures variation of bathymetry, water level, sinuosity, and shoreline; and
- Computing time for a one-year, hydrodynamic, temperature, sediment, and water quality simulation is less than 12 hours to allow a multiple-year simulation to be completed within a reasonable time.

The EFDC lake modeling grid was presented to stakeholders at the October 2018 Workshop. Slight modifications were made in early 2019 to extend the model grid and capture flood levels. The MRSW approved the EFDC model configuration on August 4, 2020.

Compared to the DWR's EFDC model grid (shown in Figure 3-3), the new enhanced model grid has the following advantages:

- Greater spatial resolution to capture bathymetric variation
- A more accurate quantification of the reservoir stage – volumetric storage relationship, as shown in Figure 3-4, to improve simulation of lake residence time
- Improved grid cell alignments with the causeway constrictions, as shown in Figure 3-5 as an example, to better simulate flow restrictions.

Bathymetry data obtained from the UNRBA bathymetric survey of Falls Lake was used to assign the bottom elevation for each grid cell. Averages of these point measurements were assigned to the model grid cells where data were available. The accuracy and scope of the modeling effort relative to grid development was greatly aided by the bathymetric study. The Inverse Distance Weighting (IDW)[1] method was used for bathymetry interpolation for model grid cells without data (empty cells shown on Figure 3-6). It should be noted that accuracy of the extrapolated bottom elevations for those upper lake shallow cells as shown in Figure 3-7 is unknown. Bottom elevations of the model grid cells for the causeway flow restrictions were reviewed and confirmed with the bathymetry data.

Figure 3-7 shows the locations of the old river channel and UNRBA/Alperin sediment core samples in relation to the model grid for reference. For more information regarding the sediment core sampling see the UNRBA website (https://unrba.org/resource-library).

Additional information regarding the model configuration for EFDC is provided in Appendix A.

[1] http://pro.arcgis.com/en/pro-app/help/analysis/geostatistical-analyst/how-inverse-distance-weighted-interpolation-works.htm

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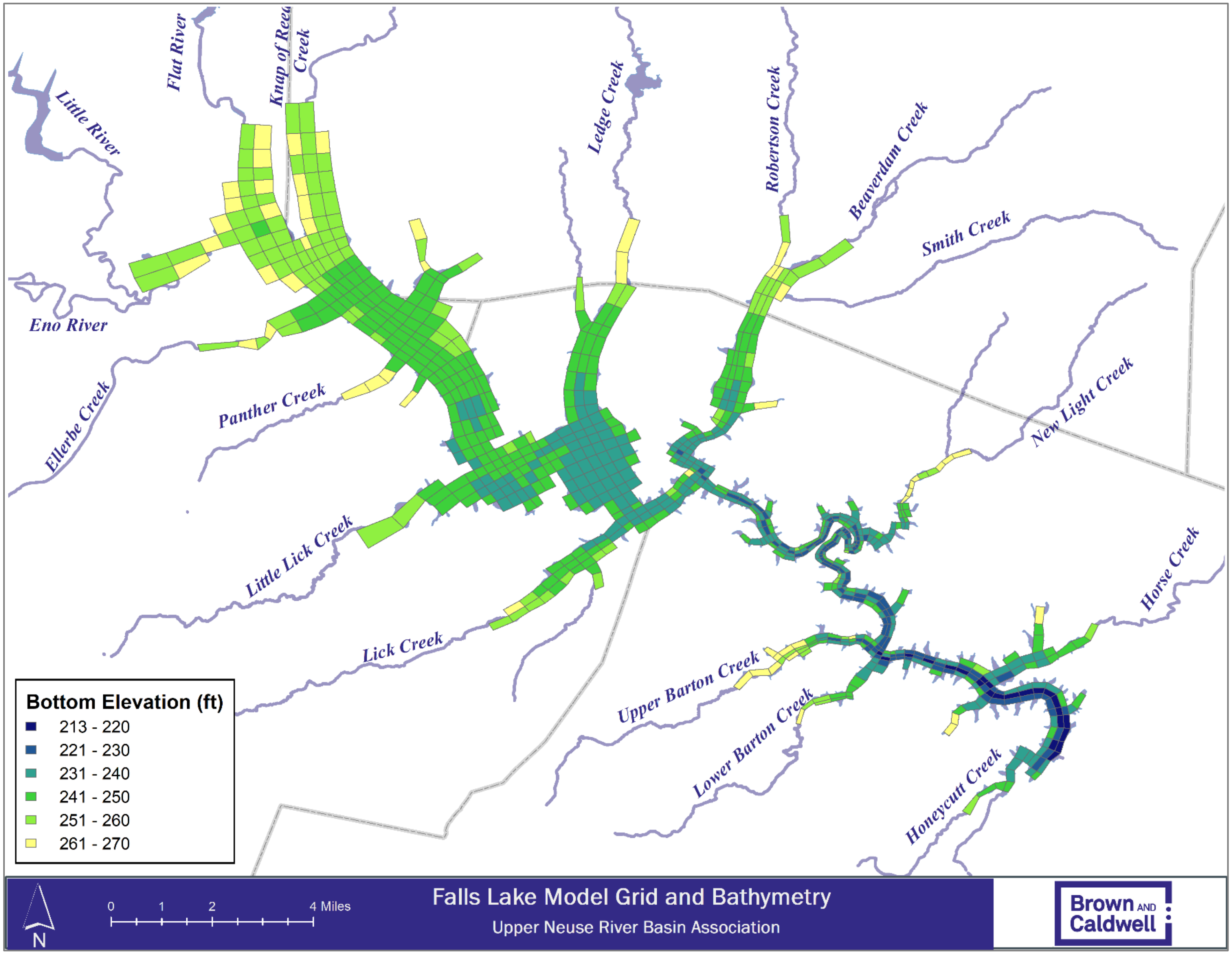

Figure 3-2. UNRBA Falls Lake EFDC Model Grid with Simulated Bathymetry

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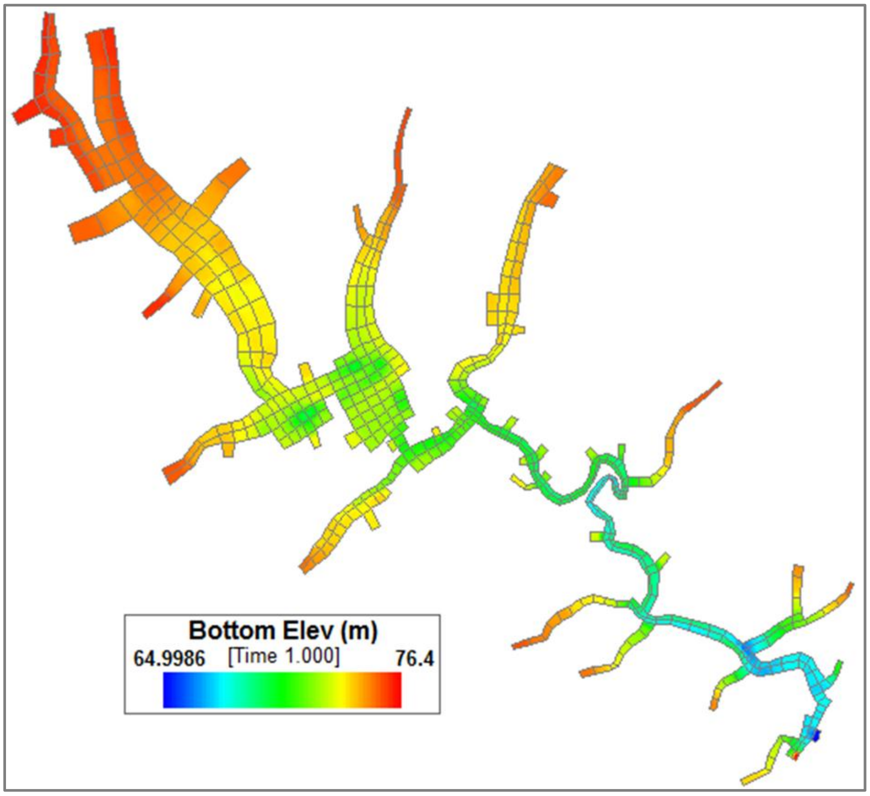

Figure 3-3. DWR Falls Lake EFDC Model Grid with Simulated Bathymetry

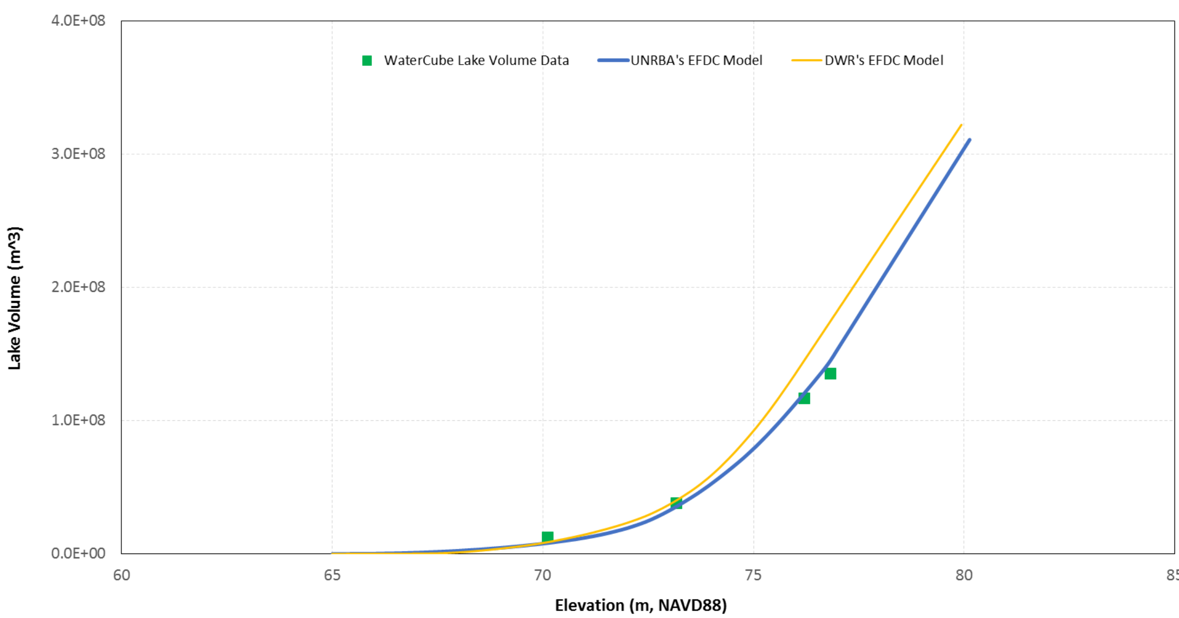

Figure 3-4. Stage-Volume Relationship of the Model Grid versus Measured Stage-Volume of the Lake

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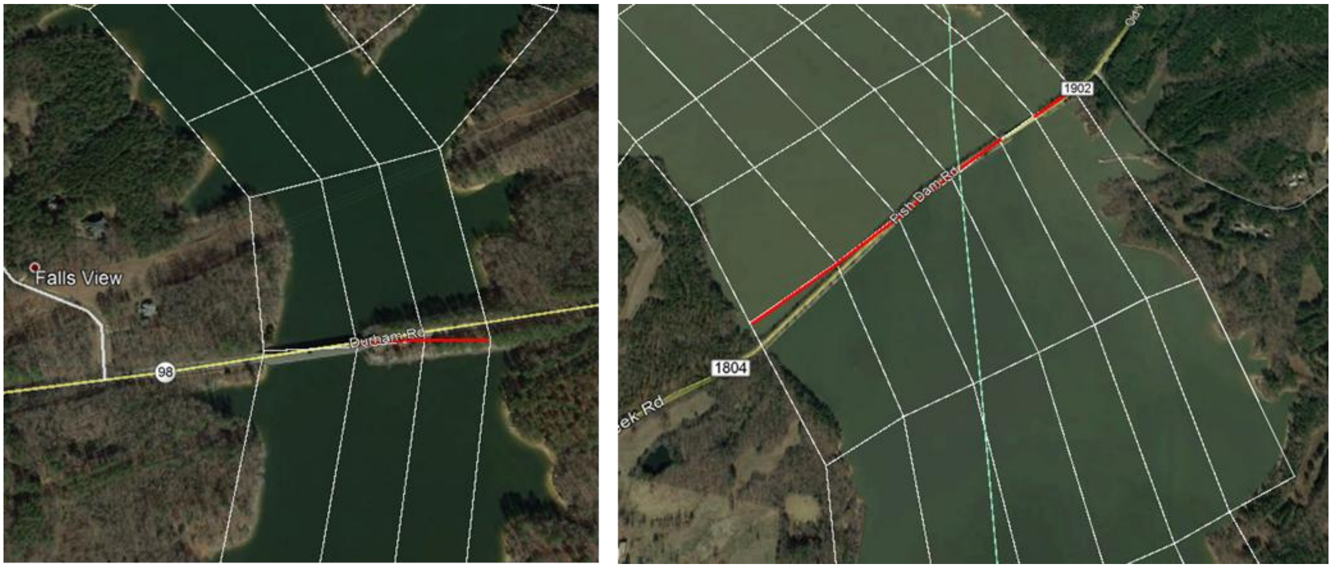

Figure 3-5. Comparison of the UNRBA Model Grid Alignments at Two Causeway Constrictions (Red Lines Represent Where Flow is Blocked by the Causeway)

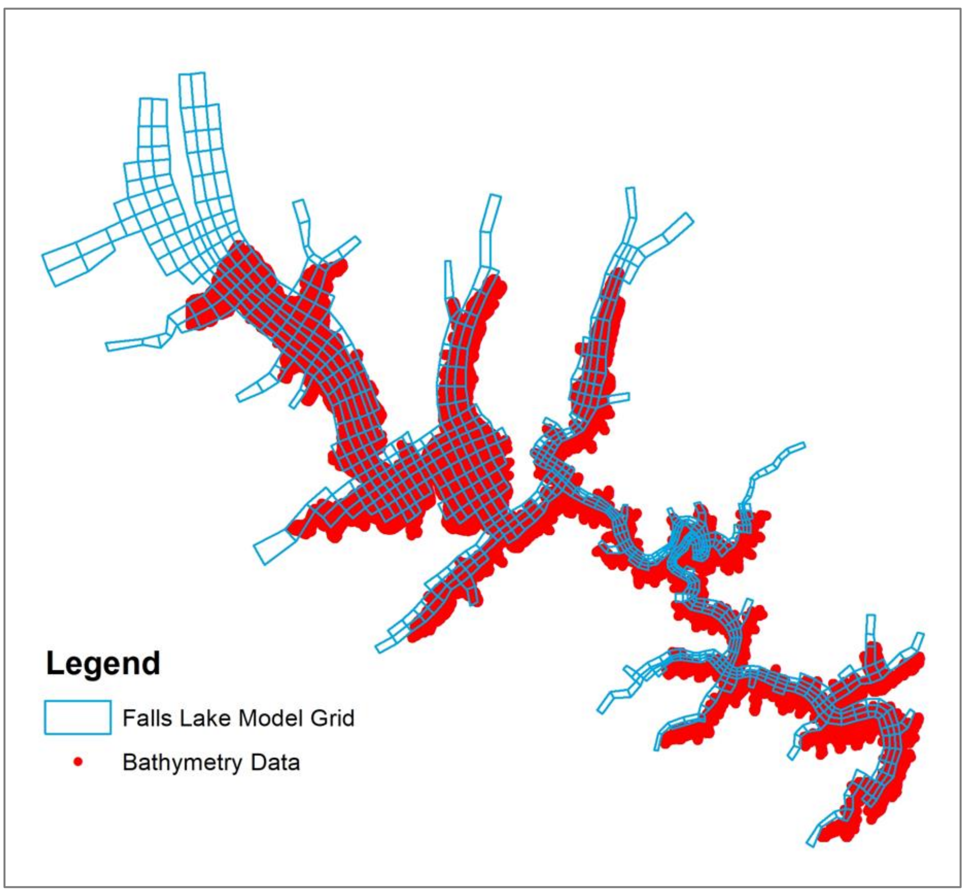

Figure 3-6. Falls Lake model grid and locations of bathymetry data points

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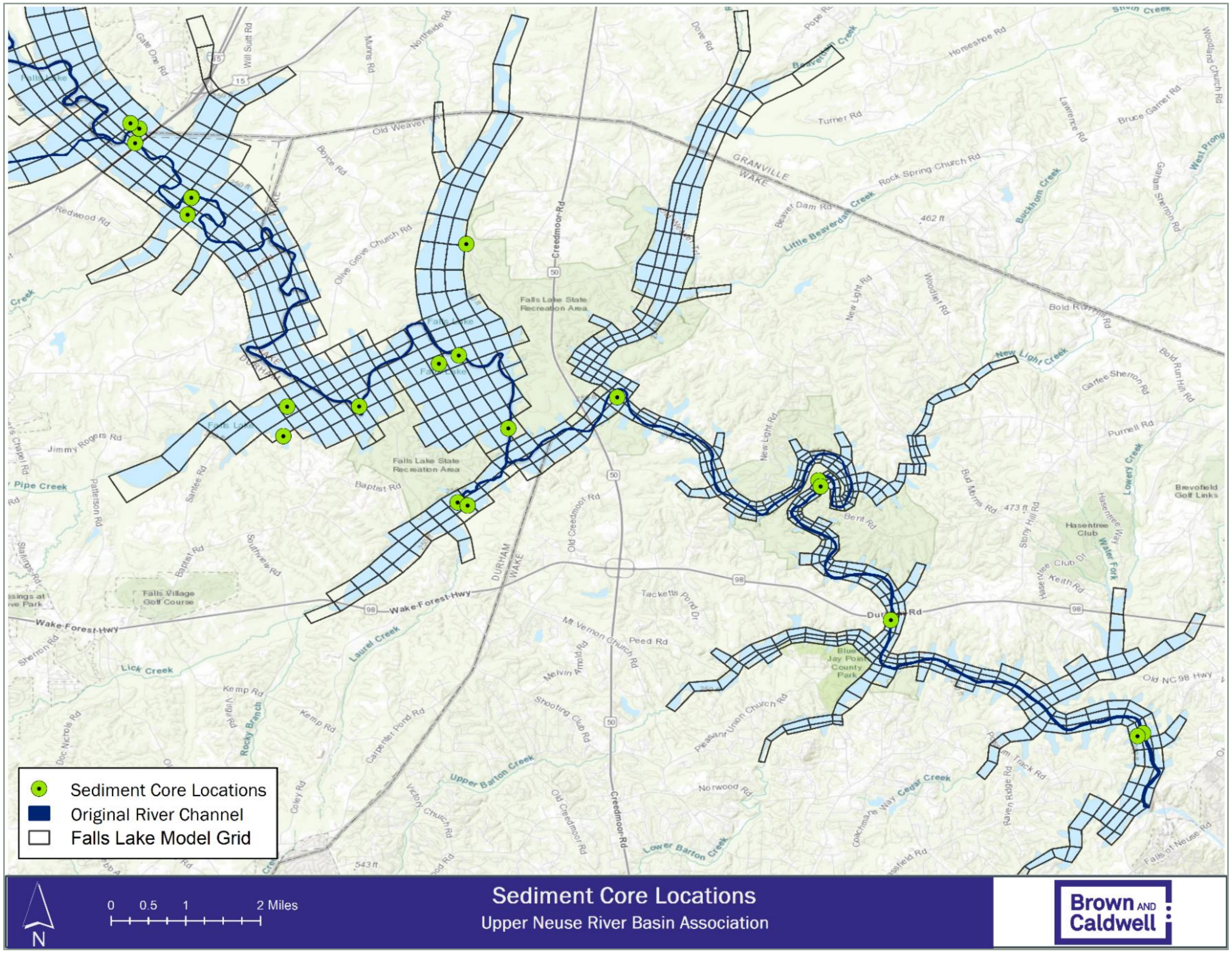

Figure 3-7. Locations of the old Neuse River channel and sediment core samples

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Model coefficients and parameters for the EFDC water quality model are defined for four water quality "zones" (Figure 3-8). These zones allow the model to simulate varying conditions associated with lake morphometry, geology, water movement and their effects on water column and algal kinetics. Zone 1 includes the portion of the lake above I-85, Zone 2 includes the portion of the lake between I-85 and Hwy 50, Zone 3 includes the portion of the lake below Hwy 50 to the dam, and Zone 4 includes the embayment arms of the lake. Kinetic coefficients determined for calibration of the algae model are presented in Appendix A.

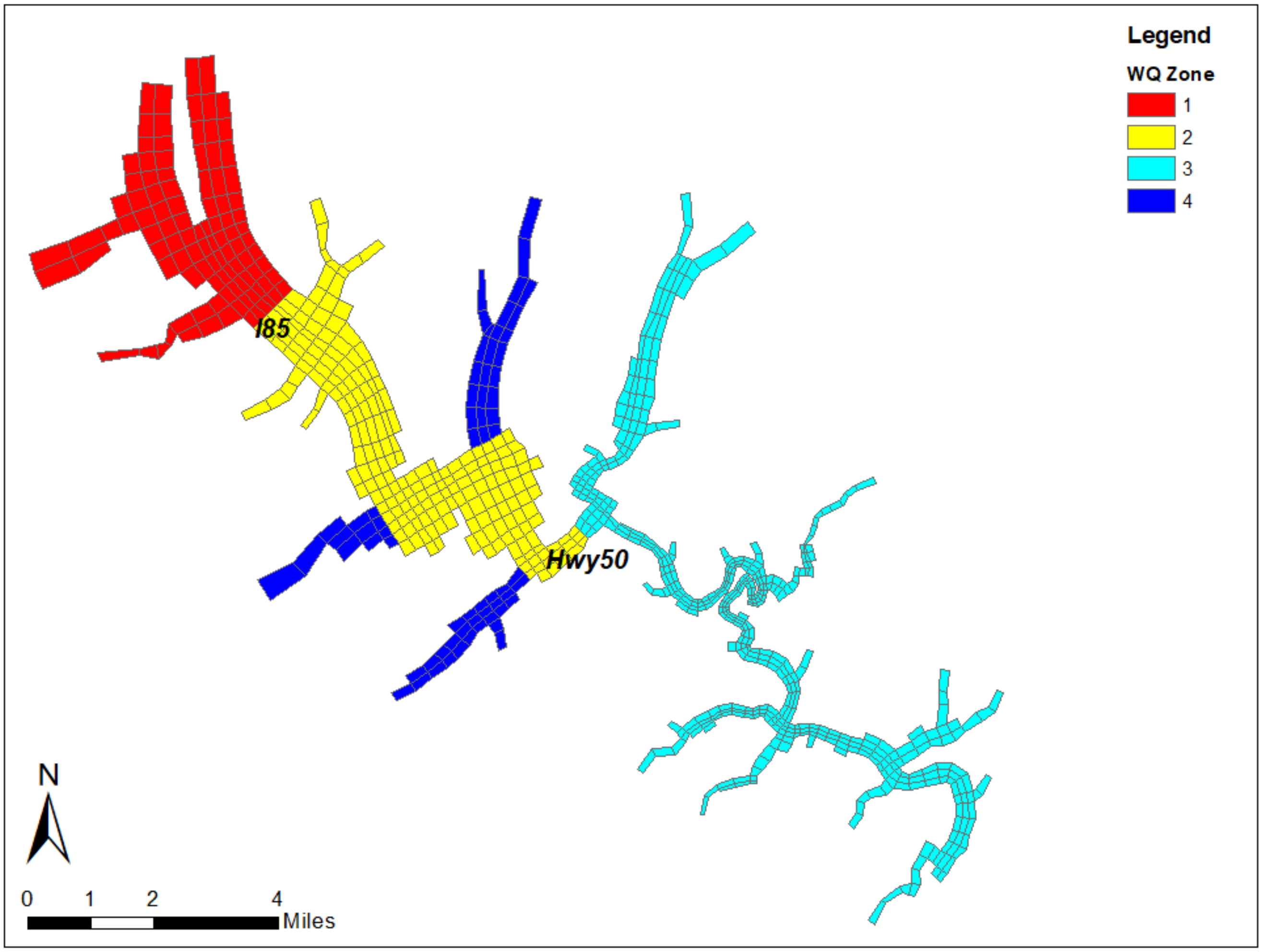

Figure 3-8. Spatial Water Column and Algae Kinetic Zones Defined for Falls Lake; Zone 1: above I-85, Zone 2: between I-85 and Hwy 50, Zone 3: below Hwy 50, Zone 4: embayment arms of the lake

The EFDC sediment diagenesis model requires specification of initial conditions for the content of particulate organic matter (as carbon, nitrogen, and phosphorus) and porewater concentrations of inorganic nutrients (as ammonia, nitrate, and phosphate). Setting the initial conditions for the sediment bed is an important step in the lake modeling process as it establishes the starting point from which the sediment diagenesis model performs its calculations and moves toward a dynamic equilibrium. A UNRBA special study led by Dr. Marc Alperin (University of North Carolina-Chapel Hill) was conducted during June and July 2015 to evaluate sediment bed conditions in Falls Lake (Alperin, 2018). The study looked at sediment cores collected from more than twenty (20) locations along the lake, as shown in Figure 3-7, and provides information on the characteristics of the lake sediments. The initial sediment bed organic material concentrations at each cell for the sediment diagenesis module were calculated by linear interpolation using

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the average sediment thickness at each cell and organic material concentration data collected at fifteen (15) locations by the UNRBA. This analysis resulted in setting the initial organic material concentrations for 15 zones in Falls Lake (Figure 3-9).

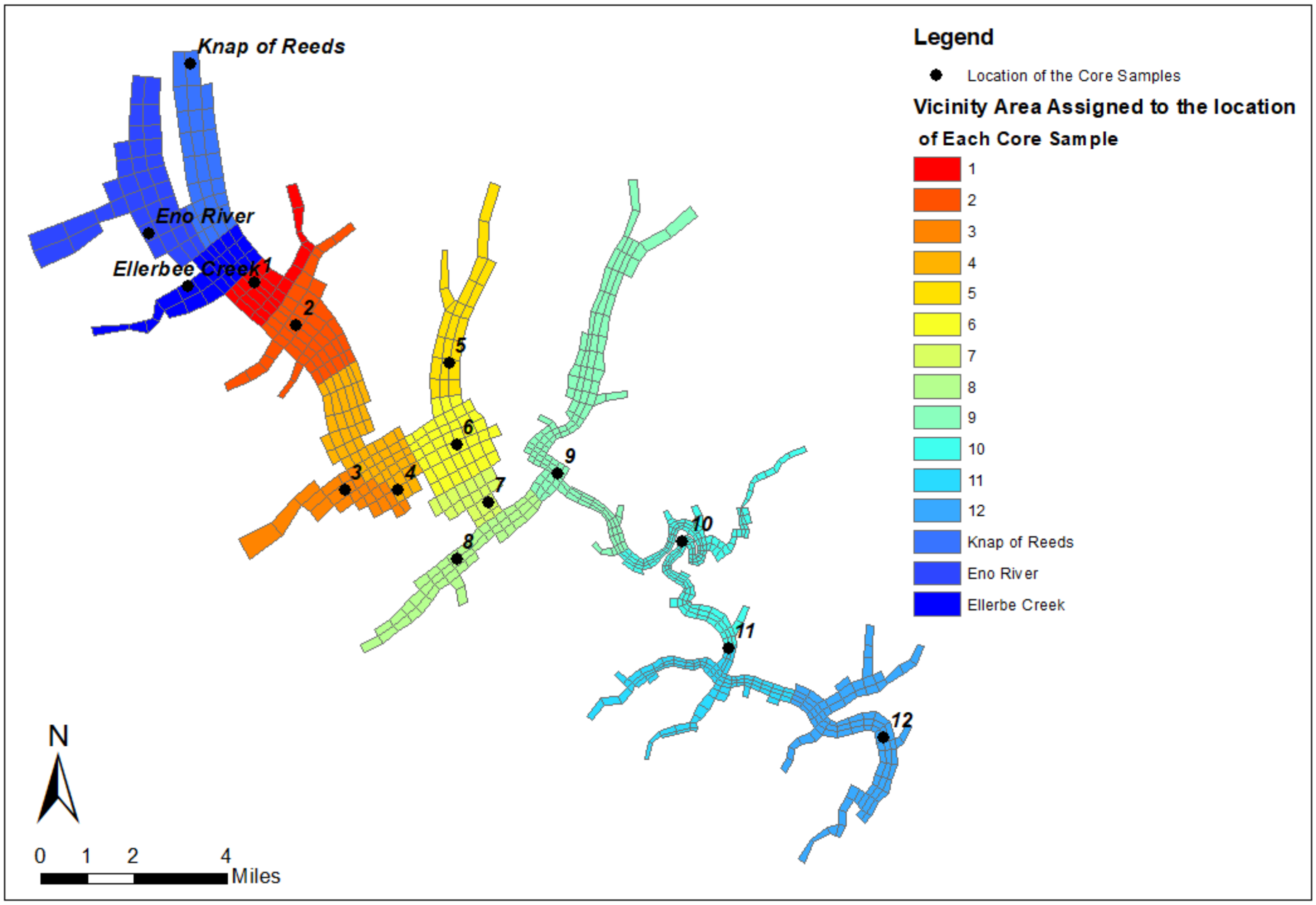

Figure 3-9. Location of the UNRBA/Alperin Core Samples and the Vicinity Area Assigned to the Location of each Core Sample

3.2 Falls Lake WARMF

The WARMF Lake model was selected by the UNRBA as a simpler, segment-based model which generally allows for shorter model run times. The water column for each segment is dynamically divided by the model (the user does not specify the number of layers) into a maximum of 40 layers, with fewer layers utilized when the lake level falls, or in shallow regions. Each layer is approximately 0.75 meters thick. Water can move from one segment into adjacent segments via advection but cannot move in different directions within a model timestep. The MRSW decided that modifying WARMF Lake to simulate bi-directional flow within a segment was not in the scope of the project and would be costly in terms of schedule and budget. The Falls Lake EFDC model provides hydrodynamic simulations that do account for bi-directional flow.

The model is directly linked to the WARMF watershed model and operates on a 6-hour time step. As with the UNRBA Falls Lake EFDC model, WARMF Lake simulates 2015 to 2018 with 2014 serving as an initialization year. Meteorological inputs for WARMF Lake are based on the WARMF watershed model and are documented in the UNRBA Watershed Model Report (BC and Systech Water Resources 2023).

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During meetings with the MRSW, the modeling team provided data summaries and recommendations for segmentation of Falls Lake. Based on feedback received during these meetings from the MRSW, DWR staff, and NC Collaboratory-funded “third-party” reviewers, the main part of Falls Lake was split at major constrictions to form six mainstem segments (four above Highway 50 and two below) (Figure 3-10). Eight lake arms were also defined to simulate these areas. The lake segmentation and the goal of calibrating each segment to stations located near the downstream end was approved by the MRSW during their November 2020 meeting. The purpose of calibrating the segments to the downstream end is to accurately represent transport of material from one segment to the next and to simulate water quality near the City of Raleigh drinking water intake.

The lake segmentation and the goal of calibrating each segment to stations located near the downstream end was approved by the MRSW during their November 2020 meeting.

The bathymetry of the Falls Lake WARMF modeling segments was developed using the UNRBA bathymetric survey of Falls Lake and the shoreline and road shape files as described for the EFDC model in Section 3.1. Appendix B provides the stage area curves for the mainstem segments and lake arms.

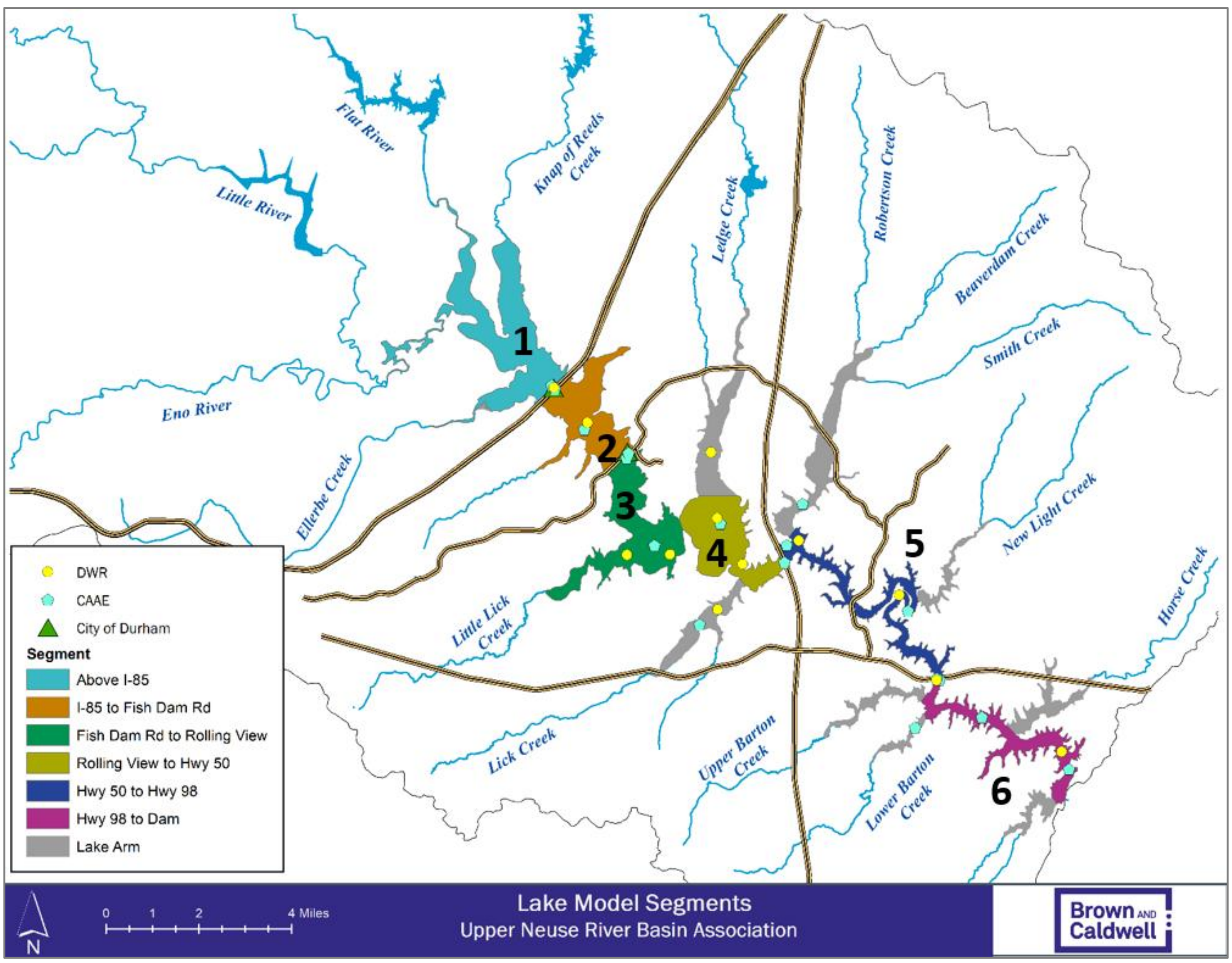

Figure 3-10. WARMF Lake Modeling Segments

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3.3 Falls Lake Statistical/Bayesian Model

3.3.1 Spatial and Temporal Configuration

The statistical/Bayesian model of Falls Lake represents the lake as three segments. The upper most segment includes the lake upstream of Fish Dam/Cheek Road, the middle segment is between Fish Dam/Cheek Road and just downstream of Highway 50, and the lower segment is downstream of Highway 50 to the dam (Figure 3-11). These segments have unique geometries with the upper and middle segments being relatively shallow and wide and the lower segment being narrower and deeper. The volume of Falls Lake is approximately equivalent upstream and downstream of Highway 50 (BC 2019). Data collected from Beaverdam Lake are not included in the Falls Lake statistical/Bayesian model because it is considered a separate waterbody with its own water quality assessment.

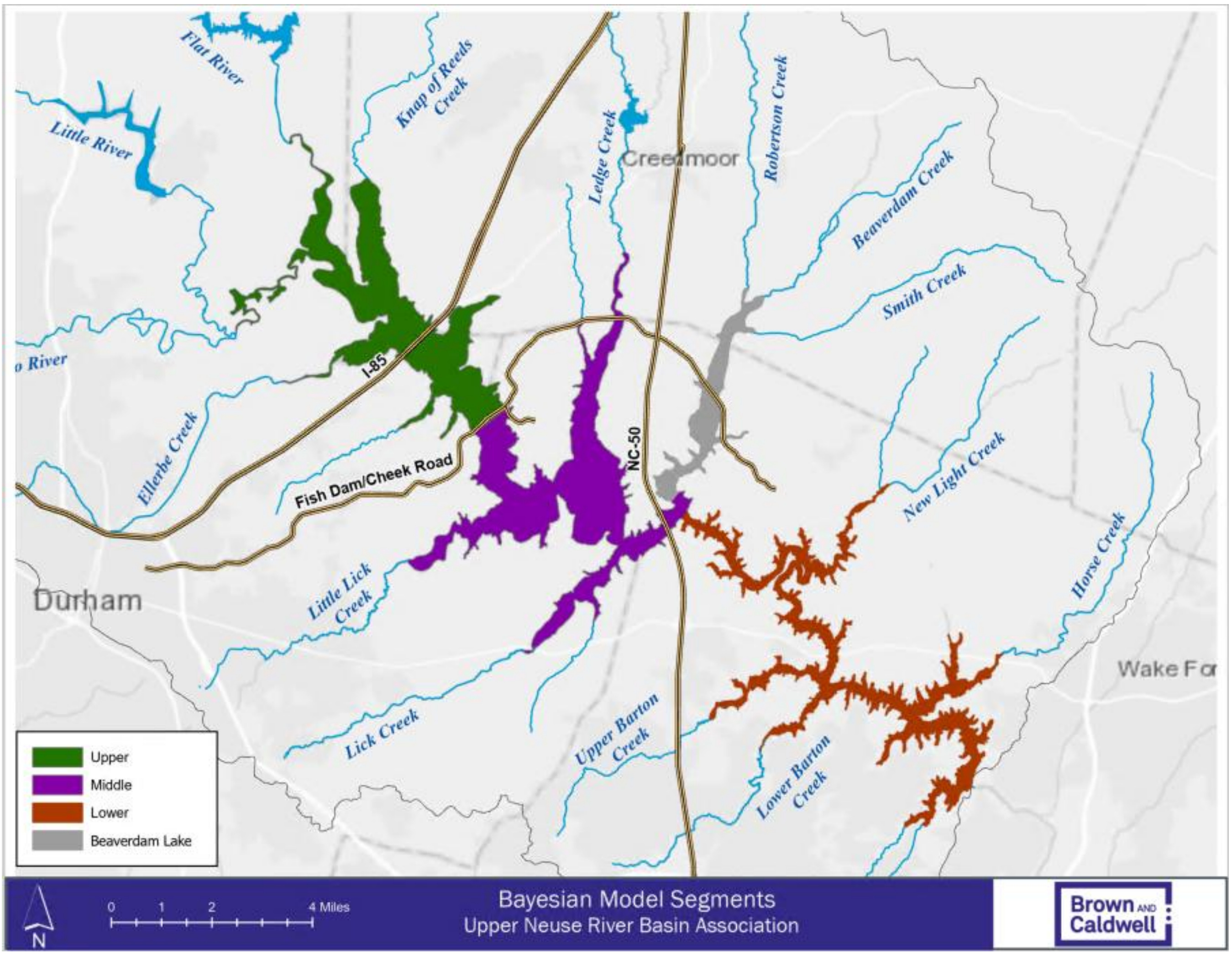

Figure 3-11. Statistical/Bayesian Modeling Segments

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The Falls Lake statistical/Bayesian model was developed to evaluate monthly and annual trends in loading patterns, lake water quality, and satisfaction with designated uses. This model summarizes, and enables simulation of, the water quality represented by photic zone composite sampling collected by several organizations. Photic zone composite samples represent the depth of the water column over which light penetrates to support photosynthesis. Based on the availability of data collected in Falls Lake, the statistical modeling period spans from the mid-1980s, after the lake was filled, to the 2020s. Data collected in the lake in the 1980s are very different than other years because the lake had recently filled and the decay of recently flooded organic material remaining on the lake bottom resulted in very high nutrient concentrations. These high levels of nutrients led to high chlorophyll-a concentrations. All three of the fish kills reported in Falls Lake that were attributed to algal blooms occurred in this post-filling period (before 1989).

All three of the fish kills reported in Falls Lake that were attributed to algal blooms occurred in this post-filling period (before 1989).

3.3.2 Model Variables

The model network for the statistical/Bayesian model is shown in Figure 3-12. Model inputs are shown on the left (blue boxes) and include season, total phosphorus load, total nitrogen load, and precipitation. Model outputs are shown around the perimeter (pink boxes) and include parameters with regulatory thresholds and those affecting designated uses and management of the lake. The unmarked boxes in the middle are intermediary nodes to connect inputs and outputs. Three separate networks were developed to understand the relationships among the 23 variables for the upper, middle, and lower lake segments.

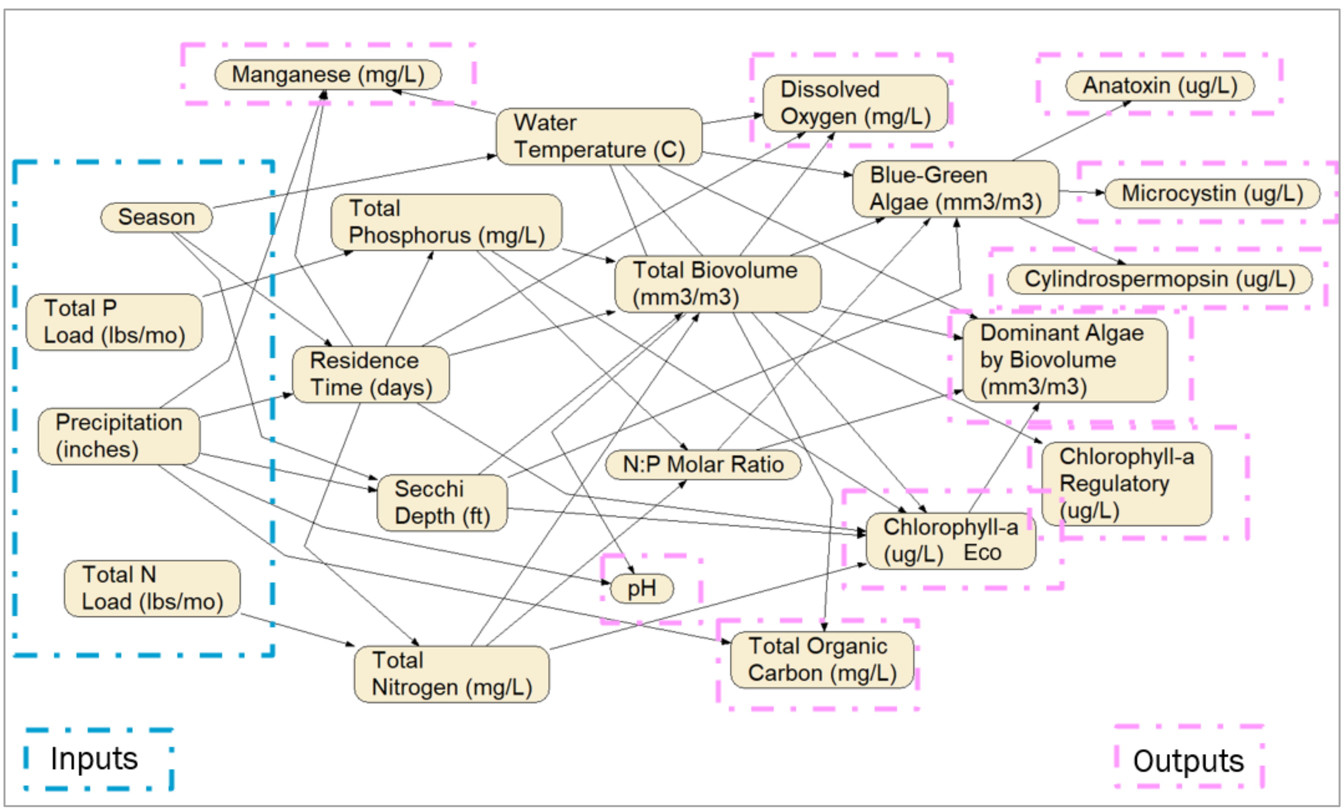

Figure 3-12. Statistical/Bayesian Model Network

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3.3.3 Data Categorization

The primary data sets acquired and formatted to configure the Falls Lake statistical/Bayesian model are summarized in Section 4. More information is provided about the sources, formatting, and merging of these datasets in Appendix C.

The statistical/Bayesian model places individual data points for each variable into categories to understand relationships among parameters and user-specified model endpoints. The categories are established based on user feedback to provide meaningful comparisons in response to changing inputs. Categories can be based on a regulatory limit for parameters with established standards or guidelines (e.g., above or below a standard). Categories can also be defined by ranking the observations from lowest to highest and then splitting the ranked observations into bins containing an equal number of measurements (i.e., rank-based binning). Categories can also be based on best professional judgement of subject matter experts (SMEs) with in-depth knowledge of the parameters and the relationships among them. Table 3-1 describes the type of binning and application to the UNRBA Statistical/Bayesian Model based on input from the TAW and SMEs. Visualization of example data sets within each bin are provided in Section 4.8.

Table 3-1. Summary of Data Categorization for the UNRBA Statistical/Bayesian Model

Type and Description	Application
Regulatory limits: Using water quality standards, published guidelines or thresholds to set the cutoff between one category and another.	Dissolved oxygen, pH, chlorophyll-a, algal toxins, algal biovolume
Rank-based binning: Sorting all measurements from lowest to highest and establishing bins so the number of observations in each bin is the same.	All water quality and hydrologic parameters that do not have regulatory limits or known thresholds that would impact designated uses. This approach was selected to represent the variability of the system without introducing preconceptions into the categories.
Best professional judgment: Based on TAW and SME inputs	Example ecological thresholds for chlorophyll-a, management categories for manganese and total organic carbon

3.3.4 Development of Conditional Probability Tables (CPTs)

The model uses “co-occurring” observations of multiple variables to develop conditional probability tables (CPTs). These tables summarize the probability that a given value for one variable will be observed given the observed valued for other variables. The probabilities are expressed as percentages with 0 percent meaning the outcome will not happen and 100 percent meaning it will happen. For example, when precipitation has been low during the warm season, the data show that water temperature is more frequently measured in the high category than the low category. This translates to a CPT with higher probability of high (versus moderate or low) water temperatures under similar conditions.

By intent, the model is built upon available data from Falls Lake, rather than expert inference or data from other systems. Therefore, limitations of the model primarily reflect the high variance in observed relationships among variables in Falls Lake. Also, although Falls Lake is one of the most studied lakes in the USA with an abundance of sampling, all combinations of all variables values (e.g., high, moderate, low) have not been observed on any given date. In some cases, this is because a particular combination of observations would be unlikely (e.g., cool water temperatures in the warm season and vice versa). In others it is a knowledge gap because sampling has not occurred under all combinations of values across the history of the lake. When a date-segment match across potential categories was not observed in a segment, the following steps were used to populate the CPTs so that all combinations of inputs have values on which to base the probability of an outcome:

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- **Alternative 1: Expand time frame**. First, within the segment, the time frame was expanded to half-month. Then, if no matches were found, the window was again expanded to the full month.
- **Alternative 2: Expand spatial extent**. If expanding the time window did not result in matches locally, data from the neighboring segment (middle for the upper or lower segment and lower for the middle segment) was evaluated for date, half-month, and then monthly matches. If no matches were found, the spatial extent was again expanded to include all lake units and the time-based search for matches repeated.
- **Alternative 3: Interpolate between known values**. For combinations of values that still had no observations, the CPT values for the most similar set of observations were identified and averaged. For example, if no matches defined the probability of a Moderate outcome for a given variable, but the probability of Low and High outcomes was known based on observations, the Moderate value was entered as the average of the High and Low probabilities.

All CPTs were reviewed to ensure they conformed to rational mathematical and ecological expectations. In some cases, the rarity of observations resulted in 0% (never) or 100% (always) probability entries. These values were converted to 0.1% and 99.9%, respectively, to indicate that while rare, we did not have data to support such extreme expectations within the models. For example, the warm season never having a water temperature observation of 32°F. In these cases, the probability of outcomes was set to 0.1 percent.

For many of the model variables, the values in their CPT table are mostly from data collected in the same segment on the same day, the same segment within the month, or an adjacent segment on the same day. For example, chlorophyll-a **ecological** has five input variables (total nitrogen concentration, total phosphorus concentration, Secchi depth, residence time, and water temperature). Each of these input variables has three to five categories that represent the data (e.g., low, medium, high). The CPT table for chlorophyll-a **ecological** has 1,125 rows of probabilities representing all possible combinations of input scenarios. Figure 3-13 shows that for chlorophyll-a **ecological** in the upper lake, approximately 60 percent of the values in the CPT come from observations that were either matched by date in the same segment or by date in an adjacent segment. Approximately 15 percent of the values come from data collected in the same segment within the half-month. None of the other matching methods including interpolation make up more than 10 percent of the values. For chlorophyll-a **regulatory**, the only input variable in the network is total biovolume, and there are three possible input scenarios (low, medium, or high biovolume). Figure 3-14 shows that in the upper lake, all four possible input scenarios have conditional probabilities based only on observations collected in the same segment on the same date.

Appendix C summarizes the number of match types for each of the predicted variables in the network.

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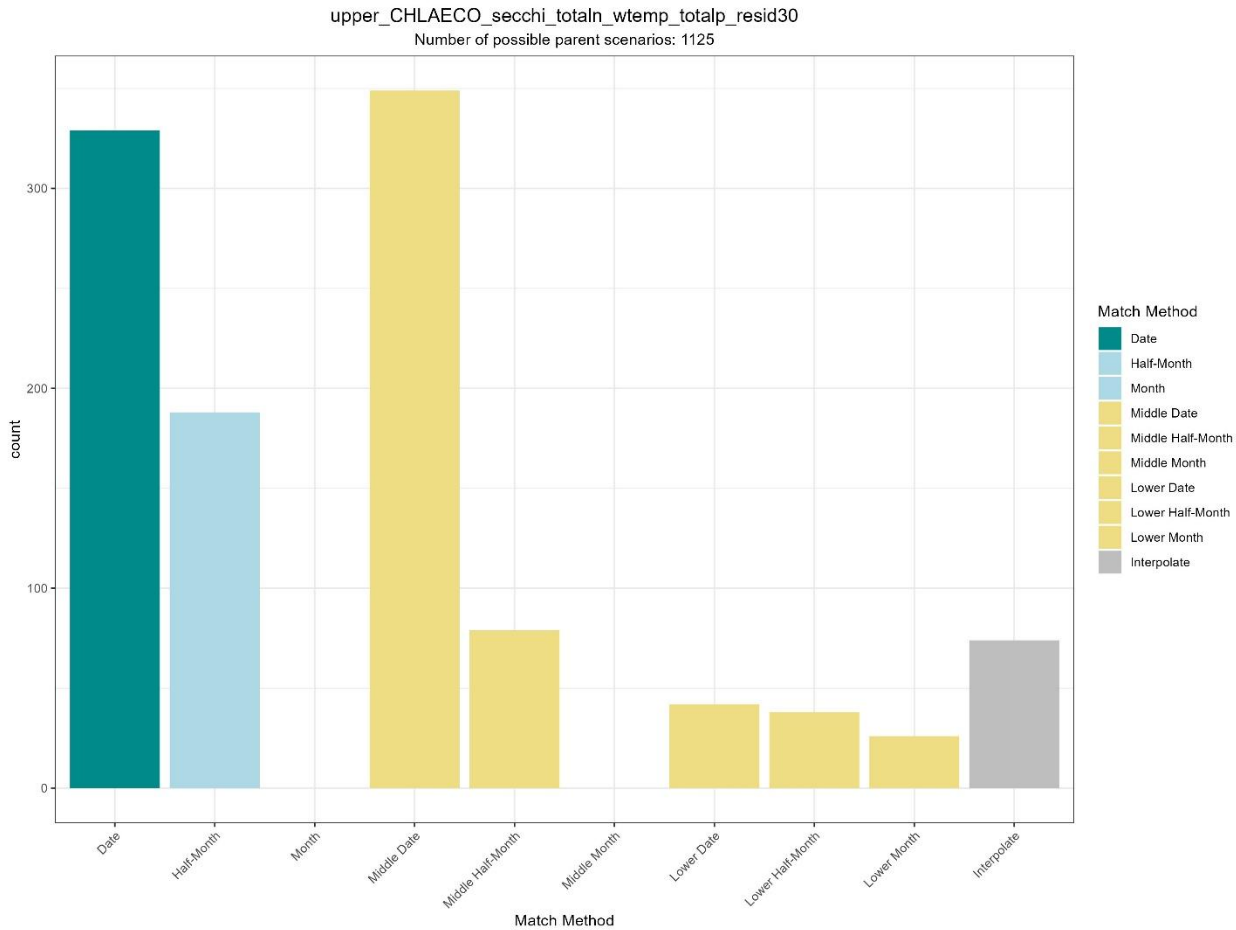

Figure 3-13. Number of Match Types for the Chlorophyll-a Ecological, Upper Lake Conditional Probability Table

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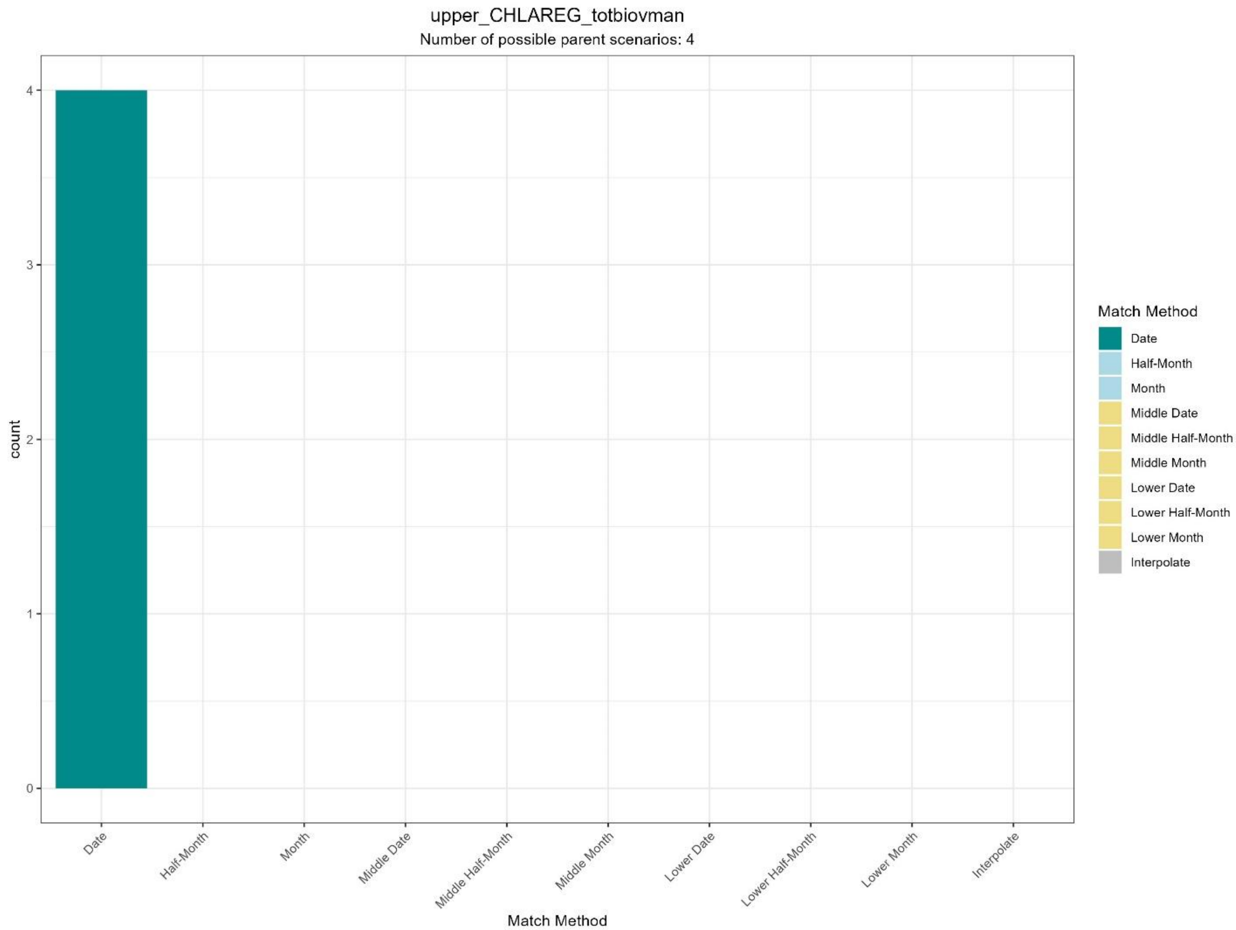

Figure 3-14. Number of Match Types for the Chlorophyll-a Regulatory, Upper Lake Conditional Probability Table

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Section 4

Summary of Data Sources and Model Inputs

Many organizations including the UNRBA, NC Collaboratory, USGS, DWR, WRC, CAAE, Cities of Durham and Raleigh, USACE, USFS, and EPA have conducted studies on Falls Lake or its tributaries, and this work has informed development of the three UNRBA lake models. These data have been supplemented with regional and national datasets including the Center for Disease Control One Health Harmful Algal Bloom System (OHHABS) and the National Atmospheric Deposition Program (NADP) to fill data gaps. Compared to similar studies and modeling efforts, the amount of data, level of information available, and number of researchers involved in this study is extraordinary.

Each of the three Falls Lake models incorporate data from various sources for model development and calibration. Table 4-1 summarizes the monitoring data, research studies, and previous evaluations including the data range, organization, and applicability to the UNRBA Falls Lake models. These data and reports are available through external hyperlinks.

Section 4.1 through Section 4.5 describe development of model inputs using long-term records to develop estimates for the UNRBA Statistical/Bayesian model for atmospheric deposition, tributary loading, releases from sediments, and transport of material from one segment of Falls Lake to the next downstream segment. These sections describe the uncertainties associated with these estimates, particularly further back in time. However, these estimates are not required to be exact, but rather to categorize relative loading to Falls Lake as very low, low, medium, high, or very high.

Section 4.6 and Section 4.7 summarize long-term data for lake residence time and percent of the lake volume within dissolved oxygen concentration thresholds. Lake residence time indicates how long the water remains in the lake. Longer residence times are conducive to higher algal growth rates compared to shorter residence times when other factors are held constant. The percent of the lake volume within certain dissolved oxygen thresholds provides an indication of the amount of suitable habitat for aquatic organisms. Nutrient enriched reservoirs that experience algal blooms can have dissolved oxygen issues when the algae die and decay. If sufficient oxygen is not present, large fish kills can occur. Section 4.8 summarizes fishery health data provided by the NC Wildlife Resource Commission. Section 4.11 summarizes the reported fish kills that have occurred on Falls Lake (all prior to 1997) which provide context for evaluating impacts to the aquatic life designated use.

Section 4.12 summarizes the available studies related to nutrient releases from the sediments of Falls Lake and provides visual and contextual summaries of the key data sets used to develop this input for the UNRBA lake models.

Section 4.13 summarizes input provided by the Technical Advisors Workgroup (TAW) established for development of the UNRBA Statistical/Bayesian model. The TAW included representatives of several lake user groups (e.g., recreation and drinking water treatment).

During calibration of both EFDC and WARMF Lake, challenges with simulating observed chlorophyll-a in the validation years (2017 and 2018) were noted. Section 4.14 describes meetings with DWR modeling staff and subject matter experts on model testing and validation.

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Locations of USGS stream flow and water level gages are provided in Figure 4-1. These gages were first used to calibrate the stream flows simulated with the WARMF watershed model and then used to inform model development for EFDC and WARMF Lake. Locations of watershed water quality monitoring stations are shown in Figure 4-2; these stations were used to calibrate the WARMF watershed model and ensure that simulated delivered nutrient and total organic carbon loading to Falls Lake is reasonable. Locations of Falls Lake water quality and algal composition data collection are shown in Figure 4-3. The lake water quality stations were used to inform model development and calibrate the UNRBA EFDC and UNRBA WARMF Lake models for water quality as described in the UNRBA Modeling QAPP. Table 4-2 lists the assignment of the Falls Lake water quality stations to the WARMF Lake segments or EFDC model grid and indicates if the station was evaluated for calibration performance. WARMF Lake segment numbers with a decimal point indicate the segment is an arm and which main lake segment it is attached. Table 4-2 also lists the lake modeling segment for the UNRBA Statistical/Bayesian model.

For both WARMF Lake and EFDC, streamflow and pollutant loading from the watershed were obtained from the WARMF watershed model. Development, calibration, model performance, model review, and results of scenario analyses for the watershed model are described in the UNRBA Watershed Model Report. Watershed changes impacting nutrient loading and their effect on lake water quality is the primary focus of the modeling effort. Linking the watershed and lake models is critical both to model development and use of the models in the evaluation of management alternatives.

Once the NC Collaboratory was formed, the UNRBA worked closely with the staff and researchers to ensure their research studies provided additional information to supplement the UNRBA monitoring efforts and provide new information to support modeling. The NC Collaboratory-funded studies included water movement and circulation, nitrification and denitrification rates, algal toxin evaluations, and several others. Previous studies conducted by the UNRBA included a Falls Lake bathymetry, sediment depth and sediment quality, light extinction, constriction point water movement and water quality, and model evaluations. The UNRBA studies are summarized in the UNRBA 2019 Monitoring Report. The NC Collaboratory reports are available at https://nutrients.web.unc.edu/resources/. Coordination between the UNRBA and NC Collaboratory ensured these efforts were not duplicated.

One key study for the hydrodynamic model was conducted by Luettich et al. (2023). This team studied water circulation in Falls Lake by measuring the water velocity at two (2) locations, Fish Dam and Hwy 98. The researchers identified a strong along-lake flow in response to inflows and dam operation, as well as a 5.5-hour oscillation that occurs frequently along the lake. The oscillation although relatively small (due to the minimal inflows or minimal discharge), can dominate the velocities and create a bidirectional flow when the lake stratifies in summer months. Luettich et al. (2023) observed the bidirectional flow during August 2020 at Hwy 98, mostly flowing downstream towards the dam at the surface and flowing upstream along to the bottom. The UNRBA modeling team discussed these results with Dr. Luettich and confirmed the EFDC model was simulating similar patterns. Dr. Luettich presented his work to the UNRBA Path Forward Committee (PFC) and Modeling and Regulatory Support Workgroup (MRSW) at their July 2021 meeting.

The UNRBA models were developed with significant input from the NC Collaboratory researchers and modeling staff at DWR. Researchers funded by the NC Collaboratory have also been studying nutrient-related processes in Falls Lake since 2019. Some of these researchers also provided “third-party” and subject matter expert review of the lake and watershed models. The results of these research studies have been incorporated into the development of the lake models developed by the UNRBA. For example, researchers found that denitrification in the lake arms significantly reduces nitrogen before reaching the main part of the lake. They also measured rates of nitrogen fixation by blue-green algae where the algae can “import” nitrogen from the atmosphere to support their growth. The researchers found that rates of nitrogen fixation in Falls Lake are currently low. Reports on these and other studies funded by the NC Collaboratory are available online at https://nutrients.web.unc.edu/resources/. The UNRBA models were developed with significant input from the NC Collaboratory researchers and modeling staff at DWR. Organizations that

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would like to conduct their own review can request the necessary files and model executables from the UNRBA Executive Director, Forrest Westall, at forrest.westall@unrba.org.

Table 4-1 provides additional examples of how NC Collaboratory studies were incorporated into the UNRBA lake models.

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Table 4-1. Relevant Studies and Reports to Support UNRBA Falls Lake Modeling				
Study	Date Range and Location	Organization	Summary of Results or Link to Data	Applicability
WATERSHED STUDIES, TRIBUTARY AND LAKE DATA, AND TRIBUTARY LOADING EVALUATIONS TO FALLS LAKE				
Compilation of watershed and lake data to support planning for the reexamination	1999 to 2012 Watershed and Falls Lake	DWR, USGS, Local Governments,	UNRBA review of water quality data for Falls Lake and the Watershed by organization, sampling depth, month, year, etc. (Task 2 Report)	While this evaluation period does not overlap with the UNRBA Study Period, previous DWR sampling included water quality sampling at deeper depths in the water column. Distributions of past water quality summarized by depth provide a reasonableness check on EFDC and WARMF Lake simulations relative to predicted water quality in the bottom layers.
Measurement of nutrient, TSS, and total organic carbon from forested areas	2008 to 2013, forested headwater catchments in the Falls Lake watershed	US Forest Service	Measured loading rates from forested areas and comparison to simulated loading rates under varying rainfall conditions is provided in the UNRBA WARMF Watershed Modeling Report. Published data are available in Boggs et al. (2012).	While this evaluation period does not overlap with the UNRBA Study Period, these studies were used to provide a reasonableness check on WARMF-simulated loading rates for forested areas. When WARMF was evaluated for similar rainfall conditions to the Forest Service monitoring studies conducted in the Falls Lake watershed, simulated rates were similar to measured rates (baseflow and storm event runoff).
Tributary water quality monitoring to support UNRBA watershed model development	Aug. 2014 to Oct. 2018, Watershed and Falls Lake	UNRBA Routine Monitoring	Data summarized in the UNRBA 2019 Annual Report Raw data are available on the UNRBA Resource Library.	Watershed data was used to calibrate the WARMF watershed model which provides stream flow and water quality concentrations delivered to Falls Lake for both WARMF Lake and EFDC.
Tributary high flow sampling to support UNRBA watershed model development	Grab sampling targeting precipitation events on largest 5 tributaries or corresponding with routine monitoring events, Aug 2014 to Dec. 2018	UNRBA Special Study	Distribution of concentrations by flow percentile in the 2019 Annual Report in Section 3.4.1; and partial results summarized in a different format in Results summarized in the 2016 Annual Report, Section 4.2	Watershed data was used to calibrate the WARMF watershed model which provides stream flow and water quality concentrations delivered to Falls Lake for both WARMF Lake and EFDC.
Tributary storm event sampling to support UNRBA watershed model development	Automated samplers deployed April, September, and October 2015 on Ellerbe Creek and Eno River capturing four or more distinct storm peaks for each tributary.	UNRBA Special Study	Results summarized in the 2016 Annual Report, Section 4.1	Watershed data was used to calibrate the WARMF watershed model which provides stream flow and water quality concentrations delivered to Falls Lake for both WARMF Lake and EFDC.

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Table 4-1. Relevant Studies and Reports to Support UNRBA Falls Lake Modeling				
Study	**Date Range and Location**	**Organization**	**Summary of Results or Link to Data**	**Applicability**
Sediment and carbon inputs to Falls Lake	Flat River, Eno River, Little River and Ellerbe Creek August 2019 to March 2020	NC Collaboratory	Results summarized in McKee et al. (2023)	This study concludes that most of the particulate organic matter entering Falls Lake originates from soil organic matter, freshwater algae (likely from upstream impoundments) and fertilizer. The cores from Falls Lake only indicate soil organic matter in the carbon signature. Average sedimentation rates in Falls Lake from 0.7 cm/yr to 1 cm/yr. The study concludes that ". If other reservoirs are similar in nature to Falls Lake, then the organic carbon accumulating in reservoirs (to offset growing CO2 concentrations in the atmosphere) is primarily from the carbon from reservoir watersheds which are better preserved and stored in reservoir bottom sediments. This conclusion is contrary to the idea that the source of the sedimentary carbon in bottom sediments results from the input of excess nutrients to reservoirs that results in large seasonal algae blooms and low oxygen waters." For Falls Lake, the dominant source of carbon is from the watershed, and that is comprised mostly of soil organic matter.
Empirical estimates of loading to Falls Lake	1980's to present at four tributaries with historic data (Flat River, Eno River, Knap of Reeds, and Ellerbe Creek	DWR water quality data and USGS stream flow data	See Section 4.2 of this report	Provides historic loading (total nitrogen and total phosphorus) to the UNRBA Statistical/Bayesian model
Historic water quality measurements.	Several locations in Falls Lake and the watershed	DWR and USGS data	EPA Water Quality Portal	Historic lake data used to evaluate long-term trends in Falls Lake. Historic water quality data from the watershed used to develop annual average ratios of total organic carbon to total nitrogen to develop historic loading estimates of total organic carbon from the historic loads of total nitrogen described in the previous row.
WARMF simulated loading to Falls Lake	2014 to 2018 for seventeen tributary inputs	UNRBA Watershed Model	Summarized in the UNRBA Watershed Modeling Report	Simulated stream flows and water quality concentrations provide input to EFDC, WARMF Lake, and the UNRBA Statistical/Bayesian model
CBOD5 in lake loading in lake samples	August 2014 to December 2015 for seventeen tributary inputs	UNRBA Routine Monitoring	Data summary provided in the UNRBA 2016 Annual Report, Section 3.2 (parameter discontinued the following year) Raw data are available on the UNRBA data portal available in the UNRBA Resource Library.	Approximately 95 percent of the organic material entering Falls Lake is in the dissolved form; see description of development of labile and refractory constituents for EFDC model in Appendix A

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Table 4-1. Relevant Studies and Reports to Support UNRBA Falls Lake Modeling				
Study	Date Range and Location	Organization	Summary of Results or Link to Data	Applicability
Falls Lake profile data	2014 to 2018	DWR, CAAE, City of Durham	DO summarized in the 2019 Annual Report in Section 5.1.7.4;	Profile data used in EFDC and WARMF Lake for model calibration to ensure appropriate simulation of thermal stratification
Falls Lake UV254 and absorbance data	August 2014 to -October 2018	UNRBA Routine Monitoring	Included each year with 2014 to 2018 summarized in the 2019 Annual Report in Section 3.3.2	Provides additional lake data to support the evaluation of disinfection byproduct formation simulated in the UNRBA Falls Lake Statistical/Bayesian model
LAKE BATHYMETRY, LAKE SEDIMENT EVALUATIONS, INTERNAL LOADING FROM LAKE SEDIMENTS, and ATMOSPHERIC DEPOSITION TO SURFACE OF FALLS LAKE				
UNRBA Falls Lake bathymetry and sediment depth study (Water Cube)	Falls Lake, 2016	UNRBA Special Study	Results summarized in the UNRBA 2019 Annual Report in Section 5.4	Data used to establish the EFDC model grid and the WARMF Lake segments and to estimate the thickness of sediment across the bottom of Falls Lake
Quantifying sediment nutrient processing in Falls Lake (Dr. Michael Piehler)	Between July 2019 and August 2022, a series of sampling campaigns were conducted along a transect of 6 main channel stations and at 10 creek arm sites to measure N2 fixation and the biological, physical, and chemical characteristics at each site.	NC Collaboratory	Results summarized in final report (NC Collaboratory 2023), Piehler (2020), and Smiley et al. (2023). Researchers conclude that 1) policies aimed at reducing anthropogenic nitrogen inputs could mitigate water quality degradation to some extent but will likely not prevent algal blooms completely and that 2) excess nitrogen may be a characteristic of urban reservoir systems, and water quality standards should reflect that.	Data informs simulation of nutrient processing in the EFDC and WARMF Lake models for Falls Lake. Research confirmed that nitrogen fixation was an insignificant component of the Falls Lake nitrogen balance (~1 percent) and omission of this source from the Falls Lake models would not introduce significant uncertainty. Researchers indicated that most of the nitrogen and phosphorus within Falls Lake are bound up in plankton biomass and that neither nitrogen nor phosphorus is available in great excess. The three lake models for Falls Lake developed by the UNRBA also indicate that nutrient concentrations are relatively low.
Falls Lake sediment nutrient release (DWR)	June 2006	DWR	Results summarized in the 2019 Annual Report	Similar results to more recent sediment flux evaluations conducted by DWR and UNRBA when adjusted for temperature
Falls Lake sediment quality and nutrient release study (Dr. Marc Alperin)	June 8 and 10, 2015; 27 locations in Falls Lake	UNRBA Special Study	Alperin (2018) summarized in the 2019 Annual Report in Section 5.5.	Data provides initial conditions of lakebed sediments for simulation in the EFDC and WARMF Lake models for Falls Lake; nutrient release estimates provide a reasonableness check on model simulations
Falls Lake sediment nutrient release	June 2018	EPA	Flexner (2019) summarized in the 2019 Annual Report in Section 5.5.	Nutrient release estimates provide a reasonableness check on model simulations

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Table 4-1. Relevant Studies and Reports to Support UNRBA Falls Lake Modeling				
Study	**Date Range and Location**	**Organization**	**Summary of Results or Link to Data**	**Applicability**
Atmospheric deposition to the lake surface for the UNRBA Study Period	2014 to 2018 for nitrogen, phosphorus, and total organic carbon	UNRBA based on data from CASTNET, NADP, and NC State Climate Office	Summarized in the UNRBA Watershed Modeling Report	Provides estimates of wet and dry deposition for WARMF Lake and EFDC models. See Section 4.1 for long-term estimates used for the UNRBA statistical/Bayesian model.
WATER BALANCE AND WATER MOVEMENT IN FALLS LAKE				
Flow and water quality at two Falls Lake constrictions	January 2016; Oct./Nov. 2016	UNRBA Special Study	January 2016 event 2016 Annual Report, Section 4.5 Oct/Nov 2016 event, 2017 Annual Report, Section 4.2	Provides water movement and water quality data for comparison to simulated values during high flow conditions
In situ observational study of falls lake	ADCPs were deployed at 4 locations: I-85, Fish Dam/Cheek Road, Hwy 50, Hwy 98; Nov 2019 to Dec 2020 Temperature profilers deployed at 3 downstream locations; also collected PAR data and YSI measurements at deployment/ redeployment 11/2019 and 6/2020	NC Collaboratory	Results summarized by Luettich et al. (2023). The researchers report that residence time in Falls Lake can be as short as weeks and as long as 5 years. Residence times in the side arms due to the exchange flow vary between 4.6 to 16.4 days, with the shorter residence times more common during the summer months.	EFDC modelers compared simulated water movement and velocities for 2015 to 2018 to those measured by Dr. Luettich in 2019 and 2020 to confirm the general patterns, directions, and magnitudes of flow were consistent with observations.
Evaluation of Falls Lake residence time	2014 to 2018	UNRBA	2014 to 2018 data summarized in the 2019 Annual Report in Section 5.8	Provides reasonableness check for EFDC and WARMF Lake and provides inputs to UNRBA Statistical/Bayesian model.
Precipitation, UNRBA study period	2015 to 2018 6-hour rainfall	NC State Climate Office	Summarized in the UNRBA Watershed Modeling Report	Provides 6-hour rainfall at 78 locations in the watershed for the watershed and lake models
Precipitation, historic record	1990 to 2020 at 60 stations with variable periods of collection	National Oceanic and Atmospheric Administration (NOAA)	Global Historical Climatology Network	Used to evaluate rainfall trends over time (rainfall depth, number of days of rain, wet and dry periods, identification of extreme events) for the UNRBA Statistical/Bayesian model.
Falls Lake water supply withdrawals	2005-2007, 2014-2018	City of Raleigh	Daily data provided by City of Raleigh	Used to develop daily time series of withdrawals for EFDC and WARMF Lake

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Table 4-1. Relevant Studies and Reports to Support UNRBA Falls Lake Modeling				
Study	**Date Range and Location**	**Organization**	**Summary of Results or Link to Data**	**Applicability**
Falls Lake water level	1991 to 2022, gages located at Beaverdam Dam and Falls Lake Dam	USGS	Beaverdam Creek at Dam Near Creedmoor, NC – 0208706575 Falls Lake Above Dam NR Falls, NC - 02087182	Both gages were used for hydrodynamic calibration of the EFDC model for the UNRBA Study Period (2015 to 2018); the Falls Lake gage was used for hydrologic calibration of WARMF Lake for the UNRBA Study Period. The long-term record at the Falls Lake Dam was used by the UNRBA Statistical/Bayesian model to generate daily average, annual average, monthly variation, 30-day rolling average, and daily change in water level data inputs.
Falls Lake dam releases	1983 to 2023	USGS	Neuse River Near Falls, NC - 02087183	Used to specify the discharge from Falls Lake to the Neuse River for the WARMF Lake and EFDC models
LIGHT EVALUATION AND PHOTOSYNTHESIS				
Light attenuation and Secchi depth data collected within Falls Lake	Mid 1980s to early 1990s and 3 locations in Falls Lake, October 2015	DWR	Results summarized in the 2016 Annual Report, Section 4.7; Light Attenuation Falls of the Neuse Reservoir 10-2015.pdf; Model Evaluation Report, Section 3.1.3	Confirms assumption that the photic zone can be reasonably approximated as twice the Secchi depth; provides information on background light extinction in Falls Lake for EFDC and WARMF Lake
Jordan Lake - Effects of nutrient and light limitation on phytoplankton dynamics	Jordan Lake, July 2017 to June 2018	NC Collaboratory	Results summarized by Paerl and Hall (2019)	While this study was not conducted on Falls Lake, this evaluation of photosynthesis rates, light saturation, and shade adaption provides a reasonable starting point for calibration of these rates for the Falls Lake EFDC and WARMF Lake models.
LAKE PROCESSES, ALGAL SPECIES, AND ALGAL GROWTH				
Cyanobacterial N2 fixation and denitrification in Falls Lake	July 2019 and early July 2020: Profiles of temperature, conductivity, dissolved oxygen, pH; Photosynthetically active radiation (PAR); Photic zone composite nutrient and silicate samples; chlorophyll-a, taxa, POC and PON	NC Collaboratory	Results summarized by Hall and Paerl (2023): "Based on the mass balance and direct core measurements of denitrification it appears that denitrification exceeds N2 fixation and that the balance of these microbial processes result in a net loss of N from Falls Lake. Net loss of N could help maintain N limited phytoplankton which is consistent with N limited growth observed in nutrient addition experiments conducted in spring and summer 2021. Most of the N and P within Falls Lake are bound up in plankton biomass. P is not available in great excess and appeared to be an important constraint	Provides information to set initial reaction rates in WARMF Lake and EFDC pertaining to nitrogen reactions

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Table 4-1. Relevant Studies and Reports to Support UNRBA Falls Lake Modeling				
Study	**Date Range and Location**	**Organization**	**Summary of Results or Link to Data**	**Applicability**
			on N2 fixation. This situation of N limitation but with the potential for stimulation of N2 fixation by P suggests that dual management of N and P is warranted for preventing undesirable levels of phytoplankton biomass in Falls Lake.	
Evaluation of nutrient limitation	Using UNRBA routine monitoring data (2014 to 2018)	UNRBA	Data summarized in the 2019 Annual Report in Section 5.9	Provides context for evaluating simulations by WARMF Lake and EFDC along with NC Collaboratory research studies
Evaluation of DWR EFDC model sensitivity to lability	The lability of POC was an assumed parameter for DWR's 2006 EFDC model, along with the assumption that 50 percent of all incoming carbon was delivered in particulate form (as POC). Assumptions used by DWR to build their Falls Lake EFDC model and relevant data to consider	UNRBA evaluation of DWR model	Model Evaluation Report, Section 3.1.2	Provides information regarding previous EFDC model. UNRBA routine Monitoring has since shown that POC accounts for only about 5 percent of the organic carbon entering Falls Lake.
Algal species data	Three locations in Falls Lake monthly	DWR	2014 to 2018 data summarized in the 2019 Annual Report in Section 3.3.2; historic data summarized in Appendix D	Provides algal cell densities and biovolumes to determine seasonal trends in algal groups and support calibration of WARMF Lake and EFDC.
Assessment of Zooplankton-Phytoplankton Relationships in Falls Lake	Zooplankton data from Falls Lake were provided by Dr. Sandra Cooke. Zooplankton samples were collected at ten CAAE monitoring stations approximate monthly from 2009 to 2012. Chlorophyll-a was measured by CAAE using fluorometry.	NC Collaboratory	Results summarized by Hall and Piehler (2023)	In 2021, EPA issued proposed models to calculate site-specific chlorophyll-a standards based on the relationship between phytoplankton (algae) and zooplankton (small organisms that eat algae and are eaten by small fish). The UNRBA had requested the raw zooplankton data for incorporation into the statistical/Bayesian model but was not able to obtain the data. Dr. Nathan Hall was able to obtain the data and evaluated the relationship proposed by EPA for Falls Lake and other southeastern reservoirs. He found the approach was not appropriate Falls Lake. For this reason, the statistical modeling team did not further pursue the raw zooplankton data.
ALGAL TOXIN DATA				
Falls Lake algal toxin data	Six locations, three toxins, 2007-2012, raw intake measurements; Monthly data collected at multiple stations from 2016 to 2018	City of Raleigh	2016 to 2018 data summarized in the 2019 Annual Report in Section 5.10	Provides data for the Statistical/Bayesian model regarding conditions in Falls Lake and concentrations of algal toxins

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Table 4-1. Relevant Studies and Reports to Support UNRBA Falls Lake Modeling				
Study	**Date Range and Location**	**Organization**	**Summary of Results or Link to Data**	**Applicability**
Cyanotoxin presence and year-round dynamics in Falls Lake	2019-2021 (toxin adsorption to SPATTs, toxin concentrations, field parameters)	NC Collaboratory	Results summarized by Schnetzer and Pierce (2023): "Maximal toxin concentrations from monthly collections did not exceed regulatory thresholds established by the World Health Organization. However, accumulated dissolved toxins were detected by the passive in situ samplers. Algal biomass alone is not a reliable indicator of cyanotoxin exposure risk in Falls Lake."	Provides data for the Statistical/Bayesian model regarding conditions in Falls Lake and levels of algal toxins
One Health Harmful Algal Bloom System	Voluntary reporting by States, launched in 2016; data through 2020	Center for Disease Control (CDC)	Provides data on reported events in terms of environmental conditions, water quality and algae monitoring data, human health, and animal effects	Provides data for the Statistical/Bayesian model regarding conditions in other states that have reported human health events or animal incidents associated with harmful algal blooms and environmental conditions during the event
ADDITIONAL DESIGNATED USE DATA AND EVALUATIONS				
Reported fish kills	1986 to 2020, statewide database	NCDEQ	See additional description in Section 4.8	Used in the UNRBA Statistical/Bayesian model to understand water quality conditions when fish kills have been reported and to evaluate the aquatic life designated use
In lake fish type and quantity	Black crappie and largemouth bass every other year, alternating spring and fall depending on the species; primarily in deeper part of lake	Wildlife Resource Commission (WRC)	Data provided to Ashton Drew via personal communication (K. Rundle, November 2021)	Data are collected every other year for each species, so not directly included in the UNRBA Statistical/Bayesian model which has been developed with monthly data. This data provides context when evaluating output from the UNRBA Statistical/Bayesian model.
Additional raw water characteristics (turbidity, manganese, pH, temperature)	2013 to 2018	City of Raleigh	Data discussed with E. Buchan on May 2022; originally acquired by UNRBA for 2019 Annual Report	Used in the UNRBA Statistical/Bayesian model to understand how water quality conditions affect drinking water treatment.
Boat ramp study	2000; Falls, Jordan, and Kerr Lakes	Colorado State University	The purposes included documenting current use of the lake, determining boater perceptions of their visits, and identifying the nature and magnitude of boating conflicts (2013 USACE Falls Lake Master Plan)	The study found that boater experiences were being negatively impacted at peak periods of use by the high level of motorboat traffic on the reservoir. Provides context and background to the statistical/Bayesian model; not directly applied given it is a single survey.
Falls Lake recreational use assessment	2005 to 2015	UNRBA	Trips and trip types (2005 to 2015), facility limitations, summarized in the 2016 Annual Report, Section 4.9; Different data are summarized in the 2019 Annual Report in Section 5.11	Data are summarized annually, so not directly included in the UNRBA Statistical/Bayesian model which has been developed with monthly data. This data provides context when evaluating output from the UNRBA Statistical/Bayesian model.

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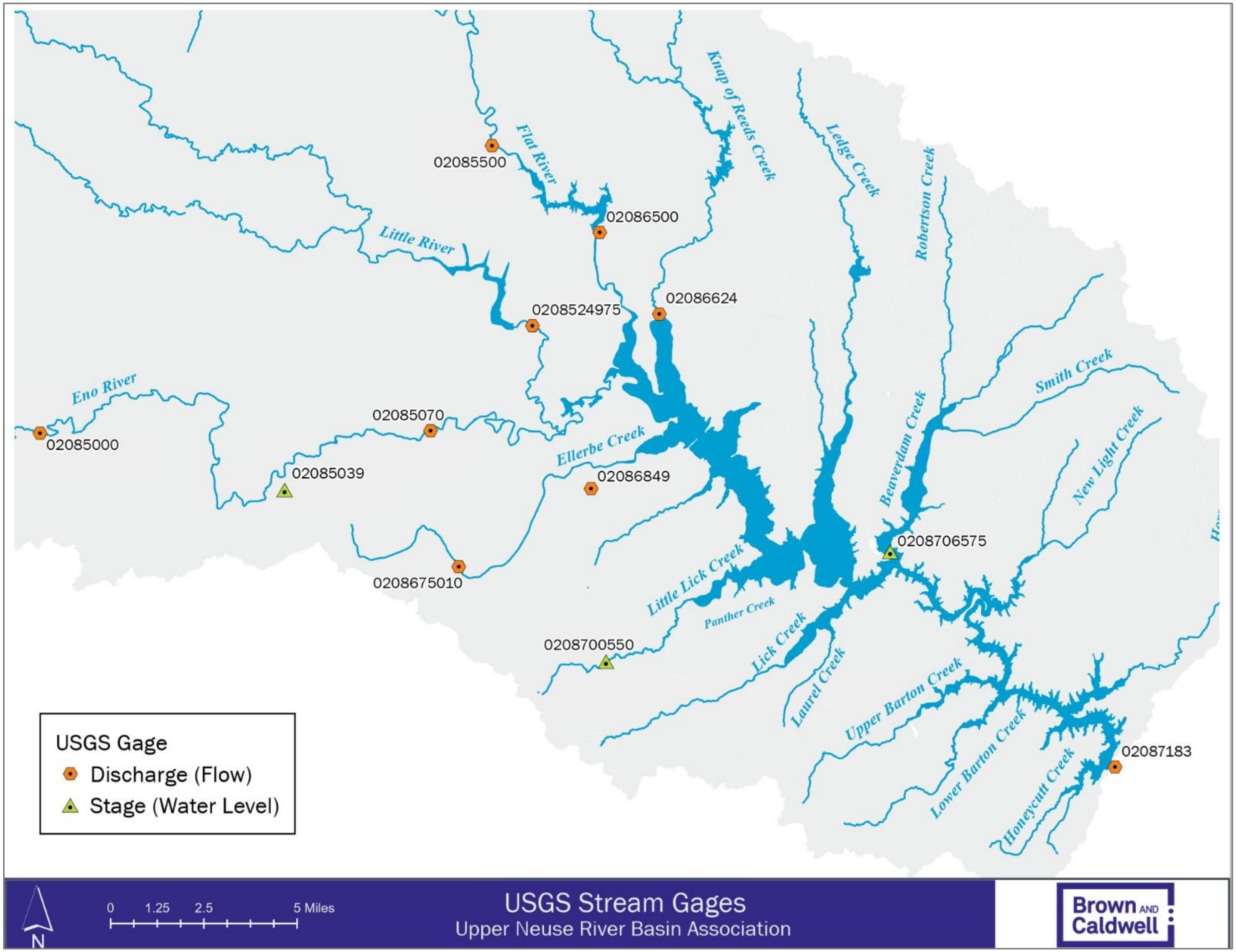

Figure 4-1. Locations of USGS Flow and Water Level Gages

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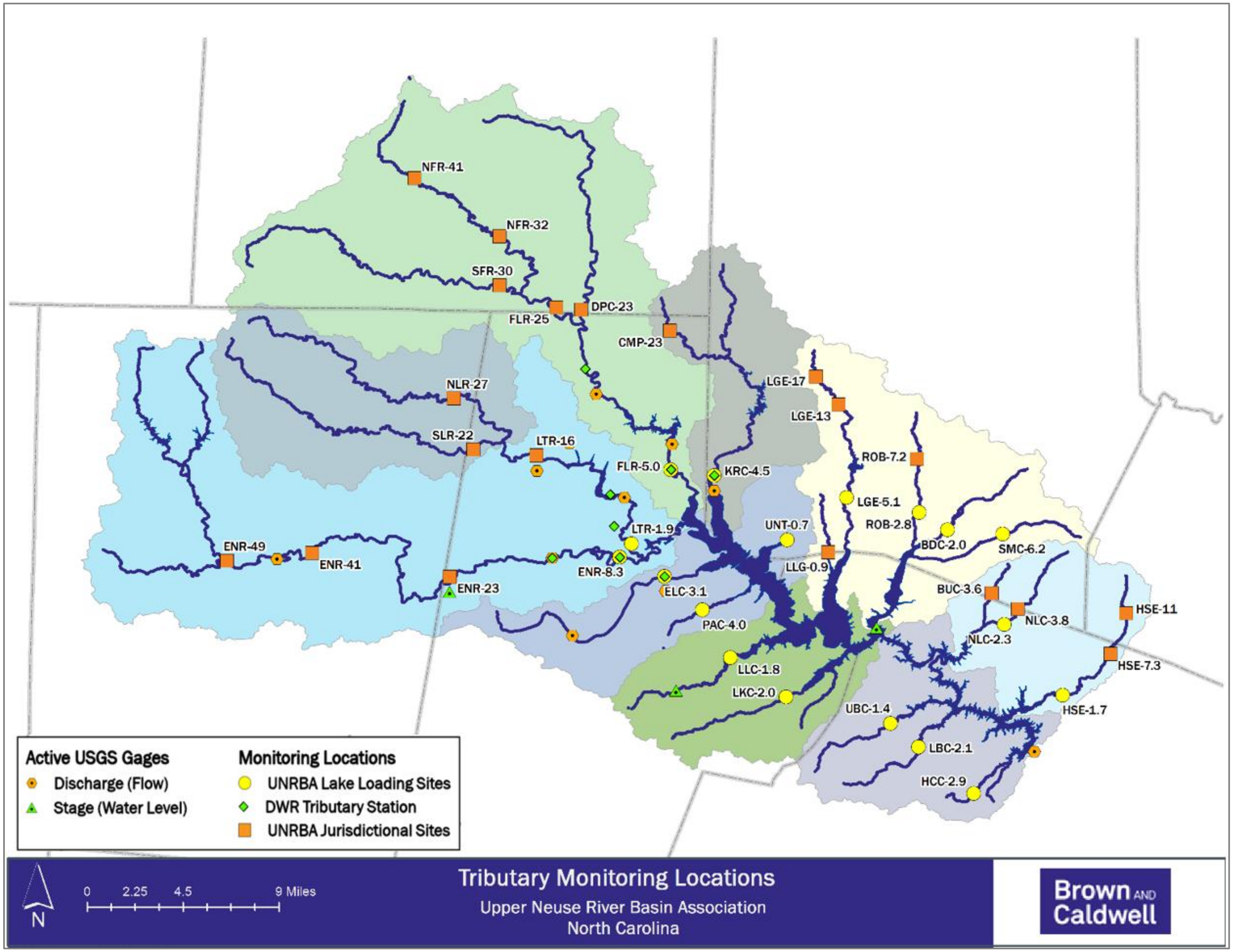

Figure 4-2. Locations of Watershed Water Quality Monitoring Locations

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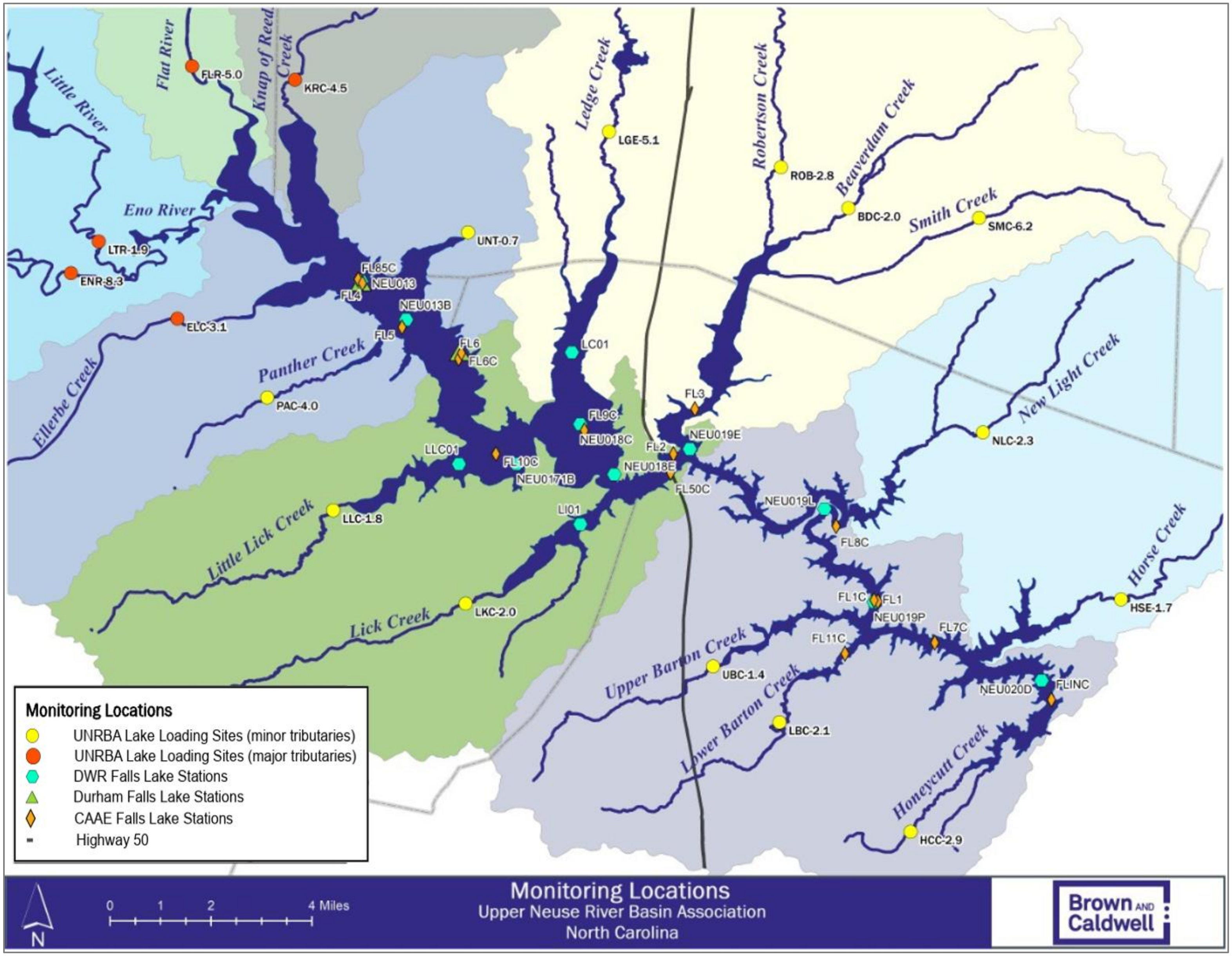

Figure 4-3. Locations of Falls Lake Monitoring Locations

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Table 4-2. Station Locations and Applications to the Falls Lake Models											
Station	Organization	Location description	Latitude	Longitude	Statistical Model Lake Segment	Waterbody Type	Frequency	Parameter Types[1]	WARMF Segment Number	WARMF Type	EFDC Type and Grid Cell for Calibration Stations (I, J)
FL-DS4	City of Durham	near I-85, "ND Downstream 3"	36.07013	-78.77954	Upper	Main	Seasonal, Weekly	Field, chemical	1	Calibration	Informative
FL-H50-S	UNRBA	at Hwy 50 Constriction, shelf	36.01547	-78.69104	Middle	Main	Variable	Field, chemical	4	Informative	Informative
FL-H50-T	UNRBA	at Hwy 50 Constriction, thalweg	36.01507	-78.69079	Middle	Main	Variable	Field, chemical	4	Informative	Informative
FL-I85-S	UNRBA	at I-85 Constriction, shelf	36.06974	-78.77977	Upper	Main	Variable	Field, chemical	1	Informative	Informative
FL-I85-T	UNRBA	at I-85 Constriction, thalweg	36.07006	-78.77933	Upper	Main	Variable	Field, chemical	1	Informative	Informative
FL-SR1801	City of Durham	at State Road 1801, “ND Downstream 4"	36.05010	-78.75125	Upper	Main	Seasonal, Weekly	Field, chemical	2	Calibration	Informative
LC01	DWR	in the Ledge Creek arm	36.04991	-78.71906	Middle	Arm	Monthly	Field, chemical	4.1	Informative	Calibration (34, 29)
LI01	DWR	in the Lick Creek arm	36.00070	-78.71664	Middle	Arm	Monthly	Field, chemical	4.2	Informative	Calibration (39, 43)
LLC01	DWR	downstream of Little Lick Creek	36.01792	-78.75146	Middle	Arm	Monthly	Field, chemical	3	Informative	Calibration (47, 33)
NEU013	DWR	upstream of I-85	36.07024	-78.77945	Upper	Main	Monthly	Field, chemical	1	Calibration	Calibration (42, 17)
NEU013B	DWR	downstream of I-85	36.05928	-78.76656	Upper	Main	Monthly	Field, chemical	2	Calibration	Calibration (43, 21)
NEU0171B	DWR	between Little Lick and Ledge Creeks	36.01799	-78.73492	Middle	Main	Monthly	Field, chemical	3	Calibration	Calibration (42, 36)
NEU018C	DWR	downstream of Ledge Creek	36.02932	-78.71670	Middle	Main	Monthly	Field, chemical	4	Informative	Calibration (35, 35)
NEU018E	DWR	upstream of Lick Creek	36.01494	-78.70696	Middle	Main	Monthly	Field, chemical	4	Calibration	Calibration (34, 40)
NEU019E	DWR	downstream of Beaverdam Impoundment	36.02220	-78.68529	Lower	Main	Monthly	Field, chemical	5	Informative	Calibration (26, 43)

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Table 4-2. Station Locations and Applications to the Falls Lake Models											
Station	Organization	Location description	Latitude	Longitude	Statistical Model Lake Segment	Waterbody Type	Frequency	Parameter Types[1]	WARMF Segment Number	WARMF Type	EFDC Type and Grid Cell for Calibration Stations (I, J)
NEU019L	DWR	downstream of New Light Creek	36.00507	-78.64668	Lower	Main	Monthly	Field, chemical	5	Informative	Calibration (33, 75)
NEU019P	DWR	at Hwy 98 (Durham Road)	35.97838	-78.63248	Lower	Main	Monthly	Field, chemical	5	Calibration	Calibration (33, 95)
NEU020D	DWR	upstream of dam	35.95591	-78.58444	Lower	Main	Monthly	Field, chemical	6	Calibration	Calibration (12, 98)
FL1	NC_CAAE	Falls Lake 1	35.97854	-78.63138	Lower	Main	Monthly	Field, chemical	5	Calibration	Informative
FL1C	NC_CAAE	Falls Lake 1 Channel	35.97892	-78.63249	Lower	Main	Monthly	Chla, SecchiD	5	Informative	Informative
FL2	NC_CAAE	Falls Lake 2	36.02080	-78.68999	Middle	Main	Monthly	Field, chemical	4	Calibration	Informative
FL3	NC_CAAE	Falls Lake 3	36.03368	-78.68384	Beaverdam Impound-ment – not included	Arm	Monthly	Field, chemical	5.1	Informative	Informative
FL4	NC_CAAE	Falls Lake 4	36.07088	-78.78034	Upper	Main	Monthly	Field, chemical	1	Calibration	Informative
FL5	NC_CAAE	Falls Lake 5	36.05711	-78.76779	Upper	Main	Monthly	Field, chemical	2	Calibration	Informative
FL6	NC_CAAE	Falls Lake 6	36.04812	-78.75155	Upper	Main	Monthly	Field, chemical	2	Calibration	Informative
FL6C	NC_CAAE	Falls Lake 6 Channel	36.04971	-78.75078	Upper	Main	Monthly	Chla, SecchiD	2	Calibration	Informative
FL7C	NC_CAAE	Falls Lake 7 Channel	35.96674	-78.61510	Lower	Main	Monthly	Chla, SecchiD	6	Informative	Informative
FL8C	NC_CAAE	Falls Lake 8 Channel	36.00009	-78.64336	Lower	Main	Monthly	Chla, SecchiD	5	Informative	Informative
FL9C	NC_CAAE	Falls Lake 9 Channel	36.02758	-78.71553	Middle	Main	Monthly	Chla, SecchiD	4	Informative	Informative
FL10C	NC_CAAE	Falls Lake 10 Channel	36.02082	-78.74087	Middle	Main	Monthly	Chla, SecchiD	3	Calibration	Informative
FL11C	NC_CAAE	Falls Lake 11 Channel	35.96362	-78.64082	Lower	Arm	Monthly	Chla, SecchiD	6.2	Informative	Informative
FL4C	NC_CAAE	Falls Lake I85 Channel, later FL85C	36.06973	-78.77912	Upper	Main	Monthly	Field, chemical	1	Calibration	Informative
FL85C	NC_CAAE	Falls Lake I85 Channel, formerly FL4C	36.06973	-78.77912	Upper	Main	Twice per month	Field, chemical	1	Calibration	Informative

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Table 4-2. Station Locations and Applications to the Falls Lake Models											
Station	Organization	Location description	Latitude	Longitude	Statistical Model Lake Segment	Waterbody Type	Frequency	Parameter Types[1]	WARMF Segment Number	WARMF Type	EFDC Type and Grid Cell for Calibration Stations (I, J)
FL50C	NC_CAAE	Falls Lake Hwy 50 Channel	36.01538	-78.69083	Middle	Main	Twice per month	Field, chemical	4	Calibration	Informative
FLINC	NC_CAAE	Falls Lake Intake Channel	35.95039	-78.58167	Lower	Main	Twice per month	Field, chemical	6	Calibration	Informative
LC1	NC_CAAE	Lick Creek 1	35.99603	-78.72359	Middle	Arm	Variable	Field	4.2	Informative	Informative

1. *Field Parameters include temperature, dissolved oxygen (DO), pH, and conductivity. Chemical parameters include nutrients, chlorophyll-a (Chla), total organic carbon, and associated measurements like Secchi depth (SecchiD). At some stations, only chlorophyll-a and Secchi depth were measured (Chla, SecchiD).*

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4.1 Long-Term Estimates of Atmospheric Deposition to the Surface of Falls Lake

As described in Table 4-1, the UNRBA WARMF model was used to develop rates of total nitrogen, total phosphorus, and total organic carbon deposition from the atmosphere to the surface of Falls Lake for the EFDC and WARMF Lake models (2015 to 2018). For the UNRBA statistical/Bayesian model, a longer record is needed.

To develop monthly estimates of wet and dry atmospheric deposition to the lake surface for the UNRBA statistical/Bayesian model, CASTNET models providing annual simulated total (ammonia plus nitrate) nitrogen deposition rates were used. The CASTNET models provide rates of wet, dry, and total (wet plus dry) nitrogen deposition in kilograms per hectare per year for 2000 to 2020 at Candor, NC (approximately 95 miles southwest of Falls Lake). These CASTNET models use both wet deposition data (National Atmospheric Deposition Data) and the dry concentration data for nitrogen in the atmosphere (CASTNET data). The models are available online at the NADP site: https://nadp.slh.wisc.edu/.

To apportion the CASTNET modeled wet and dry annual loads (2000 to 2020) to each month of the modeled period, weekly wet nitrogen deposition data (National Atmospheric Deposition Program) and weekly average dry nitrogen concentration data (CASTNET data) were used. This approach retained the total annual trends in simulated wet, dry, and total nitrogen estimated by CASTNET and allowed for those loads to be reasonably assigned to the months of each year within 2000 to 2020 using monitoring data.

To provide estimates for the full period of record for Falls Lake, linear regressions were developed using the available data across three periods.

shows the progression of data availability and estimation techniques for three periods, each with a different amount of data and information. For 1991 to 1999, estimates of wet and dry deposition were developed using linear-regressions of the wet deposition measurements or dry concentration data and the wet or dry deposition rates estimated for 2000 to 2020. For 1991 to 1999, wet deposition measurements and dry concentration data are available to extend the linear regressions for dry and wet deposition. For the 1980s, only wet deposition measurements are available. To extend the total nitrogen deposition estimates to cover the 1980s, a regression of wet deposition measurements and total deposition rates was developed using the data and information for 1991 to 2020. Thus, the farther back in the record, the greater uncertainty with the deposition estimates.

Monthly deposition rates (kilograms per hectare per year) were converted to monthly loads (pounds per month) using conversion factors and the surface area of Falls Lake at normal pool (12,410 acres or 5,022 hectares) based on the data reported by the USACE (http://epec.saw.usace.army.mil/FALLPERT.TXT).

Table 4-3. Available Data and Methodology to Develop Estimates of Monthly Total Nitrogen Deposition to Falls Lake

Period	Available Data and Information	Progression of Methodology to Develop and Extend Monthly Estimates
2000-2020	Weekly wet deposition and dry concentration data Annual estimates of wet and dry deposition based on CASTNET models	Weekly wet deposition measurements (rainfall concentration times precipitation depth) and “dry” air concentration data were used to apportion the annual load into the weeks of the year. Weeks with higher measurements received a higher portion of the annual load and weeks with lower measurements received a lower portion. Weekly loads were summed to provide monthly estimates of total nitrogen deposition (wet plus dry) for use in the statistical/Bayesian model. The weekly wet and dry measurements were used with the weekly wet and dry apportioned loads to develop regression equations to estimate wet and dry loads for 1991 to 1999 which do not have annual CASTNET models but do have weekly measurements of wet deposition and dry concentrations.

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Table 4-3. Available Data and Methodology to Develop Estimates of Monthly Total Nitrogen Deposition to Falls Lake		
Period	**Available Data and Information**	**Progression of Methodology to Develop and Extend Monthly Estimates**
1991-1999	Weekly wet deposition and dry concentration data	The weekly wet deposition and dry concentration data were used along with the wet and dry deposition regressions developed for 2000 to 2020 to develop weekly estimates for 1991 to 1999. The weekly estimates were then summed to monthly for use in the statistical/Bayesian model. The weekly wet deposition measurements were used with the total (wet plus dry) weekly deposition estimates for 1991 to 2020 to develop a regression equation for estimating total nitrogen deposition for 1979 to 1990.
1979-1990	Weekly wet deposition	The regression equation based on weekly wet deposition measurements and total (wet plus dry) weekly deposition for 1991 to 2020 was used to estimate total deposition for 1979 to 1990 using the available weekly wet deposition data. Weekly loads were summed to provide monthly estimates of total nitrogen deposition (wet plus dry) for use in the statistical/Bayesian model.

Figure 4-4 shows the monthly nitrogen deposition estimates for the period 1979 to 2020 using the methods described in Table 4-3. Figure 4-5 shows the annual estimates based on summing the monthly estimates. The dark line on the figures shows the total (wet plus dry) depositional load. The light line shows the wet component of the load which is significantly affected by precipitation amount. The dry component of the load is the difference between the total and the wet load. After 2003, the UNRBA estimates using the CASTNET and NAPD models and data show a downward trend in total depositional load (wet plus dry). The wet deposition load is more variable than the total load but also shows a decreasing trend after 2003.

The UNRBA long-term estimates shown in Figure 4-4 and Figure 4-5 are similar to published research on national and state-level long-term trends in atmospheric deposition. Baumgardner et al. (2002) compared estimates of deposition based on CASTNET data, simulated dry depositional velocities, and NADP data from 1990−1993 and 1997−2000. The article notes declines in sulfur deposition but not nitrogen over this ten year period. The UNRBA annual estimates of total nitrogen deposition to Falls Lake over this period range from 63,000 pounds per year to 75,000 pounds per year (Figure 4-5). While there is variability from year to year, there is not an evident trend upward or downward between 1990 and 2000 in total load. Du et al. (2014) evaluated wet deposition data from 1985 to 2012. They found for the southern US, ammonia wet deposition increased but nitrate wet deposition decreased and that the cumulative effect was no overall change in the wet nitrogen deposition over this period. This is similar to the long-term estimates developed by the UNRBA shown in Figure 4-5 for 1985 to 2012. These wet deposition estimates generally range from 34,000 to 71,000 pounds per year, with one estimate in 1986 of 107,000 pounds per year, but there is not an upward or downward trend in wet deposition between 1985 and 2012. The NC Department of Air Quality (DAQ) (2023) reports trends in air emissions rather than deposition loads. This report indicates that emissions of nitrogen oxides have decreased 72 percent statewide from 1990 to 2020. DAQ attributes these reductions to the 2002 Clean Smokestacks Act which addressed coal fired electric plants requiring technology improvements and shifting many to natural gas. DAQ also reports that North Carolina's Renewable Energy and Energy Efficiency Portfolio Standard reduced the state's reliance on fossil-fueled electricity generation from 96 percent in 2005 to 20 percent in 2022. From 1998 to 2022, these initiatives reduced emissions of nitrogen oxides from electricity-generating facilities by over 90 percent. Nitrogen oxide emissions from passenger vehicles and trucks have declined by 69 percent from 1990 to 2020. DAQ attributes these reductions to "the federal Tier 1 emissions standards from 1994-1999, national low-emissions vehicle standards from 1999-2003, Tier 2 emissions standards from 2004-2010, heavy-duty vehicle standards from 2007-2010, and Tier 3 vehicle emissions and fuel standards from 2017-2025."

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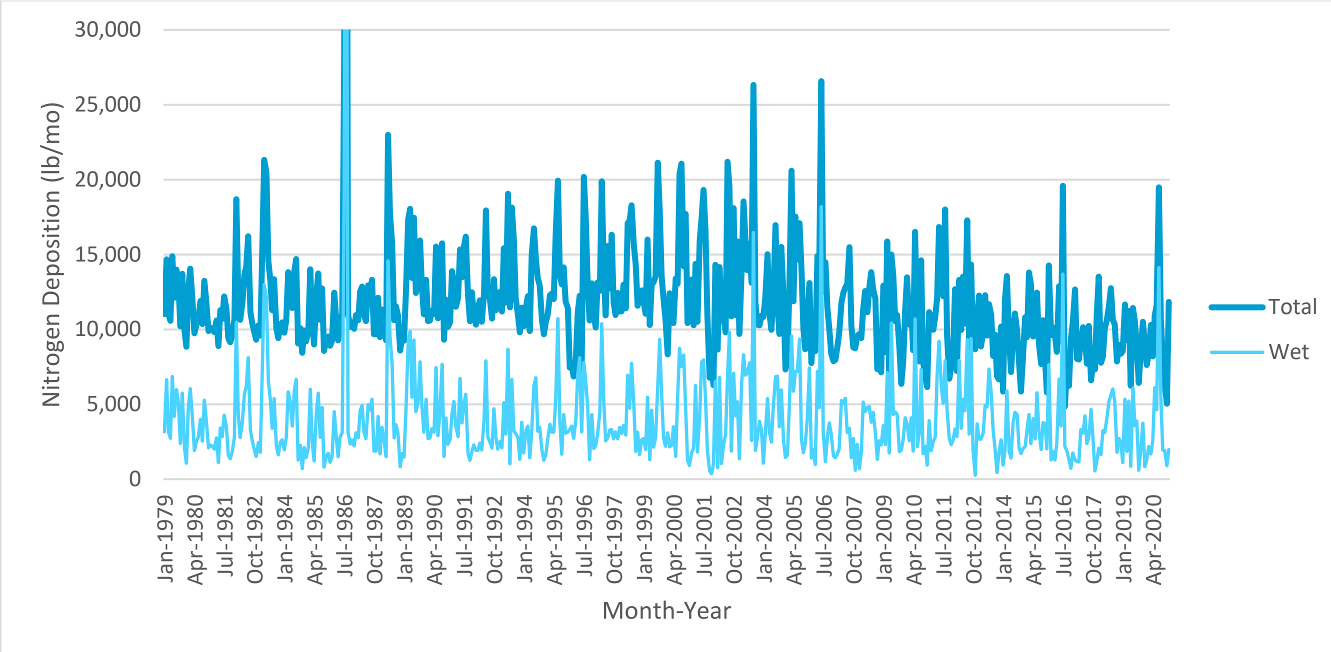

Figure 4-4. Estimation of Monthly Total Nitrogen Deposition Loads to Falls Lake (Wet plus Dry)

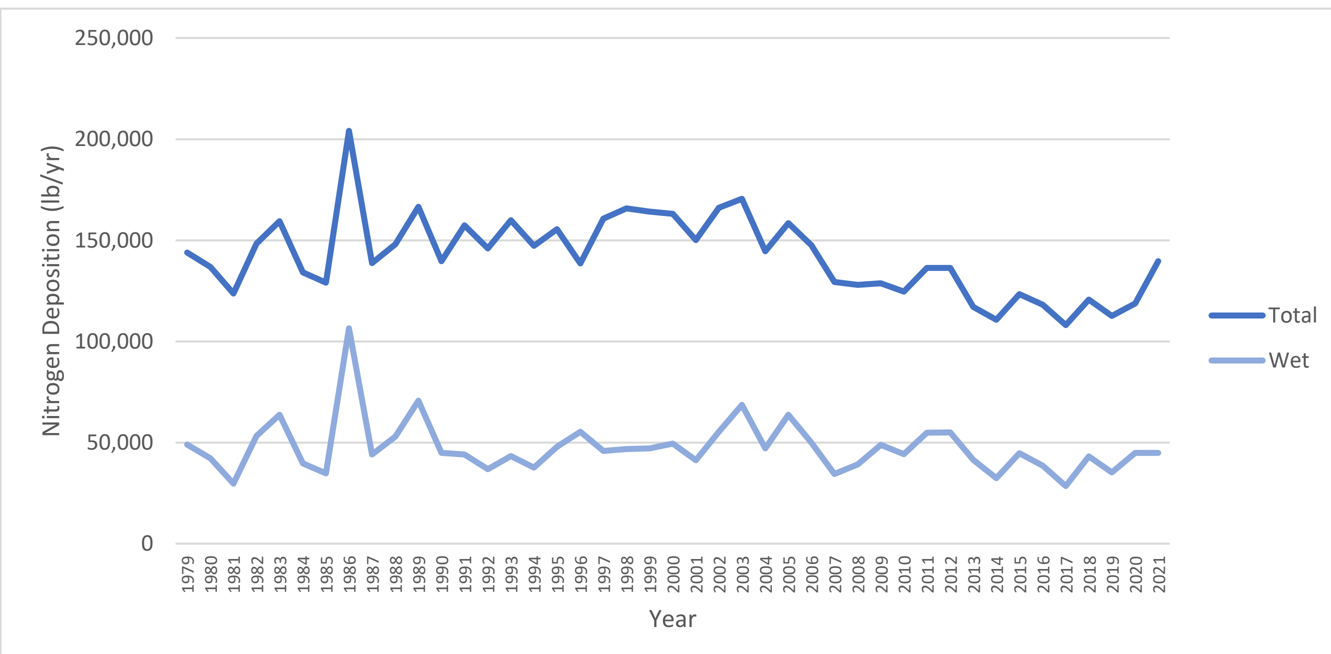

Figure 4-5. Estimation of Annual Total Nitrogen Deposition Loads to Falls Lake (Wet plus Dry)

Neither CASTNET nor NADP include total phosphorus or total organic carbon monitoring data or model estimates. To develop monthly atmospheric deposition estimates of total phosphorus and total organic carbon for the UNRBA statistical/Bayesian model, the ratio of total nitrogen deposition to total phosphorus deposition or total organic carbon deposition provided by the UNRBA watershed model and summarized in the UNRBA Watershed Model Report was applied to the monthly estimate of total nitrogen deposition. Local

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data including information on total phosphorus and total organic carbon were used in the WARMF watershed model. However, the watershed modeling covers only the period 2014 to 2018 so this approach provides only rough estimate of total phosphorus and total organic carbon deposition for the earlier years.

Annual loads from atmospheric deposition are relatively small compared to other sources and comprised approximately 6 percent of the average annual total nitrogen load to Falls Lake and 1 percent of the average annual total phosphorus and total organic carbon loads to Falls Lake during the UNRBA Study Period (UNRBA Watershed Model Report). Therefore, the simplifying assumptions and the uncertainties in the historic estimates are not expected to introduce significant uncertainty into the total loading estimates for the lake (categorized as very low, low, medium, high, or very high) that were used to develop the total loading input for the UNRBA statistical/Bayesian model. These assumptions and methods could be refined in future versions of the model as needed. The middle segment receives the highest part of the load from atmospheric deposition because it has the greatest surface area.

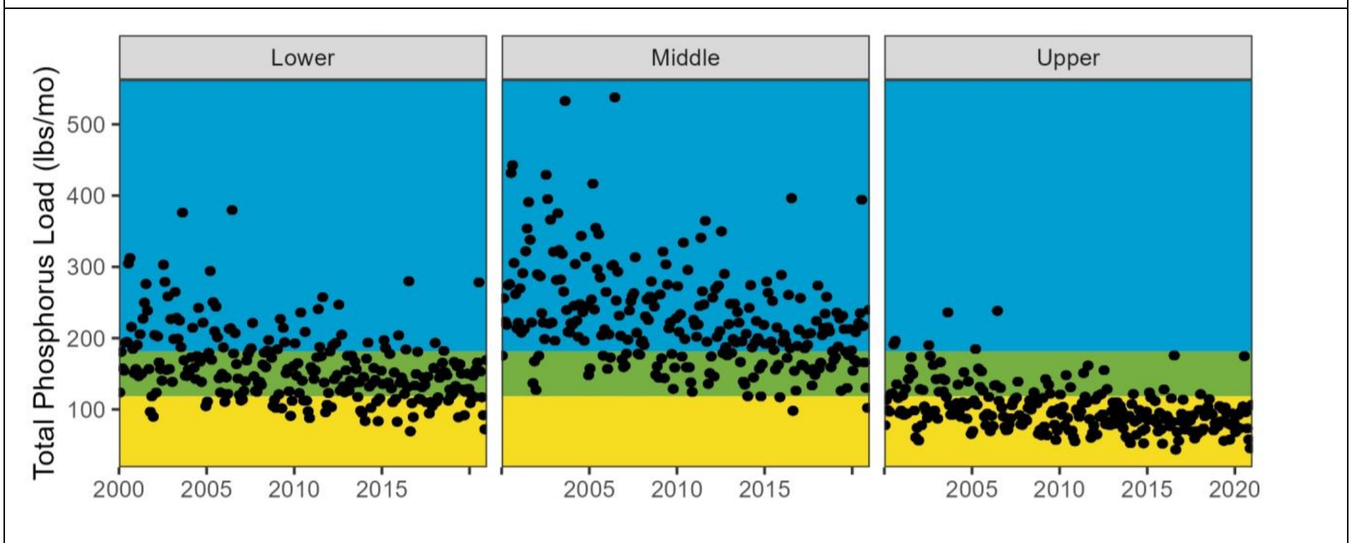

Figure 4-6. Estimation of Monthly Total Nitrogen (top) and Total Phosphorus (bottom) Deposition Loads to Falls Lake by Segment

Figure 4-7 and Figure 4-8 summarize the estimated nutrient loading from atmospheric deposition directly to Falls Lake for total nitrogen and total phosphorus, respectively. Loads are presented in units of 1,000 pounds for easier visibility and comparison to more significant sources of nutrient loading. For the statistical/Bayesian model, water quality data are compared to the preceding 30-day estimate of nutrient loading to the lake. These figures display the preceding 30 days of load for input to the statistical/Bayesian model.

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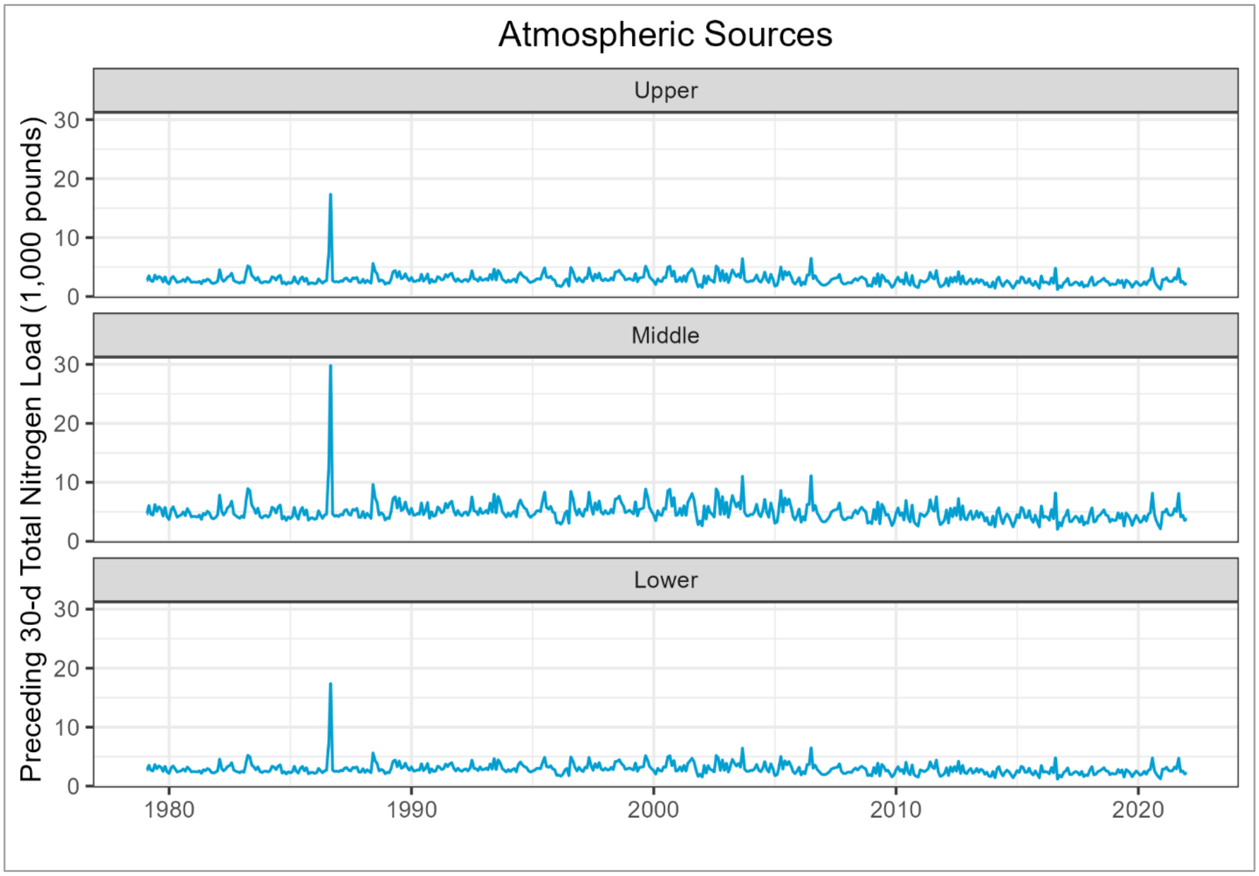

Figure 4-7. Preceding 30-day Total Nitrogen Load to Falls Lake Segments from Atmospheric Deposition

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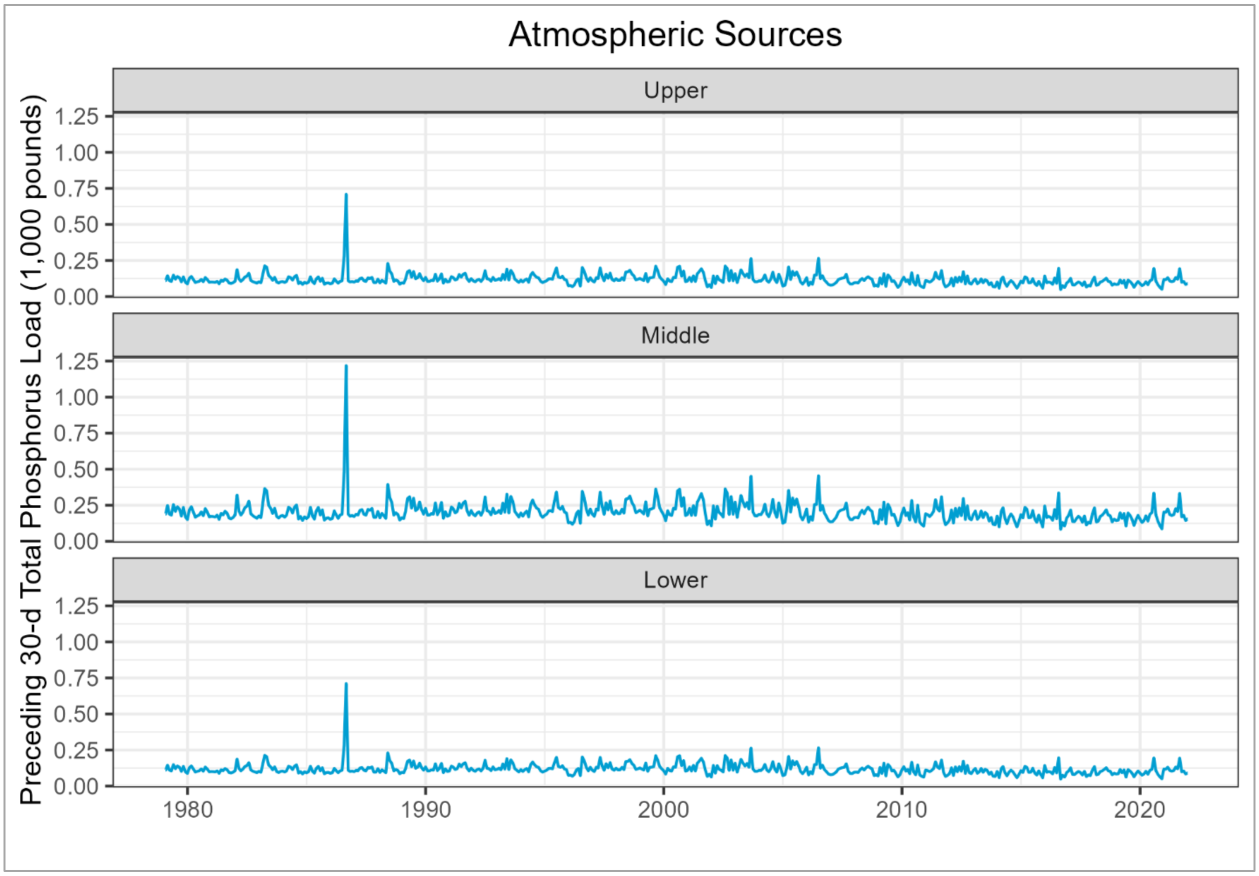

Figure 4-8. Preceding 30-day Total Phosphorus Load to Falls Lake Segments from Atmospheric Deposition

4.2 Long-Term Estimates of Watershed Loading to Falls Lake

To develop monthly estimates of total nitrogen and total phosphorus loading to Falls Lake from the watershed for the Statistical/Bayesian lake model, historic stream flow data and water quality data were obtained from USGS and DWR. A relatively simple method of estimating relative loading was developed using daily mean flows on each of the five gaged tributaries and the average monthly concentration observed by USGS or DWR towards the mouth of each tributary. For the statistical/Bayesian modeling, these estimates are not intended to be exact but rather indicate whether loading was very low, low, medium, high, or very high. Data gaps were filled using information from other flow gages or upstream water quality monitoring locations when needed.

Data gaps are still present in the tributary loading estimates when long periods were not gaged or monitored. For this evaluation of loading to Falls Lake, each of the five main tributaries to the lake require an estimate. Because Ellerbe Creek and Knap of Reeds Creek include a major wastewater treatment plant (discharging more than one million gallons per day), gaps in these datasets could not be easily filled. To fill in missing data at Knap of Reeds Creek in October through December 2015, the UNRBA monitoring station KRC-4.5 was used. For the other tributaries, the consistent, long-term measurements at USGS and DWR stations was used.

Table 4-4 summarizes the list the USGS flow gage and USGS or DWR water quality monitoring station used to estimate monthly loads from each of the five gaged tributaries.

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Table 4-4. USGS Flow Gages and USGS or DWR Water Quality Monitoring Stations used to Estimate Monthly Nutrient Loads Delivered to Falls Lake			
Tributary (Drainage Area in square miles)	USGS Flow Gages	Primary USGS and DWR Downstream Water Quality Stations	Supplemental Water Quality Stations
Eno River (141)	02085070	02085070, 02085079, 02085284, J0770000, J0810000	Not applicable
Flat River (168)	02086500	02086500, J1100000	J1070000 (above Lake Michie)
Little River (98.9)	0208524975	02085262, J0840000 (in Little River Reservoir)	Not applicable
Knap of Reeds (43)	02086624	02086624, J1210000	KRC-4.5 (UNRBA monitoring station)
Ellerbe Creek (21.9)	02086849	J1330000	Not applicable

Of the five gaged tributaries, only Eno River does not include large sub-impoundments or a large wastewater treatment plant relative to the size of the subwatershed. Monthly estimated loads from the Eno River watershed were scaled by drainage area to estimate the monthly loads delivered to Falls Lake for areas downstream of the five USGS gages listed in Table 4-4 or areas draining to ungaged tributaries. While this approach may not be precise for each tributary, it is sufficient to categorize total monthly loads delivered to the lake ranging from very low to very high to provide inputs to the statistical/Bayesian model. Table 4-5 summarizes the ungaged drainage areas to each of the three lake segments. The drainage area at the Eno River gage is listed in Table 4-4.

Table 4-5. Drainage Areas Used to Estimate Loading to Falls Lake from Ungaged Areas	
Segment	Ungaged Drainage Area (square miles)
Upper (upstream of Fish Dam/Cheek Road)	70.4
Middle (between Fish Dam/Cheek Road and the mouth of Beaverdam Impoundment)	133.8
Lower (from Beaverdam Impoundment to the Falls Lake Dam)	93.2

Figure 4-9 and Figure 4-10 summarizes the estimated tributary loading from the watershed to Falls Lake for total nitrogen and total phosphorus, respectively. Loads are presented in units of 1,000 pounds for easier visibility. For the statistical/Bayesian model, water quality data are compared to the preceding 30-day estimate of nutrient loading to the lake. These figures display the preceding 30 days of load for input to the statistical/Bayesian model. Gaps in these figures indicate data gaps in tributary monitoring data. These figures show that most of the tributary loading enters the upper part of the lake and that loads in the 1980s and 1990s were generally higher than loads in the mid-2000s and after.

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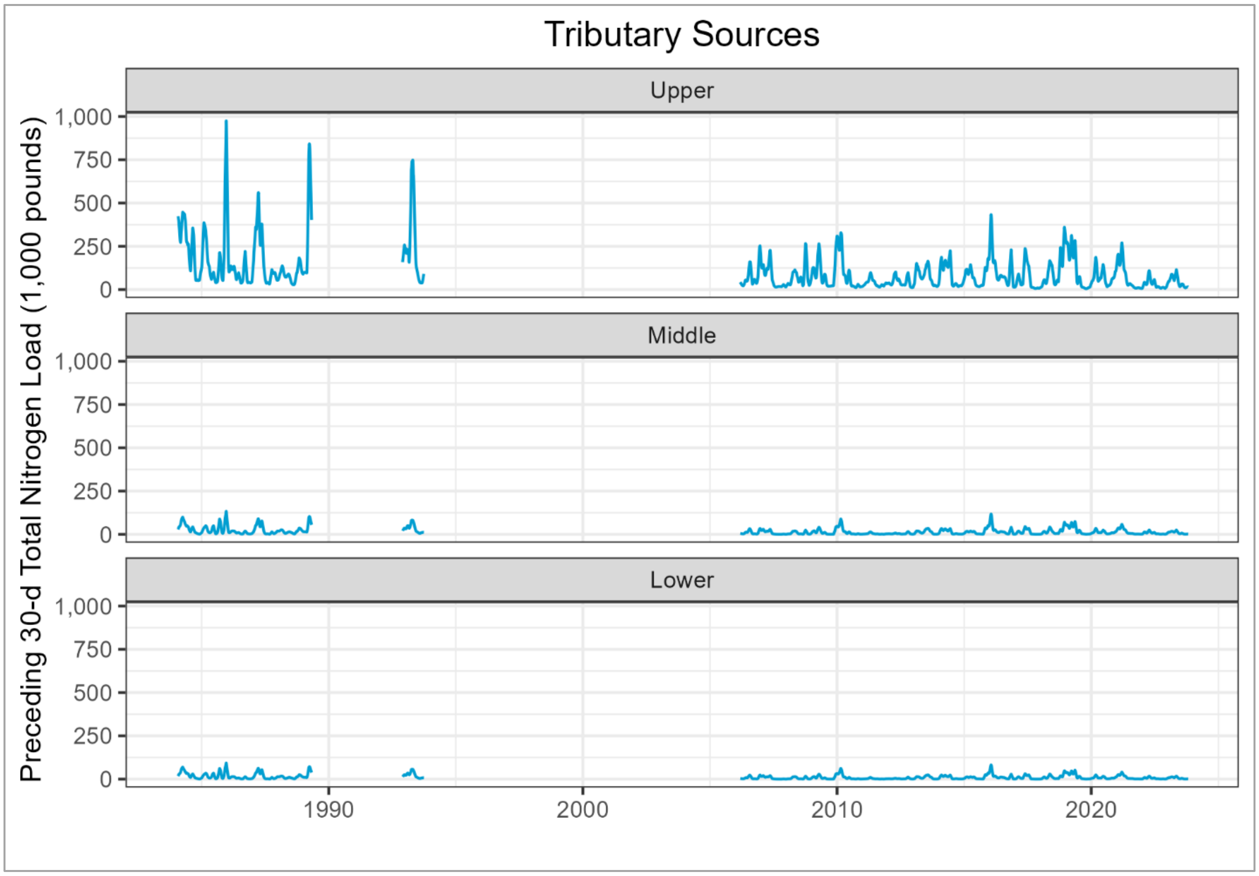

Figure 4-9. Preceding 30-day Total Nitrogen Load to Falls Lake Segments from Watershed Tributaries

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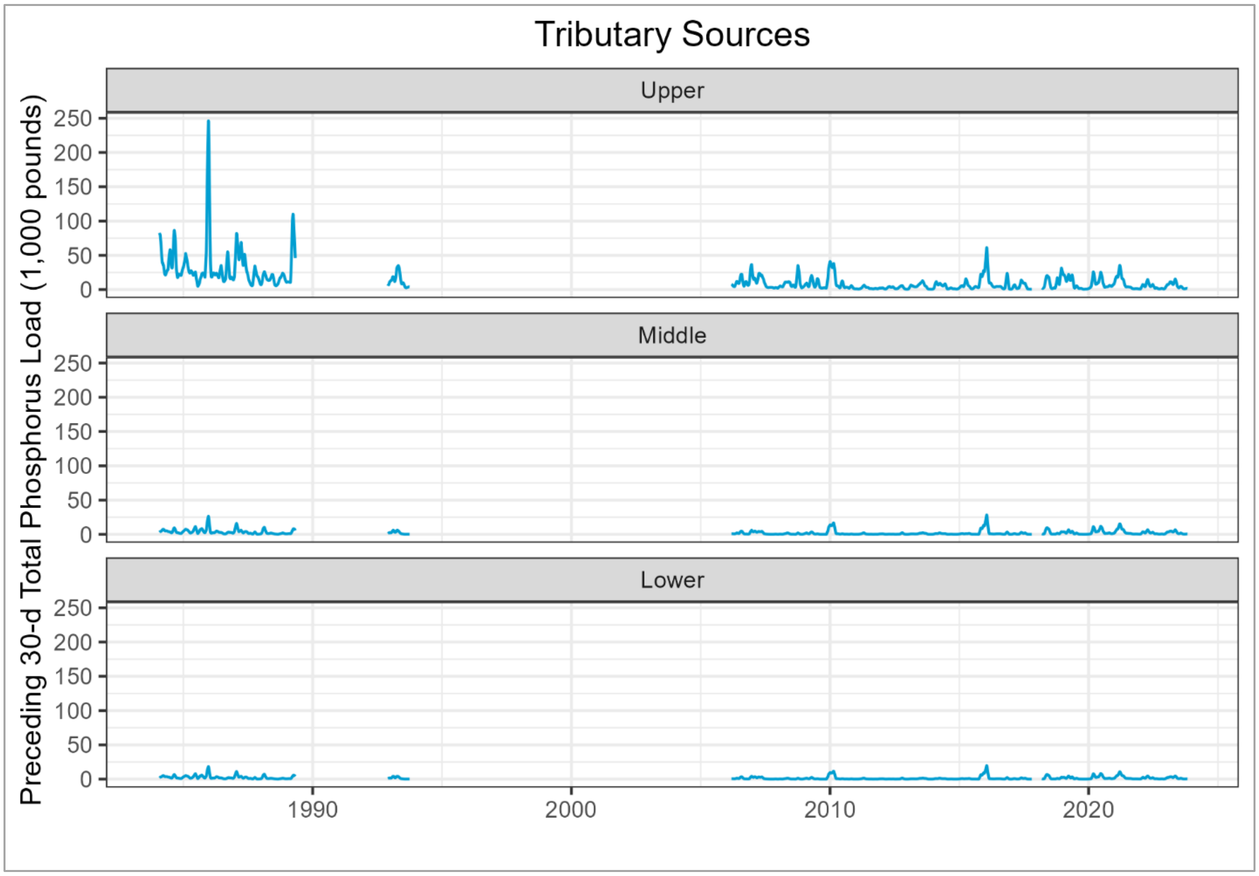

Figure 4-10. Preceding 30-day Total Phosphorus Load to Falls Lake Segments from Watershed Tributaries

4.3 Summary of Studies Related to Internal Nutrient Releases from Lake Sediments

As organic material (algae, leaves, etc.) settles to the bottom of a lake and decays, nutrients may be released into the overlying water. This process is often referred to as internal loading or internal nutrient flux. The release of phosphorus from sediments is limited by the presence of oxygen and other chemical processes. Phosphorus releases are minimal when the water layer above the sediments contains oxygen. However, phosphorus can still be released via diffusion if porewater concentrations of phosphate (in the pore spaces of the lake sediments) are higher than bottom water concentrations of phosphate. Phosphorus releases are slower in the presence of iron or aluminum which are abundant in the Falls Lake watershed (BC and Systech Water Resources 2023). Nitrogen releases from the sediments are not limited as much by the presence of oxygen and are primarily in the ammonia form. In Falls Lake, ammonia releases are higher in areas with thicker accumulation of unconsolidated sediments (UNRBA 2019 Monitoring Report) and in warmer months especially when dissolved oxygen concentrations are very low (anoxic) (Smiley et al. 2023).

During the subject matter review process for the lake models, particular attention was focused on the WARMF Lake and EFDC model simulations of internal nutrient releases from lake sediments. Several studies are available from Falls Lake that have evaluated this source of loading (Table 4-6). Each study used different methods and spatial resolution, and all have been conducted in spring or summer. While each study provides valuable information, none can be considered exact measurements of lake-wide nutrient flux rates, particularly since the depth of accumulated sediments varies significantly across the lake bottom (Figure 4-11). Sampling locations represent discrete areas in the lake, and the surface area of a

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benthic chamber or sediment core is orders of magnitude less than even the EFDC model grid cell areas. Within and among the studies, the monitoring studies demonstrate the variability in nutrient release rates from the Falls Lake sediments. This variability was also noted by the researchers who presented at the 2023 Falls Lake Nutrient Management Study Symposium hosted by the NC Collaboratory.

Figure 4-11 shows the depth of sediment accumulated along the bottom of Falls Lake and the location of sediment core extractions that were used to evaluate sediment quality in 2015 by Dr. Marc Alperin (Alperin 2018). To develop the previous lake wide nutrient flux estimates using the sediment core data collected by Dr. Alperin, Brown and Caldwell staff overlaid the sediment thickness data and oxygen profile data with the nitrogen and phosphorus flux estimates provided by Dr. Alperin. As part of the UNRBA bathymetric survey of Falls Lake, 4 million sediment thickness data points were collected. Dissolved oxygen profile data are available from DWR lake monitoring stations. Intersection of the sediment thickness data with the sediment cores and flux estimates provided by Dr. Alperin in the channel, slope, and shelf of the lake at 27 locations showed a strong correlation between nitrogen release and sediment thickness. An empirical relationship (r2=0.71) was used to estimate lake wide nitrogen flux rates using the sediment depth data collected by UNRBA (UNRBA 2019 Monitoring Report). Above Highway 50, the annual flux rate of total nitrogen was estimated to be approximately 70,000 pounds per year. Below Highway 50 (including the Beaverdam impoundment), the annual nitrogen flux rate was estimated to be approximately 140,000 pounds of nitrogen per year. Thus, the total nitrogen flux was approximately 210,000 pounds per year based on Dr. Alperin's study and the Brown and Caldwell extrapolation using the sediment thickness data collected in Falls Lake.

Phosphorus releases occur through diffusion processes from the pore water into the overlying water and release of bound phosphorus at the sediment water interface under anoxic conditions. The sediment-core estimates reflect the pore water diffusion processes and result in approximately 4,000 pounds per year of phosphorus release. Brown and Caldwell staff (UNRBA 2019 Monitoring Report) overlaid the dissolved oxygen profile data to estimate the additional phosphorus release from the lake sediments using the sediment phosphorus concentration data reported by Alperin for the top 3 cm of each core and equations provided by Nürnberg (2009). An additional 10,000 pounds of phosphorus were estimated to be released from the Falls Lake sediments annually for a total rate of 14,000 pounds per year.

More recently, Dr. Michael Piehler, funded by the NC Collaboratory, conducted additional core sampling in Falls Lake in October 2019, May 2020, and August 2020 and tributary sediments in July 2021. These data were extrapolated to develop annual, lake wide estimates of nutrient fluxes: 530,000 pounds per year of ammonia and 40,200 pounds per year of nitrate (NC Collaboratory 2023, Piehler 2020, and Smiley et al. 2023). Phosphate releases were estimated at 10,500 pounds per year of phosphorus (personal communication, Michael Piehler to Alix Matos December 1, 2022). In terms of losses or sinks, approximately 18,700 pounds per year of organic nitrogen are lost to the sediments and approximately 530,000 pounds per year of nitrate are lost to denitrification. Dr. Nathan Hall also has conducted nutrient balance studies on Falls Lake. Using a mass balance approach, he estimates nitrogen loss due to denitrification of approximately 163,000 pounds per year (Hall and Paerl 2023).

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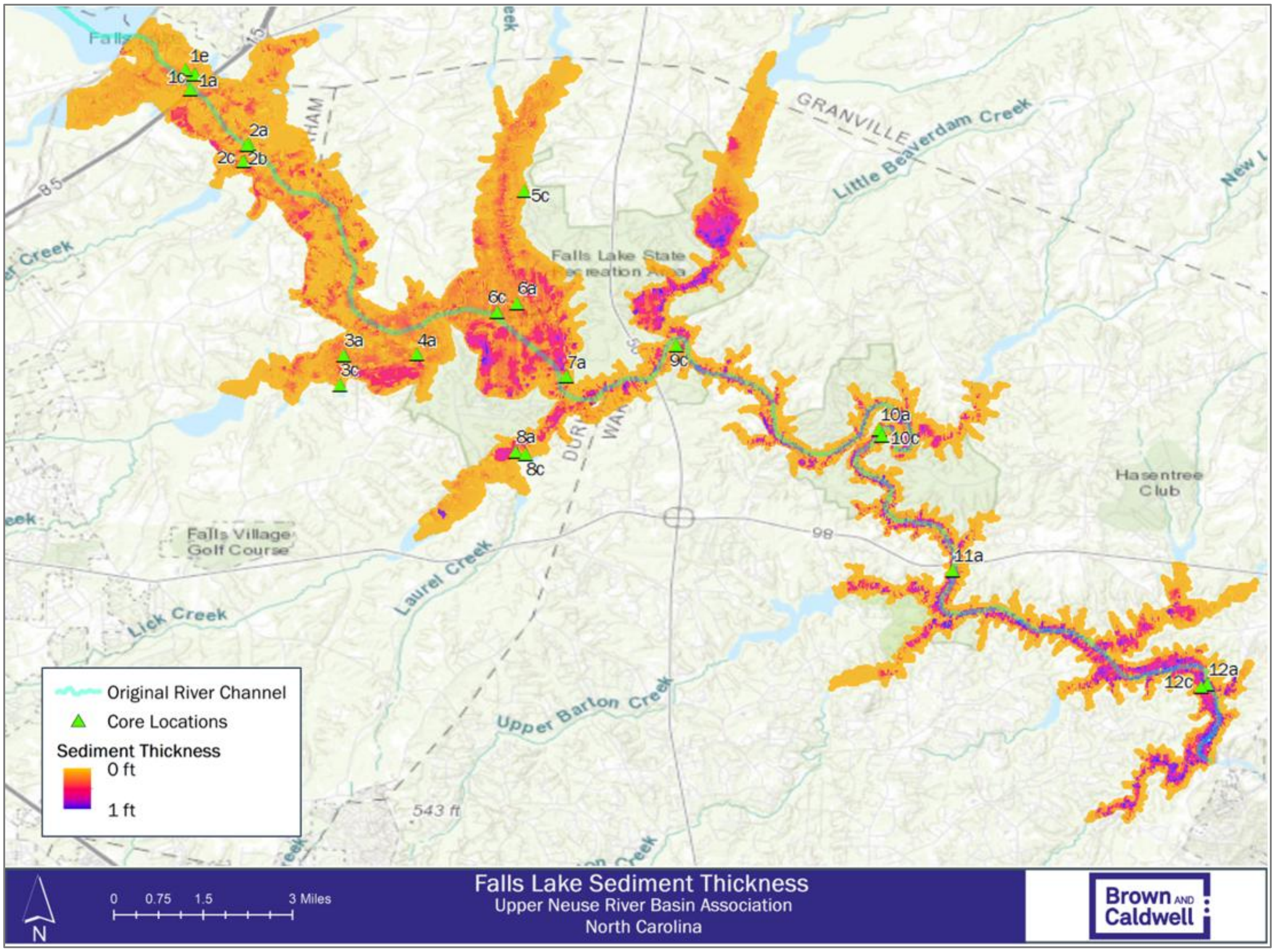

Figure 4-11. Sediment-Depth Accumulation and Location of Sediment Cores in Falls Lake

Table 4-6 summarizes the estimated flux rates or lake-wide loading estimates reported by each study. Estimated rates vary widely within and across the studies because conditions across sites are very different in terms of the amount of organic material that accumulates and subsequently decays. Water temperatures and the presence of oxygen also affect nutrient releases from lake sediments. The more sites monitored in a study, the wider the range of reported flux rates. Empirical models that apply these data using other information about Falls Lake (sediment depth and oxygen profiles) and mechanistic models that simulate the settling and decay of organic material provide additional information regarding the importance of internal nutrient loading from lake sediments. Calibration of simulated water quality with WARMF Lake and EFDC constrains the amount of nutrients that can be simulated as released from the sediments. If a model greatly overestimates the nutrient releases from the lake sediments to the water column, that could also increase simulated water column concentrations and potentially impede calibration of the water column concentrations. If the lake is strongly stratified, the mixing of bottom water and surface water is limited. During fall turnover, high bottom water concentrations can be moved to the surface layers of the lake.

In 2022, Daniel Obenour and Smitom Borah provided literature reviews of internal nitrogen and phosphorus loading from eutrophic and hypereutrophic reservoirs. These reviews provide context for the Falls Lake-specific studies and how those compare to other lakes and reservoirs. The literature review demonstrates generally higher phosphorus fluxes for eutrophic reservoirs. The reviews have been compiled in Appendix E of this report.

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Table 4-6. Summary of Studies Related to Internal Nutrient Releases from Falls Lake Sediments	
Organization, Month-Year, Method, Locations	**Observations**
DWR, April 2006, benthic chambers Site 1 –NEU018E (upstream from Hwy 50) Site 2 –NEU013B (downstream from Hwy 85) Summarized in the UNRBA 2019 Monitoring Report	Site 1: Results from the Nutrient Flux testing showed no significant increase of TKN, NO_2 + NO_3, or P total concentrations in the bottom waters. Ammonia (avg. +0.01 g/m^2/day) was being released from the sediment into the overlying water during the day of the test. The NH_3 flux rate for replicate chambers ranged from +0.008 gr/m^2/day to +0.0132 gr/m^2/day. Water temperature was ~19.8°C. Site 2: NH_3 (avg. + 0.05 g/m^2/day) was being released from the sediment into the overlying water during the day of the test. The NH_3 flux rates for replicate chambers ranged from +0.043 gr/m^2/day to +0.058 gr/m^2/day. Nutrient results for Site 2 also indicate TKN flux entering the bottom water from the sediment. Concentrations of NO_2 +NO_3 and P total were not significantly increasing in the bottom water at Site 2 as a result of nutrient flux. Water temperature was ~20.3°C.
Dr. Marc Alperin, June and July 2015, sediment cores at 27 locations including channel, slope, and shelf locations (Alperin 2018)	Deeper stations had much higher (two orders of magnitude) bottom water ammonia concentrations than shallow stations; nitrate and phosphate concentrations averaged less than 0.01 mg/L and were similar across all stations. Ammonia flux rates ranged from 0.001 to 0.09 g/m^2/day and phosphate flux ranged from 9.3E-6 to 0.0005 g/m^2/day. Nitrogen fluxes from sediment cores collected along the main stem were more than three times higher than cores collected nearby, but outside of the historic channel. Nitrogen fluxes were lower in the upper, shallow segment of Falls Lake. At deeper stations in the middle lake, sediments accumulate, and nitrogen releases are higher. The lower lake has somewhat uniform nitrogen releases more typical of the upper, shallow part of the system. The Falls Lake sediments contain a reactive pool of organic material that may release nutrients for 10 to 40 years depending on the location, hypothetically assuming no additional inputs of nutrients or organic material to the lakebed.
EPA, June 2018, benthic chambers in the upper, middle, and lower lake (Flexner 2019); summarized in the UNRBA 2019 Monitoring Report	NH3 flux rates ranged from 0.023 g/m2/d at the upper lake to 0.161 g/m2/d at the lower lake. Total phosphorus flux rates ranged from -0.0024 g/m2/d at the upper lake (a net loss) to 0.02 g/m2/d in the lower lake.
UNRBA Integration of sediment depth and oxygen profile data (UNRBA 2019 Monitoring Report) Lake wide estimates using sediment depth data collected at over 4 million locations in the lake and dissolved oxygen profile data collected at DWR lake monitoring stations.	Intersection of the sediment depth data with the sediment cores sampled by Dr. Marc Alperin in the channel, slope, and shelf of the lake at 27 locations showed a strong correlation between nitrogen release and sediment depth. The observed relationship was used to estimate lake wide nitrogen releases (approximately 200,000 lb-N/yr, approximately 12 percent of the watershed load) using the sediment depth data collected by UNRBA. Phosphorus releases were estimated at 14,000 lb-P/yr, approximately 12 percent of the watershed load. Phosphorus estimates were based on porewater and overlying water phosphorus concentrations to estimate diffusive flux and the Nürnberg (2009) equation to estimate phosphorus flux under low dissolved oxygen conditions. Phosphorus releases occur through diffusion processes and are more significant during anoxic (low oxygen) conditions at the sediment water interface. Spatial evaluation of bottom dissolved oxygen data was used to estimate phosphorus fluxes associated with the sediment cores.
Dr. Michael Piehler, sediment cores Six main lake (October 2019, May 2020, and August 2020) and six tributary locations (July 2021); (NC Collaboratory 2023, Piehler 2020, and Smiley et al. 2023)	Denitrification removes roughly the amount of ammonia released from lake sediments (approximately 240,000 kg-N/yr or 530,000 lb-N/yr) (Smiley et al. 2023); this estimate is approximately twice that the UNRBA estimates. Phosphate releases are estimated at 4,800 kg-P/yr or 10,600 lb-P/yr (personal communication, Michael Piehler to Alix Matos (December 1, 2022); this estimate is about three-fourths of the UNRBA estimates. Lake wide estimates are based on extrapolation of measurements from the main stem of the lake across the lake bottom.
Hall and Paerl (2023) measured nitrogen fixation rates to constrain the nitrogen budget estimates for Falls Lake. Study included 5 samplings at 6 main channel stations (2019-2020), 5 samplings at 10 tributaries (2021), and 2 summer samplings at 6 main channel and 10 tributary stations (2022).	Tributary stations fix more nitrogen than the main stem lake stations. Nitrogen fixation is approximately 2,300 kg N/yr or 5,000 lb-N/yr (approximately 1 percent of nitrogen load from the watershed). Estimates loss of nitrogen from denitrification at 74,000 kg-N/yr or 163,000 lb-N/yr (approximately 10 percent of the watershed load).

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Table 4-6. Summary of Studies Related to Internal Nutrient Releases from Falls Lake Sediments	
Organization, Month-Year, Method, Locations	Observations
Estimated internal phosphorus loading from Piedmont reservoirs (Appendix E)	Internal phosphorus loading can delay water quality improvements by 10-100 years. In Jordan Lake, phosphorus releases from lake sediments have been steady over the past four decades. Phosphorus releases are largest in the summer months; releases ranged from approximately 0.1 $g/m^2/month$ (0.003 $g/m^2/d$) in the winter months to approximately 0.5 $g/m^2/month$ (0.017 $g/m^2/d$) in the summer months. Nitrogen releases from Jordan Lake sediments ranged from 2.62 $/m^2/month$ (0.087 $/m^2/d$) in the winter to 9.25 $/m^2/month$ (0.308 $g/m^2/d$) in the summer.

Figure 4-12 and Figure 4-13 summarize the total nitrogen and total phosphorus loading, respectively, from lake sediments to each Falls Lake segment. These estimates are based on the EFDC simulations for 2014 to 2018 as described in Section 5 and summarized here for comparison to other historic loading estimates. Estimates are not available for previous years. Following reservoir filling, internal nutrient loading was likely higher due to the decay of vegetation and debris that remained on the lake bottom. However, the contribution of lake sediments to the total load is relatively small. To extend the period of the nutrient loading estimates across the past four decades, the statistical/Bayesian model assumes the same seasonal nutrient releases from lake sediments across all model years. While this is not likely accurate, particularly in the earlier years, it should not greatly affect the categorization of loading to Falls Lake as relatively high, moderate, or low. Loads are presented in units of 1,000 pounds for easier visibility. For the statistical/ Bayesian model, water quality data are compared to the preceding 30-day estimate of nutrient loading to the lake. These figures display the preceding 30 days of load for input to the statistical/Bayesian model.

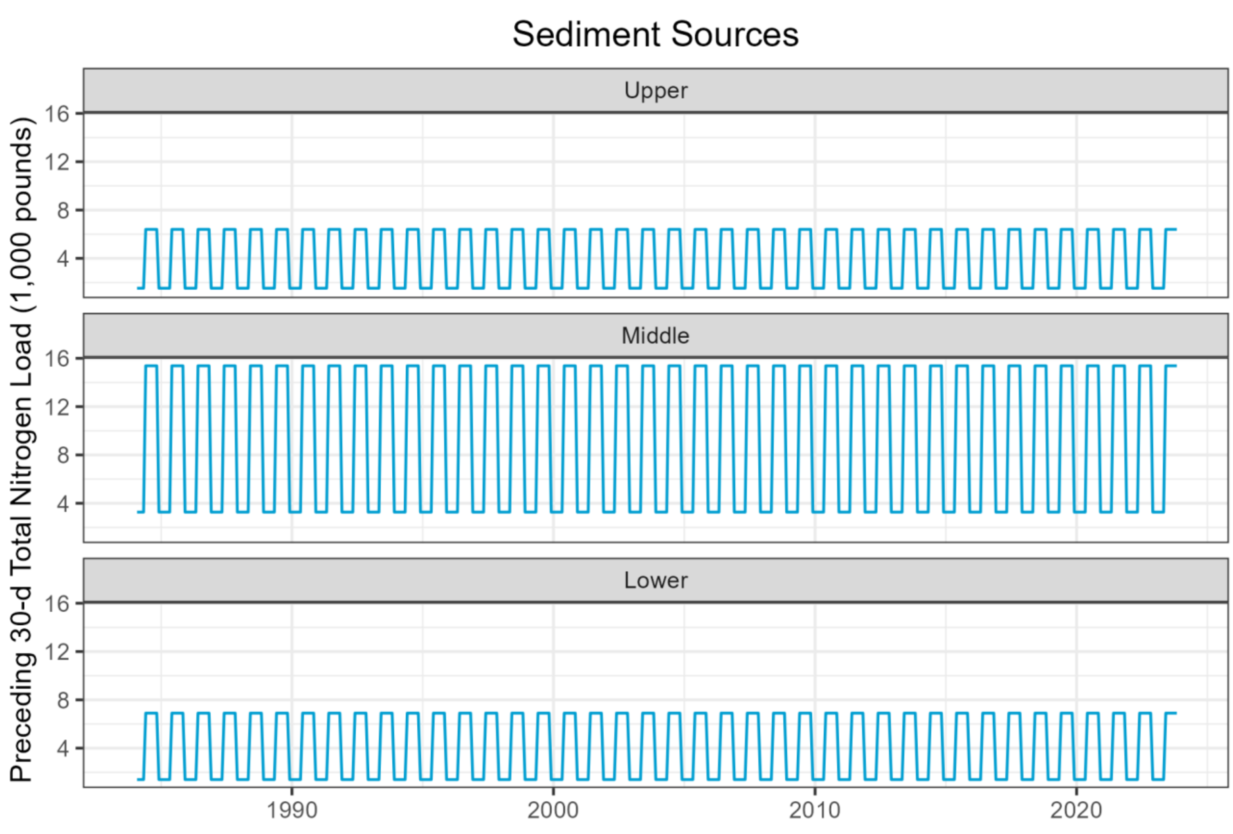

Figure 4-12. Preceding 30-day Total Nitrogen Load to Falls Lake Segments from Lake sediments

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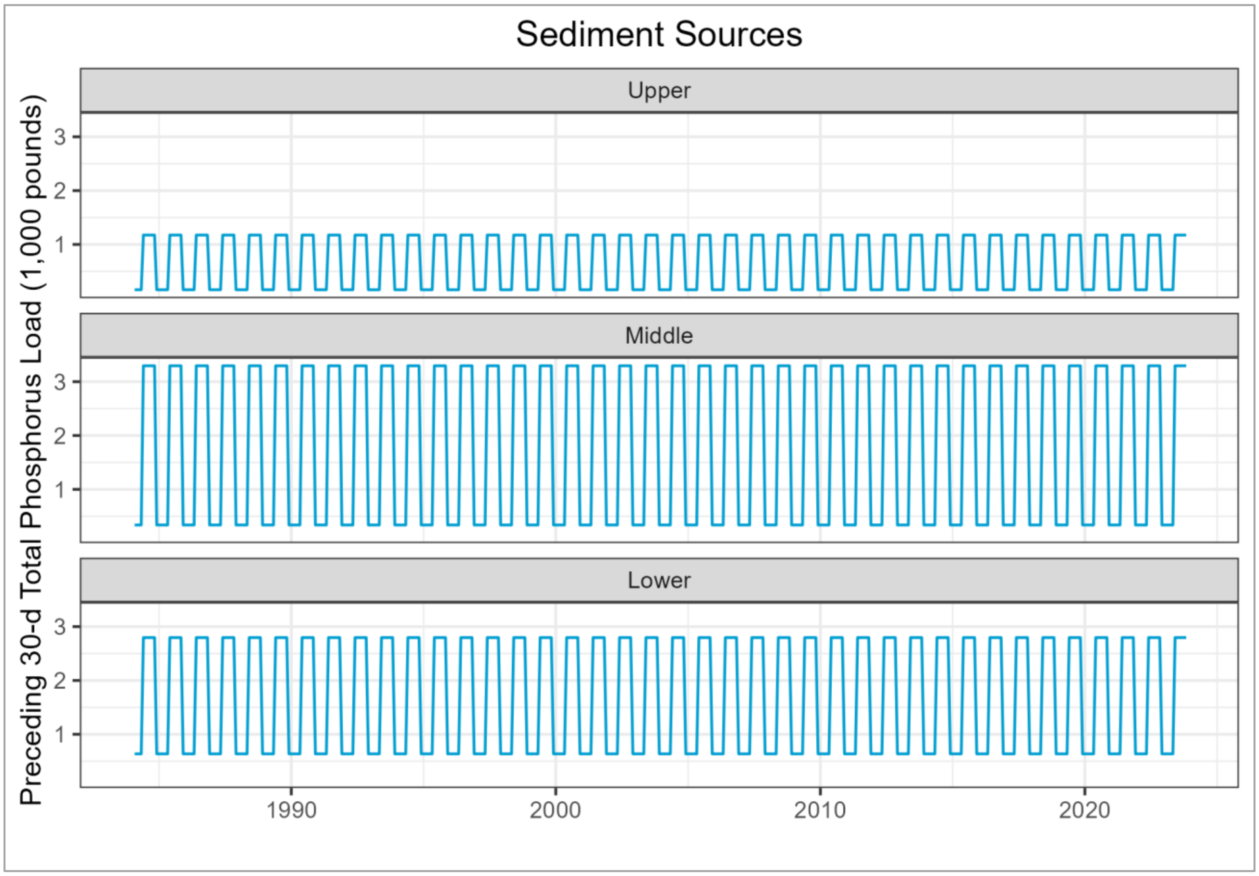

Figure 4-13. Preceding 30-day Total Phosphorus Load to Falls Lake Segments from Lake Sediments

4.4 Long-Term Estimates of Loading from Upstream to Downstream Falls Lake Segments

In addition to loads from tributaries, atmospheric deposition, and lake sediments, the UNRBA Statistical/Bayesian model also includes estimates of load from each upstream lake segment to the downstream segment. To develop transport factors from one segment to the next, SPARROW regression equations for impoundments (Moorman et al. 2014) were used. This approach was summarized previously by (Cardno ENTRIX 2014) to estimate trapping in and transport from impoundments in the Falls Lake watershed.

Annual average tributary flows for the upper five tributaries were downloaded from USGS for each of the downstream flow gages (Table 4-4). For years where the annual average flow statistic was not available, an estimate was generated by scaling the average annual flow on the Eno River to the ratio of the average annual flows of the tributary to the Eno River. A ratio of flows was used rather than drainage area because these tributaries either have a large sub-impoundment or a major wastewater treatment plant. For the non-gaged tributaries which have neither a large sub-impoundment nor a major wastewater treatment plant, the ratio of the drainage areas was used to scale the average annual Eno River flow.

Hydraulic load for each Falls Lake segment was calculated from the average inflow and segment surface area using the SPARROW method. The annual transport factor of total nitrogen and total phosphorus from the upper segment to the middle segment and the middle segment to the lower segment were calculated for

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1980 to 2022 (Figure 4-14). These annual factors were applied to the monthly loads from the tributaries, atmospheric deposition, and loading from lake sediments to account for the hydrologic variability in transport. During dryer years, less material is transported from one segment to the next relative to wetter years where material is moved through the system more readily. Phosphorus transport is less than nitrogen transport from one segment to the next due to settling of phosphorus sorbed to sediments. These factors are rough estimates of historic transport of material based on annual hydrologic condition, but sufficient to characterize the relative loading to each segment as very low, low, moderate, high, or very high.

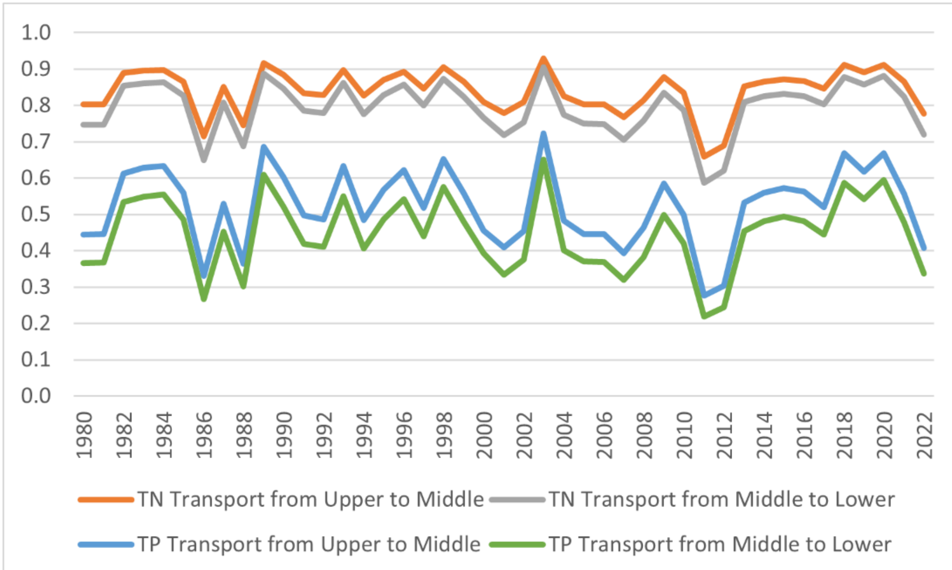

Figure 4-14. Annual Transport Factors from Upstream Segments Applied to Monthly Loads Delivered to Falls Lake

Figure 4-15 and Figure 4-16 summarizes the passthrough loading from the upper segment to the middle segment and the middle segment to the lower segment for total nitrogen and total phosphorus, respectively. Passthrough loads to the upper segment are zero because there is not a segment upstream. Passthrough loads are only estimated if loads from the other three sources are available. Gaps on the figures represent periods where the tributary loading estimate was missing. Loads are presented in units of 1,000 pounds for easier visibility. For the statistical/Bayesian model, water quality data are compared to the preceding 30-day estimate of nutrient loading to the lake. These figures display the preceding 30 days of load for input to the statistical/Bayesian model.

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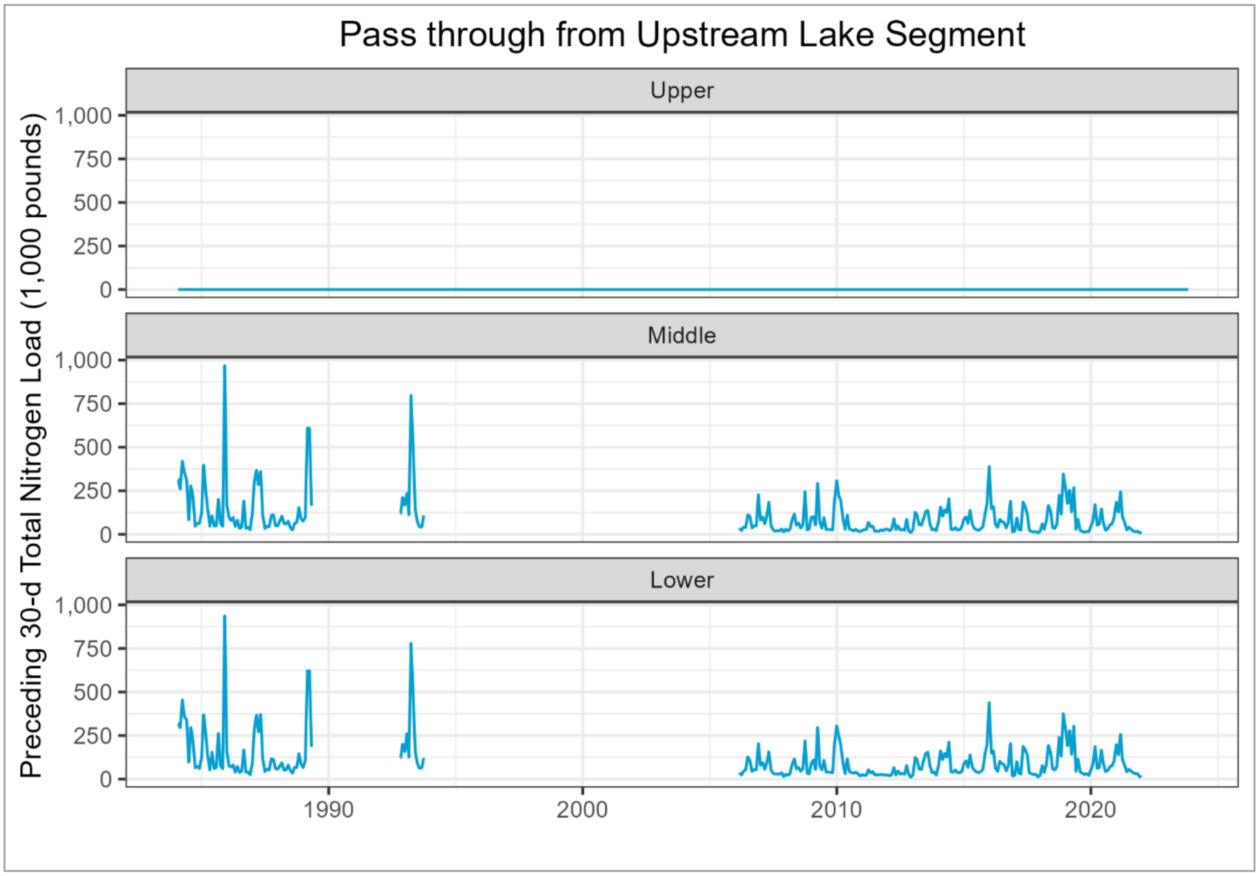

Figure 4-15. Preceding 30-day Total Nitrogen Passthrough Load from the Upstream Segment when Applicable

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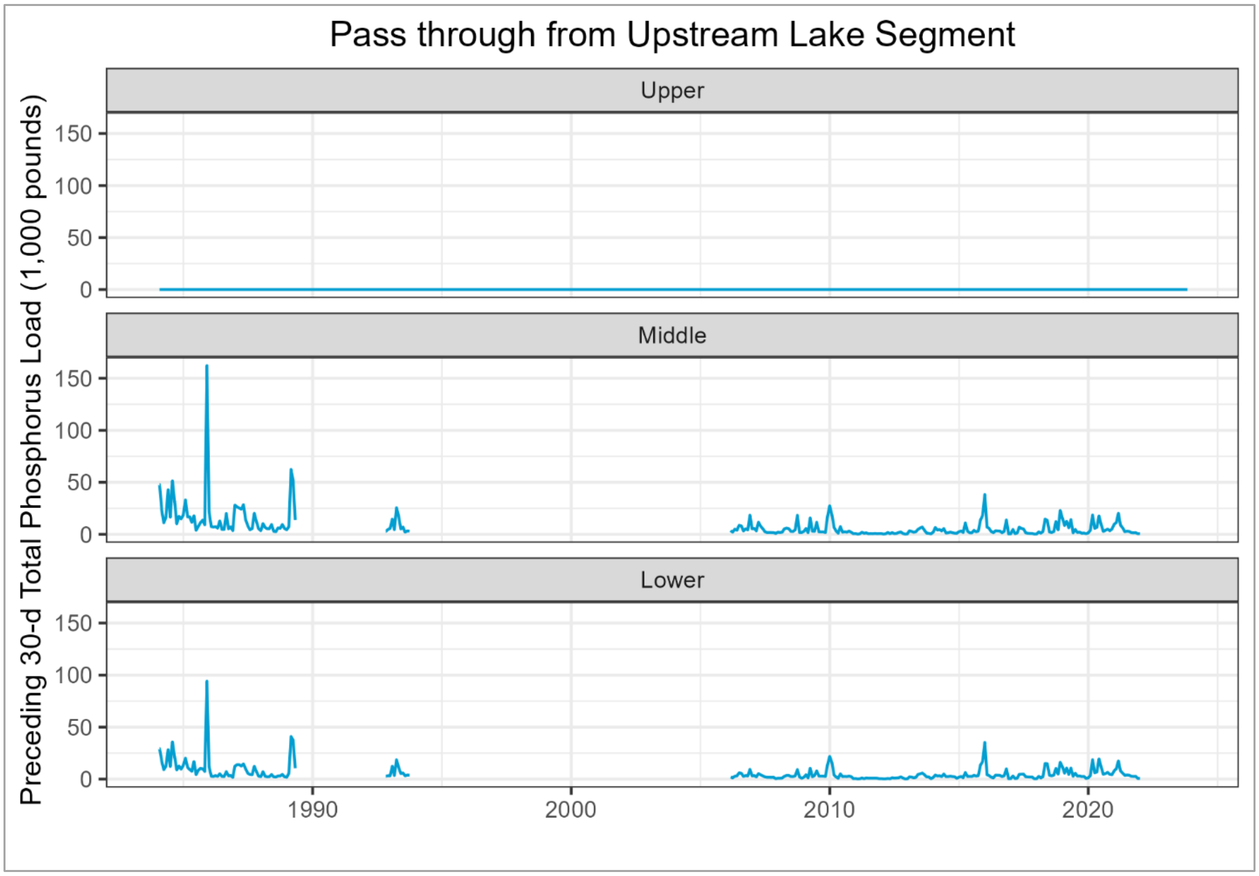

Figure 4-16. Preceding 30-day Total Phosphorus Passthrough Load from the Upstream Segment when Applicable

4.5 Summary of Historic Loading to Falls Lake

Sections 4.1 through 4.4 describe how historic loading estimates for direct atmospheric deposition to Falls Lake, watershed tributary loading, lake sediments, and passthrough from an upstream Falls Lake segment contribute loading to each of the three Falls Lake segments. Figure 4-17 and Figure 4-18 summarize the estimated nutrient loading from all sources to Falls Lake for total nitrogen and total phosphorus, respectively. Gaps in the figures are due to gaps in estimates of tributary loading. Loads of both nutrients have decreased since the 1980s and 1990s. Loads are presented in units of 1,000 pounds for easier visibility. For the statistical/Bayesian model, water quality data are compared to the preceding 30-day estimate of nutrient loading to the segment. These figures display the preceding 30 days of load for input to the statistical/Bayesian model.

For comparison, DWR (2021) evaluated flow-weighted estimates of loading to Falls Lake back to 2006. These values divide the delivered load by the stream flow volume for the five major tributaries to Falls Lake. DWR reports that total nitrogen loads from 2006 to 2019 **decreased by 20 percent**, and the total phosphorus loads **decreased by 50 percent**.

Figure 4-19 and Figure 4-20 show the percent contribution to the total delivered load from direct atmospheric deposition to Falls Lake, watershed tributary loading, lake sediments, and passthrough from an upstream Falls Lake segment. The predominant source of loading to the lake is the 770 square mile watershed.

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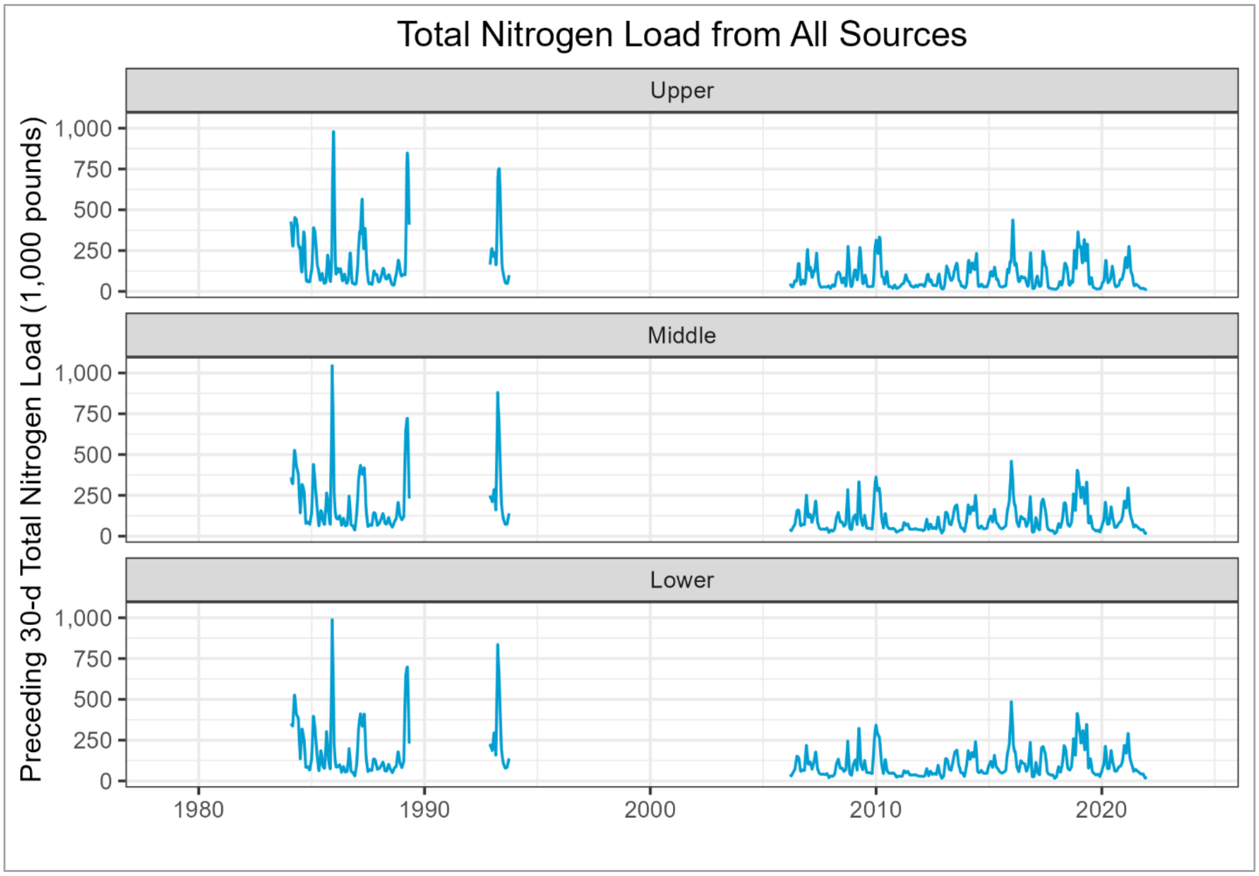

Figure 4-17. Preceding 30-day Total Nitrogen Load to Falls Lake from Atmospheric Deposition, Watershed Tributary Loading, Lake Sediments, and Passthrough from the Upstream Segment

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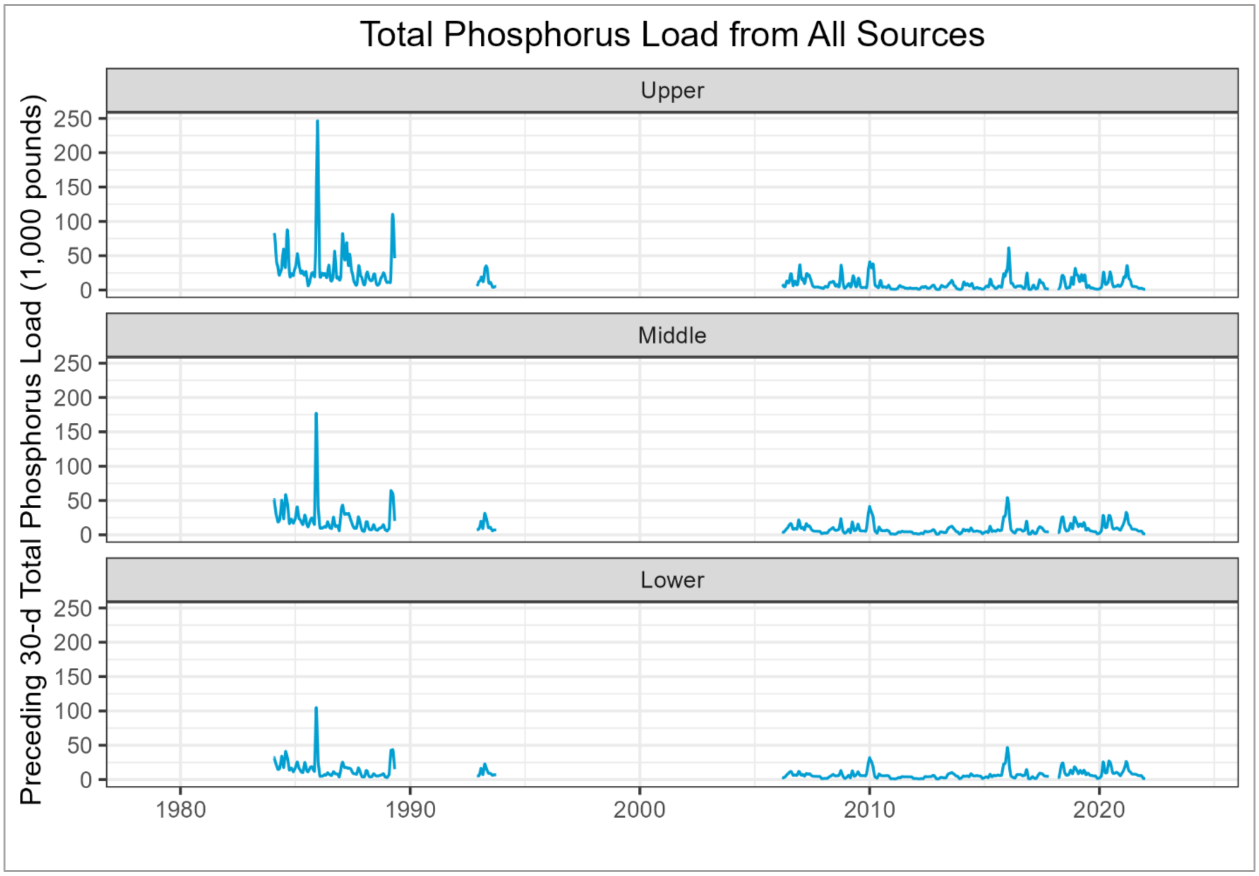

Figure 4-18. Preceding 30-day Total Phosphorus Load to Falls Lake from Atmospheric Deposition, Watershed Tributary Loading, Lake Sediments, and Passthrough from the Upstream Segment

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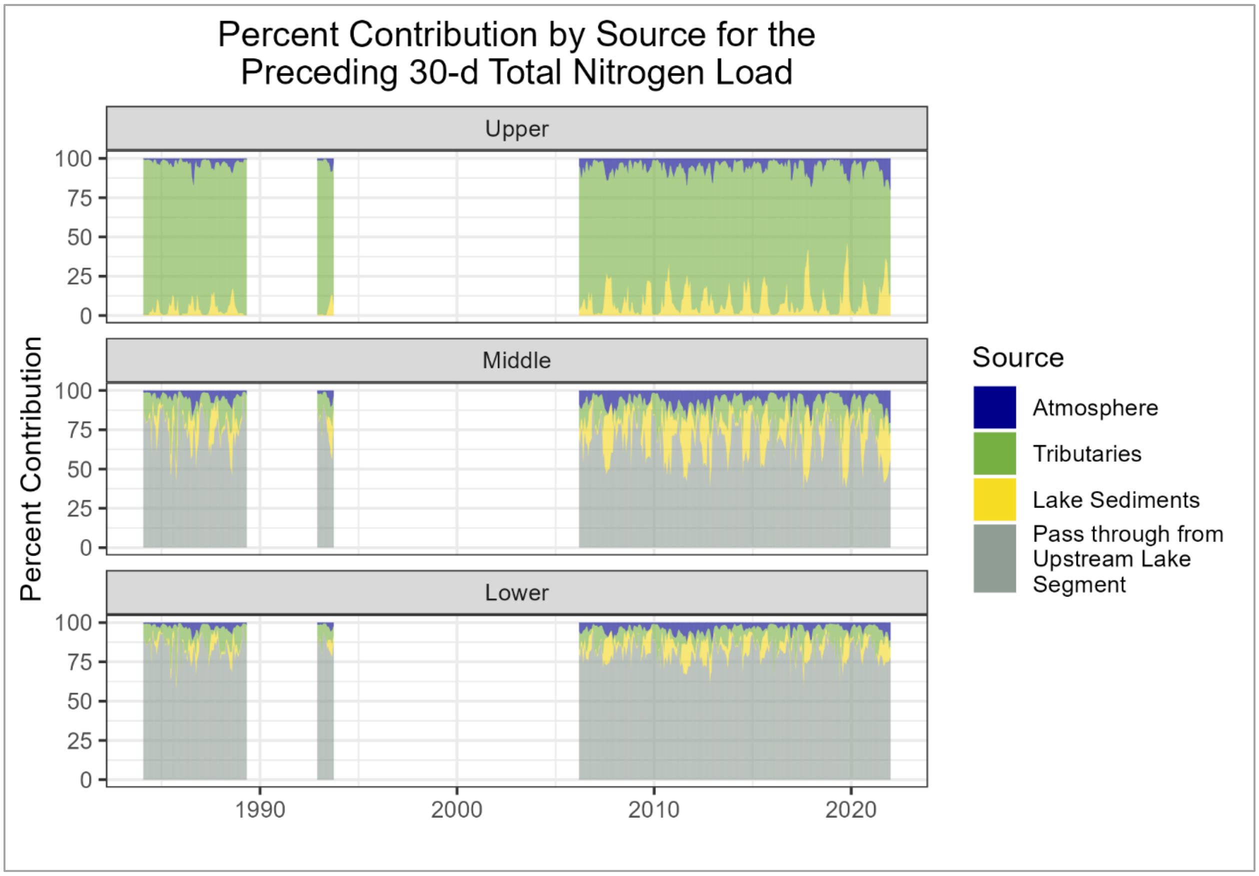

Figure 4-19. Percent Contribution to the Preceding 30-day Total Nitrogen Load to Falls Lake from Atmospheric Deposition, Watershed Tributary Loading, Lake Sediments, and Passthrough from the Upstream Segment

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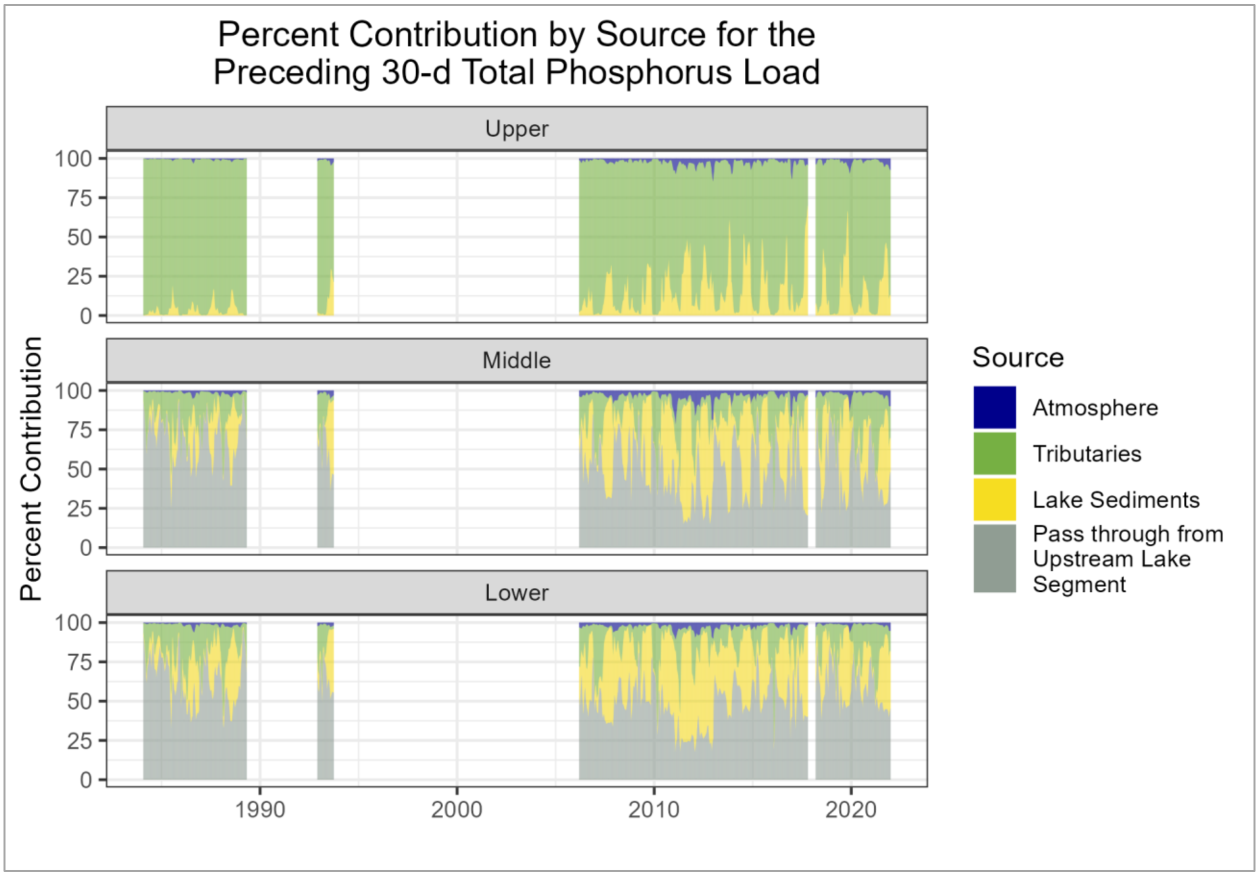

Figure 4-20. Percent Contribution to the Preceding 30-day Total Phosphorus Load to Falls Lake from Atmospheric Deposition, Watershed Tributary Loading, Lake Sediments, and Passthrough from the Upstream Segment

Annual nutrient loads can also be weighted by the annual precipitation. Regulated entities complying with air and water quality requirements have achieved significant reductions in precipitation-weighted loading since the 1980's (Figure 4-21). The timing of rainfall events also affects delivered load. The same amount of annual rainfall occurring over several large storm events will deliver more load than if the rain occurs as smaller storms throughout the year. Back-to-back large storms saturate soils and result in higher stream flows and delivered loading.

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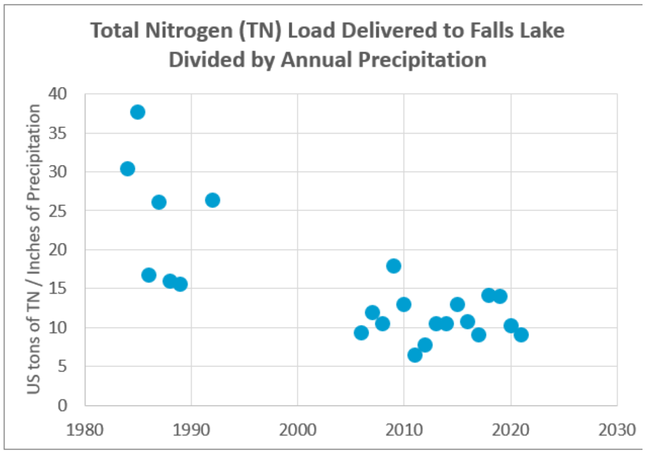

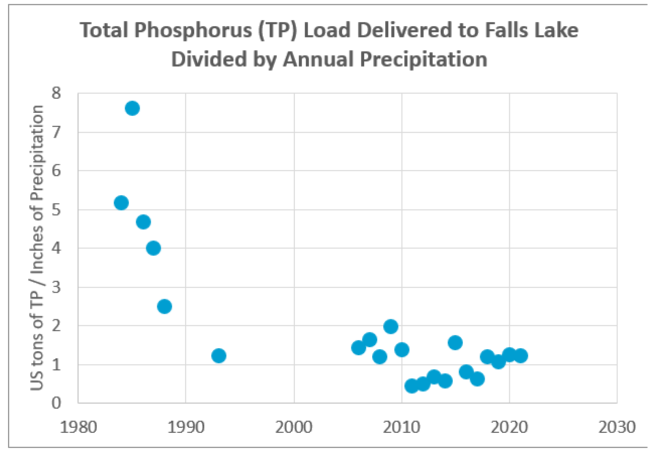

Figure 4-21. Precipitation-Weighted Total Nitrogen (left) and Total Phosphorus (right) Loads to Falls Lake

4.6 Residence Time

Residence time indicates the average amount of time a parcel of water resides in a waterbody before being discharged downstream. Longer residence times allow more time for algal growth and shift the proportion of nutrient loading coming from lake sediments rather than upstream watershed sources. For Falls Lake, the residence time is controlled by bathymetry and the inflows to and outflows from the lake. These include inflows from the upstream watershed, lake operations controlled by the USACE, water supply withdrawals by the City of Raleigh, evapotranspiration from the lake surface, and precipitation to the lake surface. Assessments for 1990 to 2020 were developed based on availability of tributary inflow data, reservoir outflow data, and water level data.

Figure 4-22 shows the 30-day, rolling average residence time using rank-based bins which have an equivalent number of observations in each bin. For residence time, three bins are used to categorize the data with one-third of the values in each bin. The low bin (yellow) has a 30-day, rolling average residence time less than 90 days. The moderate bin has a 30-day, rolling average residence time between 90 and 323 days. The high bin has a 30-day, rolling average residence time greater than 323 days. The overall median value of the 30-day rolling average is 215 days. One very extreme event (2007 historic drought) is a pronounced outlier in the residence time series with a residence time over 1500 days.

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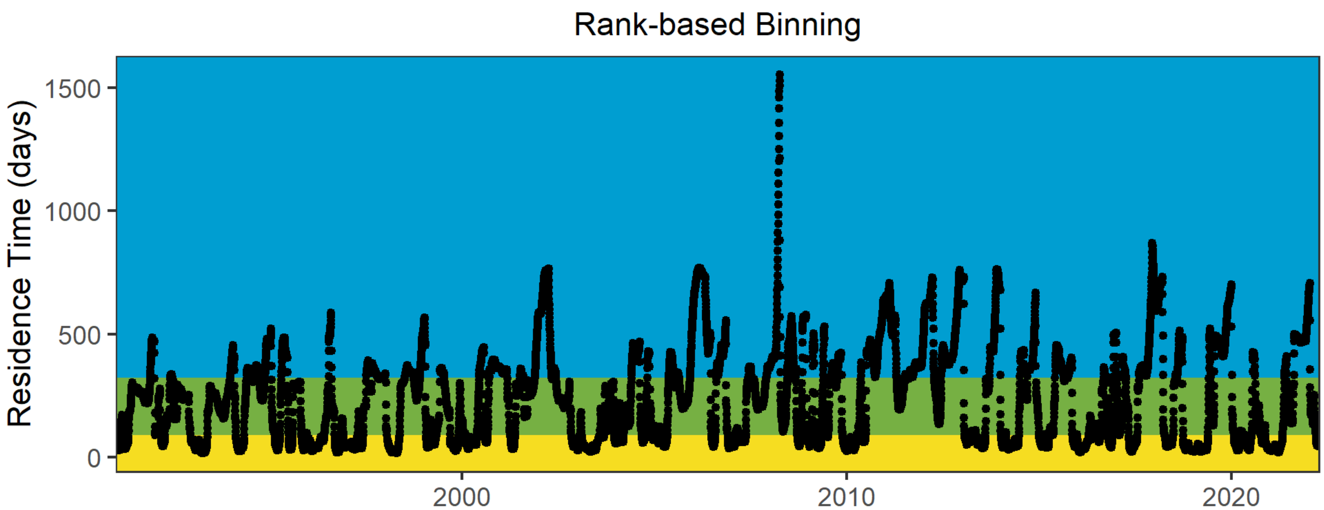

Figure 4-22. 30-day Rolling Average Residence Time with Rank-Based Bins (Equivalent Number of Observations)

4.7 Percent of Lake Volume within Dissolved Oxygen Thresholds

The presence of dissolved oxygen in a waterbody is essential to the survival of aquatic organisms. NC sets an instantaneous minimum dissolved oxygen concentration (4 mg/L) as the water quality standard.

DWR has collected dissolved oxygen profile data in Falls Lake since 1990 (with some gap periods). Brown and Caldwell used this profile data, USGS water level data, and the UNRBA bathymetric survey data to estimate the monthly volume of water in Falls Lake within three categories: greater than or equal to 4 mg/L, less than 4 mg/L and above 1 mg/L, and less than 1 mg/L to indicate anoxic conditions.

Figure 4-23 shows the monthly estimates as a percentage of the total volume for the areas of the lake upstream or downstream of Highway 50. The volume of the lake upstream and downstream of Highway is approximately equal as summarized in the UNRBA 2019 Monitoring Report. Seasonal cycles are evident with higher percentages of low dissolved oxygen water in the warmer summer months when the lake becomes stratified. There is generally a greater volume of low dissolved oxygen water downstream of Hwy 50 where the reservoir is much deeper. Even in the warmer season, approximately half of the lake has dissolved oxygen concentrations above 4 mg/L, so there are always well oxygenated waters present in Falls Lake.

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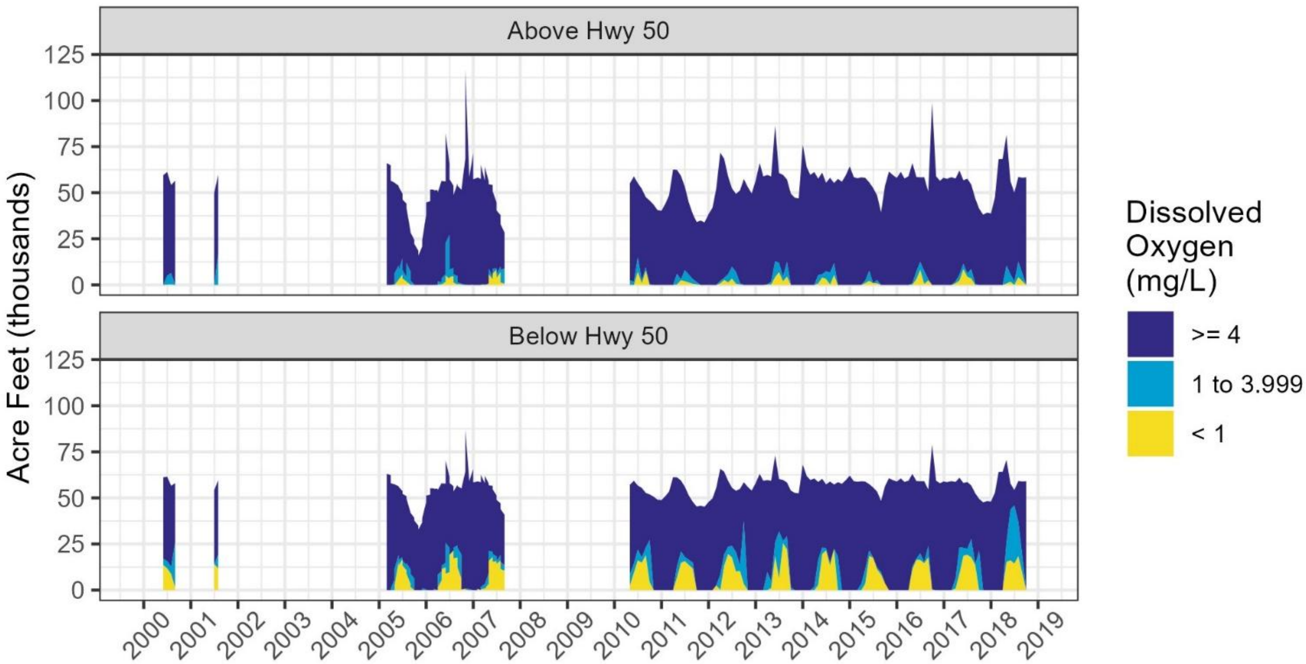

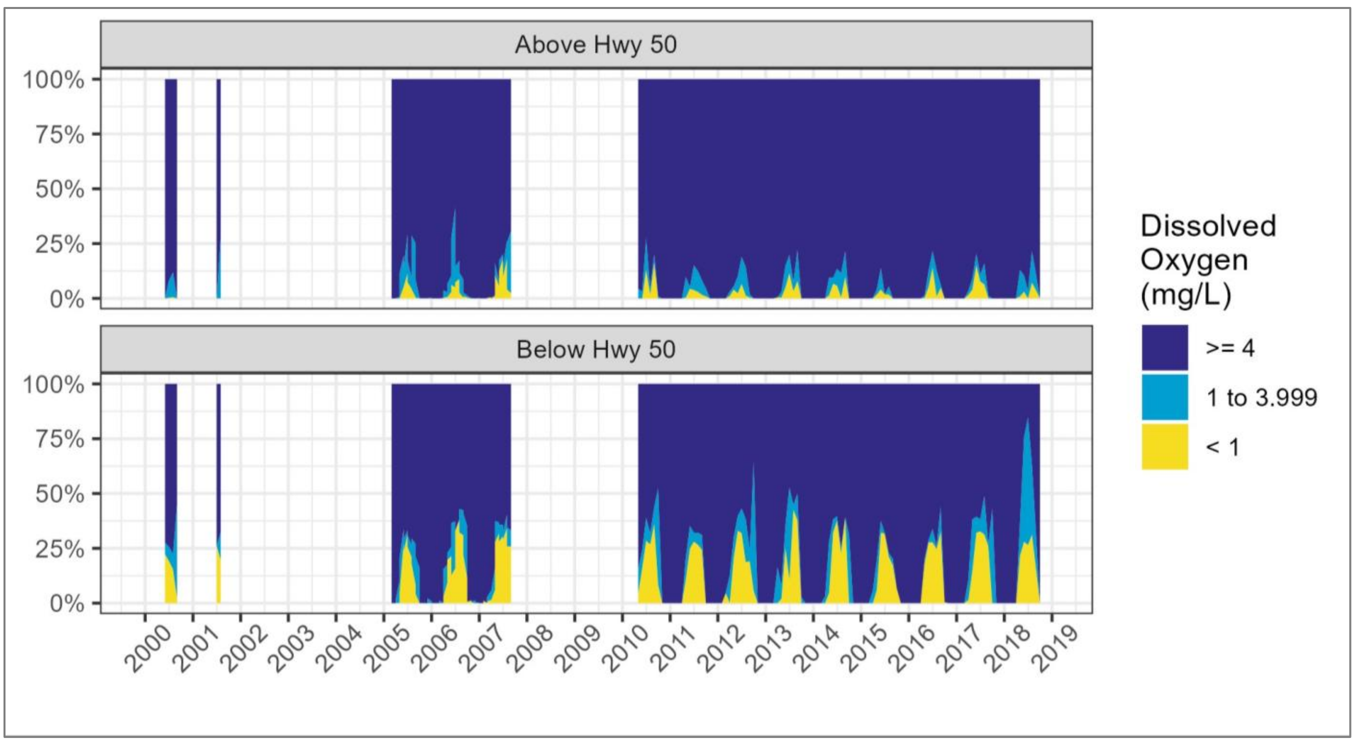

Figure 4-23. Monthly Mean Dissolved Oxygen Volume (top) and Percent of Total Lake Volume (bottom); gaps are due to lack of data

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Figure 4-24 shows the monthly percentage of the volume across the entire lake that is less than 4 mg/L. The low category (yellow) represents one-third of the estimates where DO was less than 4 mg/L; the percent of lake volume containing DO concentrations less than 4 mg/L is less than 0.03 percent of the total volume for one-third of the estimates. The moderate category (green) represents the middle third of the estimates where the percent of the lake volume with DO concentrations less than 4 mg/L is between 0.03 percent and 15.6 percent of the total volume. The high value represents the top third of the estimates where the percent of the lake volume with DO concentrations less than 4 mg/L is higher than 15.6 percent. The overall median for the estimates is 3.1 percent of the lake volume having less than 4 mg/L of DO.

Figure 4-25 shows the profile measurements of dissolved oxygen concentration data for the entire lake with bins assigned for less than 1 mg/L, between 1 mg/L and less than 4 mg/L, and greater than 4 mg/L. The profile measurements were used to estimate the percent of lake volume above or below a threshold. For the UNRBA Statistical/Bayesian model, only concentrations collected within the photic zone were included.

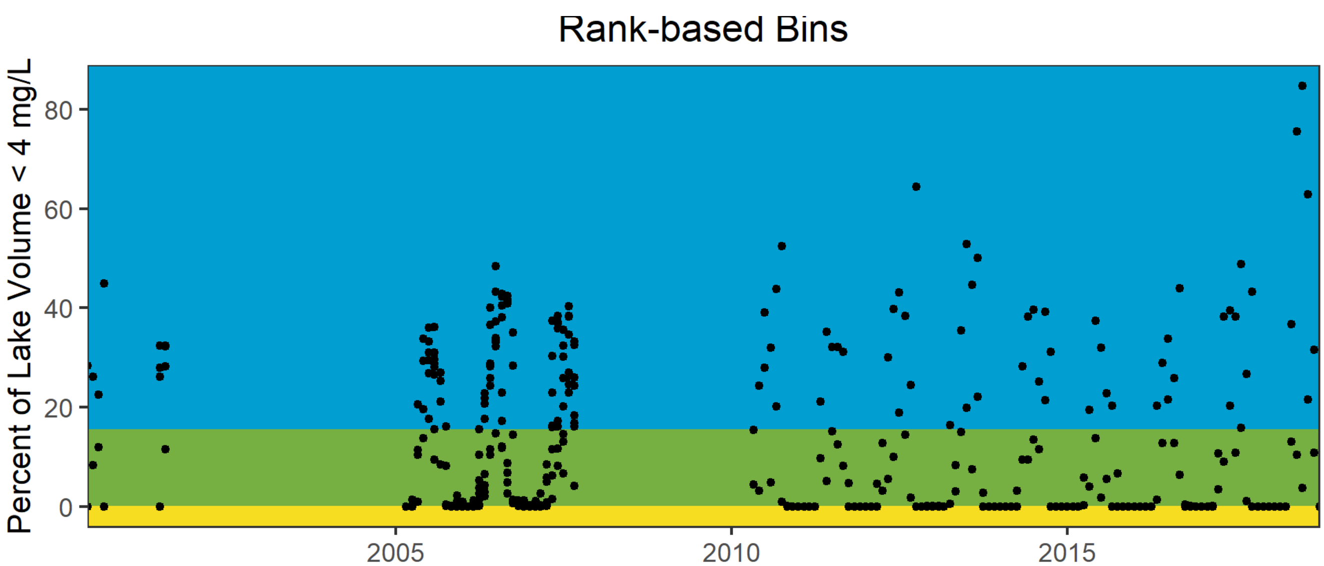

Figure 4-24. Monthly Percent of Lake Volume Less than 4 mg/L Dissolved Oxygen with Rank-Based Bins (Equivalent Number of Observations in Each Bin)

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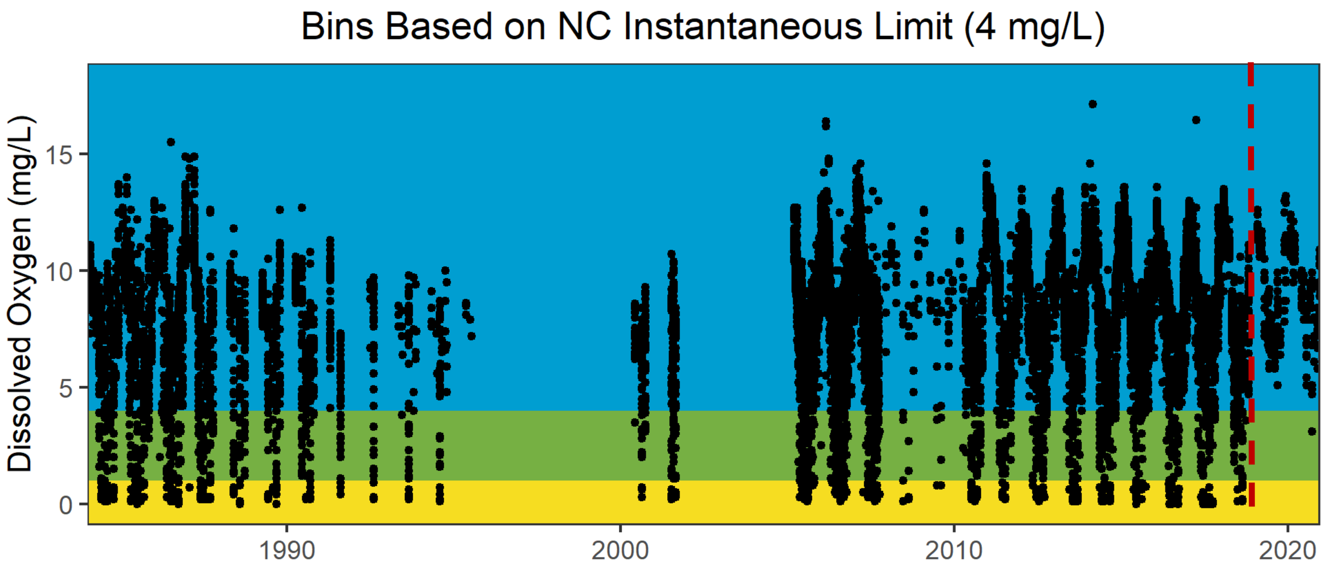

Figure 4-25. Depth Profile Dissolved Oxygen Concentrations with Bins Based on Thresholds of 4 mg/L and 1 mg/L (data available on STORET after 2018 do not include depth profile measurements; see dashed line)

4.8 Dissolved Oxygen Measurements within the Top Four Meters of the Lake Surface

Section 4.7 presents dissolved oxygen (DO) measurements collected from the surface to near-bottom of Falls Lake (profile measurements) to calculate the percent of the lake volume within the regulatory thresholds. Because the percent of lake volume estimates did not change significantly through time other than having a strong, repeated seasonal signal, the UNRBA Statistical/Bayesian model was developed to evaluate conditions for the photic zone. Profile measurements were screened to exclude those collected at greater than four meters depth to approximate those collected from the photic zone.

Figure 4-26 shows the measurements collected in all three lake segments through time relative to the regulatory bins. Data collected after 2018 do not include depth profile measurements and are assumed photic-zone composite measurements. Prior to this change, there are measurements of DO less than 4 mg/L within four meters of the lake surface. After this change there are very few. Assuming samples within the four-meter depth are representative of the photic zone may not be accurate, and the model may represent a higher distribution of concentrations that are lower than the regulatory thresholds when that appears unlikely.

Figure 4-27 displays the monthly distributions of the data. Concentrations are most impacted by season in the upper lake, with lower concentrations observed during the summer months. This trend dampens moving downstream to the middle and then lower segments of Falls Lake. Figure 4-28 shows the annual distributions of dissolved oxygen collected at less than four meters depth. In the upper part of the lake, dissolved oxygen concentrations have increased over time. This signal is still present but dampens moving from the middle to lower segments of the lake.

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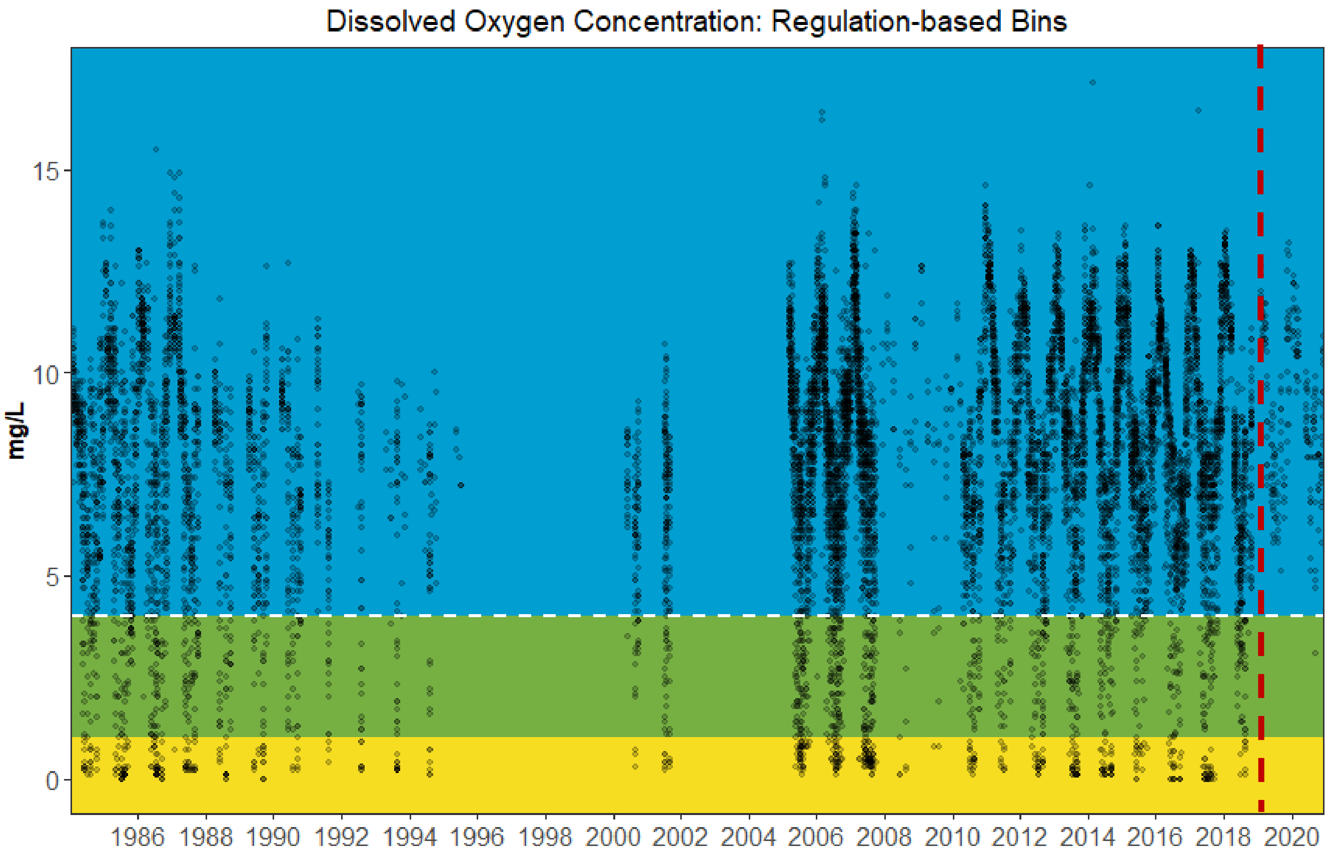

Figure 4-26. Dissolved Oxygen Measurements Collected at Less than Four Meters Depth with Bins Based on Thresholds of 4 mg/L and 1 mg/L (data available on STORET after 2018 do not include depth profile measurements; see dashed line)

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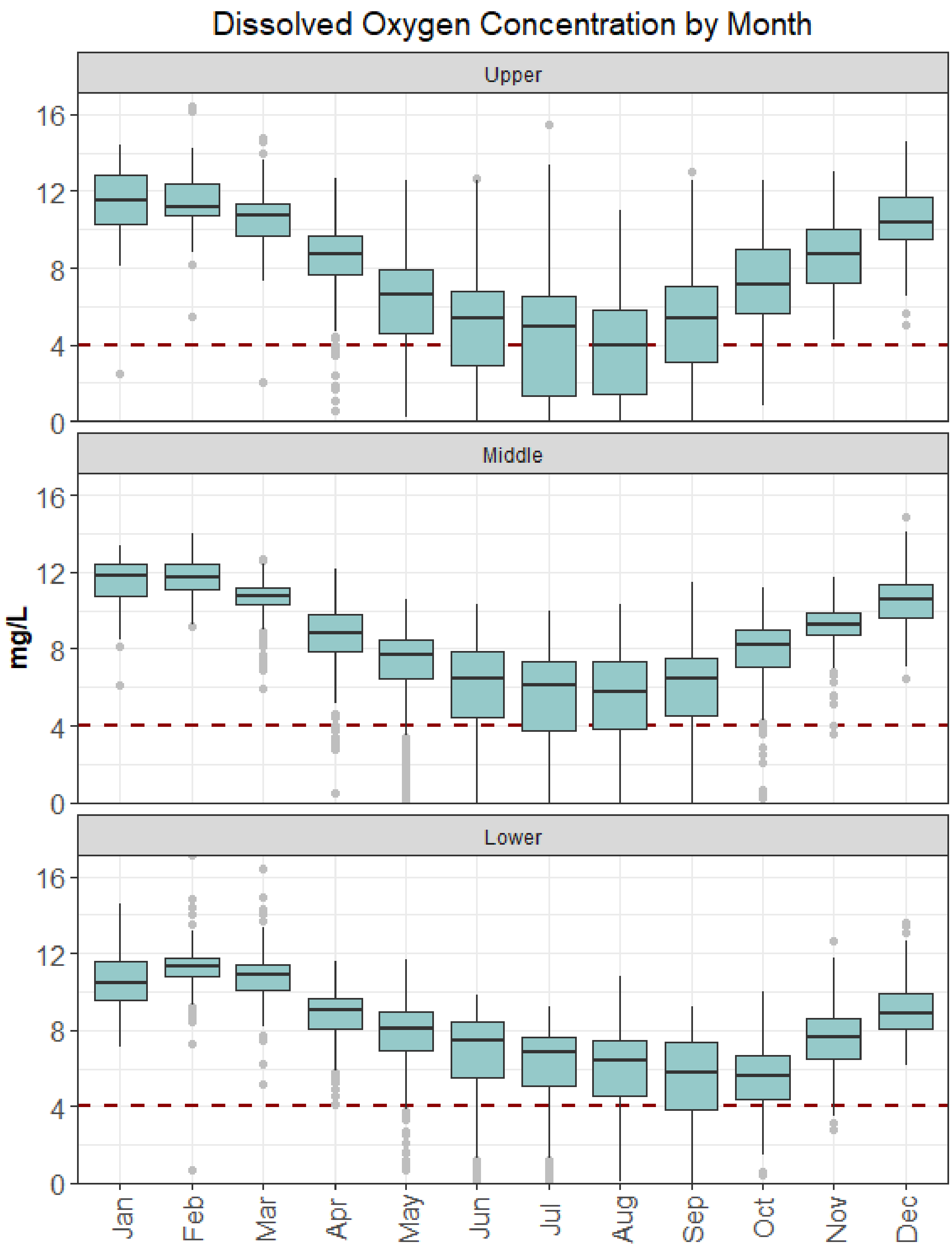

Figure 4-27. Distribution of Dissolved Oxygen Measurements Collected at Less than Four Meters Depth by Month

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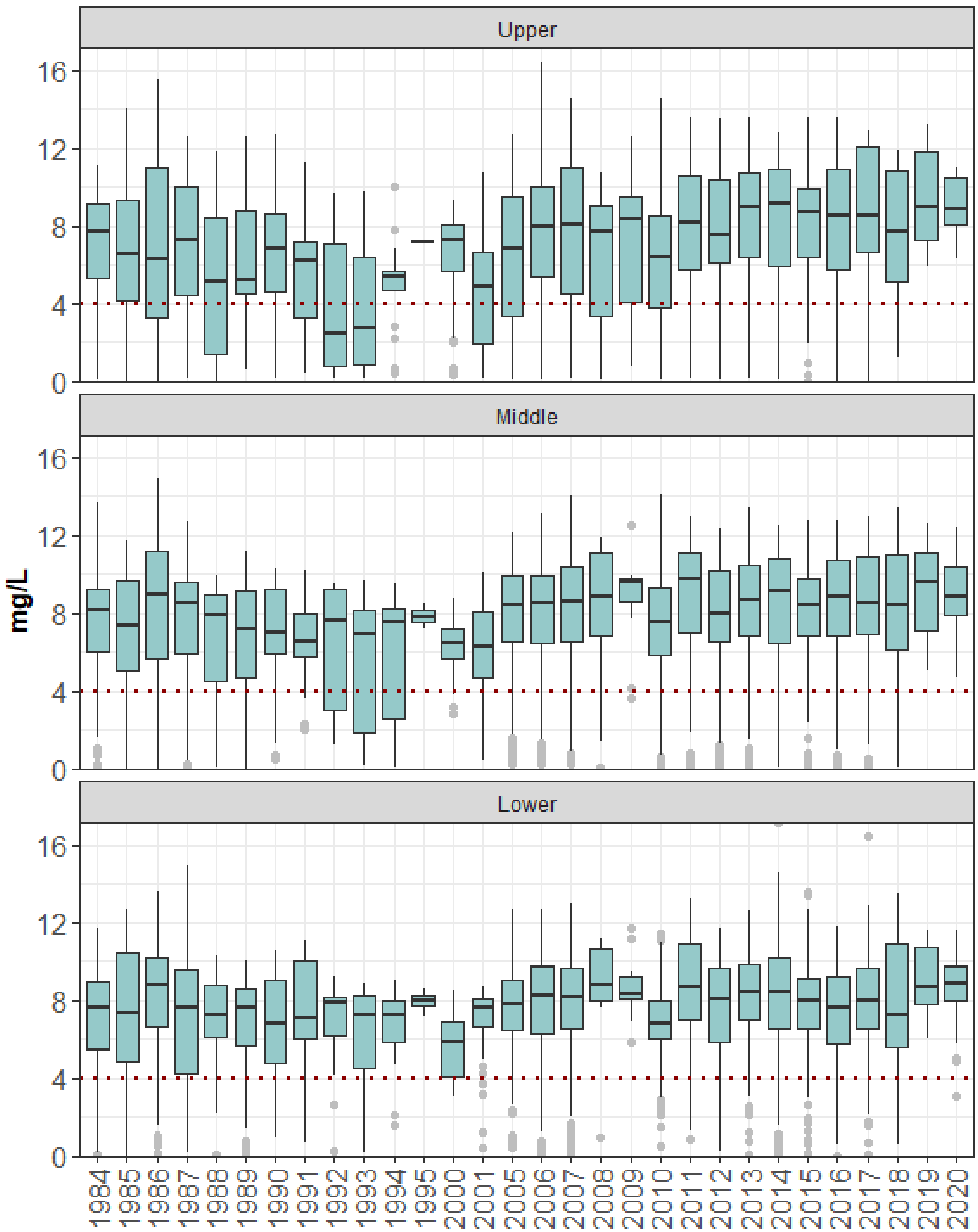

Figure 4-28. Distribution of Dissolved Oxygen Measurements Collected at Less than Four Meters Depth by Year (data

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4.9 pH Measurements within the Top Four Meters of the Lake Surface

The UNRBA Statistical/Bayesian model also includes measurements of pH within the top four meters of the lake surface. The NC water quality standards require that pH remain above 6 and below 9.

Figure 4-29 shows the measurements collected in all three lake segments through time relative to the regulatory bins (less than 6, between 6 and 9, greater than 9). pH measurements outside of the 6 to 9 range occur infrequently. Most of these measurements occurred shortly after the reservoir was filled and in 2018 which was a high rainfall year receiving approximately 60 inches at the Raleigh Durham International airport.

Figure 4-30 displays the monthly distributions of the data. There does not appear to be a strong seasonal signal for pH. Figure 4-31 shows the annual distributions. pH has generally increased in all three segments of the reservoir since it was filled. The majority of the low pH measurements observed in 2018 occurred in the upper segment.

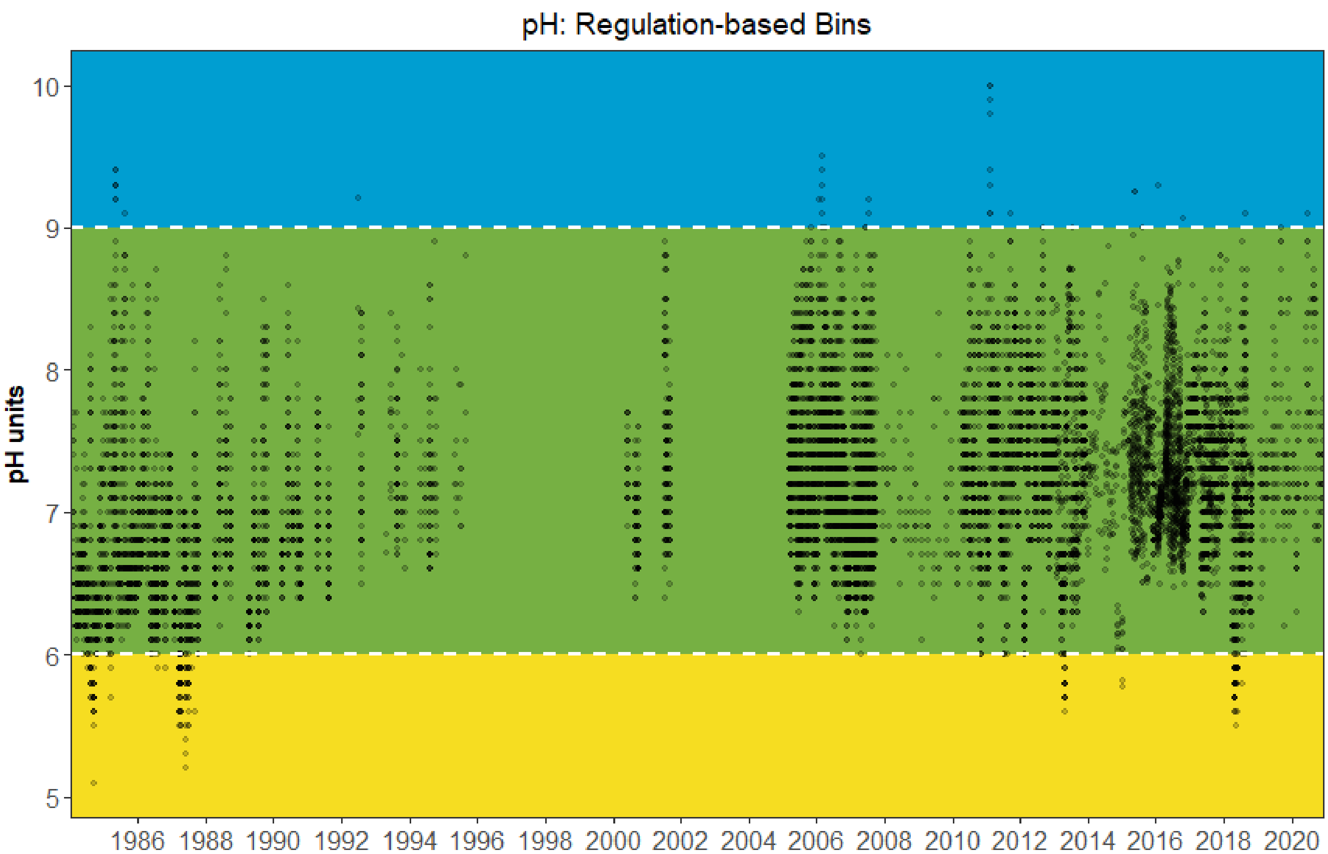

Figure 4-29. pH Collected at Less than Four Meters Depth with Bins Based on Thresholds of 6 and 9

Use of contents on this sheet is subject to the limitations specified at the beginning of this document.

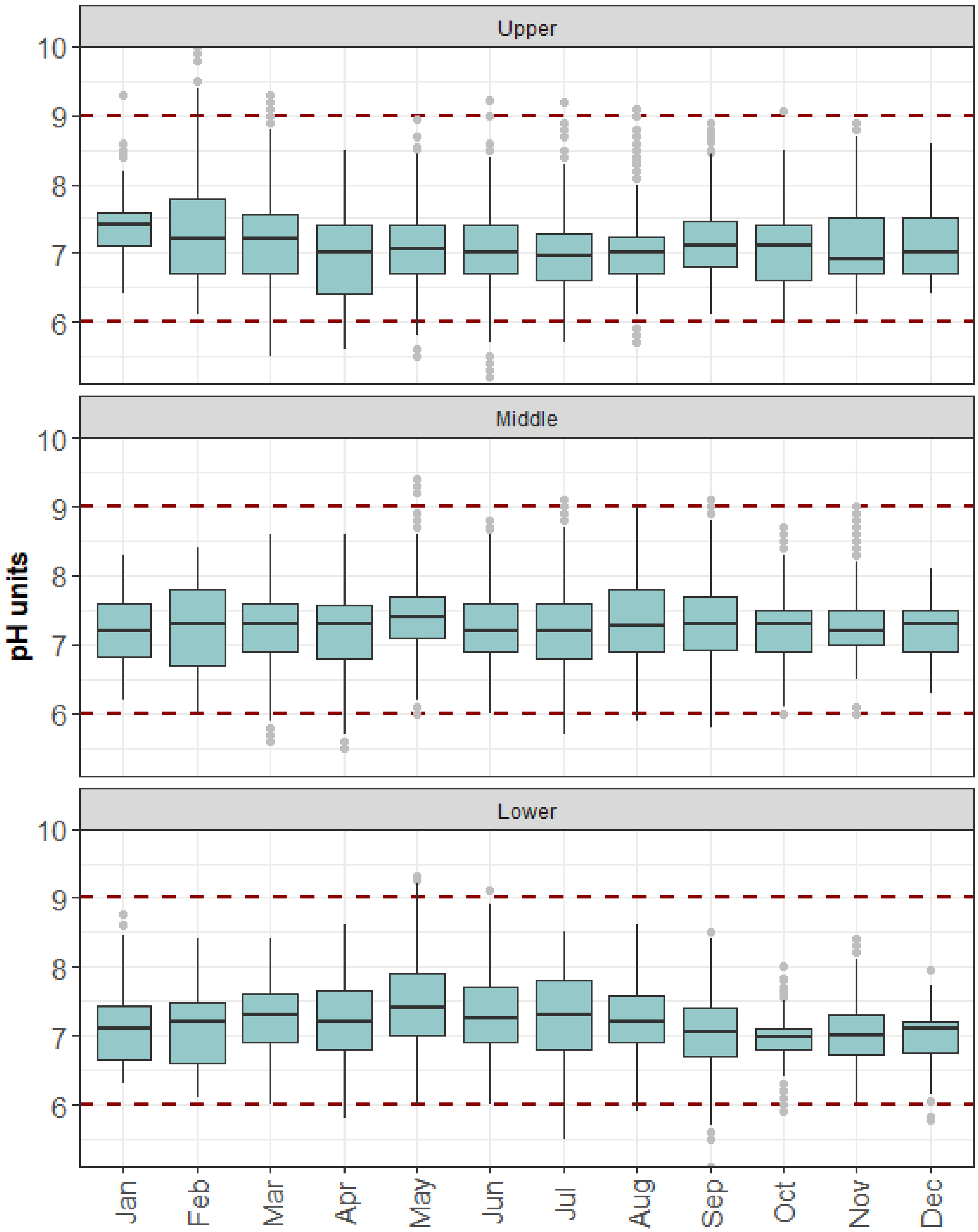

Figure 4-30. Distribution of pH Measurements Collected at Less than Four Meters Depth by Month

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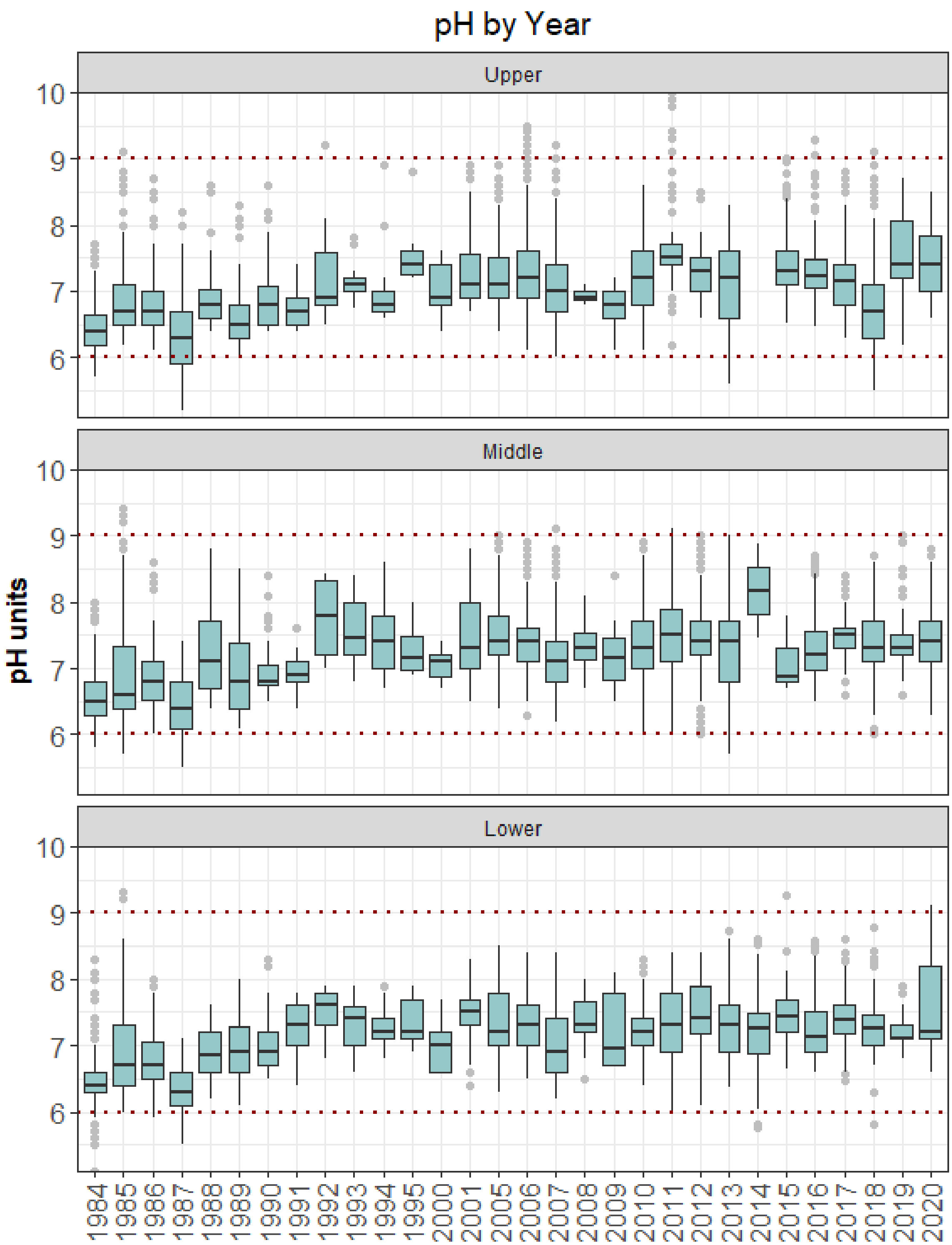

Figure 4-31. Distribution of pH Measurements Collected at Less than Four Meters Depth by Year

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4.10 NC Wildlife Resources Commission Fish Data

The NC Wildlife Resources Commission (WRC) provided data on recreational fisheries (Figure 4-32 through Figure 4-34). Species monitored include Crappie and Large Mouth Bass. Surveys are conducted every other year, alternating by species. Data are used as a “snapshot” status of the quality of the recreational fishery. These data are also used to set size and creel limits. Data are intended to indicate the quality of the Falls Lake fishery, but all data are collected downstream of Highway 50. Since the 1990s, the data vary year by year, but do not indicate a consistent trend up or down. Staff from WRC participated in in the UNRBA TAW, and their input on the health and stability of the Falls Lake fishery is summarized in Section 4.13.

The WRC data are not sufficiently refined to provide monthly assessments for the three Falls Lake statistical modeling segments. However, this information provides important context for the aquatic life designated use in relation to observed water quality and reductions in nutrient loading to Falls Lake.

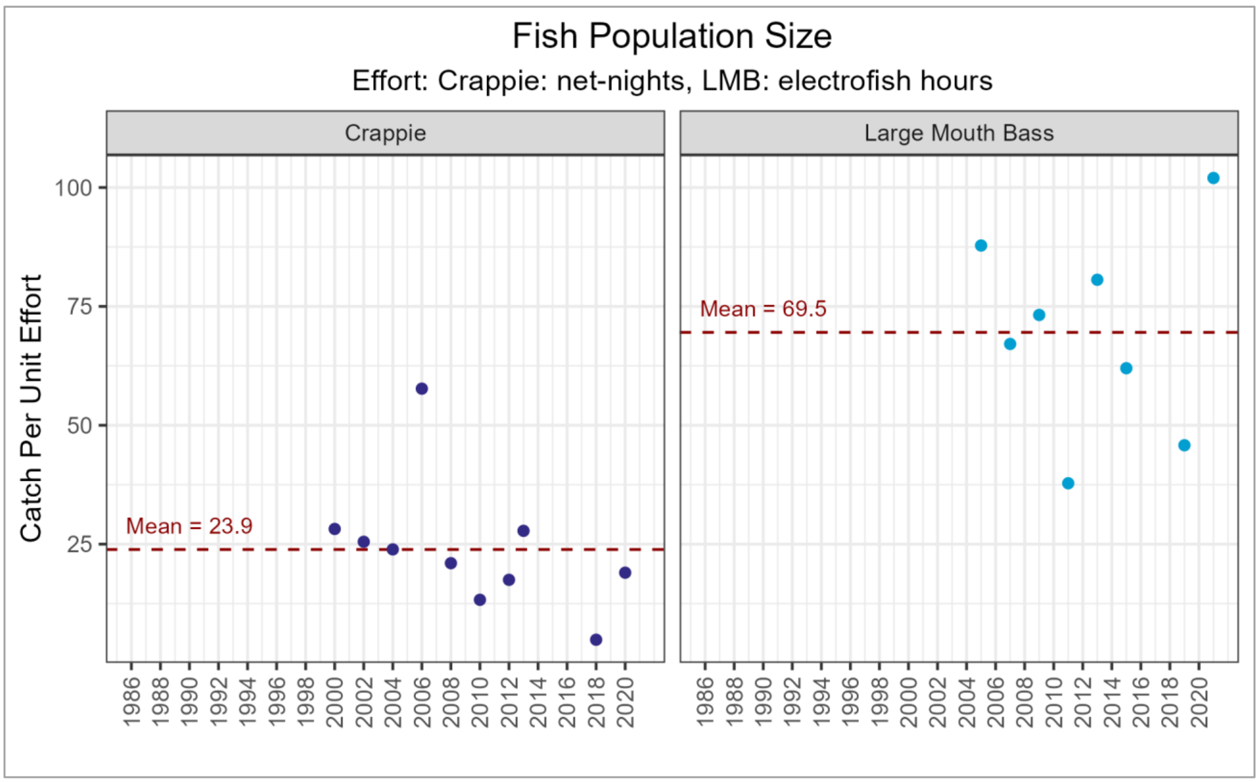

Figure 4-32. Fish Population Size as Catch Per Unit Effort for Crappie and Large Mouth Bass

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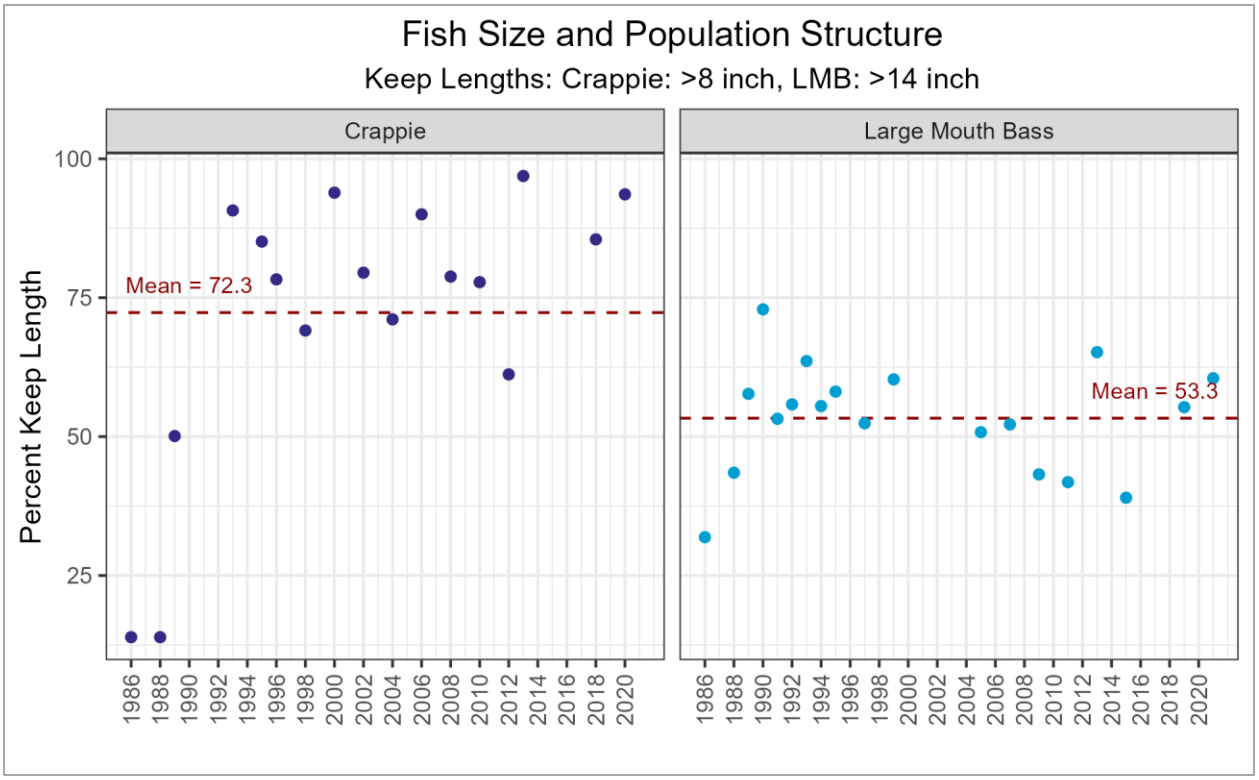

Figure 4-33. Fish Size and Population Structure as Percent Over Keep Length for Crappie and Large Mouth Bass

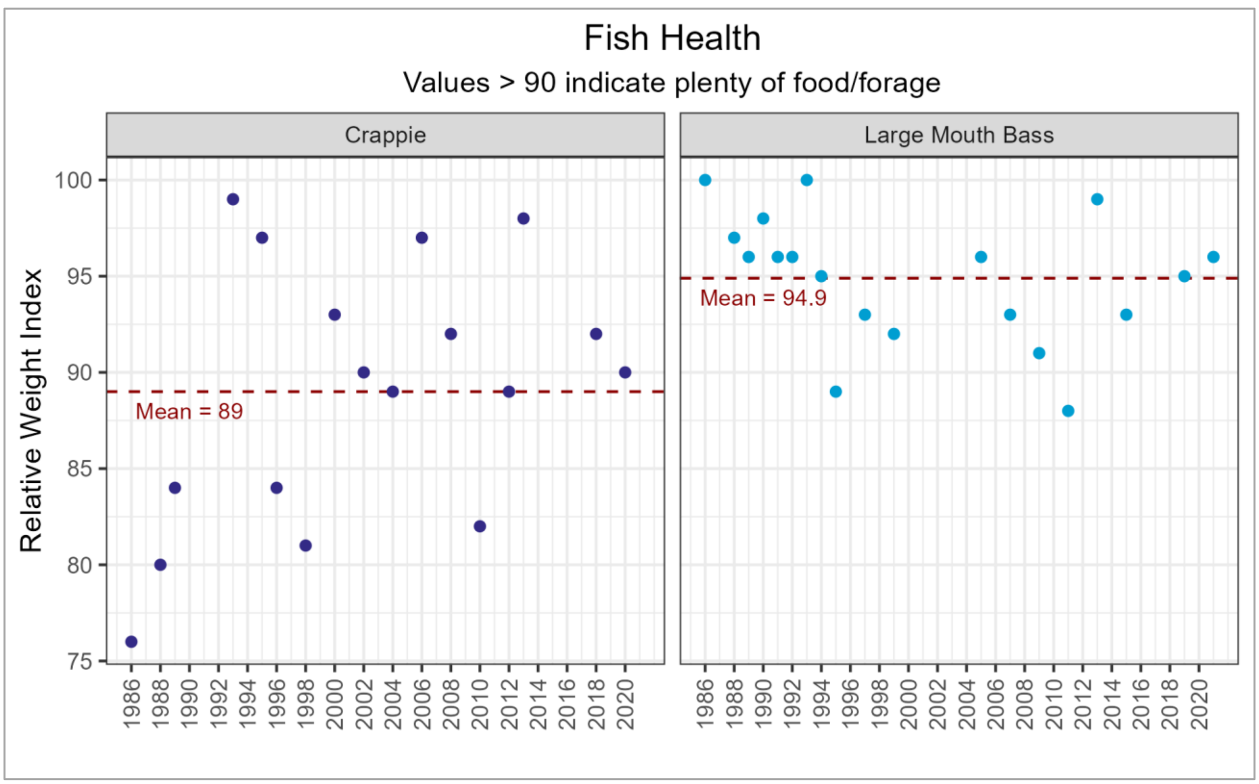

Figure 4-34. Fish Health Relative Weight Index for Crappie and Large Mouth Bass

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4.11 Reported fish kills

NCDEQ maintains a statewide database of reported fish kills, and this database was used to assess nutrient-related impacts to the aquatic life designated use. The types of summary statistics for events vary and may include the number of fish killed, species affected, duration of the event, and the acreage affected. Annual reports summarizing the historic data are available online: https://www.deq.nc.gov/about/divisions/water-resources/water-resources-data/water-sciences-home-page/nc-fish-kill-activity/fish-kill-events.

The database was evaluated for 1986 to 2020 to identify reported fish kills on Falls Lake. Falls Lake reported fish kill data were provided to the UNRBA following a data request. Over this 34-year period, only six fish kills have been documented on Falls Lake. Reported fish kills were attributed to algal blooms that occurred post filling (i.e., "new reservoir syndrome"), post-hurricane low dissolved oxygen, cold temperatures, or disease. All fish kill events attributed to algae blooms or post-hurricane low dissolved oxygen occurred before 1997. Algal composition data are not available for the years when fish kills occurred in Falls Lake, so this dataset cannot be directly integrated into the UNRBA Statistical/Bayesian model. It does provide important context for the aquatic life designated use in relation to observed water quality and reductions in nutrient loading to Falls Lake.

It is important to note that reported fish kills are "presence-only" observations. The data only indicate if an event was reported, not if an event occurred. There have been more users over time on the lake, so more opportunities exist for fish kill observations. For example, visitation to Falls Lake increased from 1 million in 2020 to nearly 1.5 million in 2021 (WRAL news article on the 2022 NC State Parks press release). However, reports of fish kills on Falls Lake are very rare and have not increased with increasing use of the resource. DWR created a fish kill reporting application for cell phones in 2018.

Figure 4-35 shows the number of events, location, and cause of fish kills reported for Falls Lake. Three of the events were attributed to algal blooms, and all of these occurred in the upper segment of the lake. One bloom was attributed to low dissolved oxygen due to an extreme hurricane event. Two events were classified as "other" causes which were suspected disease or cold events.

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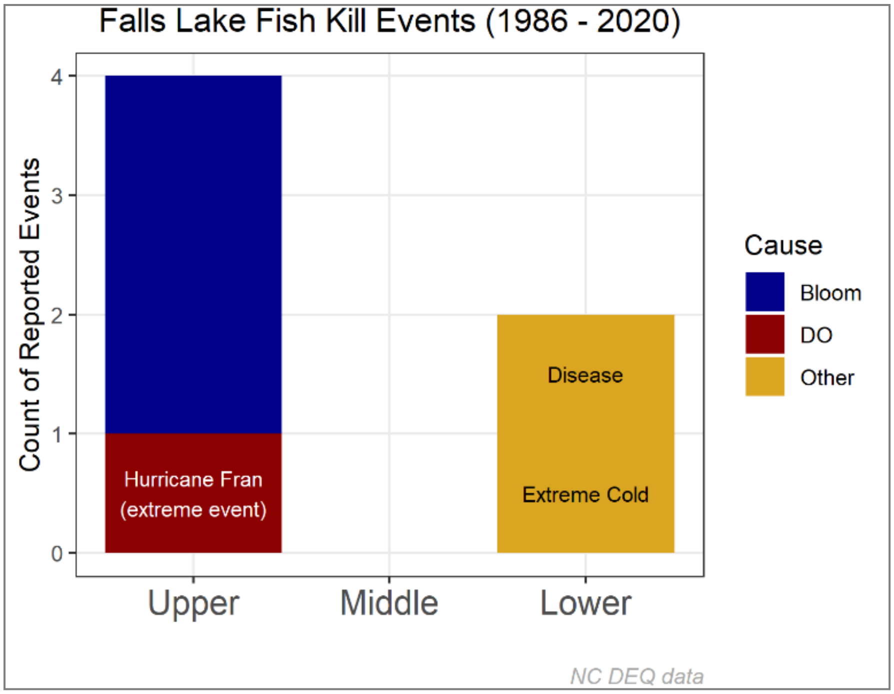

Figure 4-35. Location, Cause, and Number of Reported Fish Kill Events on Falls Lake

Figure 4-36 shows the reported mortality, cause, and date of the reported fish kills on Falls Lake. The mortality associated with the bloom-related fish kills is small relative to the post-hurricane low dissolved oxygen and disease events. Bloom-related events were reported in the months of June or July and have not been reported since the 1980s. Bloom events are more likely to be reported when water-based recreation activity is highest, so it is notable that more kills have not been documented with increased opportunity to observe and report kills.

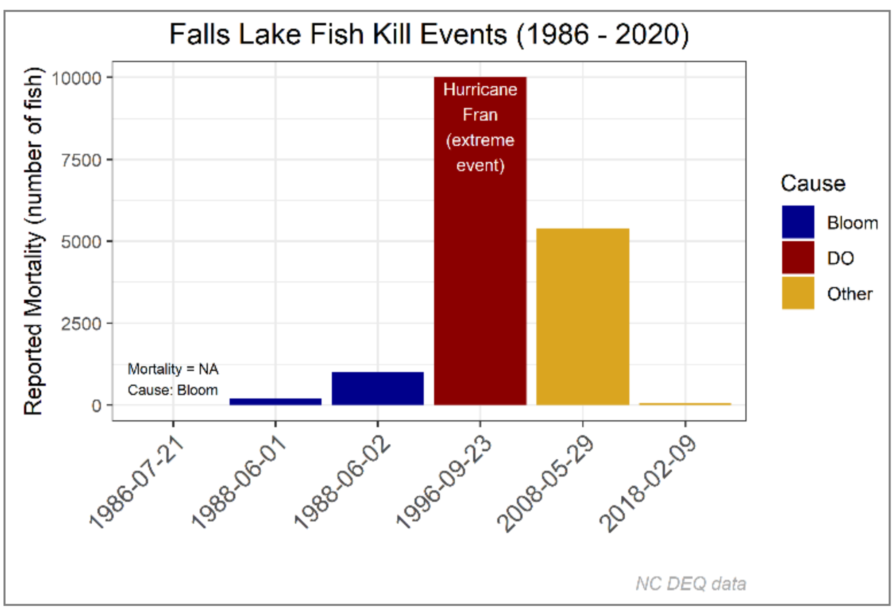

Figure 4-36. Date, Cause, and Number of Reported Mortality for Fish Kill Events on Falls Lake

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4.12 Summary of Falls Lake Water Quality and Algae Data

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). The UNRBA Monitoring Program Annual Reports summarized data collected in Falls Lake by multiple organizations including the parameters collected and the frequency. These reports are available in the UNRBA Resource Library. The comprehensive report that covers the full UNRBA study period is the UNRBA 2019 Monitoring Report.

Summary figures for the full monitoring record are provided in Table 4-7 for total nitrogen, total phosphorus, total organic carbon, chlorophyll-a, algal biovolume, and algal toxins. All figures for a parameter display the historic set of data, organized differently (by month, by year, etc.). Figures showing data organized spatially correspond to the three lake segments shown in Figure 3-11. The upper most segment includes the lake upstream of Fish Dam/Cheek Road, the middle segment is between Fish Dam/Cheek Road and just downstream of Highway 50, and the lower segment is downstream of Highway 50 to the dam.

Some box plot figures have the y-axis cropped which excludes the highest measurements from the figure. In these cases, if the full data is shown, the boxes become very small, and the figure is not very informative. For example, for the distribution of total phosphorus samples by month, the notes indicate the axis is cropped at 0.5 mg-P/L. The notes to the right of the figure provide explanation about when and where the omitted values occur.

Full page figures and additional parameters are provided in Appendix C.

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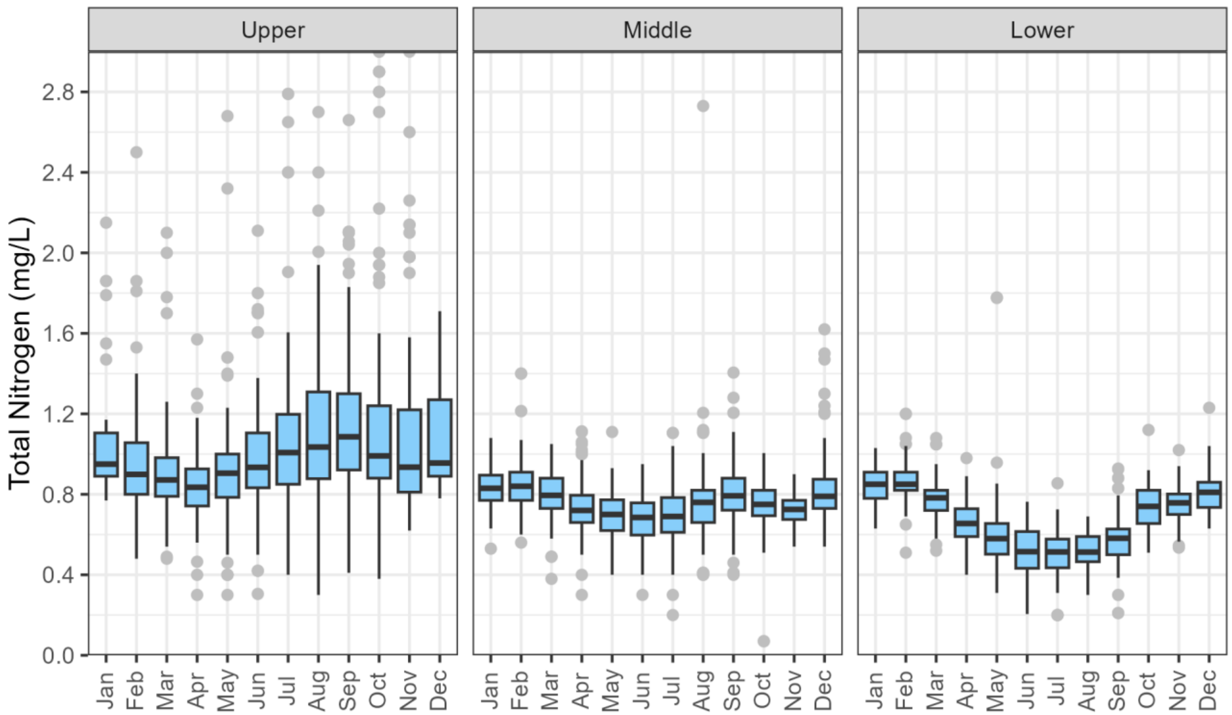
Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record	
Data Visualization	**Notes**
Total Nitrogen Photic Zone Composite Samples	
	Total Nitrogen by Month and Segment Cropped at 3 mg-N/L to better visualize the majority of the data: • Higher values with more variability in upper lake • 13 samples were above 3 mg-N/L; these are not displayed on this figure • Values above 3 mg/L occurred post filling, mid-1990s, and 2007 (historic drought) • Data are pooled for all years. Earlier years had higher TN concentrations (see figure showing the distribution by year) • Gray circles are outliers that represent 5 percent of the data

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Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record

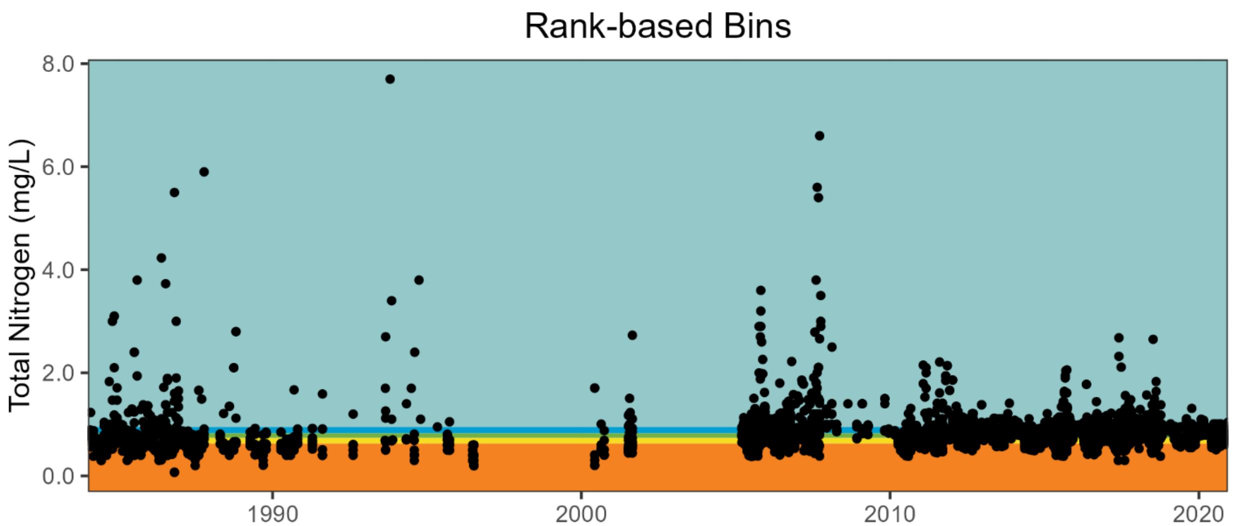
Data Visualization	Notes
	Total Nitrogen Rank-Based Bins (Even Number of Observations per Bin) • Very low (orange) (< 0.63 mg/L) • Low (yellow) (0.63 – < 0.74 mg/L)) • Moderate (green) (0.74 – <0.83 mg/L) • High (bright blue) (0.83 – < 0.95 mg/L) • Very high (gray blue) (>0.0.95 mg/L) • 80 percent of the data are less than 0.95 mg/L. The widths of the ranges for the middle three categories are very small because the variability in the data is low within these ranges. Each color represents 20 percent of the data collected in Falls Lake. The overall median value for all data is 0.78 mg/L

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Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record

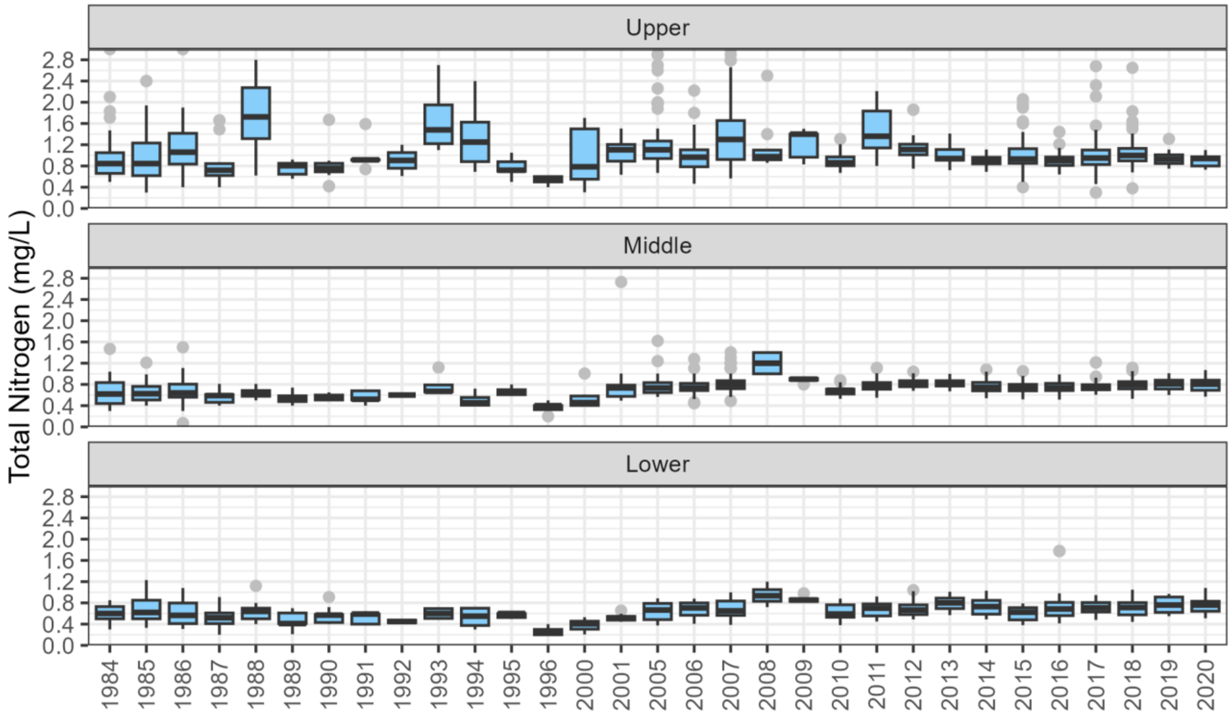
<table>
<tr><th>Data Visualization</th><th>Notes</th></tr>
<tr><td>
</td>
<td>Total Nitrogen by Year and Segment Cropped at 3 mg-N/L to better visualize the majority of the data:
• 13 samples were above 3 mg-N/L; these are not displayed on this figure
• Values above 3 mg/L (clipped from figure) occurred post filling, mid-1990s, and 2007 (historic drought)
• No clear time pattern regarding median or mean, but variance is lower (shorter boxes along a nearly straight line) in more recent years
• Higher values and higher variability in upper lake with conditions stabilizing
• Lower lake generally stable distribution through time despite conditions in the upper lake
• Middle lake is much less variable than upper lake and slightly more variable than lower lake
• Gray circles are outliers that represent 5 percent of the data</td></tr>
</table>

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Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record

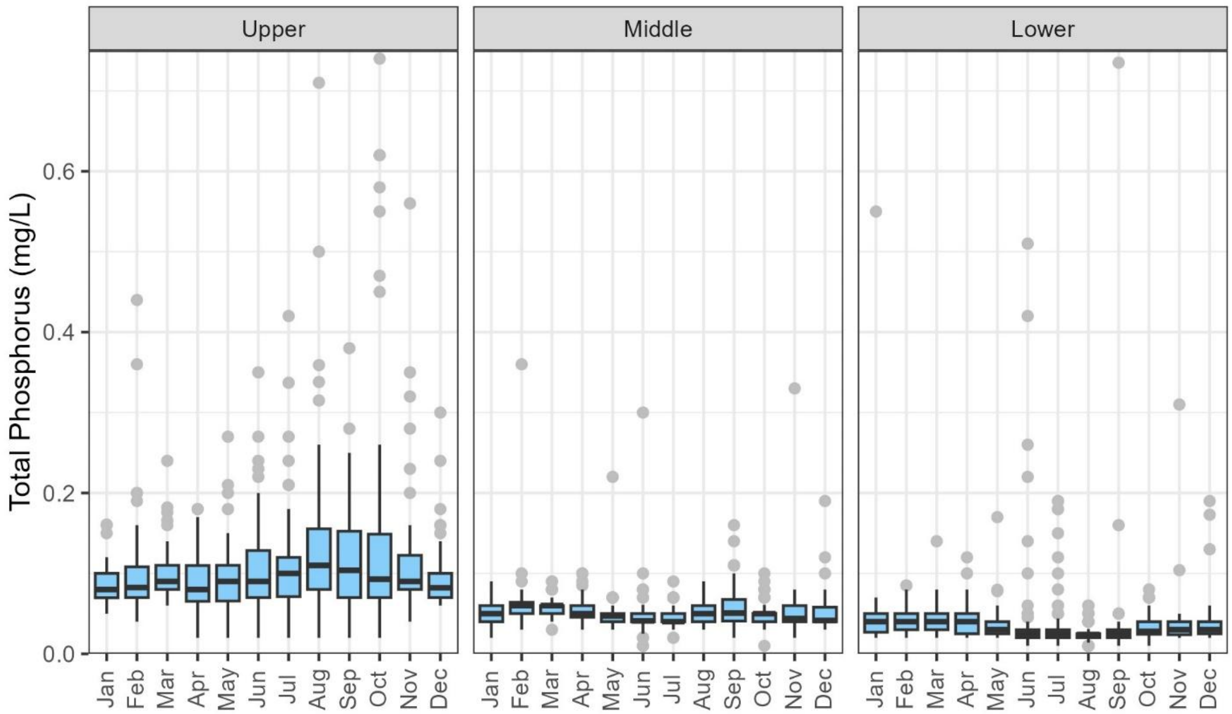
Data Visualization	Notes
Total Phosphorus Photic Zone Composite Samples	
	Total Phosphorus by Month and Segment Cropped at 0.5 mg-P/L to better visualize most of the data: • Higher values occur in the upper lake in late Summer/Fall • Data are pooled for all years. Earlier years had higher TP concentrations (see figure showing the distribution by year) • 14 samples were above 0.5 mg-P/L; these are not displayed on this figure. These values are included in the modeling except one value (1.8 mg/L). • The values above 0.5 mg/L occurred post filling, in the mid-1990s, and in 2007 (historic drought). The highest value (1.8 mg/L) was observed on November 16, 2016. The statistical modeling team and subject matter experts, Nathan Hall and Martin Lebo, decided this value should be excluded from the model because of its magnitude and comparison to other water quality parameters (chlorophyll-a, TN, and TSS) which had relatively low values at and around that station and including preceding and following months. • Gray circles are outliers that represent 5 percent of the data

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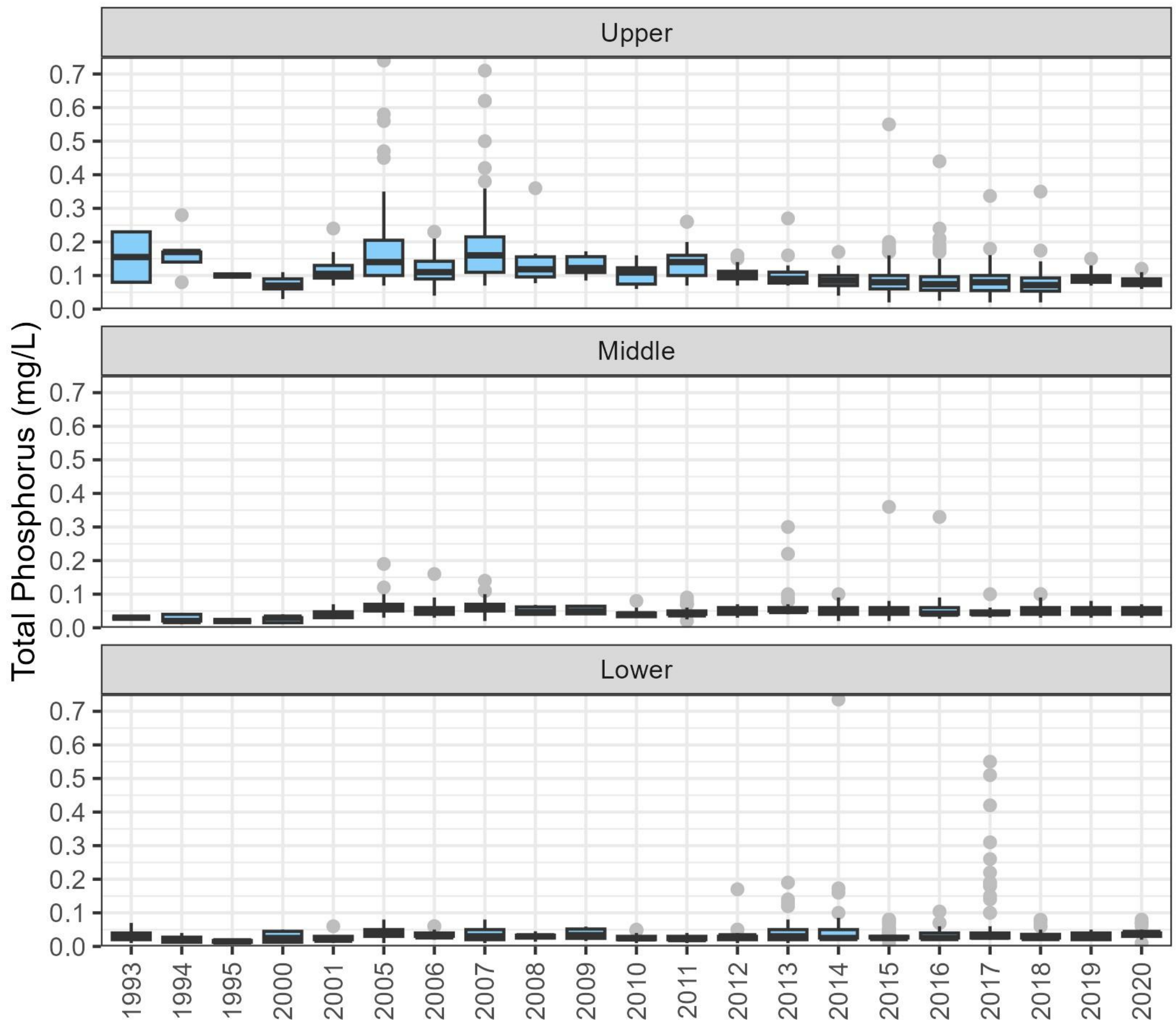
Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record

Data Visualization	Notes
	Total Phosphorus by Year and Segment Cropped at 0.5 mg-P/L to better visualize the majority of the data: • 14 samples were above 0.5 mg-P/L; these are not displayed on this figure. The values above 0.5 mg/L occurred post filling, in the mid-1990s, and in 2007 (historic drought). The highest value (1.8 mg/L) was observed on November 16, 2016. The statistical modeling team and SMEs, Nathan Hall and Martin Lebo, decided this value should be excluded from the model because of its magnitude and comparison to other water quality parameters (chlorophyll-a, TN, and TSS) which had relatively low values at and around that station and including preceding and following months. • Decrease through time in upper lake • Middle and lower lake has been relatively stable through time. • Gray circles are outliers that represent 5 percent of the data. In the lower lake, 2017 had a disproportional number of outliers.

Use of contents on this sheet is subject to the limitations specified at the beginning of this document.

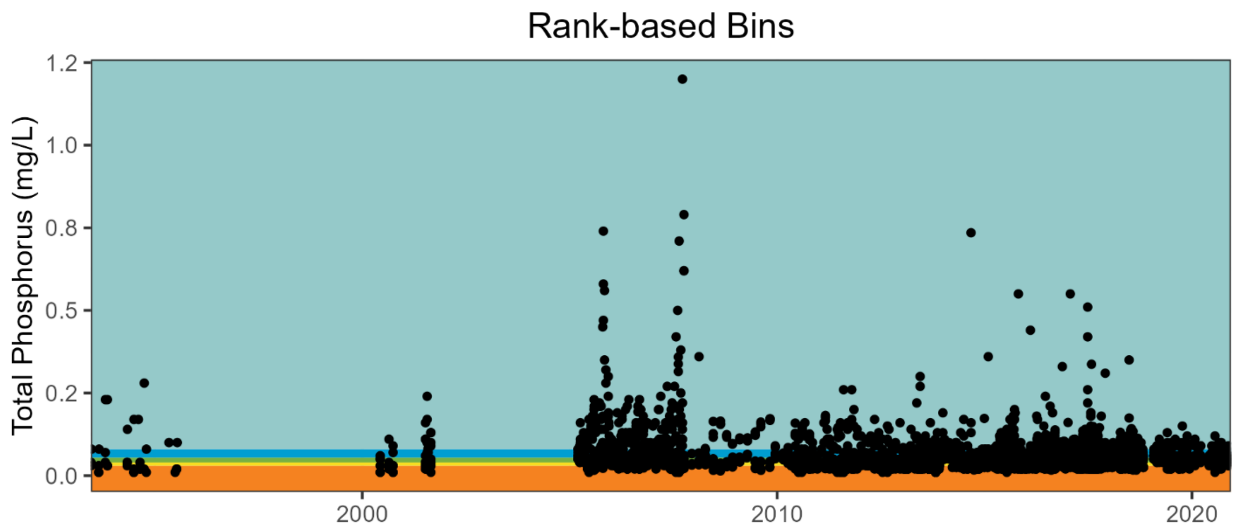
<table>
<tr><th colspan="2">Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record</th></tr>
<tr><th>Data Visualization</th><th>Notes</th></tr>
<tr><td>
</td><td>Total Phosphorus Rank-Based Bins (Even Number of Observations per Bin):
• Very low (orange) (< 0.03 mg/L)
• Low (yellow) (0.03 - 0.04 mg/L))
• Moderate (green) (> 0.04 – < 0.055 mg/L)
• High (bright blue) (0.055 - < 0.08 mg/L)
• Very high (≥ 0.08 mg/L)
• The overall median value for all data is: 0.05 mg/L
• 80 percent of the data are less than 0.08 mg/L. The widths of the ranges for the middle three categories are very small because the variability in the data is very low in these ranges. Each color represents 20 percent of the data collected in Falls Lake.
• This figure shows all of the total phosphorus data collected in Falls Lake except for one value (1.8 mg/L) that was excluded from the model based on its magnitude and comparison to other water quality parameters (chlorophyll-a, TN, and TSS) which had relatively low values at and around that station and including preceding and following months.</td></tr>
</table>

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Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record

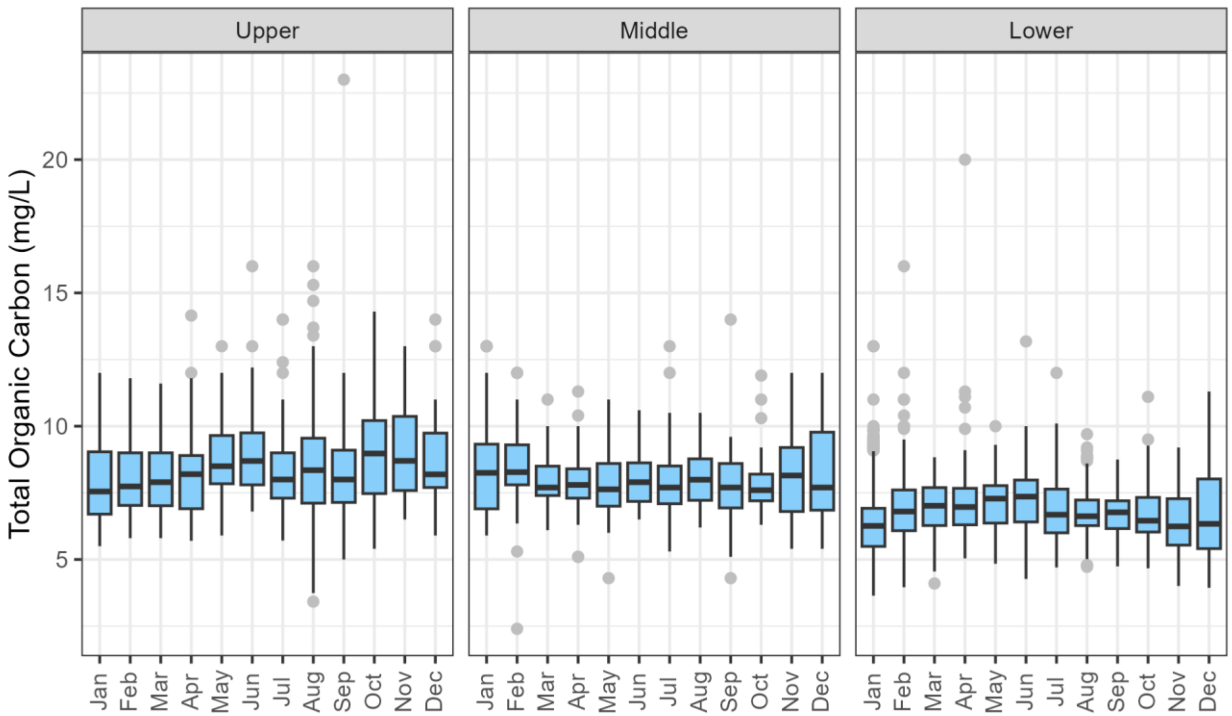
Data Visualization	Notes
Total Organic Carbon Photic Zone Composite Samples	
	Total Organic Carbon by Month and Segment: • Values decrease from upper to lower lake unit • No strong seasonal trend • Gray circles are outliers that represent 5 percent of the data

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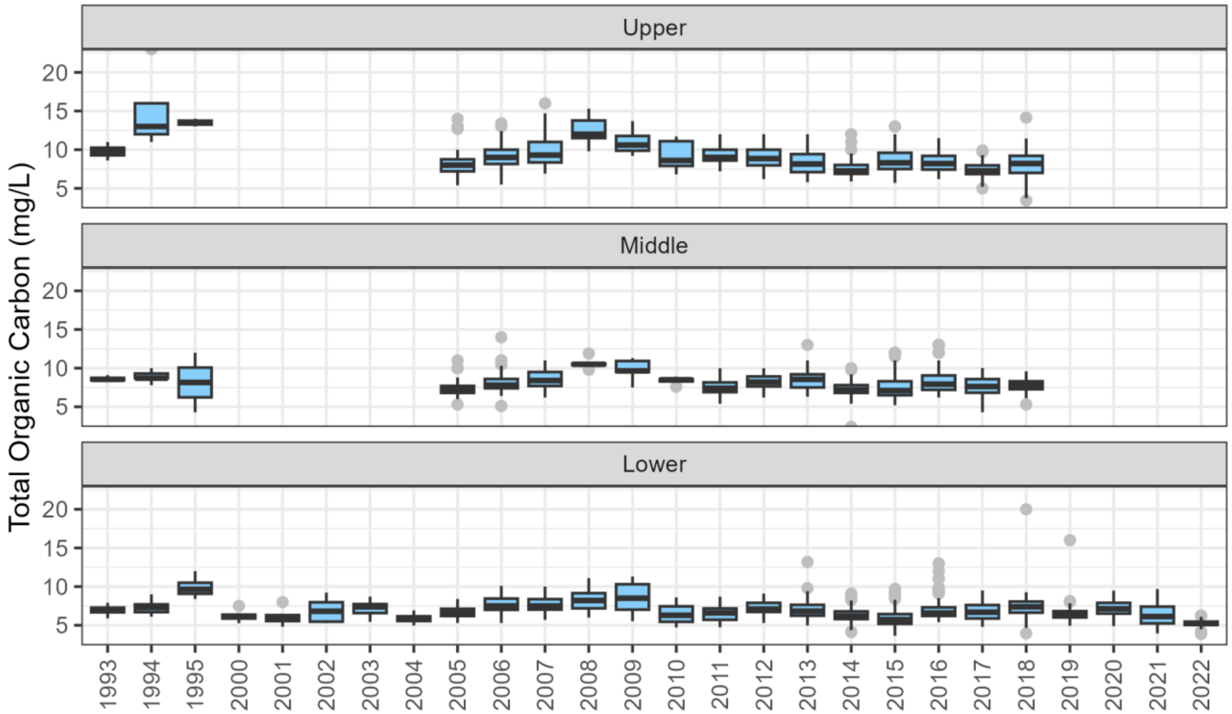
Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record	
Data Visualization	**Notes**
	Total Organic Carbon by Year and Segment: • Data gaps in upper and middle lake (x-axis is not continuous) • Shorter time series comparison • No strong trends apparent • Concentrations increased during and immediately following the drought (2005 to 2008) and then declined and seemed to have generally stabilized • Gray circles are outliers that represent 5 percent of the data

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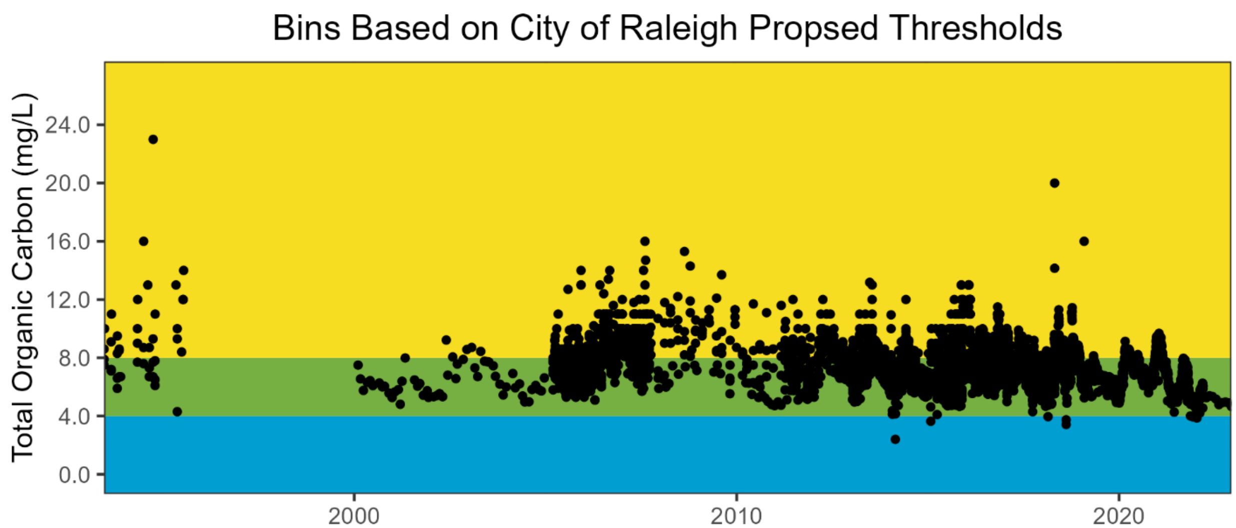
Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record	
Data Visualization	**Notes**
	Total Organic Carbon Rank-Based Bins (Even Number of Observations per Bin) • Low (blue) (< 4 mg/L) • Moderate (green) (4 – 8 mg/L) • High (yellow) (> 8 mg/L) The overall median value for all data is 7.5 mg/L

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Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record

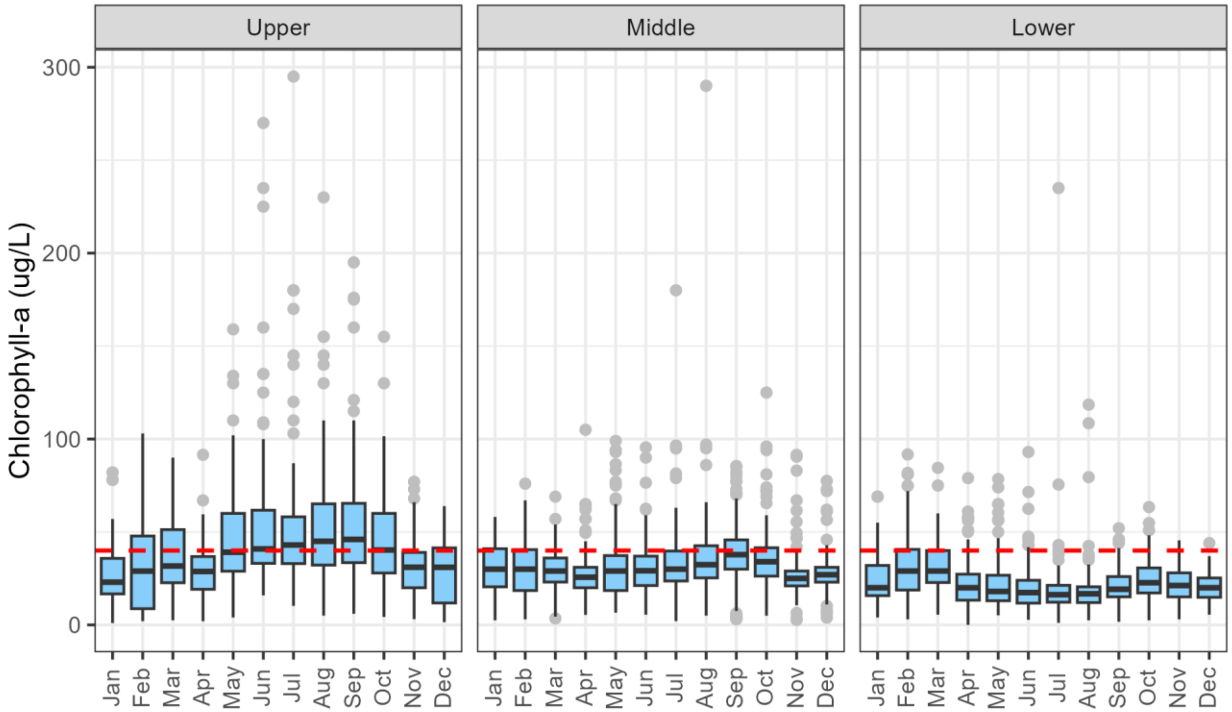
Data Visualization	Notes
Chlorophyll-a Photic Zone Composite Samples	
	Chlorophyll-a by Month and Segment: • Red dashed line is the 40 µg/L chlorophyll-a standard • Variance is highest in upper segment (samples are sparser) • Chlorophyll-a in the upper segment is higher in the warm months and lower in the cool months • Chlorophyll-a in the lower segment is usually higher in the cool months and lower in the warm months • Data are pooled across years – and earlier years had higher chlorophyll-a (see distributions by year) • Gray circles are outliers that represent 5 percent of the data

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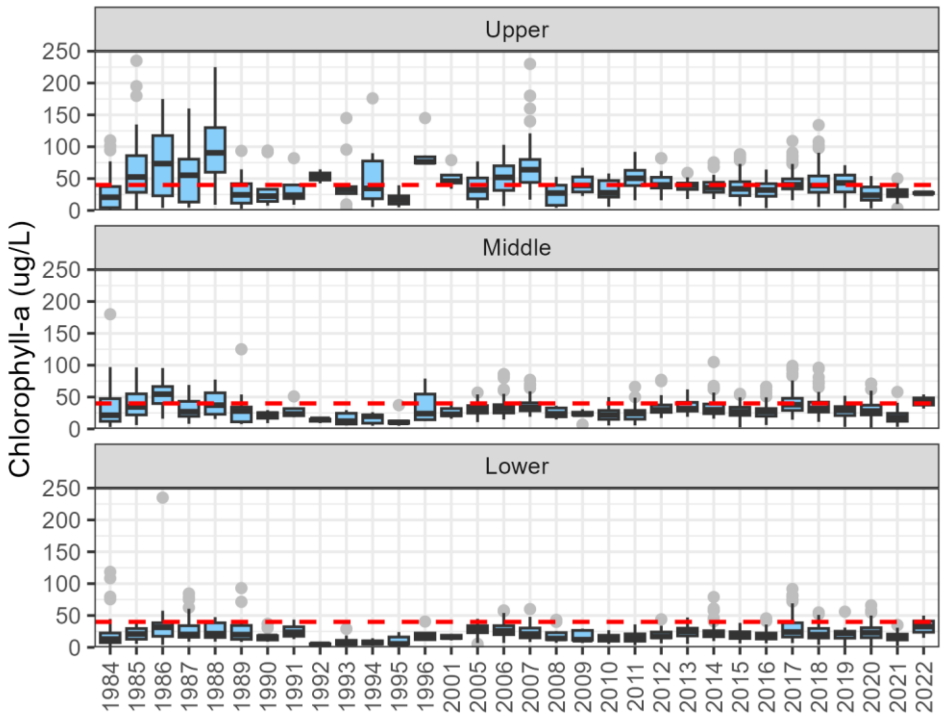
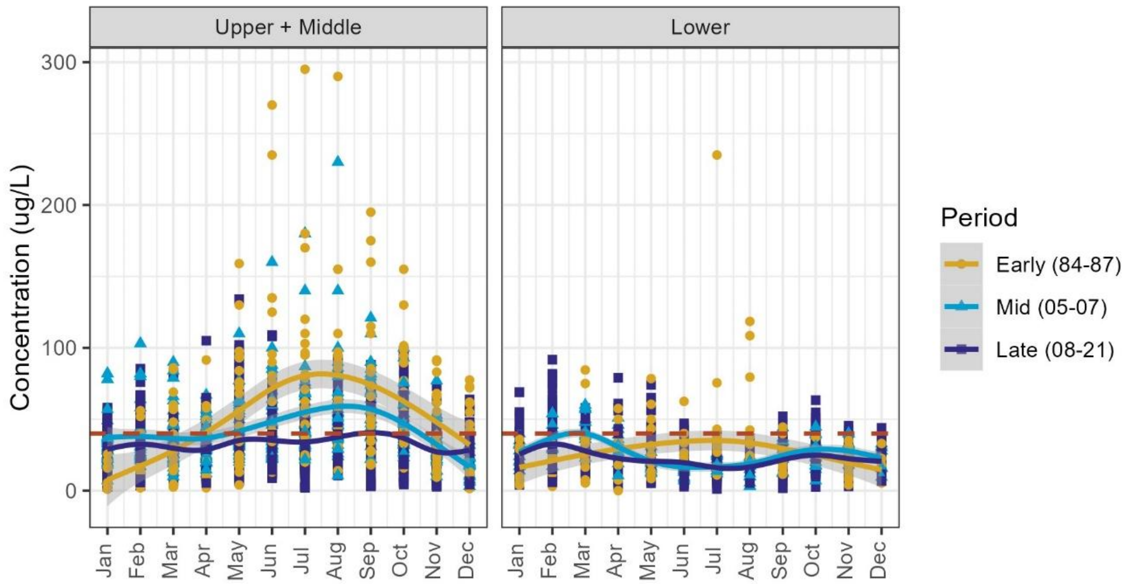
Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record	
Data Visualization	**Notes**
	Distribution of Chlorophyll-a by Year and Segment: • Red dashed line is the 40 µg/L chlorophyll-a standard • Variance is highest in upper segment before 2007 higher values in upper segment from 1988-2001 may be an artifact of sample bias (absence of winter data); high values in 2007 are due to the historic drought when the upper lake dried considerably • Variance is high in the middle segment in the mid-1980s after reservoir filling and in 1996 (Hurricane Fran) relative to other years; after 2001 variance is relatively low and majority of chlorophyll-a samples are below 40 µg/L • Outliers were more common in the lower segment after reservoir filling; variance has been relatively stable across the period of record; majority of chlorophyll-a samples are below 40 µg/L • Gray circles are outliers that represent 5 percent of the data

Use of contents on this sheet is subject to the limitations specified at the beginning of this document.

Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record

<table>
<tr><th>Data Visualization</th><th>Notes</th></tr>
<tr><td>
</td><td>Change in Seasonal Trends Over Time
• Red dashed line is the 40 µg/L chlorophyll-a standard
• Early, post-filling years (1984-1987) are represented by orange circles (samples) and orange line (default LOESS fit with 95 percent confidence interval. LOESS is locally estimated scatterplot smoothing)
• Mid years (2005 to 2007) correspond to the baseline monitoring period for the Rules during a historic drought. Samples are represented by light blue triangles. The light blue line is the default LOESS fit with 95 percent confidence interval.
• Late years (2008-2021) are represented by dark blue squares (samples) and dark blue line (default LOESS fit with 95 percent confidence interval)
• In the early years, chlorophyll-a has a strong seasonal pattern with the highest values in the warm months
• Over time, seasonal changes are less extreme, and the maximum values are lower</td></tr>
</table>

Use of contents on this sheet is subject to the limitations specified at the beginning of this document.

Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record

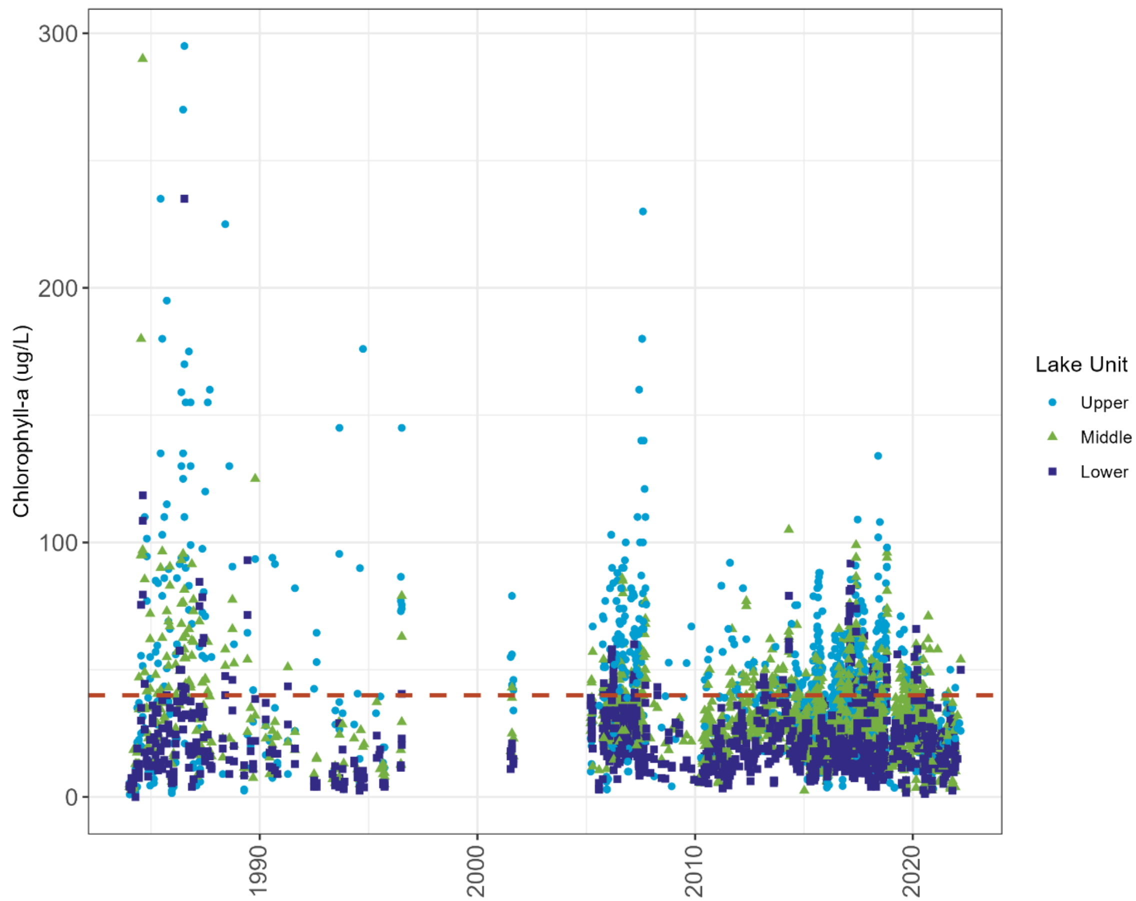
Data Visualization	Notes
	**Chlorophyll-a Samples by Segment:** • Red dashed line is the 40 µg/L chlorophyll-a standard • Upper lake samples are in light blue, middle lake in green, and lower lake in dark blue • Maximum values of chlorophyll-a have decreased since the post-filling period (1980s); values over 200 µg/L were observed in all three segments • Historic drought (2005 to 2007) had elevated values especially in the upper lake

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Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record

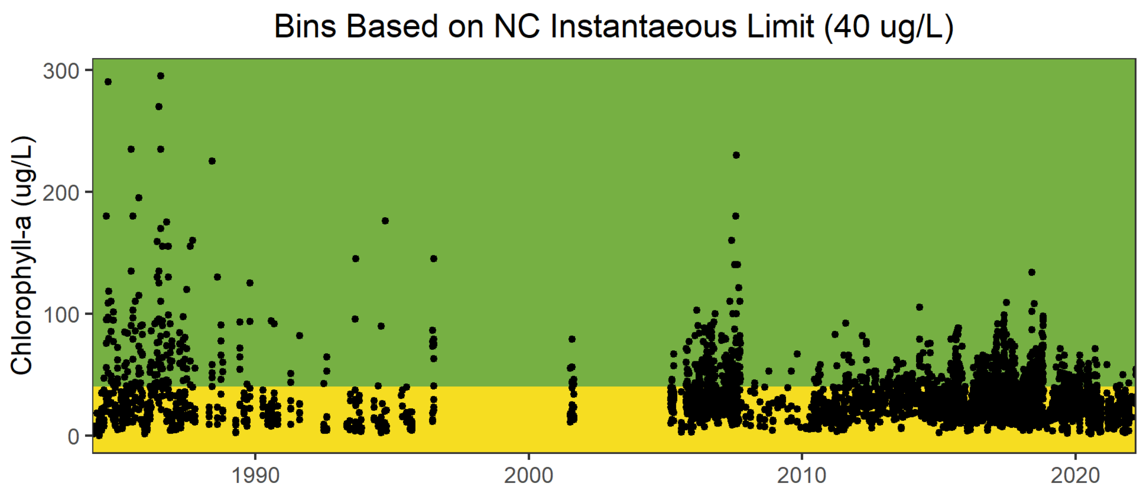
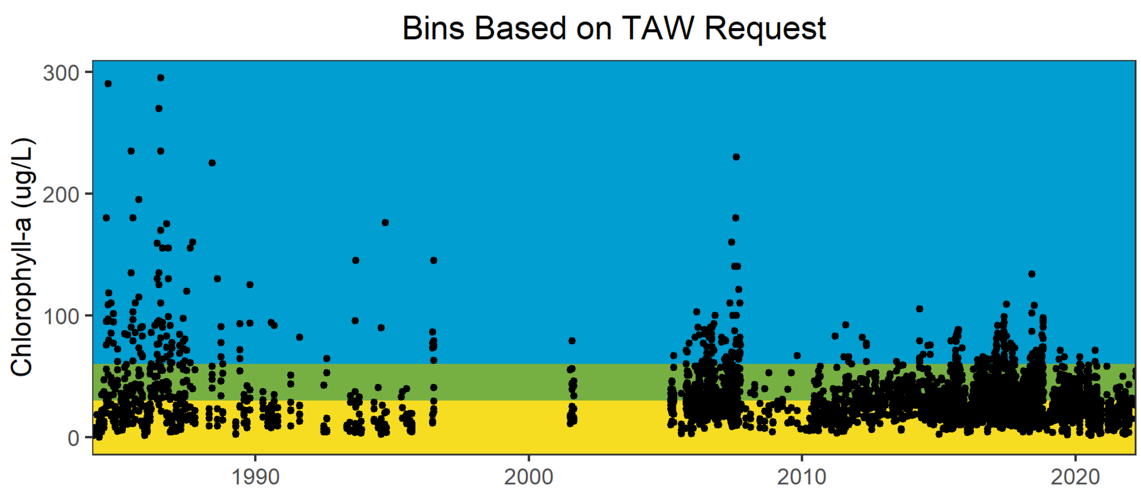
Data Visualization	Notes
	Chlorophyll-a Bins Based on 40 µg/L water quality standard • Not Exceed (less than or equal to 40 µg/L); yellow • Exceed (greater than 40 µg/L); green
	Example Ecological Bins Requested by the TAW • Low (less than 30 µg/L • Moderate (30 to 60 µg/L) • High (greater than 60 µg/L)

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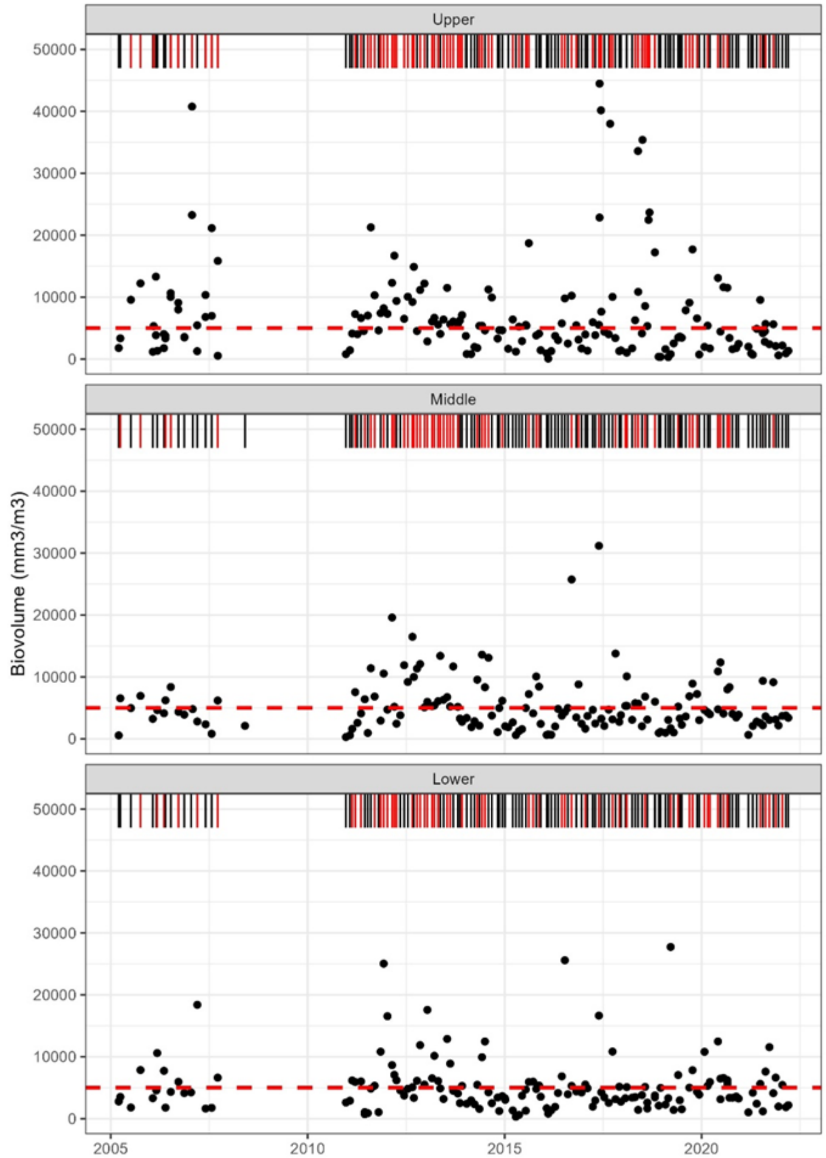
Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record	
Data Visualization	**Notes**
Algal Biovolume by Group (millimeters cubed per meter cubed, mm³/m³)	
	Total Algal Biovolume by Segment and Year • DWR threshold for "bloom" is total biovolume of 5,000 mm³/m³ (red dashed line); this threshold is not related to impact to designated uses but is a point of reference for the agency • Black bar at the top indicates the estimate was below 5,000 mm³/m³; red bar at the top indicates the estimate was above 5,000 mm³/m³ • Total biovolume at any given station frequently exceeds 5,000 mm³/m³ • Longer-duration bloom events (red bars, one after the other) appear less frequently in recent years

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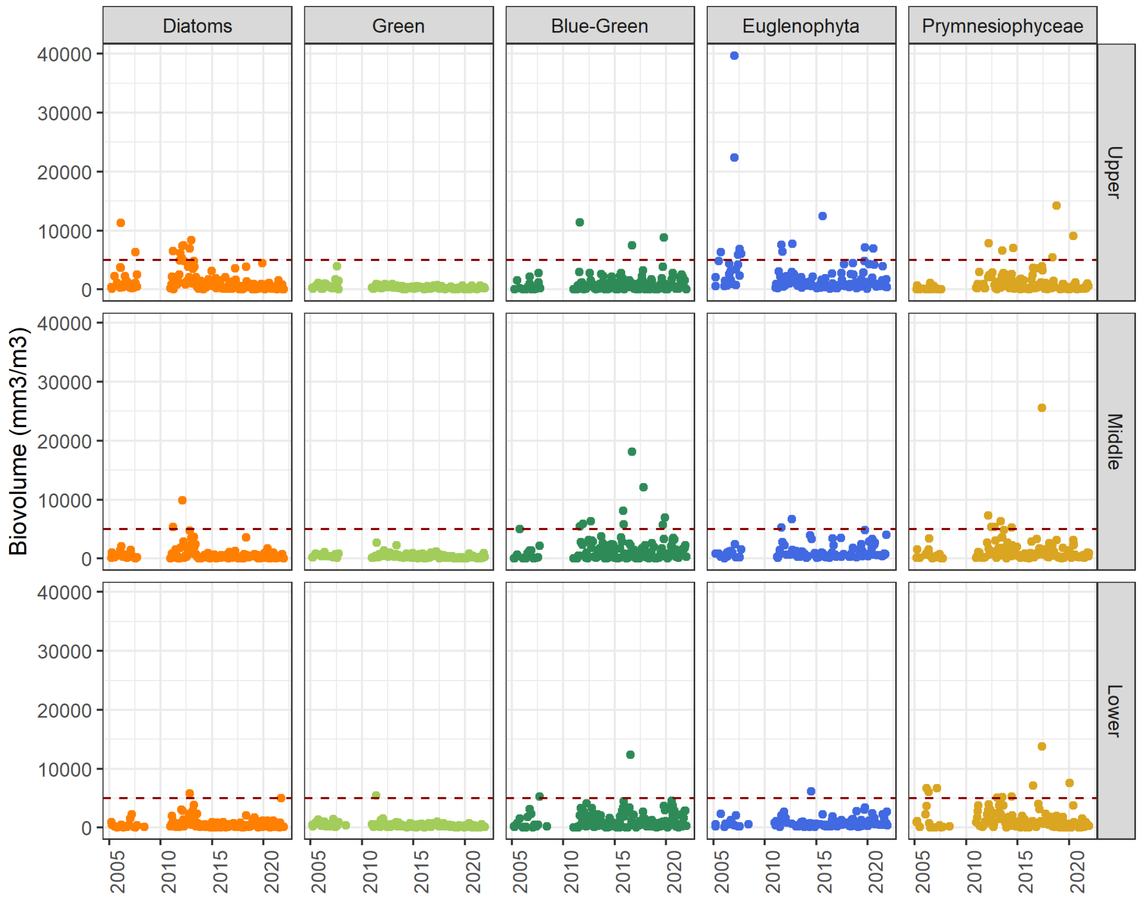
Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record

Data Visualization	Notes
	Algal Biovolume by Group, Segment, and Year • Algal genera grouped as Diatoms, Green, Blue-Green, Euglenophyta, and Prymnesiophyceae • Fewer blooms documented in downstream segments • All except Green periodically exceed 5,000 mm³/m³ (red dashed line); Greens have a consistently low biovolume • Euglenophyta have largest documented events based on biovolume • Maximum biovolumes for Diatoms and Euglenoids appear to have decreased over time; Prymnesiophyceae maximum biovolumes appear to have increased over time; the highest Blue-Green biovolumes occurred in the middle segment in the mid-2010s

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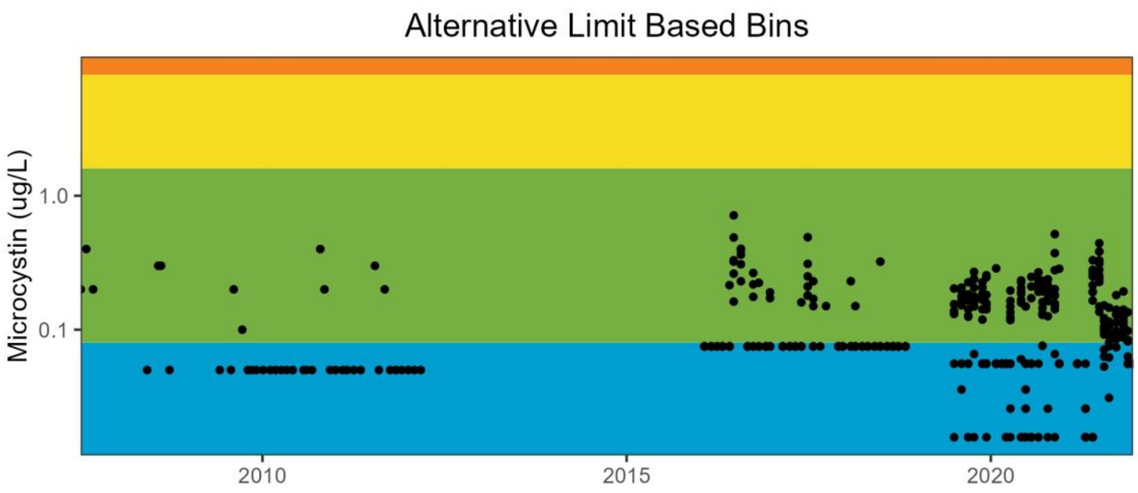
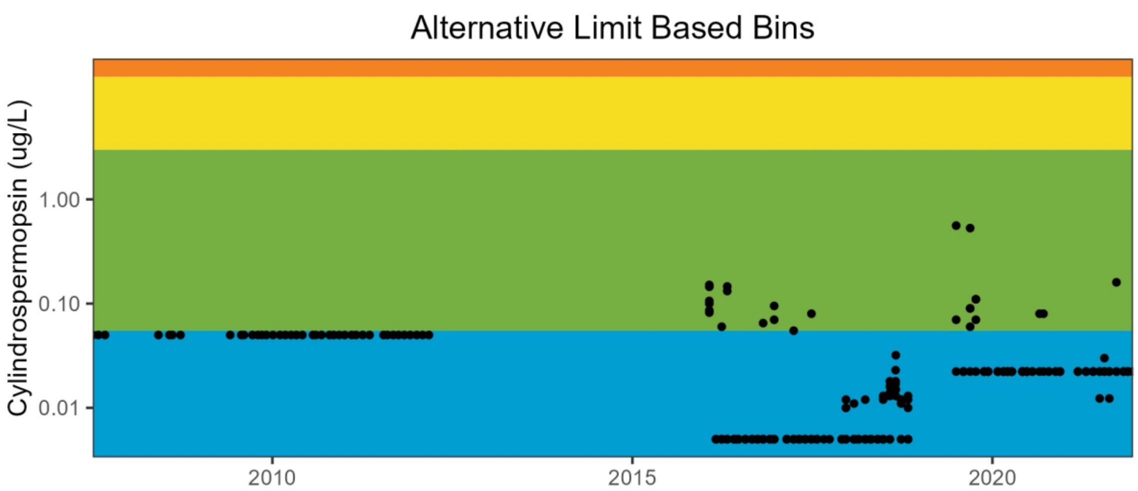
<table>
<tr><th colspan="2">Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record</th></tr>
<tr><th>Data Visualization</th><th>Notes</th></tr>
<tr><td colspan="2">Algal Toxin Data</td></tr>
<tr><td>
</td><td>Microcystin by Year Relative to EPA Guidelines for Drinking Water (1.6 µg/L) and Recreation (8 µg/L)
• Very low (less than detection to 0.08 µg/L); blue
• Low (0.08 µg/L to 1.6 µg/L); green
• Moderate (1.6 µg/L to 8 µg/L); yellow
• High (above 8 µg/L); orange
• None of the Microcystin concentrations collected in Falls Lake exceed either guideline</td></tr>
<tr><td>
</td><td>Cylindrospermopsin by Year Relative to EPA Guidelines for Drinking Water (3 µg/L) and Recreation (15 µg/L)
• Very low (less than detection to 0.08 µg/L); blue
• Low (0.08 µg/L to 3 µg/L); green
• Moderate (3 µg/L to 15 µg/L); yellow
• High (above 15 µg/L); orange
None of the Cylindrospermopsin concentrations collected in Falls Lake exceed either guideline</td></tr>
</table>

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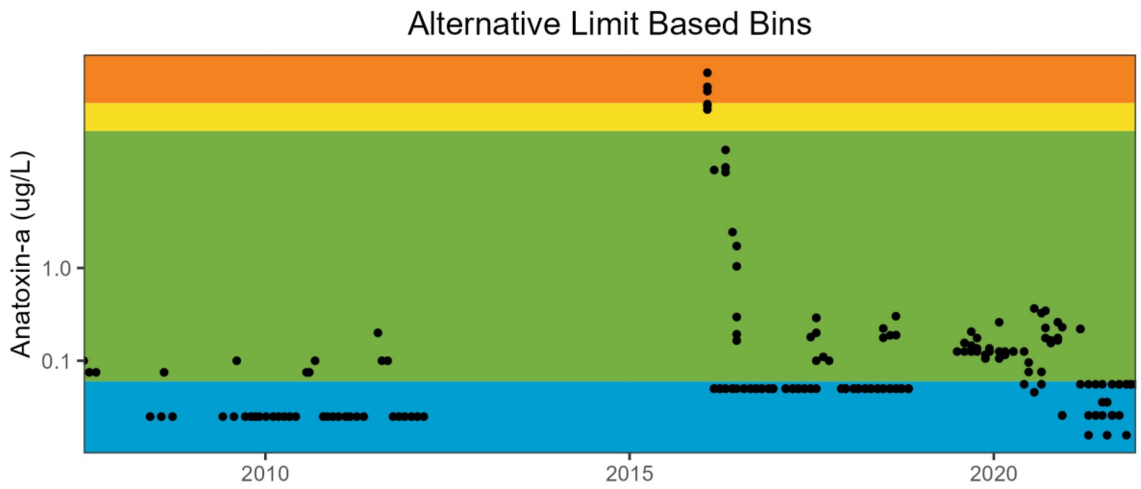
Table 4-7. Water Quality and Algal Composition Data Summaries for the Historic Record

Data Visualization	Notes
	Anatoxin by Year Relative to World Health Organization Guidelines for Drinking Water (30 µg/L) and Recreation (60 µg/L) • Very low (less than detection to 0.08 µg/L); blue • Low (0.08 µg/L to 30 µg/L); green • Moderate (30 µg/L to 60 µg/L); yellow • High (above 60 µg/L); orange Only measurements in January 2016 exceeded the Anatoxin guidelines for drinking water and recreation. Based on discussions with subject matter expert, Nathan Hall, these measurements were excluded from the model because 1) toxin producing algae are not prevalent in the summer and 2) the test used can generate false positives (Cunningham et al 2024).

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Additional figures summarizing these water quality parameters as well as others (e.g., manganese, Secchi depth, total inorganic nitrogen (ammonia plus nitrate), and pH) are provided in Appendix C. During model development, the modeling team developed comparisons of observed chlorophyll-a and biovolume data to inform calibration of the models. Comparisons of Secchi depth and chlorophyll-a data were also conducted. These additional evaluations are described in Appendix D.

4.13 Summary of the Input from the TAW on Satisfaction with Designated Uses and Additional Contacts

The UNRBA Technical Advisors Workgroup (TAW) was formed by the PFC at the January 2021 PFC meeting. The TAW is comprised of PFC and MRSW members representing cities, counties, and utilities in the UNRBA. The TAW worked with the statistical modeling team to define the output metrics for the model in terms of parameters and units. The TAW also explained what information the statistical model could provide that would be most useful to their organizations for their decision making. The TAW was also asked to identify sources of data and information that should be considered in the modeling and to provide additional contacts to broaden the input from other stakeholders.

Additional contacts provided by the TAW included representatives from DEQ, WRC, Triangle Fly Fishers, state and local parks and recreation departments, USACE, US Fish and Wildlife Service (FWS), water supply facility operators and laboratories, local water-based recreational businesses, watershed organizations and river keepers, and the NC Department of Public Health. These contacts were asked similar questions as the TAW about available data, information, and decision making regarding the designated uses of Falls Lake. Not all contacts were available for discussion. In addition to the data summarized in the preceding sections, the following information or comments were provided by organization:

- USACE
  - Provided boat ramp study from 2000 by Colorado State University. Includes Falls, Jordan, and Kerr lakes
  - Shared link to the Falls Lake Master Plan (USACE 2013) which states that “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.”
- NC State Parks
  - Did not have any new water quality data or contacts to recommend beyond what we already had.
  - Recommended boat survey data (see above) and beach water testing data (related to bacteria not nutrients)
  - Empirical data include visitation counts (which they have for many years) and possibly the car counter surveys which are periodically conducted on the weekend to ask people paying entrance fees if they are there to swim, fish, hike, etc.
  - No known record keeping of complaints; most complaints relate to "too crowded" or negative personal interactions, or trash/facility needs; more related to guest experience than water quality concerns. Recalls one or two reports of rashes over the years but not considered water quality related and not reported further to their knowledge.
  - Willing to serve as expert and willing to track down visitation data, if needed.
  - Visitation to Falls Lake increased from 1 million in 2020 to nearly 1.5 million in 2021 (WRAL news article on the 2022 NC State Parks press release).

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- Ellerbe Creek Watershed Association
  - They do not have data of direct impacts of their actions on the lake, but they hope their efforts (model with and without 30000 conserved acres) and planned efforts of conservation groups and cities (e.g., Durham watershed management plan) will be represented among the scenarios evaluated.
  - Mentioned City of Durham list of raingardens; wondered if such small scale but potentially important data is considered (see watershed modeling report)
  - Have a large network of community resource users to which they could distribute surveys, etc.; especially minority groups whose uses are often overlooked (e.g., minority fisher communities)
- Triangle Fly Fishers
  - Extensive knowledge of fish species, methods, and locations on Falls Lake and tributaries
  - Noted annual variability in fish species; causes unknown (e.g., simple ecology or response to stressor)
  - Does not have additional data, but does have access to several thousand members of the fishing community and willing to facilitate a survey of those users
  - Also aware of an individual who has kept logs of many aspects of personal fishing experience and is willing to contact this individual to see if there might be relevant data
- NC Wildlife Resources Commission
  - Provided data in November 2021 on recreation fisheries (Crappie and Large Mouth Bass surveys conducted every other year, alternating by species, going back many years; length/weight ratios used to calculate "snapshot" status of recreational fishery as "quality of recreational angling"; data used to set size and creel limits. It's a single lake summary with all data collected downstream of Highway 50 (i.e., only available for the lower lake segment).
  - Noted the quality of fisheries in Falls Lake is generally above average for Piedmont and not highly variable. Crappie fluctuates more than largemouth, but this is probably more a natural ecological cycle than a response to specific lake conditions.
  - Noted if we want to see problems, we'd probably have to expand our fisheries data beyond Falls Lake.
  - Noted fisheries benefit from being eutrophic (more food) to a degree. Named Sharon Harris as an interesting local case study. Hydrilla had been accidently introduced, consuming nutrients, so the lake became less eutrophic and less productive from a fishery standpoint. Later, the lake became more turbid, killing off the hydrilla, releasing nutrients, becoming more eutrophic, and improving the fishery. So, there is a "sweet spot" level of eutrophication to have clear water but great fishery. Cited an article "Can a lake be too clean" as research that studied that sweet spot.
  - The 2015 WRC Overview of the Falls Lake Largemouth Bass Fishery (2007–2015)
    - "Falls Lake supports an excellent Largemouth Bass fishery and is being appropriately regulated."
    - "Survey results indicate that the abundance of Largemouth Bass and the size structure of the fishery has been relatively stable"
- City of Raleigh (Drinking Water)
  - Drinking water concerns relevant to nutrients primarily are the potential for toxic algal blooms and levels of TOC.
  - Noted complexity of the hydro and ecological dynamics making time-space prediction hard, easier to say conditions make a bloom more/less likely than to say a bloom will/will not occur
  - It is helpful to know ahead of time if the real-time stations are picking up a large bloom

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- The City of Raleigh has monitored water quality in Falls Lake for the past two decades. Staff observed that over this period, perhaps the type and timing of blooms has become more stable. Staff indicated that so far there have been no hits of toxic algae at the drinking water intake, but there have been a couple fish kills on the lake (though maybe not bloom related – see Section 4.8). They have seen big blooms once maybe, but it wasn't a problem at the intake.
- Monitoring to date has not shown a concern in Falls Lake; results show consistently low levels.
- Expressed more concern about TOC, especially as drought/flood cycle potentially leads to more carbon load… referencing the 2008 drought event described how drought exposes and kills any veg/algae on bottom and at same time plants start to grow, then material flooded and decomposes, then when there is flooding the USACE holds back water to save downstream towns but then releases water stirring up bottom and causing pulse of TOC. Would like to know more about how nutrients influence this cycle and how proposed management might interact with this cycle.
- Provided some historical context for TOC and disinfection byproducts (DBP): vintage plant (1967) not focused on TOC. Change from free chlorine to chloramine increases risk of DBP problems. The facility has gradually but greatly improved management of TOC and DBP.
- Hopeful studies will increase knowledge of role of bottom of lake as nutrient sediment trap and if/how water releases stir up these nutrients and materials. Noted manganese is the hardest and most expensive to treat; manganese concentrations can become high when bottom material is stirred up. Concentrations above 0.45 mg/L trigger additional monitoring and may require additional treatment.

On July 11, 2022, the TAW met with the statistical modeling team to discuss the data and information pertaining to satisfaction with the designated uses of Falls Lake. The TAW was asked to provide feedback on whether or not they considered the data or available information in their decision making related to managing the designated uses. This discussion was summarized for the PFC at their [September 6, 2022 meeting](). A summary of this input follows:

- Feedback from the TAW on reported fish kills
  - Triangle Fly Fishers are frequently on Falls Lake
  - If a fish kill was noticed, they would notify their members and DWR
  - The group does not see fish kills on Falls Lake
  - The species affected is important (some are more tolerant)
  - Single versus multi-species is important (stressors differ)
  - No bloom related fish kills have been reported on Falls Lake since the post-filling period (over 30 years ago)
  - Potential categories discussed:
    - Could be species related like None, Single Species, Multi-species
    - Could be cause related like Low DO, temperature, disease, bloom
- Feedback from the TAW on algal toxins
  - Triangle Fly Fishers does not track algal toxin data in Falls Lake because toxins are consistently low.
    - If a swimming beach closure occurred due to high toxin levels, they would alert the group and that may affect their decision on where to fish.
    - The group is not concerned about exposure to algal toxins on Falls Lake (either environmental or consumptive)
  - Wake County has a response plan that includes coordination with DEQ, signage, etc. if DEQ confirms toxin exposure led to an adverse event

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  - City of Raleigh drinking water staff track toxin levels; not a concern in Falls Lake due to consistently low levels.
    - If toxin levels were found to be high in their terminal ponds, they can use granulated active carbon to remove these
    - There is not a concern that toxin levels could not be addressed at the water treatment plant
  - Food web accumulation is a potential exposure pathway, but there is no data from Falls Lake to include in the model (potential future study)
- Feedback from the TAW on algal communities
  - The City of Raleigh has two terminal reservoirs that are used for treatment of diatoms when needed
  - The City's biological laboratory handles these evaluations once a month with the Falls Lake intake sample
  - City staff noted that they have had only one issue several years ago that required treatment in the terminal ponds
  - Neither Triangle Fly Fishers nor Wake County track algal community data in Falls Lake
- Feedback from the TAW on drinking water taste and odor complaints and concerns with disinfection byproducts
  - The City of Raleigh does not have issues with taste and odor or disinfection byproducts
  - In 2023, the American Water Works Association ranked the City of Raleigh 3rd in its international ""Best of the Best" Water Taste Test"
- Feedback from the TAW on chlorophyll-a data
  - The 1980's chl-a data in Falls Lake are higher than recent. While the analytical method has changed since then, the results should be generally comparable.
  - The lack of chl-a data from 1987 to 2004 is due to the lake not being sampled, or omission of data by DEQ due to laboratory issues
  - Potential categories for evaluation
    - Regulatory
      - Not Exceed = < 40 µg/L
      - Exceed = >40 µg/L
    - Ecological (example categories for data exploration)
      - < 30 µg/L
      - 30 µg/L to 60 µg/L
      - > 60 µg/L

4.14 Comparison of Algal Density, Secchi Depth, and Chlorophyll-a Data

During calibration of both EFDC and WARMF Lake, challenges with simulating observed chlorophyll-a in the validation years (2017 and 2018) were noted. Both models were able to perform well for the calibration years (2015 and 2016) but when evaluated for the validation period, chlorophyll-a was underpredicted. Both modeling subcontractors (Dynamic Solutions and Systech Water Resources) explored adding algal groups to EFDC and WARMF Lake, respectively. Model calibration and performance are described in Section 6. This section summarizes the algal density, Secchi depth, and chlorophyll-a data evaluated.

Both models simulate the growth of algae using three groups: blue green algae (i.e., cyanobacteria), diatoms (Bacillariophyceae), and green/other algae. To simulate chlorophyll-a, each algal group has an assumed chlorophyll-a to carbon ratio. These ratios are initially set using published modeling studies and adjusted

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during model calibration. While the ratios can be set differently for each algal group, they cannot be adjusted within the algal group to reflect changing ratios due to varying environmental conditions or dominance of different algal species within the group through time. While this is a limitation, it is an accepted and standard practice for these types of models including the previous EFDC modeling conducted by DWR.

Water temperature and availability of light and nutrients (including silica for diatoms) impact/limit growth of each algal group. Key EFDC model parameters specified for each group include optimal water temperature, half saturation constant for nitrogen and phosphorus, maximum growth rate, basal metabolism rate, settling rate, and predation rate. WARMF model parameters specified for each group include minimum, optimal, and maximum water temperature; nitrogen, phosphorus, and silica half saturation; light half saturation; and growth, respiration, mortality, and settling rates.

During model calibration, the simulated chlorophyll-a concentrations are compared to the observations collected in Falls Lake. However, there is uncertainty associated with laboratory data, and the observations should not be considered exact. Model parameters are adjusted to improve the simulation with the goal of meeting the model performance criteria specified in the North Carolina Division of Water Resources (DWR)-approved UNRBA Modeling QAPP. Ranges of these parameters are well established in the literature for diatoms, blue green, and green algae (USEPA 1985 and 2019). Other algal groups are less studied and typical ranges are not available for the set of parameters required by the models.

The EFDC modelers tested the addition of two other groups of algae that are frequently dominant in Falls Lake based on the DWR algal composition data. Adding algal groups to the simulation did not improve model performance. One reason is a lack of reasonable ranges for the full suite of algae growth parameters. Another reason is that high chlorophyll-a concentrations observed in Falls Lake often do not correspond to increased algal biovolume (based on historic DWR sampling data). In other words, chlorophyll-a concentrations can be relatively high when algal biovolume is relatively low.

During development of the WARMF Lake and EFDC models for Falls Lake, the modeling team, modeling staff from the DWR, and the “third-party” reviewers funded by the NC Collaboratory met to review the lake model calibrations with a focus on chlorophyll-a. During these meetings, staff from DWR and the “third-party” reviewers requested several comparisons to inform model development and provide context for the lake model performance statistics. The comparisons of algal biovolume, chlorophyll-a concentrations, and Secchi depth for three lake stations are provided in Appendix D. To illustrate the challenges with calibration of chlorophyll-a in Falls Lake, excerpts from Appendix D are provided in this section.

High chlorophyll-a concentrations observed in Falls Lake often do not correspond to increased algal biovolume (based on historic DWR sampling data). Chlorophyll-a concentrations can be relatively high when algal biovolume is relatively low.

DWR collects water quality (e.g., nutrient and chlorophyll-a concentrations) and algae composition samples at three locations in Falls Lake. Chlorophyll-a measures the amount of green pigment in a sample and is used as an indicator of algal abundance (i.e., higher chlorophyll-a concentrations imply more algae). However, other sources of green pigment may exist in a sample, like sloughed periphyton entering from tributaries following large storms. Algae may produce more or less chlorophyll-a depending on environmental conditions. The NC water quality criterion for chlorophyll-a is 40 μg/L, applied as an instantaneous standard that applies everywhere in a waterbody.

Algal biovolume is an estimate of the volume of algae within a volume of water and has units of millimeters cubed per meter cubed (mm^3/m^3). The method involves microscopic counts of algae and estimates of biovolume for individual groups of algae (greens, diatoms, blue greens, etc.) using empirical equations.

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Biovolume estimates are uncertain relative to other types of data collected in Falls Lake. Therefore, relative rather than absolute magnitudes and trends across algal groups are the focus of this discussion. DWR uses a biovolume threshold of 5,000 mm^3/m^3 to indicate an algal "bloom", though this threshold is not indicative of a specific use impairment. When biovolume is higher, the dominant algal groups can change temporally and spatially. The most frequent groups that exceed the biovolume threshold for bloom in Falls Lake are Pymnesiophytes and Euglenoids. Note that these groups are not one of the three default groups simulated by the models. These groups are lumped into the "other" algae group and represented by one set of algal parameters.

During EFDC and WARMF Lake model development, there were elevated measured concentrations of chlorophyll-a that were not being simulated by the model. In order to understand which algal groups were dominant during these "spikes," the modeling team created time series of algal biovolume and chlorophyll-a to target further calibration efforts (e.g., top panel in Figure 4-37). To show the more general relationship between biovolume and chlorophyll-a, scatter plots of the total biovolume (all groups) were created at each station (e.g., bottom left panel in Figure 4-37). There are some samples where the biovolume is higher when chlorophyll-a is higher, but often total biovolume is low, even when chlorophyll-a is greater than 40 micrograms per liter (µg/L). To illustrate the general trends in total biovolume and chlorophyll-a for different periods, the bottom right panel in Figure 4-37 shows the average total biovolume and average chlorophyll-a for four periods: 2005 to 2007 (baseline period for the Falls Lake Rules), 2011 to 2014, 2015 to 2018 (the UNRBA study period), and 2019 to 2021. Data are not available from 2008 to 2010 to support this comparison. The percent of the total biovolume exceeding 5,000 mm^3/m^3 and the percent of chlorophyll-a concentrations greater than 40 µg/L are also shown in the bottom right panel.

While there are some observations where high chlorophyll-a corresponds to high biovolume, this is not always the case. For example, at station NEU018E, 80 percent of the time when chlorophyll-a exceeded 40 µg/L, the total biovolume was less than 5,000 mm^3/m^3 and sometimes less than half that. This phenomenon can be seen in early 2017 at both NEU018E and NEU019P (see Appendix D) where the relative magnitude of a spike in chlorophyll-a does not necessarily correspond to a comparably sized spike in biovolume. Sometimes a spike in a specific algal group causes elevated chlorophyll-a concentrations and sometimes a bloom of the same size, or larger, does not [e.g., at station NEU019P where in February 2017 the chlorophyll-a concentration was 81 µg/L and the biovolume of the dominant algal group (Prymnesiophytes) was approximately 3,200 mm^3/m^3; a few months later in May 2017, the biovolume of Prymnesiophytes was approximately 14,000 mm^3/m^3 and the chlorophyll-a concentration was lower at 65 µg/L]. Prymnesiophytes are vertically mobile and when dominant, may concentrate chlorophyll-a at the surface of the lake. Neither WARMF Lake nor EFDC are able to simulate the vertical mobility of algal groups (Appendix D).

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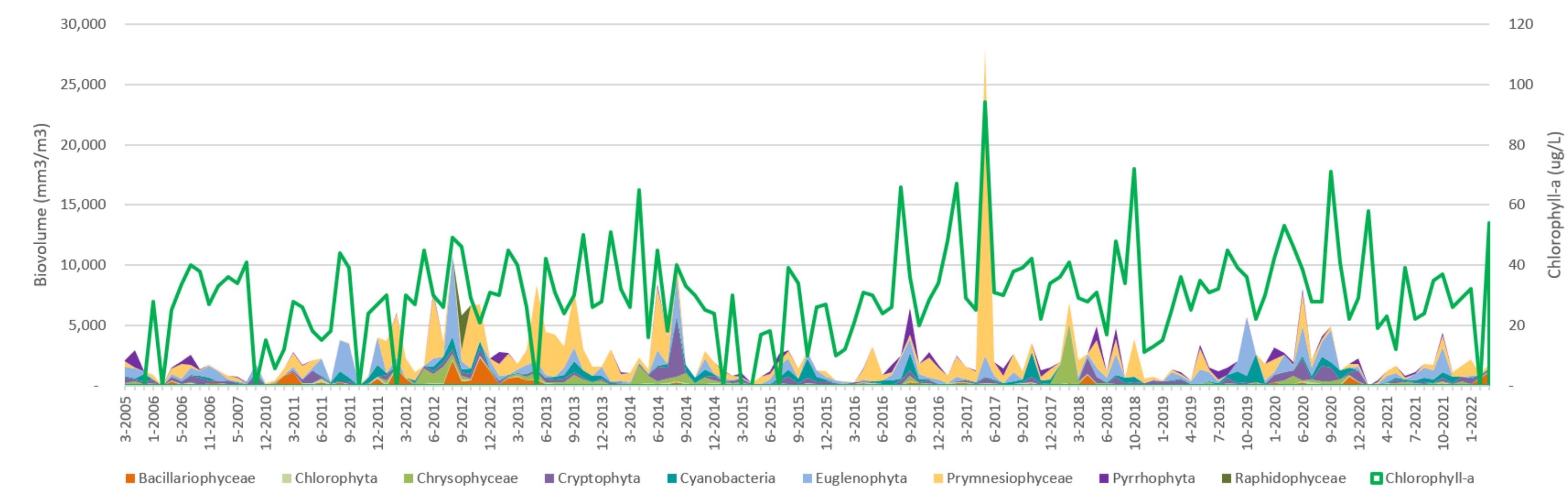

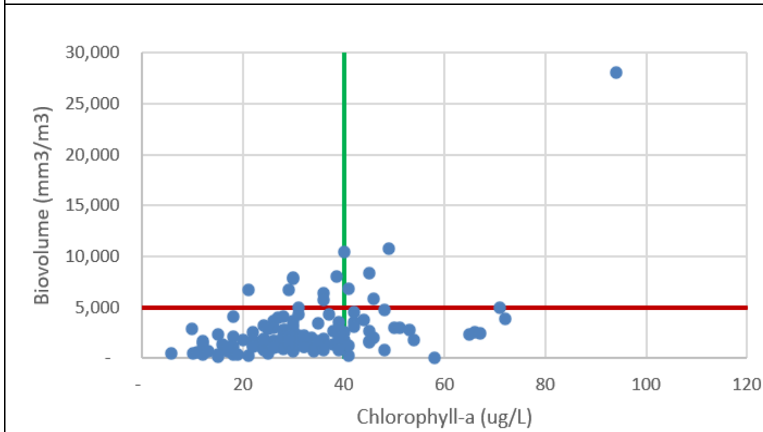

Period:	Average Total Biovolume (BV) mm^3/m^3	Percent of BV > 5,000 mm^3/m^3	Average Chl-a (ug/L)	Percent Chl-a Observations > 40 ug/L
2005 - 2007	1,354	0.0%	33.6	8.3%
2011-2014	3,513	20.8%	31.1	20.8%
2015-2018	2,520	6.4%	32.5	17.0%
2019-2021	2,150	6.1%	33.1	21.2%

2005 to 2007 is the baseline period for the Falls Lake Rules
2015 to 2018 are the UNRBA modeling years (calibration, validation)

Figure 4-37. Monthly Total (Stacked) Biovolume Estimates and Chlorophyll-a Concentrations at Station NEU018E as time series (top), scatter plot (bottom left, green line represents the chlorophyll-a standard of 40 ug/L, red line represents the biovolume "bloom" threshold), and period averages (bottom right)

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Section 5

Simulation of Internal Nutrient Loading from Lake Sediments

Large waterbodies like reservoirs can accumulate nutrient-rich organics and sediments on the lake bottom that have the potential to release nitrogen and phosphorus into the water column. However, this impact is site-specific, and Falls Lake has its own unique nutrient balance characteristics. The importance and quantification of sediment flux was identified, evaluated, and assessed throughout the monitoring and modeling process. This comprehensive assessment has established that the process of sediment nutrient cycling is an important factor in making regulatory decisions and evaluating long-term changes in the nutrient balance of this reservoir.

The UNRBA identified the critical importance of these releases on the nutrient balance of Falls Lake and developed special studies in Falls Lake to better understand these processes. Along with the bathymetric survey of Falls Lake, the UNRBA conducted a sediment depth survey and sediment quality survey of the lake. Sediment cores were extracted, analyzed, and modeled by Dr. Marc Alperin (2018) as part of a UNRBA Special Study of Falls Lake. This study provided important information about the porewater concentrations and sediment quality in Falls Lake. Several additional studies have been conducted on Falls Lake to estimate flux rates at different locations. These and more recent Falls Lake studies (Section 4.3) provide a basis of comparison to ensure the simulated nutrient releases from lake sediments are reasonable. Because these studies reflect specific sampling locations and times, the study results should not be considered a measured or known value representative of the entire lake. Rather, the studies represent the relative magnitude of this source of nutrient loading and their impact on potential water quality changes in response to management actions.

5.1 UNRBA Falls Lake EFDC

EFDC can account for internal nutrient loading in one of two ways. The DWR Falls Lake EFDC model prescribed fixed rates of release (temperature dependent) that were used to calibrate the water quality concentrations in the lake. EFDC also includes an option to simulate the processes using the sediment diagenesis module, and this option was used by Dynamic Solutions to build the UNRBA Falls Lake EFDC model.

This module simulates the cycling of nutrients and organic material between the lake water column and lake bottom sediments (settling, decomposition, nutrient release, and burial) and requires specification of particulate organic matter concentrations and porewater concentrations of inorganic nutrients. The UNRBA Lake Sediment Evaluation Special Study collected the data to prescribe the initial conditions for the Falls Lake sediments. As the model calculations proceed in the water column and sediment layers, organic material and sediments can accumulate, decay, or release constituents (nutrients, dissolved organic matter, oxygen, etc.) back into the water column. Development of the sediment diagenesis module is described in Appendix A.

Table 5-1 summarizes the lake-wide seasonal flux rates simulated by EFDC compared to other lake-wide estimates provided by researchers funded through the NC Collaboratory or from prior evaluation by the UNRBA. Not all studies summarized in Section 4.3 provided lake-wide estimates.

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For ammonia, the EFDC model estimate is between that of the Alperin 2018 estimates summarized on the UNRBA 2019 Monitoring Report and Smiley et al. (2023). Simulated flux rates of ammonia approximated the observations relatively well early in the model calibration and did not require further adjustment.

For phosphate, the EFDC estimate is four to five times higher than the estimates by Alperin/UNRBA and Smiley et al. (2023). During calibration of the EFDC model, "third-party" reviewers compared the simulated phosphate fluxes in the lower part of the lake to those reported by Flexner (2019). The simulated rates were much lower than those reported by EPA. Therefore, the modeling team altered the model parameters to increase phosphate releases from the lake sediments in the deeper parts of the lake to better match the EPA data. This change resulted in simulated lake-wide phosphate releases four or five times higher than the estimates by Alperin/UNRBA and Piehler (personal communication to Alix Matos December 1, 2022). The increased phosphate fluxes occur in deeper parts of the lake that are stratified in the summer, and much of the phosphate released during this time is trapped until fall overturn.

The EFDC model also simulates loss of nitrate to the sediment bed from the water column primarily due to the nitrate concentration gradient across the interface of the sediment bed and overlying water. This loss is provided as a negative number in Table 5-1. This loss is not the same as denitrification which is a biological process that converts nitrate to nitrogen gas. Denitrification is a loss of nitrogen from the system. While the EFDC model accounts for denitrification, it is not output in the model results.

Researchers funded by the NC Collaboratory have provided estimates of denitrification for Falls Lake. Smiley et al. (2023) estimate that the releases of ammonia from the lake sediments is nearly equivalent to the loss of nitrogen due to denitrification (approximately 530,000 pounds per year). Hall et al. (2023) estimated denitrification as approximately 163,000 pounds per year using a mass balance approach.

Table 5-1. EFDC-Simulated Nutrient Releases to and from Falls Lake Sediments Compared to Lake-wide Estimates from Studies Conducted on Falls Lake

Years	NH4 Load from Sediment Nov to Apr (lb/yr)	NH4 Load from Sediment May to Oct (lb/yr)	NH4 Total Annual Load from Sediment (lb/yr)
2015	72,792	269,095	341,888
2016	83,690	294,175	377,865
2017	41,489	219,698	261,187
2018	31,968	240,004	271,972
EFDC Average	57,485	255,743	313,228
Alperin/UNRBA	NA	NA	207,000
Smiley et al. (2023)	NA	NA	530,000
Years	**PO4 Load from Sediment Nov to Apr (lb/yr)**	**PO4 Load from Sediment May to Oct (lb/yr)**	**PO4 Total Annual Load from Sediment (lb/yr)**
2015	8,505	46,164	54,668
2016	8,895	47,658	56,554
2017	6,753	40,667	47,419
2018	5,254	45,125	50,378
EFDC Average	7,351	44,903	52,255
Alperin/UNRBA			14,000
Personal communication, Michael Piehler to Alix Matos (December 1, 2022)			10,600

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Table 5-1. EFDC-Simulated Nutrient Releases to and from Falls Lake Sediments Compared to Lake-wide Estimates from Studies Conducted on Falls Lake			
Years	NO3 Loss to Sediment Nov to Apr (lb/yr)	NO3 Loss to Sediment May to Oct (lb/yr)	NO3 Total Annual Loss to Sediment (lb/yr)
2015	-20,548	-74,872	-95,420
2016	-32,989	-79,397	-112,386
2017	-13,911	-57,561	-71,472
2018	-14,896	-66,036	-80,933
EFDC Average	-20,586	-69,467	-90,053

5.2 Falls Lake WARMF

WARMF Lake simulates the processes that lead to the accumulation and decay of organic matter on the lake bottom (e.g., algae growth and settling, sedimentation, decay rates, reaction rates, and byproducts) rather than prescribing a fixed value. WARMF Lake uses a diffusion coefficient to simulate the exchange of constituents between the water column and the underlying lake sediments. The constituents can move into or out of the sediments to achieve equilibrium with the overlying water. The diffusion coefficient does not prescribe the amount of nutrients released or accumulated in the sediments rather it modulates the rate of exchange. Initial conditions for porewater concentrations and sediment quality were set based on data collected by Dr. Marc Alperin (2018) as part of a UNRBA Special Study of Falls Lake. The rate at which chemical constituents move from the water column to the sediment and vice versa is not influenced by dissolved oxygen concentration in the WARMF Lake model which is a simplified representation of the processes. Phosphorus releases in particular are limited by the presence of oxygen at the sediment-water interface.

The Falls Lake WARMF watershed model is run five times to achieve equilibrium between nutrients applied to the land surface, and the mass of nutrients stored in the underlying soils. For the WARMF Lake model, the initial conditions of the lake sediments based on sediment core data collected by Dr. Marc Alperin are reset each time the model is run. This prevents the lake sediments from "washing out" while the watershed model stabilizes. This approach was used to reduce the uncertainty and apply the most recent sediment quality data to the modeling effort, rather than try to estimate sediment quality in Falls Lake 25 years before the calibration period and before the sediment quality data were collected.

The WARMF Lake model simulates approximately 190,000 pounds per year of ammonia released from the lake sediments compared to previous estimates by UNRBA/Alperin of approximately 207,000 pounds per year. The WARMF Lake model simulates approximately 7,000 pounds per year of phosphate released from the sediments compared to previous UNRBA/Alperin estimates of approximately 14,000 pounds per year. Note that WARMF simulates the diffusion processes only; not the oxygen-based chemistry component. Lake-wide estimates from other studies are summarized in Table 5-1.

5.3 Falls Lake Statistical/Bayesian

The average rates of nitrogen flux (ammonia release minus nitrate loss) and phosphate flux simulated by the UNRBA EFDC Falls Lake model were used to provide seasonal estimates of total nitrogen and total phosphorus releases from lake sediments for the statistical/Bayesian model (Table 5-2). The UNRBA EFDC estimates were used to provide the seasonal variation in load. The average seasonal loads were assumed constant over the model period (do not vary yearly) McKee et al. (2023) studied the accumulated sediments in Falls Lake. Their research indicated that most of the organic carbon that has accumulated in the sediments of Falls Lake is from the watershed, and that the accumulation rates have not trended up or

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down over the past 40 years. The model assumption of sediment nutrient fluxes not varying from year to year is also similar to the estimates reported for Jordan Lake (Del Giudice et al. 2019; Figure 8 and Figure 15).

The EFDC model output was summarized for the upper, middle, and lower lake segments by season. These loads are considered along with loading from the tributaries and atmospheric deposition to understand the relative magnitude of loading to Falls Lake and how it correlates to water quality concentrations observed in the lake.

Table 5-2. Seasonal Total Nitrogen and Total Phosphorus Release Rates Assumed for the Falls Lake Statistical/Bayesian Model Based on the UNRBA EFDC Falls Lake Model

Segment	Nov-Apr TN (lb/month)	May-Oct TN (lb/month)	Nov-Apr TP (lb/month)	May-Oct TP (lb/month)
Upper (upstream of Fish Dam/Cheek Road)	1,527	6,399	159	1,175
Middle (Fish Dam/Cheek Road to downstream of Hwy 50)	3,268	15,382	338	3,296
Lower (downstream of Hwy 50 to Dam)	1,401	6,902	636	2,796

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Section 6

EFDC and WARMF Lake Calibration and Validation and Statistical Bayesian Probability Distributions

EFDC and WARMF Lake model calibration involve adjustment of model coefficients that describe the physical, chemical, and biological processes occurring in Falls Lake. When possible, coefficients were held constant across the entire lake. For some coefficients, spatially varying rates were needed. Each model includes zones that allow for spatially varying rates when appropriate. Appendix A and Appendix B go into more detail about the model coefficients used for the calibrated EFDC and WARMF Lake models, respectively.

Model calibration is an iterative process where changing one coefficient may have the desired effect on one parameter (improved fit to observed data) while potentially having a worsening effect on another parameter. Decisions on whether or not to continue model calibration depend on resource constraints, project schedules, and model limitations in terms of simulating site-specific processes not well accounted for in the model framework. The UNRBA worked with the subject matter experts, “third-party” reviewers, and DWR modeling staff as the models were developed and calibrated to test variations in model coefficients, evaluate modeling results with respect to different types of available data, and determine when calibration was sufficient for the purposes of the project (i.e., understand how lake water quality would change in response to changing nutrient loads).

Model performance and acceptance criteria form the basis by which judgments are made on whether the models are sufficiently calibrated to support management planning decisions. The UNRBA Modeling QAPP describes the performance criteria for the EFDC and WARMF Lake models. Examples of performance criteria used to support model calibration include the following (additional statistics are described in the QAPP).

- RSR: normalized root mean square error (RMSE)
    - Expressed as a percentage (target is 100 percent)
    - Ratio of the RMSE to the standard deviation in the observed data for each hydrodynamic or water quality constituent
    - Abbreviated RSR (RMSE to Standard deviation Ratio)
- Percent bias where <35% is fair, <25% is good, <15% is very good)

As described in Section 3, the EFDC and WARMF Lake models have sub-minute and 6-hr model time steps, respectively. To evaluate their performance, the simulation time step containing the point-in-time observation is used for comparison. The water quality observations collected in Falls Lake by DWR and other organizations are usually photic-zone composites. As described in UNRBA Modeling QAPP, for the purpose of model calibration, only data collected under a state-approved monitoring QAPP as photic zone composite data are included in assessment of model performance. The photic-zone represents the depth over which algae can grow, and it is approximated as twice the Secchi depth. Secchi depth can change at each location and on each sampling day. DWR collects photic-zone composites for chlorophyll-a, nutrients,

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total solids, suspended solids, turbidity, and phytoplankton measurements. The EFDC and WARMF Lake models simulate the water column as several layers. Each layer represents the average condition over the thickness of the layer. The layering approaches for comparing simulated water quality to observations for the EFDC and WARMF Lake models are described in their respective sections below. Examples of time series comparisons of simulated and observed water quality for the EFDC and WARMF Lake models are provided below. Additional comparisons are provided in Appendix A (EFDC) and Appendix B (WARMF Lake).

Time series of simulated water quality are also used for comparison to observations to visualize magnitudes, seasonal patterns, etc. As with the UNRBA Watershed Model Report, the UNRBA expressed the importance of visualizing uncertainty around laboratory measurements when comparing model output. The UNRBA MRSW, DWR, and "third-party" model reviewers discussed methods and terminology to show the potential range of "observed" values using the relative percent difference (RPD) allowed by each laboratory when the evaluate field duplicates. Methods for dealing with observations less than the reporting limit were also discussed. For field measurements, the stated accuracy of field meters was used. The following methods were used to develop the time series comparison figures. Note this approach is different than that used in the UNRBA Watershed Modeling Report which relied primarily on UNRBA monitoring data rather than the lake model which relies on monitoring data from other organizations.

- For observations that were less than the reporting limit, the value is displayed as one-half the reporting limit. Vertical bars extend from a concentration of zero to the reporting limit to show the potential range. This bar is labeled "Zero to the Reporting Limit". The reporting limits change depending on the organization and parameter displayed.
- For observations that were greater than the reporting limit, vertical bars are shown on the figure and labeled in the legend as "+/- Allowable RPD of the Laboratory Duplicates"
    - CAAE observations are shown with a bar that is +/-15% of the observation point based on the CAAE monitoring QAPP
    - DWR values for chlorophyll-a, TOC, TKN, and TSS use +/-20% based on the DWR Monitoring QAPP
    - Calculated values for TN using DWR data use +-20% because the majority of the TN in Falls Lake is TKN, and the value for TKN is +/-20%
    - DWR values for ammonia, nitrate+nitrite and all phosphorus species including total use +/-10% based on the DWR Monitoring QAPP
    - City of Durham values for all parameters use +/-10% except for dissolved and total organic carbon which use +/-15% based on the City of Durham's quality control acceptance criteria
- For field parameters
    - Temperature uses +/-0.2 C labeled "+/- Typical accuracy of calibrated field meters" as provided in the City of Durham QAPP for common field meters
    - Dissolved oxygen uses +/-0.5 mg/L labeled "+/- Allowable difference between post-sampling check readings" per the DWR QAPP (this covers the typical accuracy of field meters of +-0.1 mg/L provided in City of Durham QAPP

The Falls Lake Statistical Bayesian model is developed using the historic record of water quality data and observed conditions. It provides an interactive summary of all observed data and the probabilistic relationships among variables. Rather than adjust model coefficients, like EFDC or WARMF, to fit the observations, the observations are used to generate probability distributions that indicate how frequently something has occurred.

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6.1 UNRBA Falls Lake EFDC

Calibration of the EFDC Falls Lake model for hydrodynamics and water quality is summarized in Section 6.1.1 and more fully described in Appendix A. The primary parameters of concern for the modeling are chlorophyll-a and total organic carbon (TOC). Drivers of algal growth and simulated chlorophyll-a are nutrients, light availability, hydrodynamics, etc. The modeling team worked extensively with the MRSW, DWR, and "third-party" model reviewers to refine the calibration and achieve the best fit. Adjustments to improve simulations of nutrient releases from lake sediments are described in Section 4.3 and Appendix A. Discrepancies between observed chlorophyll-a concentrations and observed algal biovolumes is described in Section 4.14 and Appendix D.

6.1.1 Layering Approach

As described in Section 3.1, the UNRBA EFDC Falls Lake model uses a Sigma-Zed grid which allows for the number of layers to vary over the model domain and maintains a uniform thickness for each layer. Each cell can use a different number of layers, though the number of layers for each cell is constant in time. The thickness of each layer varies in time to accommodate the time varying water level.

Because the layer thickness changes with the lake water level, the number of layers that represent the photic zone can vary over the simulation period. When lake levels are below normal pool (251.5 ft above mean sea level), layer thickness is approximately 0.75 meters. When lake levels are above normal pool, layer thickness is approximately 1.25 meters. Figure 6-1 shows the distribution of the Secchi depth measurements at the DWR monitoring stations in Falls Lake. The "*" on the figure shows the approximate depth of the photic zone during most conditions which is estimated as two times the 75th percentile value (i.e., two times the top of the box). The top panel of Figure 6-1 shows the depth and number of layers when lake level is below normal pool, and the bottom panel shows the depth and number of layers when lake levels is above normal pool. Note that the top layer begins at zero on the y-axis as this represents the water surface.

Table 6-1 indicates which model layers were averaged for comparison to observations based on water level in Falls Lake. Depending on the location, when water level is below normal pool, simulated values from more layers need to be averaged because the layers are thinner.

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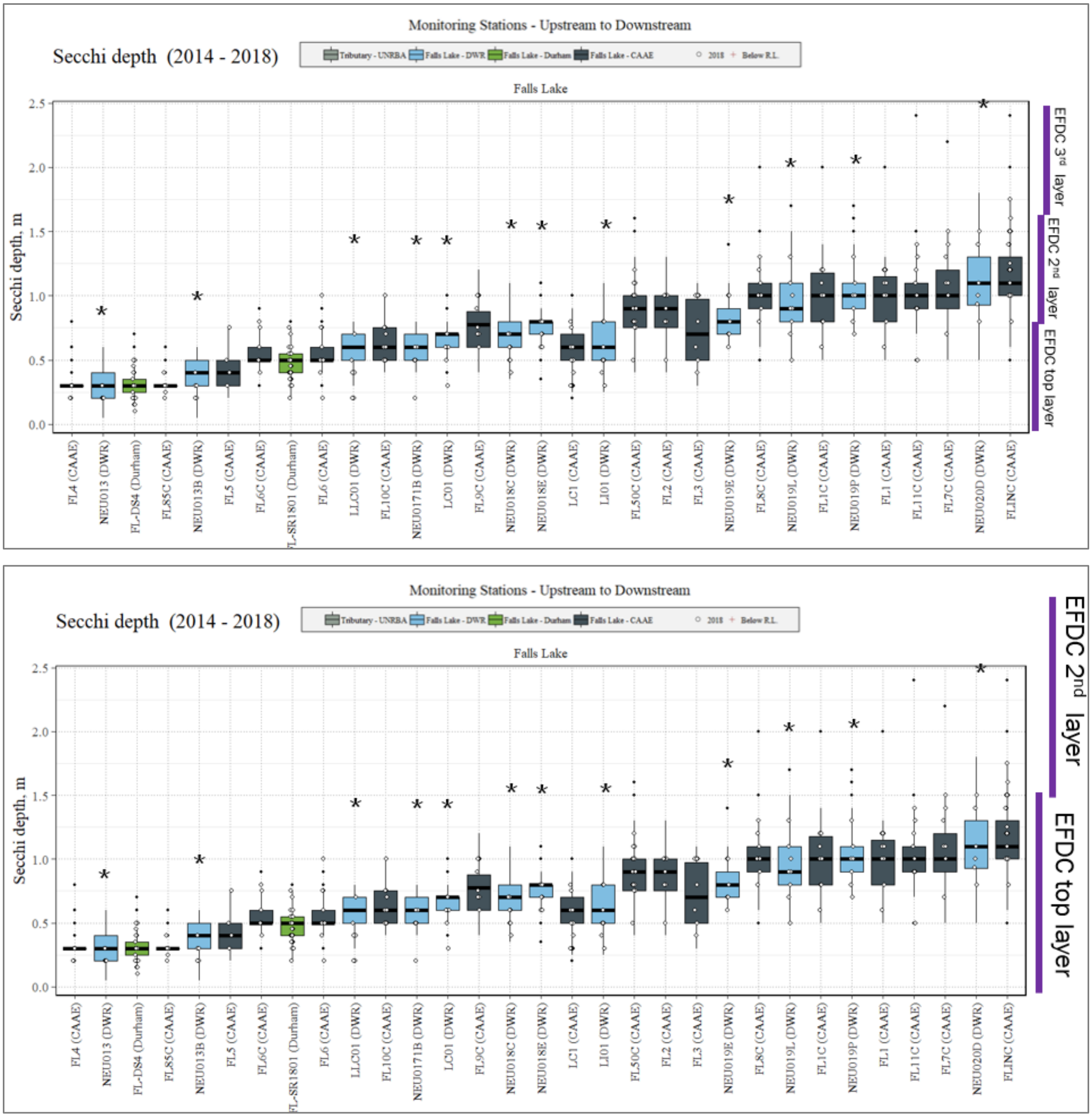

Figure 6-1. Thickness of EFDC Model Layers when Lake Levels are Below (top panel) or Above (bottom panel) Normal Pool Compared to Observed Secchi Depth over the UNRBA Study Period (2014 to 2018)

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Table 6-1. EFDC Layers to Average for Water Quality Calibration and Comparison to Photic Zone Composites		
Stations	When water level is below normal pool	When water level is above normal pool
NEU013,13B	Top layer	Top layer
LLC01; LC01; LI01; NEU017B,18C,18E,19E,19L,19P	Top 2 layers	Top layer
NEU020D	Top 3 layers	Top 2 layers

6.1.2 Model Calibration Approach

As described in Section 3.13.1, the EFDC Falls Lake model receives information from the WARMF watershed model regarding stream flows and sediment, nutrient, and total organic carbon loading. The model uses this information as well as other drivers like meteorology, water withdrawals, and lake releases to simulate the hydrodynamics, water quality, and nutrient releases from lake sediments.

The first component of model calibration is the hydrodynamics which includes water movement, water level, evaporation, and thermal stratification. Following establishment of inputs and outputs for the water balance, lake water level was calibrated to observations in Falls Lake near the dam (USGS 02087183) and Beaverdam impoundment (USGS 0208706575). As discussed in the UNRBA Watershed Modeling Report, stream flows were calibrated to observations on five of the largest tributaries to Falls Lake. There is uncertainty associated with simulated stream flows in terms of model time step versus recorded stream flow and uncertainties with the recorded stream flows themselves. Additionally, 35 percent of the watershed is associated with a tributary or near-lake drainage with no stream flow gage.

Given these uncertainties, it is common practice to add or remove small amounts of water to the system to calibrate the lake water level to observations. Simulated water levels in the UNRBA Falls Lake EFDC model were adjusted using a flow balancing approach where water was added or removed as needed near the mouths of the tributaries. Flow balancing is needed to correct uncertainties associated with stream flow calibration, ungaged tributaries in the watershed, evaporation from the lake surface, and precipitation directly on the lake. The modeling team discussed the need for flow balancing with the MRSW and DWR during a meeting on August 4, 2020. In a follow meeting held November 30, 2020, DWR modeling staff and the “third-party” model reviewers provided input on the flow balancing approach, and additional input was provided through email communications. The MRSW voted to approve a flow balancing approach that incorporated the input from DWR and the “third-party” reviewers.

The flow balancing approach used the difference in daily average observed and simulated water level to calculate the volume of water to be added or subtracted from the lake. Based on feedback from the MRSW and DWR modeling staff, the volume added or subtracted was apportioned to the model grid near each of the 17 tributary inputs based on the amount of ungaged area in each tributary. The LOESS (LOcally Estimated Scatterplot Smoothing; Cleveland & Devlin, 1988) technique was used to smooth the daily flow balances to prevent removing too much water one day just to add it back the next day. The approach is described more fully in Appendix A along with parameters adjusted to improve simulated thermal stratification compared to DWR temperature profiled data collected in Falls Lake.

Next the calibration of the UNRBA Falls Lake EFDC model focused on the water quality calibration starting with total suspended solids, nutrients, chlorophyll-a, and total organic carbon. Changes to improve these parameters can affect calibration of temperature and other water quality parameters, so this is an iterative process. Key parameters used in the calibration were settling rates for silt, clay, and organic material; algal parameters for three simulated groups (nutrient and temperature preferences, growth, respiration,

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predation, death, settling, decay rates, chlorophyll-a to carbon ratios); coefficients describing nutrient affinity for sediments; longer model initialization periods (6 years rather than 1 year) to stabilize the lake sediments; and altering the percent of organic material that decays more quickly or more slowly. Calibration of the water quality and sediment diagenesis modules are described more fully in Appendix A.

6.1.3 Model Calibration and Validation Results

Hydrodynamic Model

The hydrodynamic model was calibrated using data collected during January 1, 2015, to December 31, 2016, and validated to data collected during January 1, 2017, to December 31, 2018, as described in the UNRBA Modeling QAPP. The calibrated and validated state variables of the EFDC hydrodynamic model included stage and water temperature. Additionally, a comparison of modeled versus observed discharge during Jan 2016 and Oct 2016 showed good agreement between modeled discharge and the observed data collected as part of the UNRBA Constriction Point Special Study (BC 2019) conducted at two locations in Falls Lake.

Hydrodynamic model and water temperature performance were evaluated by a combination of visual inspection and quantitative analysis of model-data performance statistics as described in the UNRBA Modeling QAPP. Figure 6-2 shows the simulated versus observed water level at Falls Dam. Water level results for the Beaverdam gage are provided in Appendix A. Figure 6-3 provides an example of simulated versus observed water temperatures for the surface and bottom layers at station NEU018E. Performance statistics and time series comparisons for other DWR monitoring stations are provided in Appendix A.

The calibrated and validated hydrodynamic model was used to study the circulation patterns in Falls Lake. Dr. Rick Luettich presented his research on water movement in Falls Lake at the July 6, 2021, MRSW meeting. The lake modelers met virtually with Dr. Rick Luettich and "third-party" reviewer Dr. Daniel Obenour on September 21, 2021, to discuss simulation of water movement in Falls Lake. The final report for this research is summarized by Luettich et al (2023). The EFDC hydrodynamic model is simulating the magnitude of bi-directional flows observed by Dr. Luettich based on simulations at Hwy 98 and Fish Dam Road during Feb and Aug 2018. Figure 6-4 shows the simulation of bi-directional flow at Highway 98 at Fish Dam Road. Bi-directional flow can occur when the warmer surface water flows toward the dam (arrows pointing the right) and cooler bottom water flows upstream along the bottom of the lake (arrows pointing left). Examples at other locations and times are provided in Appendix A.

Overall, the performance of the Falls Lake EFDC hydrodynamic model is deemed to be acceptable. Based on the calibrated and validated hydrodynamic model, the EFDC model was approved by the MRSW and used for development of the EFDC lake water quality model. The water quality model results are presented in the next section.

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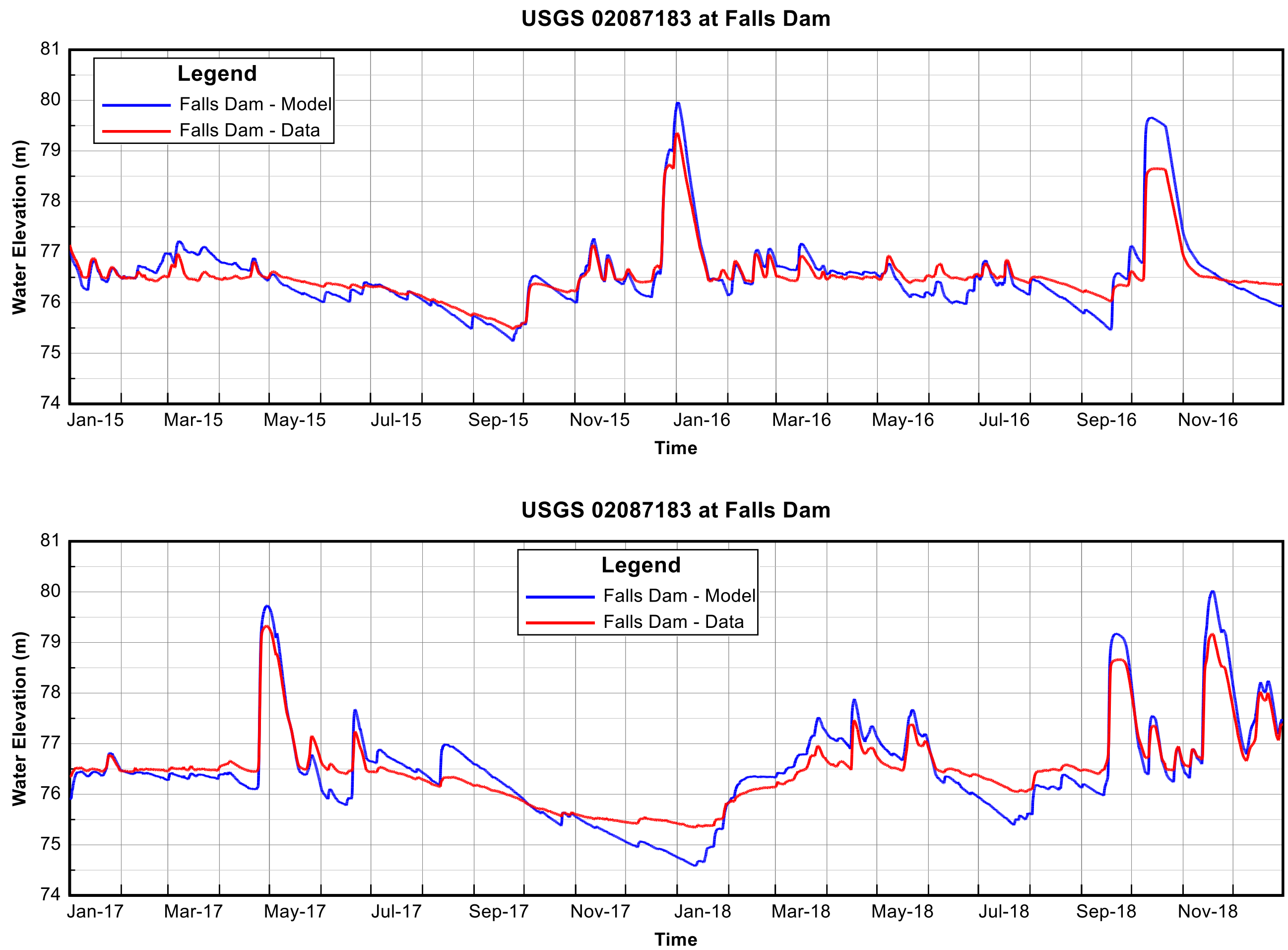

Figure 6-2. EFDC Simulated Versus Observed Water Level at USGS 02087183 at Falls Dam for the Calibration Period (2015 and 2016, top) and Validation Period (2017 and 2018, bottom)

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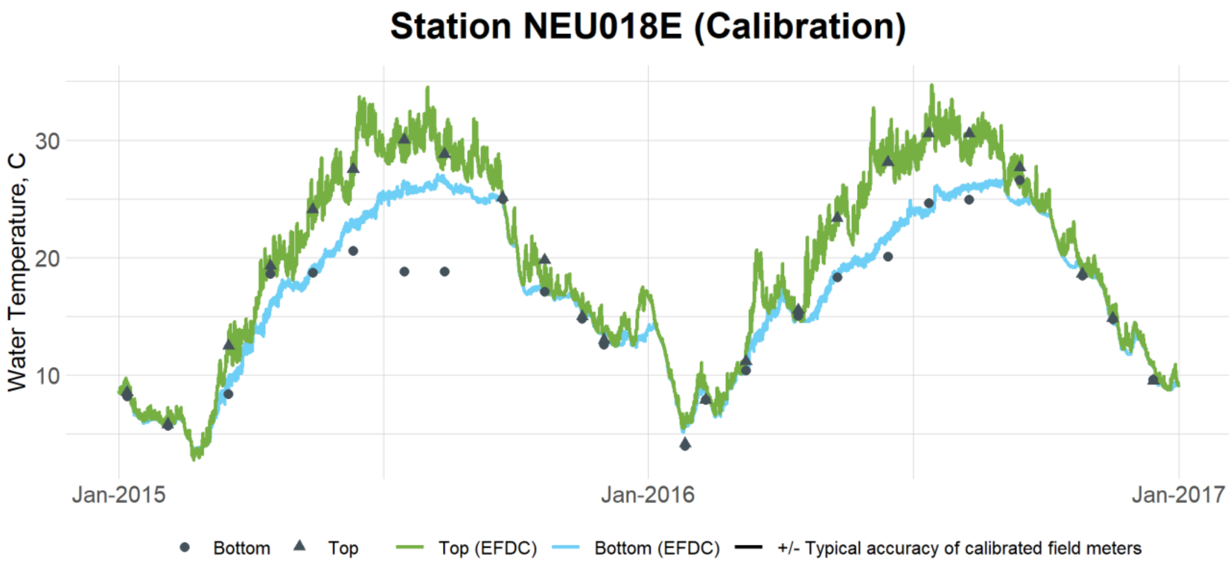

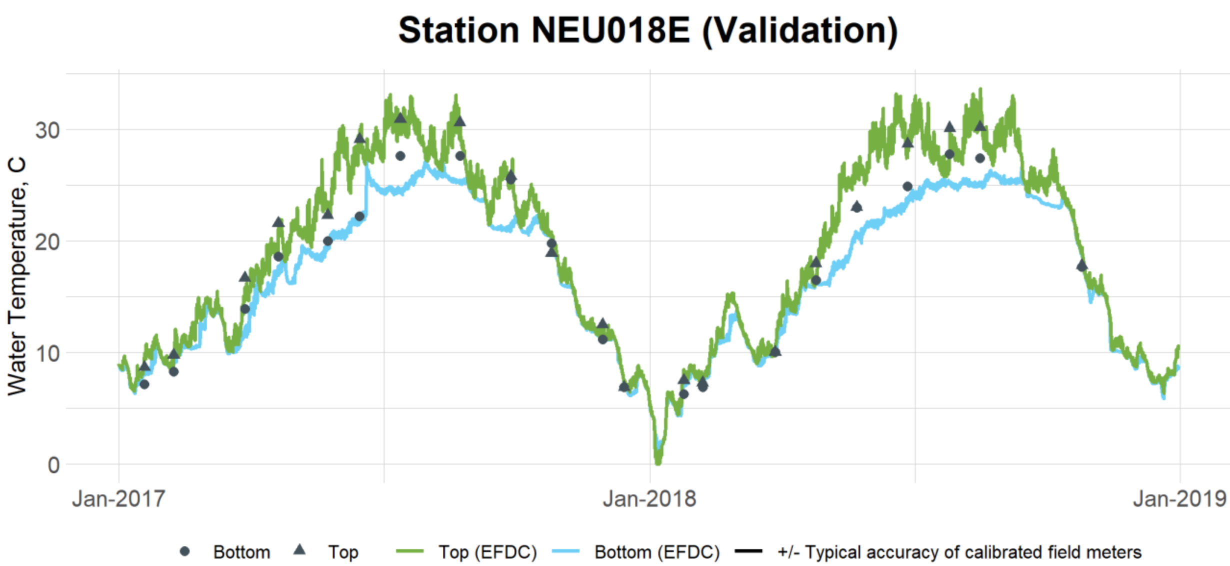

Figure 6-3. EFDC Simulated Versus Observed Water Temperature at Station NEU018E for the Calibration Period (2015 and 2016, top) and Validation Period (2017 and 2018, bottom)

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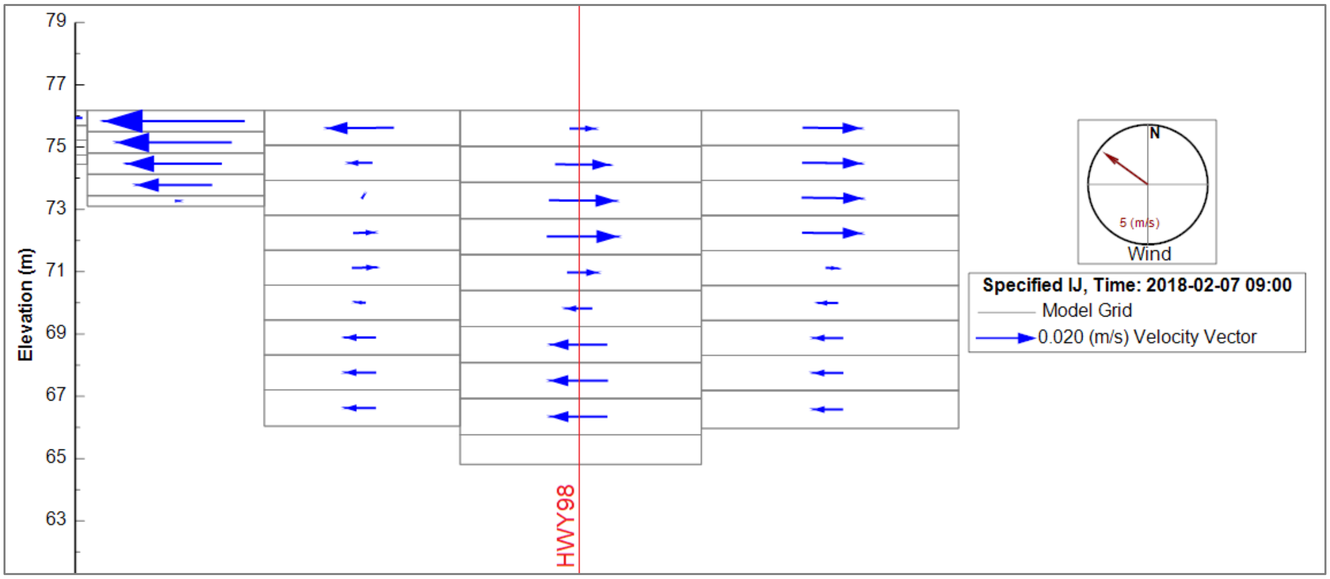

Figure 6-4. EFDC Simulated Bidirectional Flow at Hwy 98 During February 2018

Water Quality Model

A rigorous analysis of an extensive body of water quality and sediment data was performed to develop a conceptual model of the water quality and sediment conditions in Falls Lake. A detailed review process by DWR modeling staff and "third-party" model reviewers was used throughout model development to support the calibration and validation of the 3-dimensional EFDC water quality model of Falls Lake. The level of data availability and efforts to assess the model development throughout the process provides an exceptional basis for confidence in this model. DWR will conduct additional review of the modeling files and draft lake model report.

The EFDC water quality model of Falls Lake was calibrated using data collected during the two-year period from January 1, 2015, to December 31, 2016. The model was then validated to data collected during the two-year period from January 1, 2017, to December 31, 2018. The availability of four years of monitoring data including special studies on lake bathymetry, sediment depth and quality, and sediment nutrient flux was critical for this calibration/validation process. Calibrated and validated state variables in the EFDC water quality model included chlorophyll-a, organic matter, nutrients, DO, and cohesive suspended sediments.

The performance of the water quality model was evaluated by a combination of visual inspection of model-data plots and quantitative analysis of model-data performance statistics that included the RSR. "Third-party," subject matter expert, and DWR input was used to guide calibration decisions. All critical decisions were also reviewed and confirmed by the MRSW. As described in the DWR-approved QAPP, the performance targets adopted for calibration of the Falls Lake water quality model were based on the RSR and percent bias. Performance statistics, time series comparisons, and scatter plots comparing simulated to observed values are provided in Appendix A. Example time series comparisons are shown in Figure 6-5 through Figure 6-12 for the following three stations:

- Station NEU013B in the upper lake (photic layer is the top layer (10))
- Station NEU018E in the middle lake (photic layer is the top layer (10))
- Station NEU020D in the lower lake (photic layers include 10, 9, and 8 depending on the water level)

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Following several discussions with the MRSW, subject matter experts, and DWR modeling staff in 2022 to improve model performance, the MRSW approved the calibration of the EFDC model in January 2023. Best professional judgement is an important component of determining when to stop the calibration process. The additional testing performed showed that additional calibration would not yield overall improvements to the model calibration. Based on statistical skill assessment metrics, visual evaluation of model-data plots, and input from the reviewers of the modeling effort, the performance of the Falls Lake EFDC hydrodynamic and water quality model is deemed acceptable and represents a viable tool for assessing regulatory decisions for Falls Lake.

Figure 6-5 through Figure 6-12 show the EFDC-simulated water quality concentrations compared to photic-zone composite data collected at three DWR monitoring stations. These three stations represent the upper lake (NEU013B), middle lake (NEU018E), and lower lake near the dam (NEU020D). Full-page figures are provided at these and other DWR monitoring stations in Appendix A. Model performance statistics are also provided in Appendix A.

Sediment Diagenesis Model

The kinetic coefficients and model parameters values assigned to the sediment flux model were within reasonable ranges of literature values and vetted extensively throughout the review/input process. Performance of the sediment flux model was evaluated by comparing whole lake average annual internal loading of nutrients derived from the sediment flux model with empirically estimated internal loads developed from available data sources. The lake-wide average annual internal loading derived from the sediment flux model are similar in magnitude to flux rate measurements and empirical estimates of internal nutrient loading based on the available data sources. Results for the EFDC sediment diagenesis model are summarized in Section 55.1 and Appendix A.

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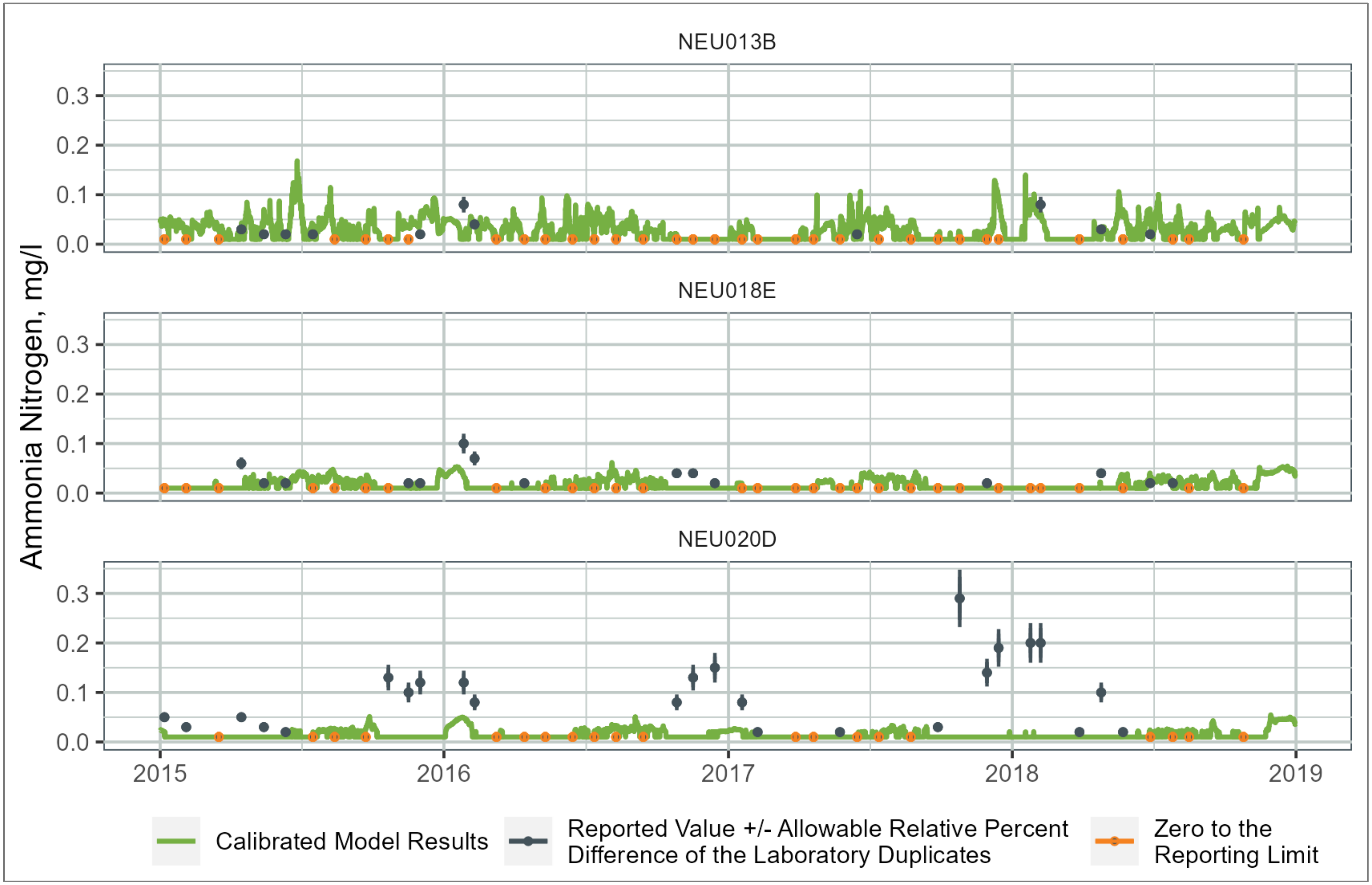

Figure 6-5. Comparison of EFDC Simulated Ammonia Concentrations to Observations at Three Stations in Falls Lake

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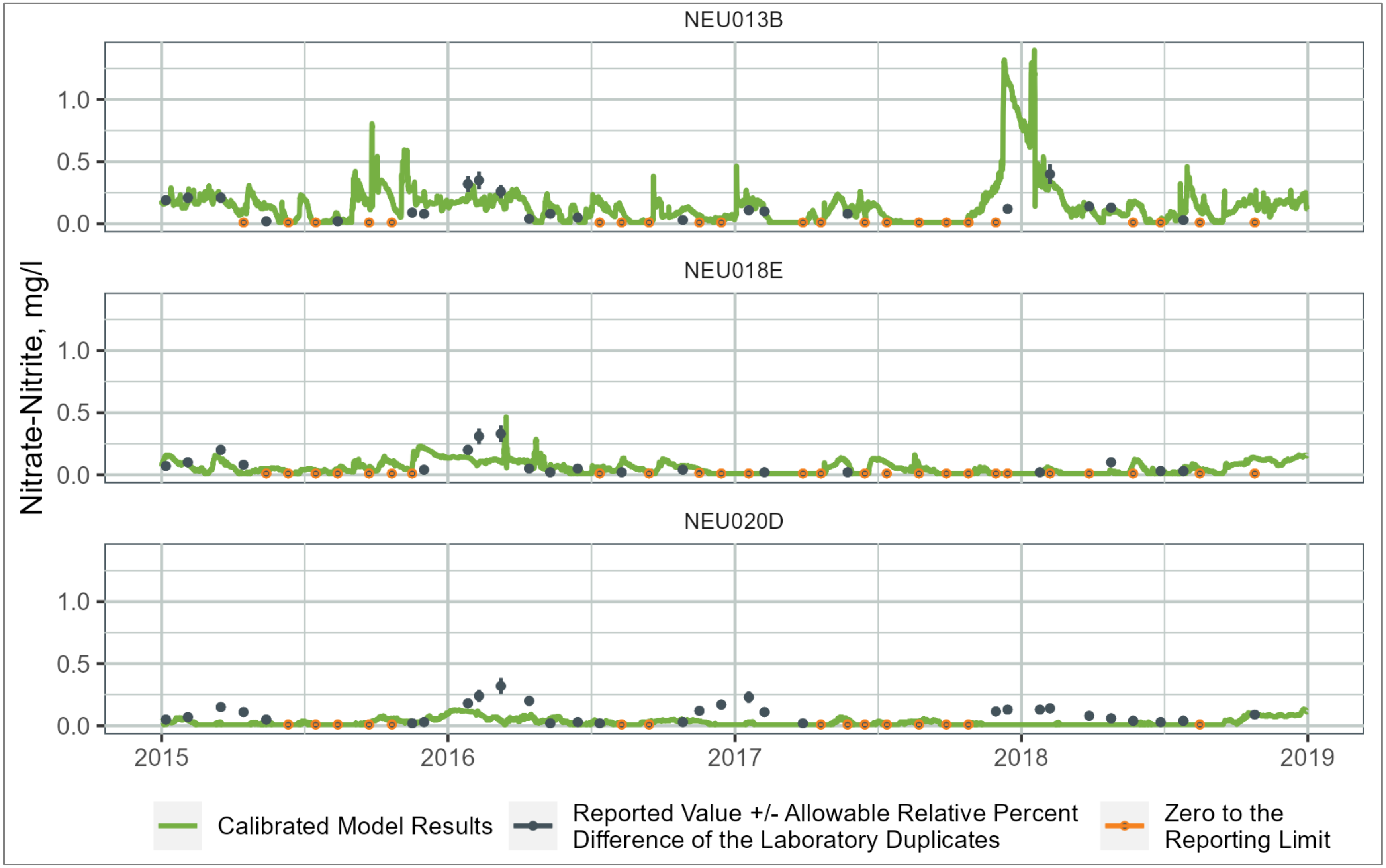

Figure 6-6. Comparison of EFDC Simulated Nitrate Concentrations to Observations at Three Stations in Falls Lake

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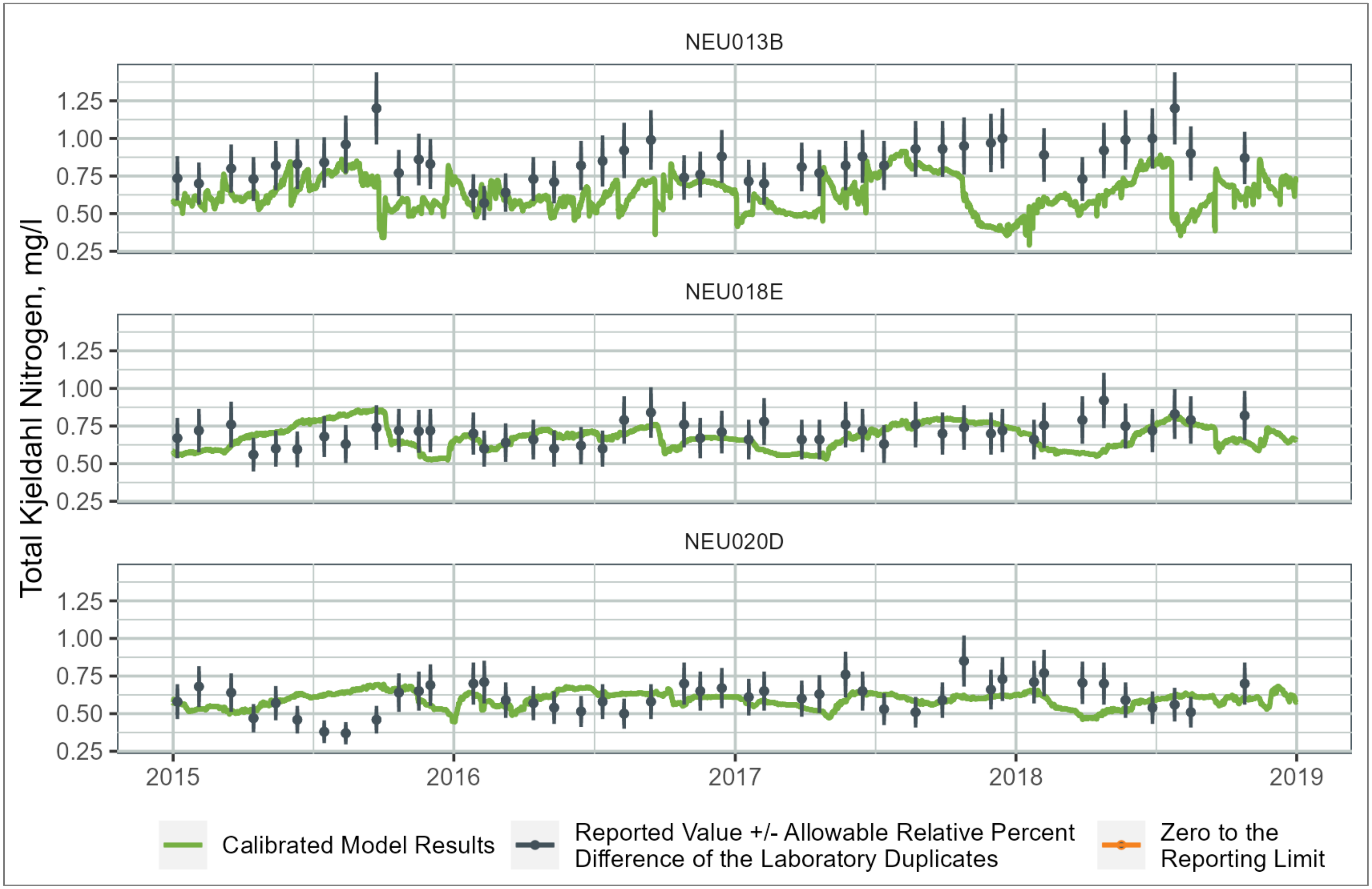

Figure 6-7. Comparison of EFDC Simulated Total Kjeldahl Nitrogen (TKN) Concentrations to Observations at Three Stations in Falls Lake

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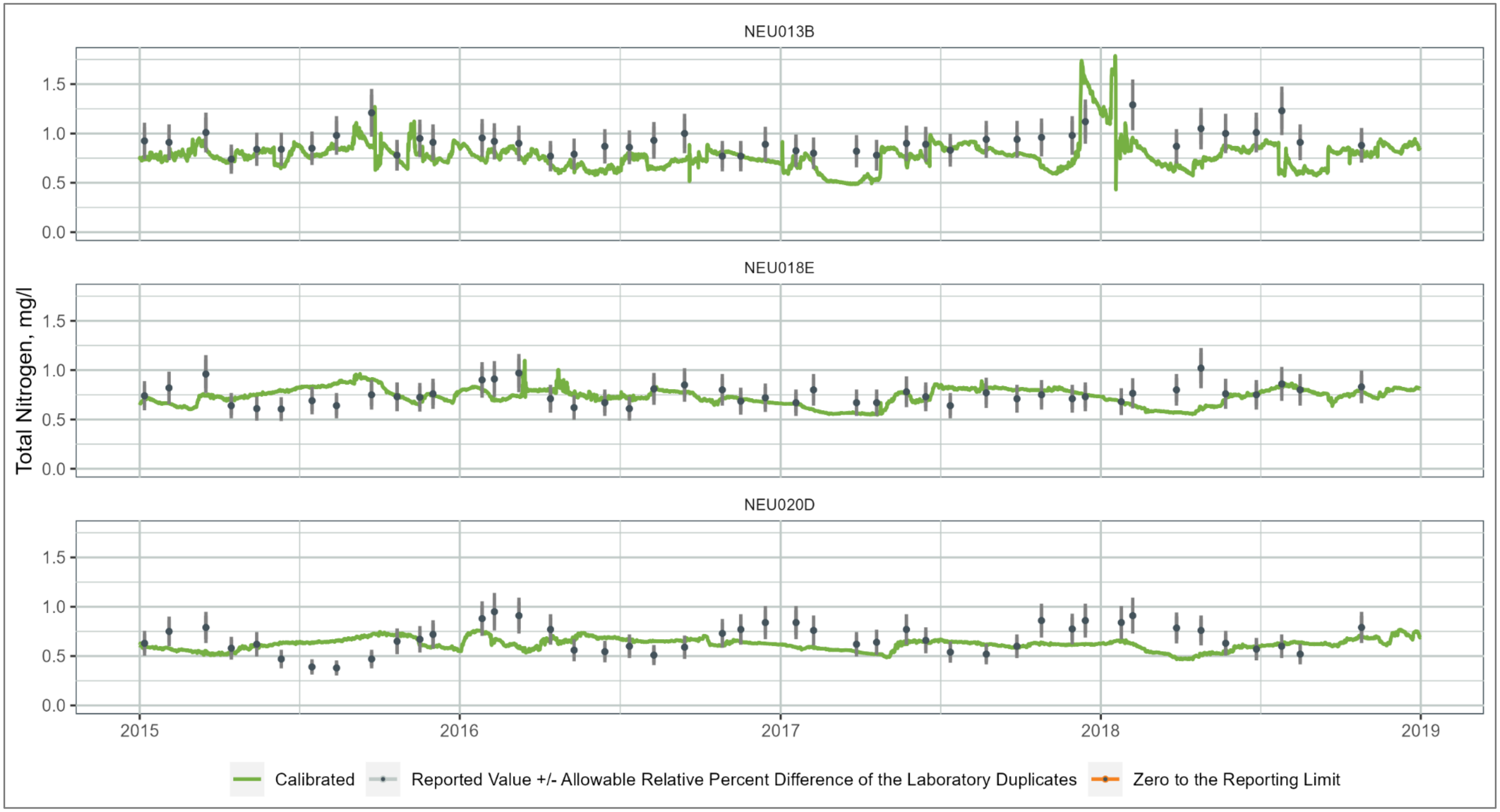

Figure 6-8. Comparison of EFDC Simulated Total Nitrogen (TN) Concentrations to Observations at Three Stations in Falls Lake

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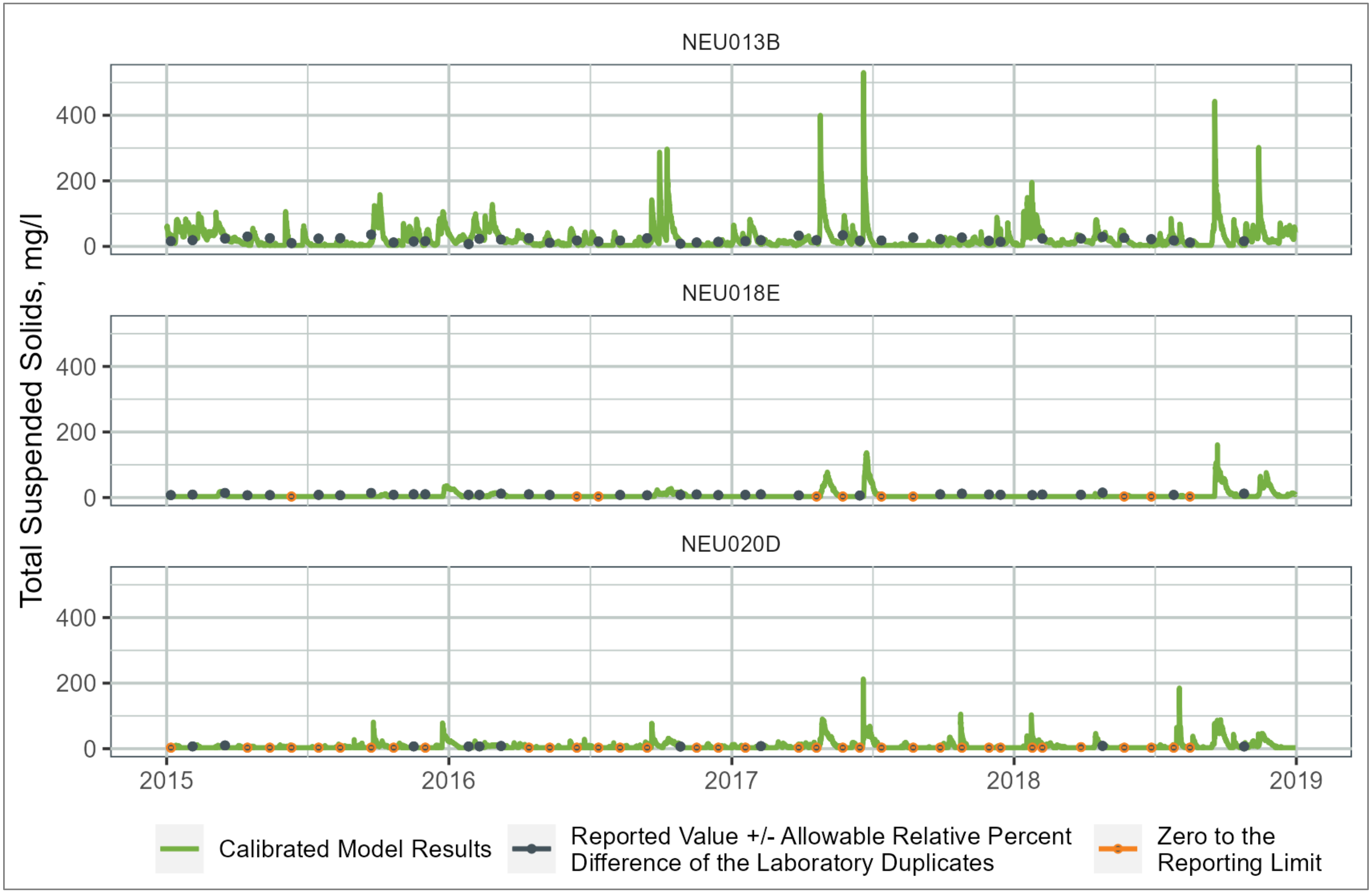

Figure 6-9. Comparison of EFDC Simulated Total Suspended Solids (TSS) Concentrations to Observations at Three Stations in Falls Lake

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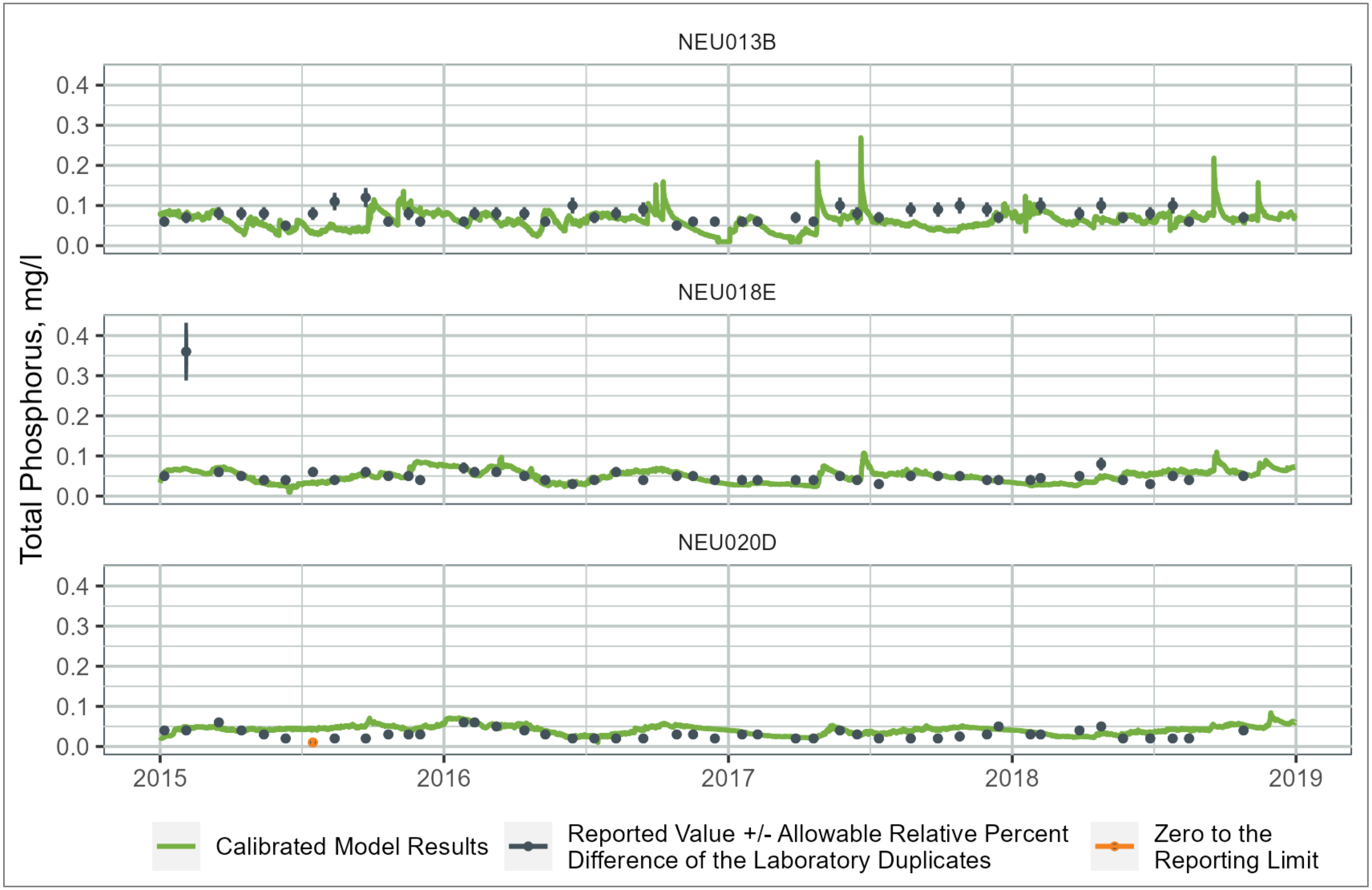

Figure 6-10. Comparison of EFDC Simulated Total Phosphorus (TP) Concentrations to Observations at Three Stations in Falls Lake

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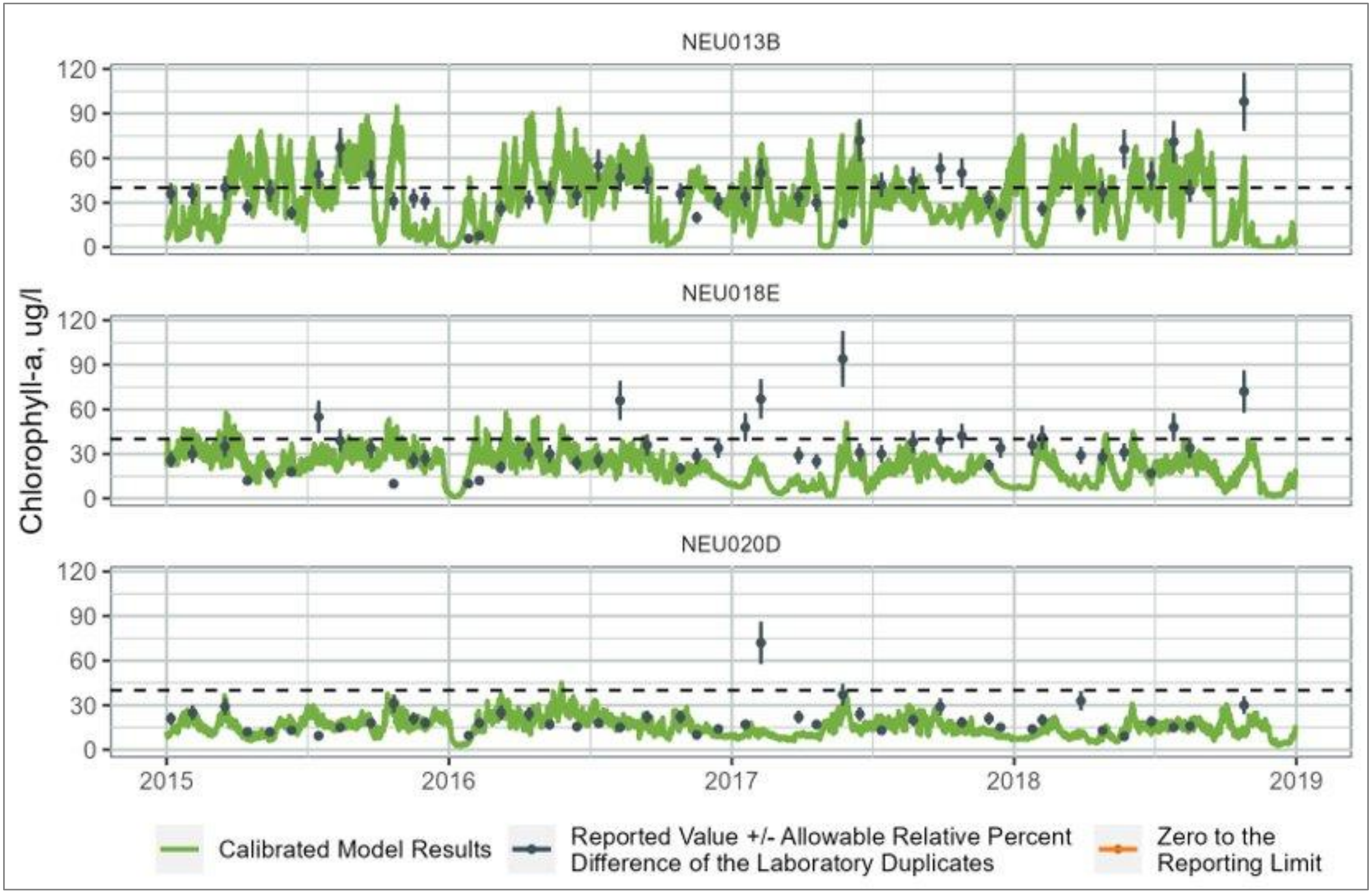

Figure 6-11. Comparison of EFDC Simulated Chlorophyll-a Concentrations to Observations at Three Stations in Falls Lake

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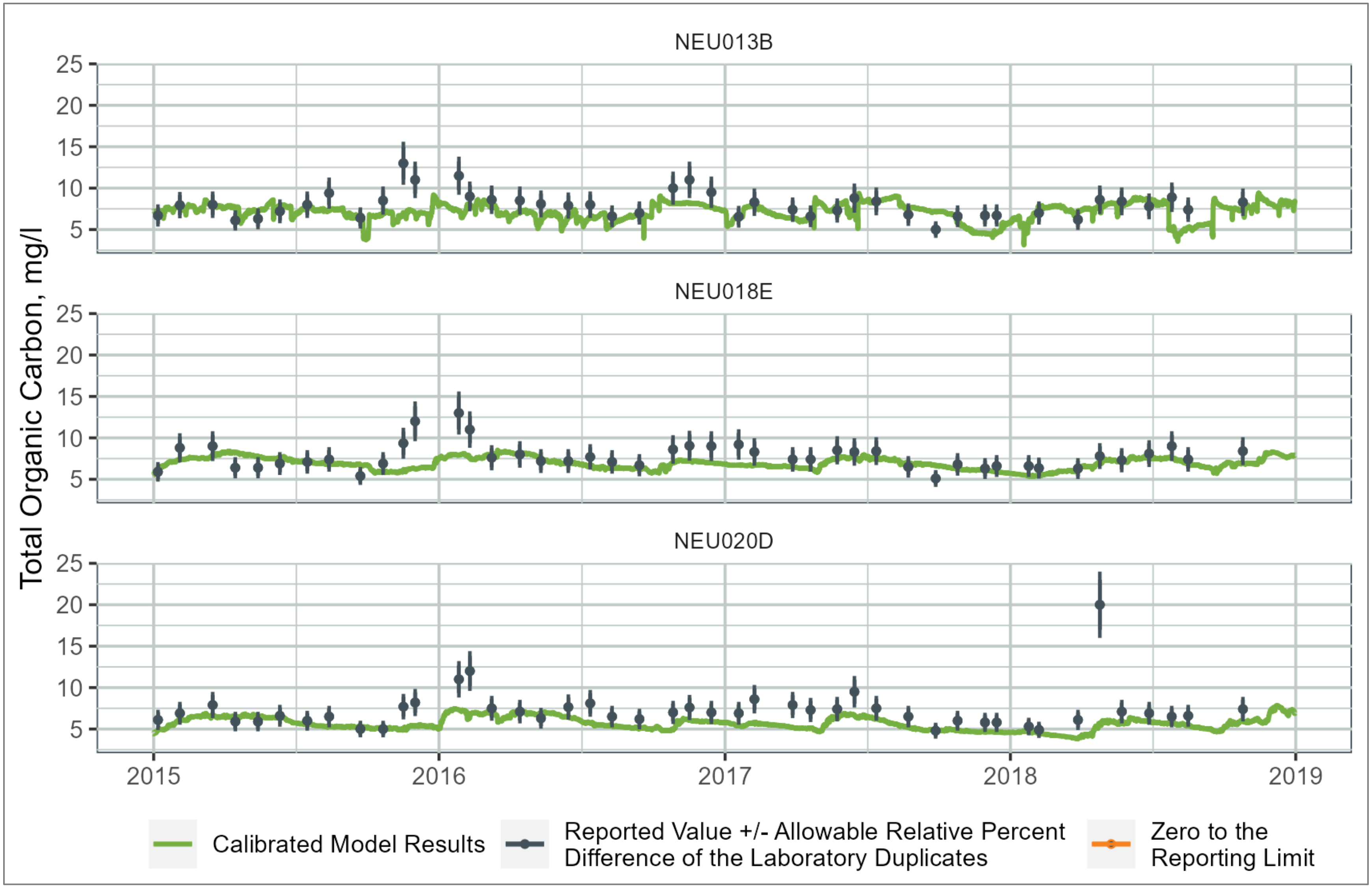

Figure 6-12. Comparison of EFDC Simulated Total Organic Carbon (TOC) Concentrations to Observations at Three Stations in Falls Lake

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6.2 Falls Lake WARMF

6.2.1 Layering Approach

On October 5, 2021, the MRSW reviewed recommendations from the modeling team on how to compare simulated water quality values to photic-zone composite data collected in Falls Lake. The discussion considered the locations of the monitoring stations with respect to WARMF Lake model segmentation and the distribution of observed Secchi depths. Only stations proximal to the downstream end of a lake model segment, along the mainstem of the lake were used for calibration. Also, monitoring had to be conducted under a State-approved QAPP and include both nutrients and chlorophyll-a.

As described in Appendix B, Segment 1 only compares simulated values for the surface layer to photic zone composite samples because the photic zone is relatively shallow. Segments 2 and 3 (between Fish Dam/Cheek Road and Highway 50) average the top two layers for comparison to photic zone composite samples. Segments 4, 5, and 6 located downstream of Highway 50 have higher Secchi depth measurements and the top three layers are averaged for comparison to photic zone composites.

6.2.2 Model Calibration Approach

For the calibration of water level, the WARMF Lake option to match observations was applied. This option reduces the calculated evaporative losses so that lake level does not drop below what was observed. When lake level is higher than simulated, the model cannot add water to the system, so lake levels may be simulated lower than observed following flood conditions.

Model coefficients used to calibrate the water quality simulation for the model segments are provided in Appendix B. Briefly, the following adjustments were made to improve the model fit to water quality observations:

- WARMF Lake does not include predation or grazing of algae as a food source. Detritus decay rates were decreased to reduce the simulated release of nutrients associated with algal decay and account for some storage in the food web.
- WARMF Lake does not simulate resuspension of material from the lakebed. Sedimentation rates and algal settling rates were adjusted to count for the net effects of settling and resuspension.
- WARMF assumes during algal respiration that algae release ammonia into the water column. WARMF is usually run as a daily simulation with a 24-hour time step that represents daily average conditions. The Falls Lake application runs on a 6-hour time step, and so the simulated ammonia concentrations in the lake have diurnal fluctuations around a mean value near the detection limit. To smooth the simulated ammonia concentrations, the release of ammonia during respiration was minimized.
- Observed nitrate concentrations in Falls Lake were higher in the winter compared to the model when default temperature coefficients were applied. To allow for more nitrification in winter months, the temperature coefficient was reduced from model default.
- Three algal groups are simulated in WARMF Lake and the user specifies the nutrient and temperature preferences, algal growth, respiration, death, settling, and decay rates separately for each group. An assumed chlorophyll-a to carbon ratio is applied to each algal group to estimate chlorophyll-a in the water column. The three groups simulated for this application are blue greens, diatoms, and “other.” The “other” group includes Prymnesiophytes, Euglenoids, greens, and other types of algae present in Falls Lake as indicated by DEQ algal composition data.
- Settling rates of sediment were adjusted to improve the simulation of total phosphorus and ammonia concentrations.

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- Algal growth rates, nitrification, denitrification, and organic material decay rates were adjusted to improve model calibration. These rates were set as lake wide values.
- Initial conditions for the lakebed were reset for each of the five iterations of the linked WARMF watershed-lake model simulation. When lakebed conditions were not reset, the 25-year simulation needed to stabilize soils in the watershed model reduced nutrients stored in the lake sediments such that the sediment quality studies conducted in 2015 were no longer represented. To ensure the model was representing conditions present in 2014 to 2018, the initial conditions of the lakebed were reset each time the model was run.
- Lake sediment-water column diffusion coefficients were adjusted to regulate the rate of exchange of constituents between the water column and the lakebed. Two sediment bed diffusion rates were set based on the average sediment depth for the segments (Figure 6-13). These two areas of the lake have different temperature regimes and different types and quantities of benthic organisms that affect diffusion from the lakebed. The average sediment depths in segments to the northwest/upstream of the line range from 0.6 to 1.3 inches and to the southeast/downstream range from 1.4 to 5.3 inches. Shallower sediment depths may not provide adequate habitat for some benthic organisms like worms that may extend 6 inches down into sediments (White and Miller 2008). Benthic organisms also prefer habitats where the water depth is ~1.5 times the depth of the photic zone (White and Miller 2008).

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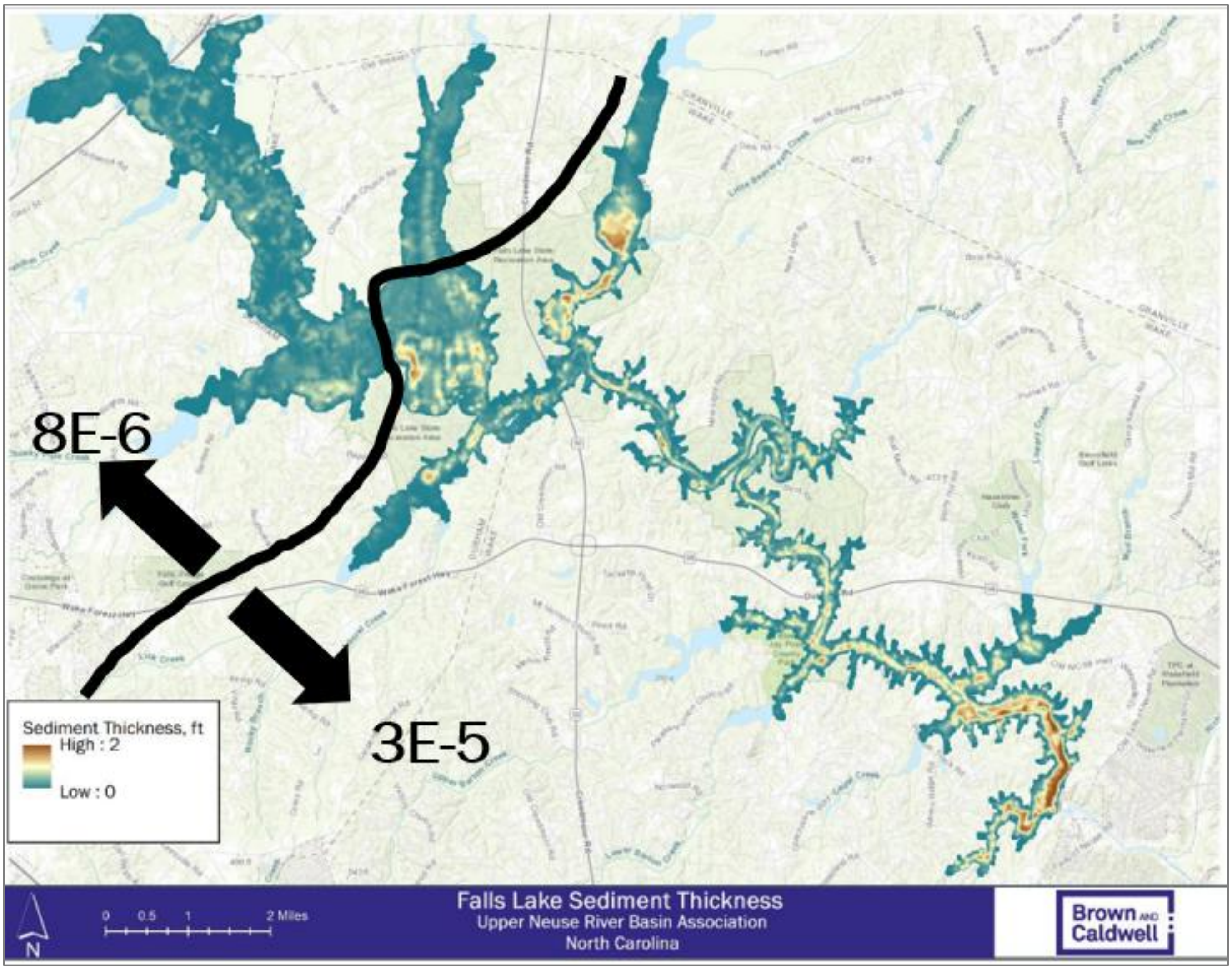

Figure 6-13. Sediment Bed Diffusion Rates Incorporated into the Calibrated WARMF Lake Model Based on Sediment Depth

6.2.3 Model Calibration and Validation Results

Like the Falls Lake EFDC model, the WARMF Lake model for Falls Lake was calibrated using data collected during the two-year period from January 1, 2015, to December 31, 2016, and validated to data collected during the two-year period from January 1, 2017, to December 31, 2018. DWR modeling staff and “third-party” model reviewers provided review and input during model development and calibration. “Third-party,” subject matter expert, and DWR input was used to guide calibration decisions. All critical decisions were also reviewed and confirmed by the MRSW. The availability of four years of monitoring data including special studies on Falls Lake was critical for this calibration/validation process. Calibrated and validated state variables in the WARMF Lake water quality model included chlorophyll-a, organic matter, nutrients, and suspended sediment parameters.

The performance of the water quality model was evaluated by a combination of visual inspection of figures (comparing simulated values to observations) as well as model performance statistics. As described in the DWR-approved QAPP, the performance targets adopted for calibration of the Falls Lake WARMF Lake water

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quality model were based primarily on the percent bias with additional statistics included for reference. Performance statistics, full-page time series comparisons, and scatter plots comparing simulated to observed values are provided in Appendix B. Example time series comparisons of WARMF-simulated water quality concentrations compared to photic-zone composite data are shown in Figure 6-14 through Figure 6-21 for the three lake segments (see segment map in Figure 3-10). These three example segments represent the upper lake (Segment 1), middle lake (Segment 4), and lower lake (Segment 6):

- Segment 1 upstream of Fish Dam/Cheek Road
- Segment 4 between Rolling View marina and Highway 50
- Segment 6 between Highway 98 and the dam

Following several discussions with the MRSW, subject matter experts, and DWR modeling staff in 2022 to improve model performance, the MRSW approved the calibration of the WARMF Lake model in January 2023. Based on model performance statistics, visual comparisons of simulated and observed data, input from the reviewers of the modeling effort, and best professional judgment, the performance of the WARMF Lake model is deemed acceptable and represents a viable tool for assessing regulatory and management decisions for Falls Lake.

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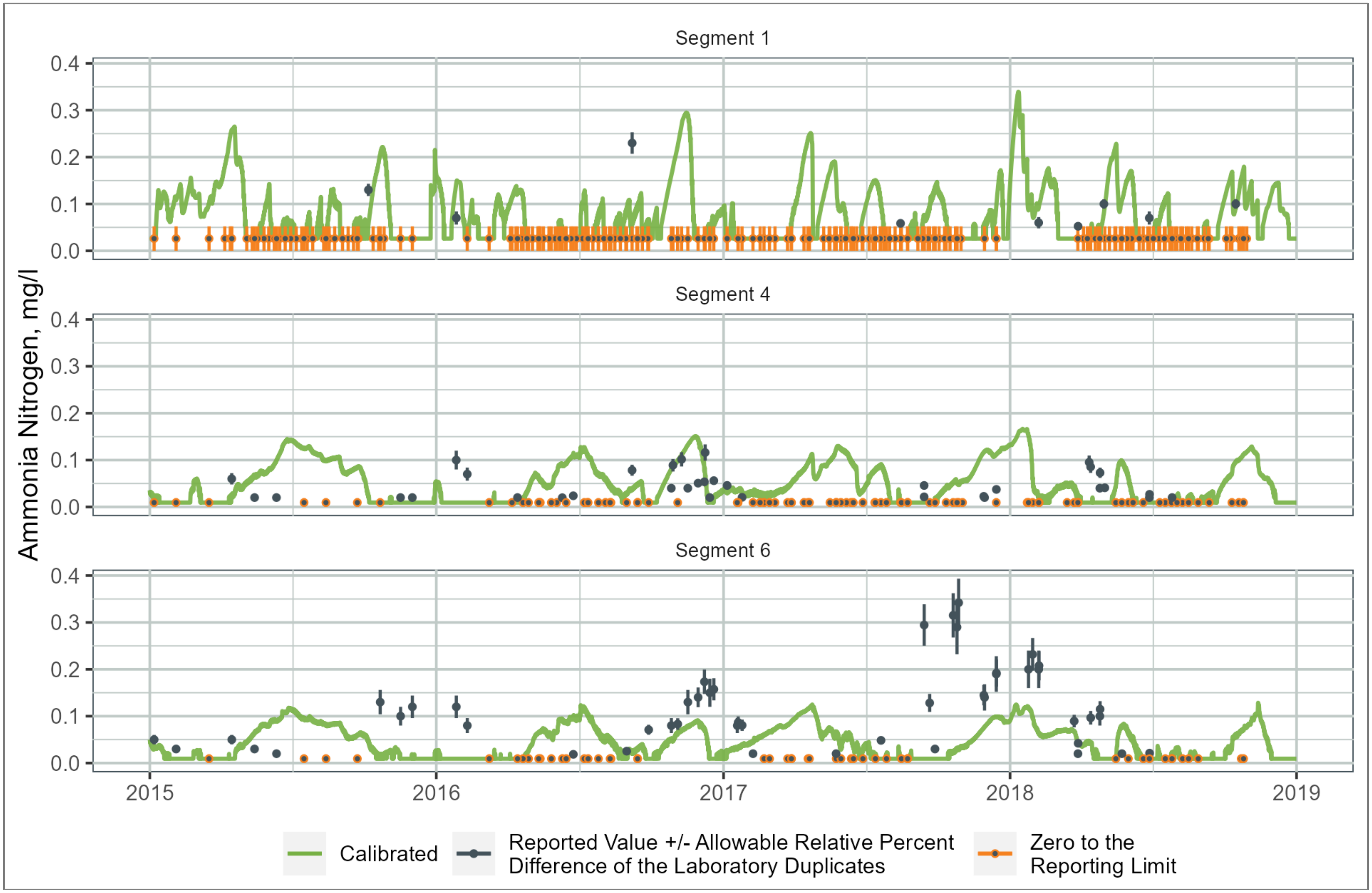

Figure 6-14. Comparison of WARMF Lake Simulated Ammonia Concentrations to Observations Collected at the Downstream End of Three Main Lake Segments in Falls Lake

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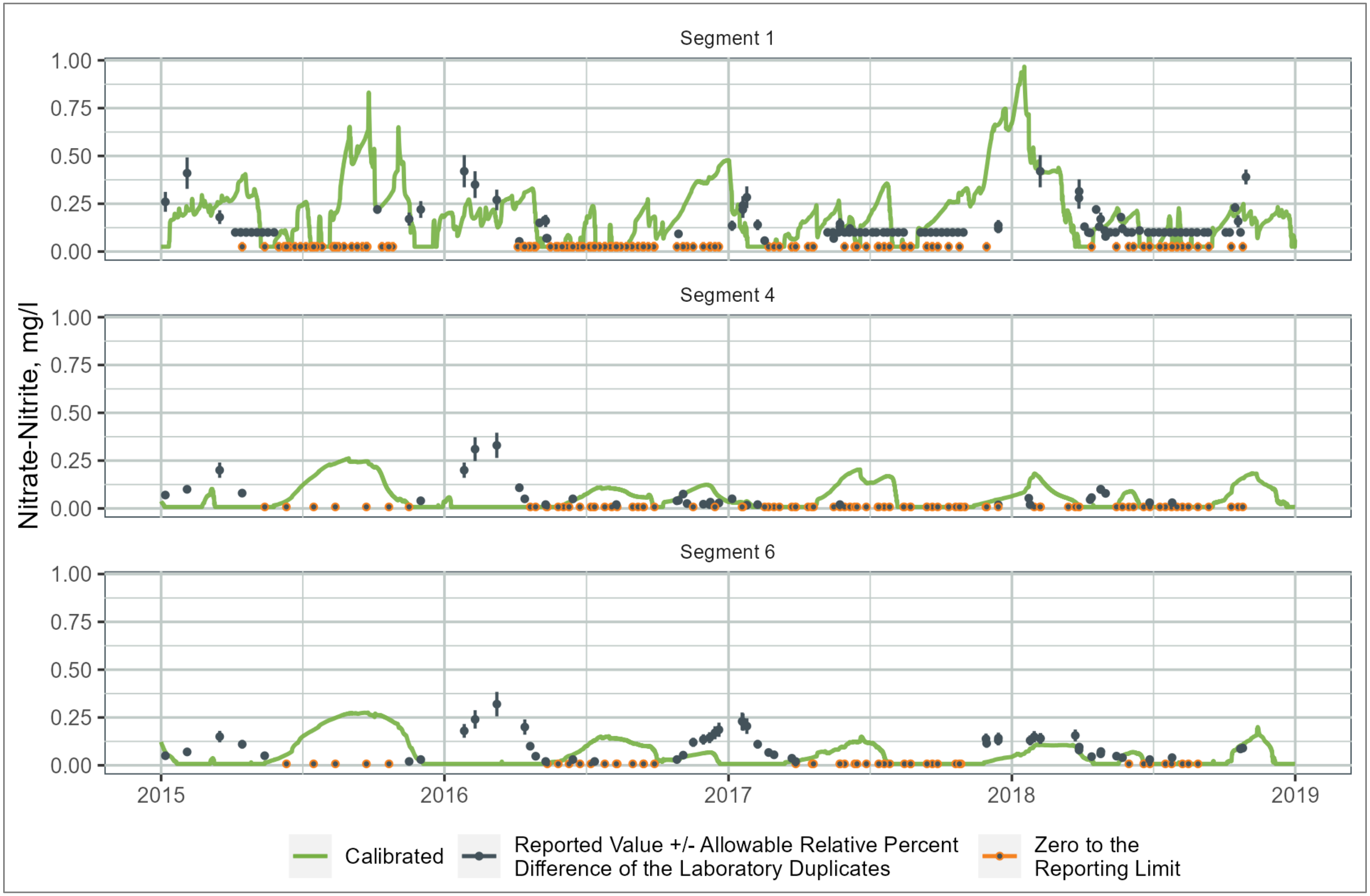

Figure 6-15. Comparison of WARMF Lake Simulated Nitrate Concentrations to Observations Collected at the Downstream End of Three Main Lake Segments in Falls Lake

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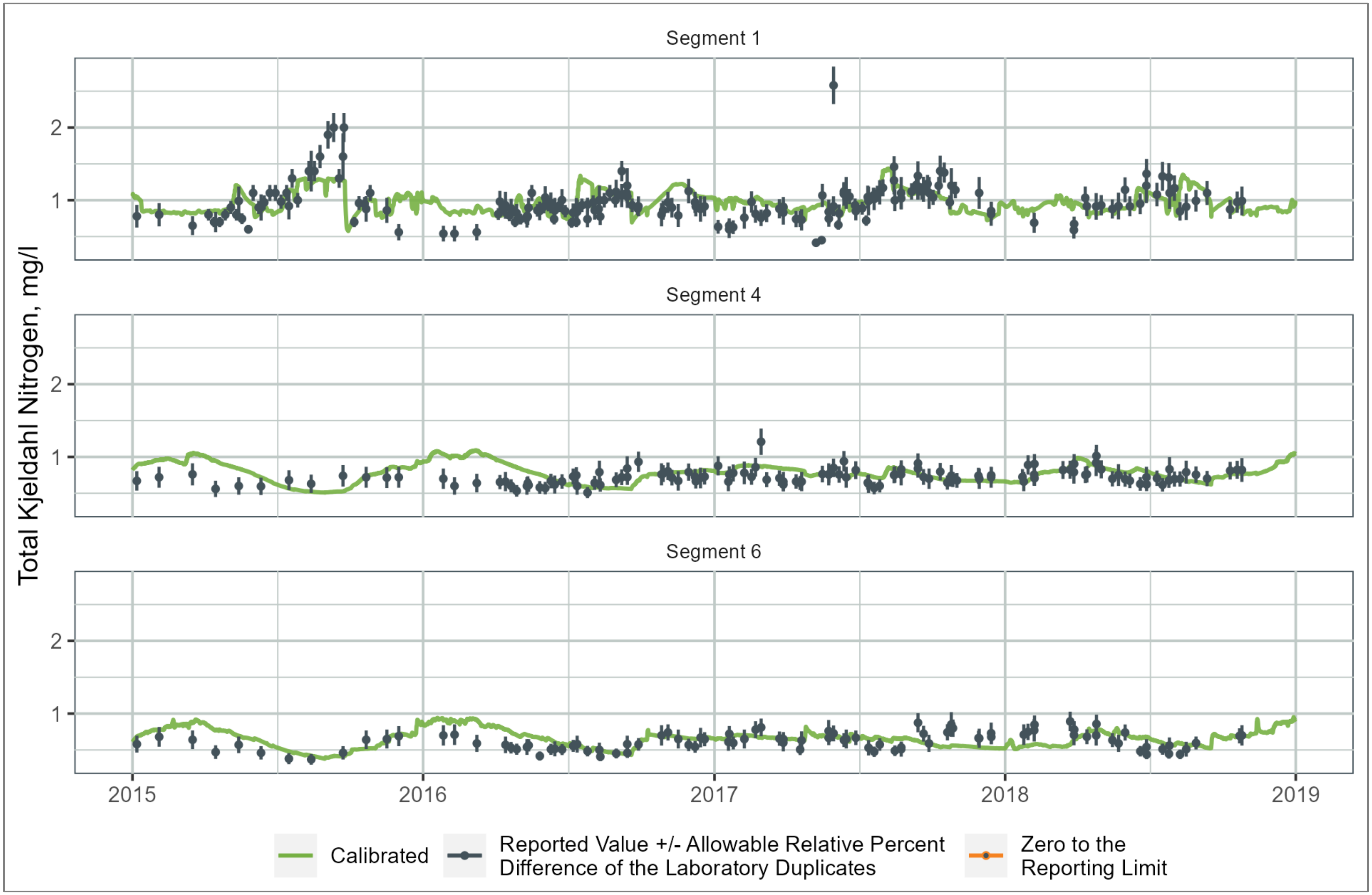

Figure 6-16. Comparison of WARMF Lake Simulated Total Kjeldahl Nitrogen (TKN) Concentrations to Observations Collected at the Downstream End of Three Main Lake Segments in Falls Lake

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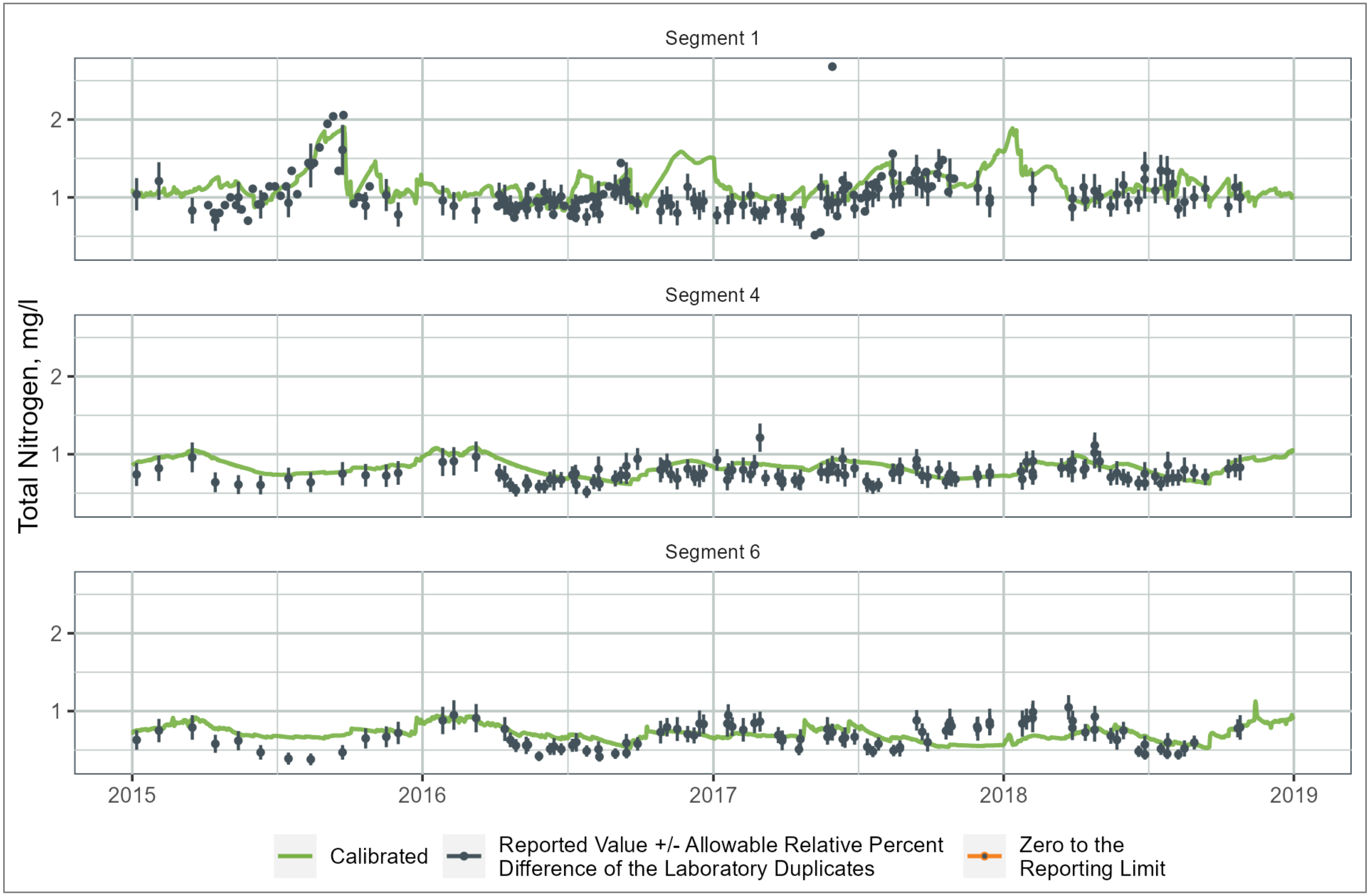

Figure 6-17. Comparison of WARMF Lake Simulated Total Nitrogen (TN) Concentrations to Observations Collected at the Downstream End of Three Main Lake Segments in Falls Lake

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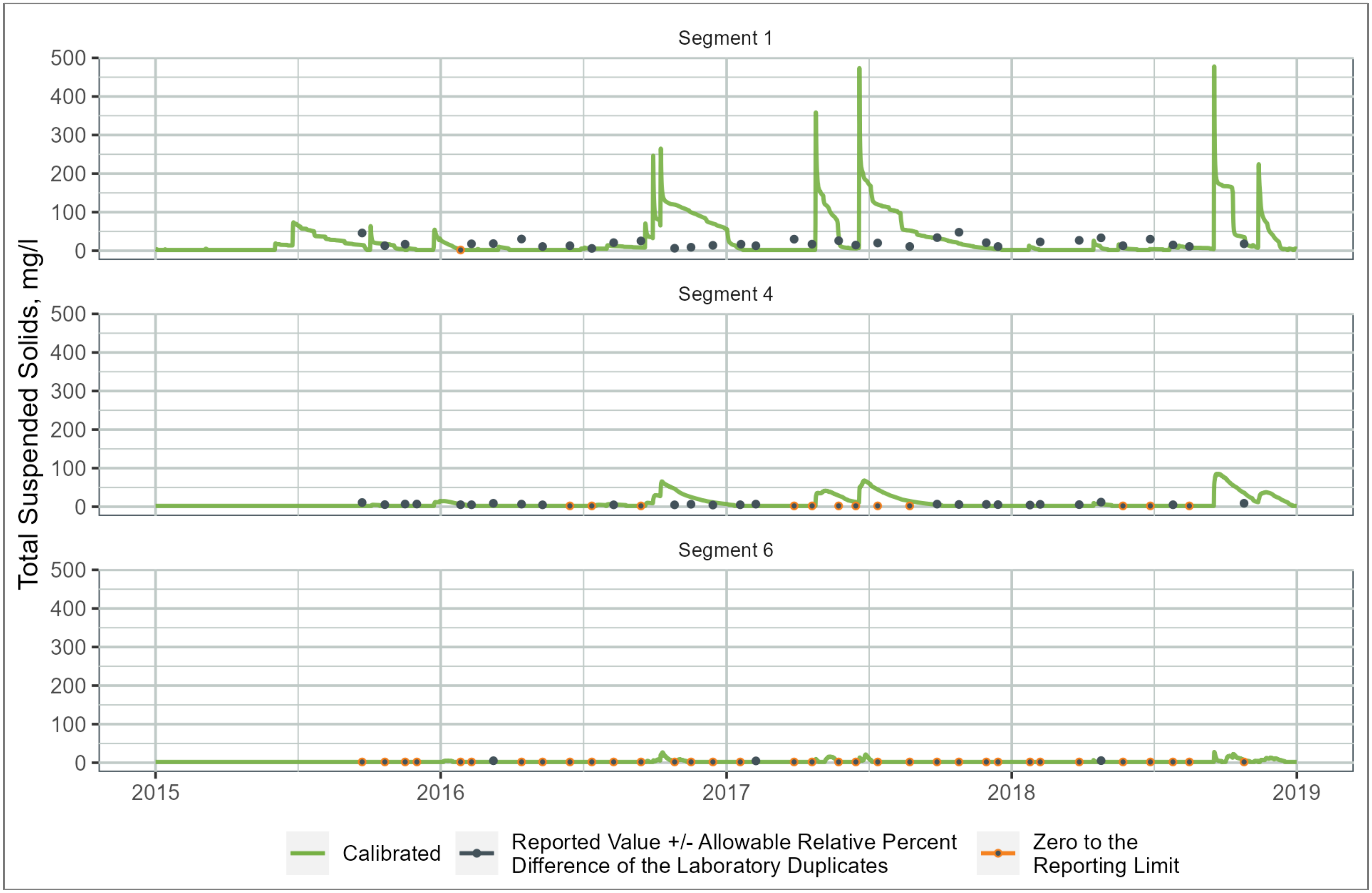

Figure 6-18. Comparison of WARMF Lake Simulated Total Suspended Solids (TSS) Concentrations to Observations Collected at the Downstream End of Three Main Lake Segments in Falls Lake

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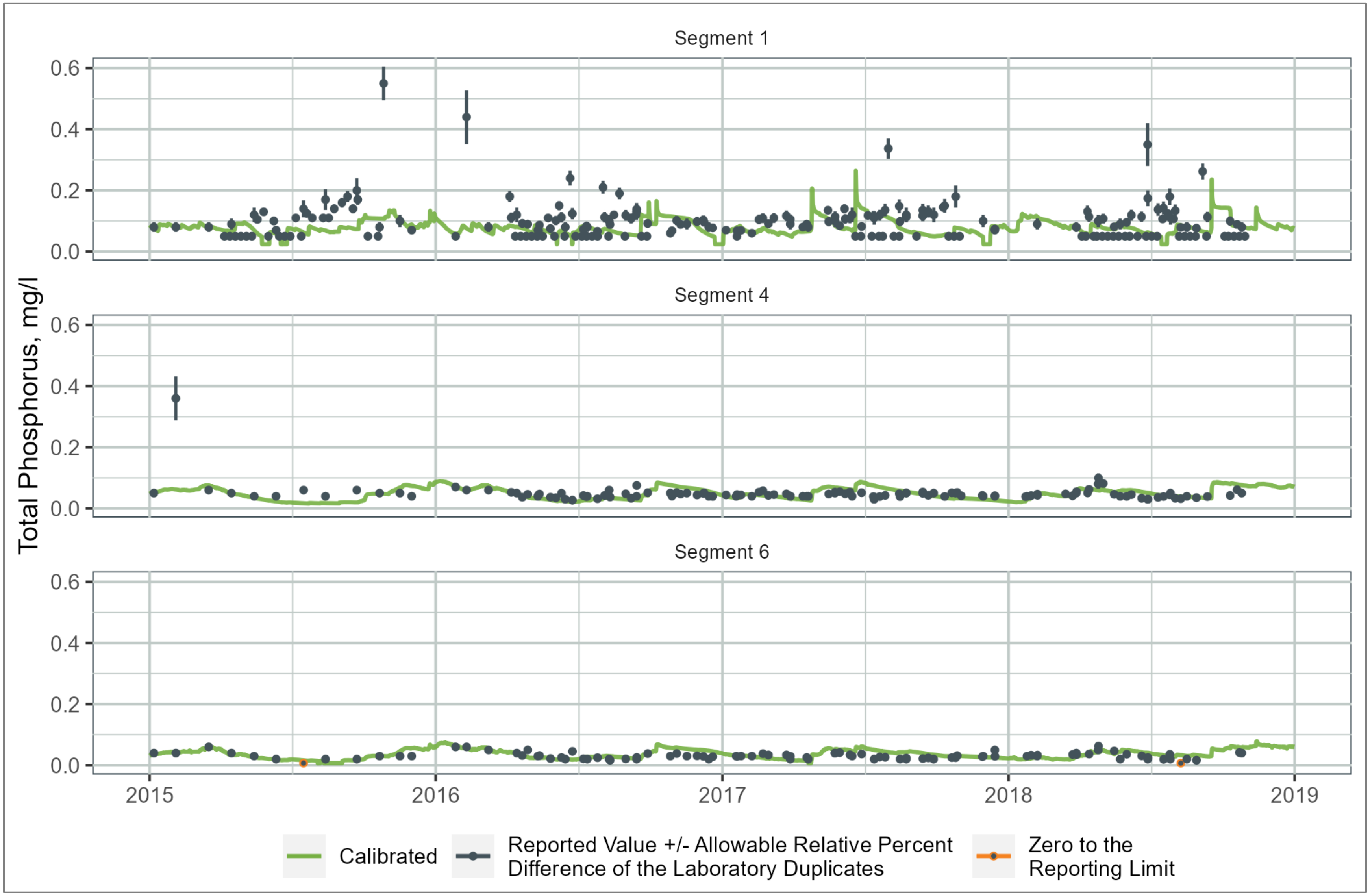

Figure 6-19. Comparison of WARMF Lake Simulated Total Phosphorus (TP) Concentrations to Observations Collected at the Downstream End of Three Main Lake Segments in Falls Lake

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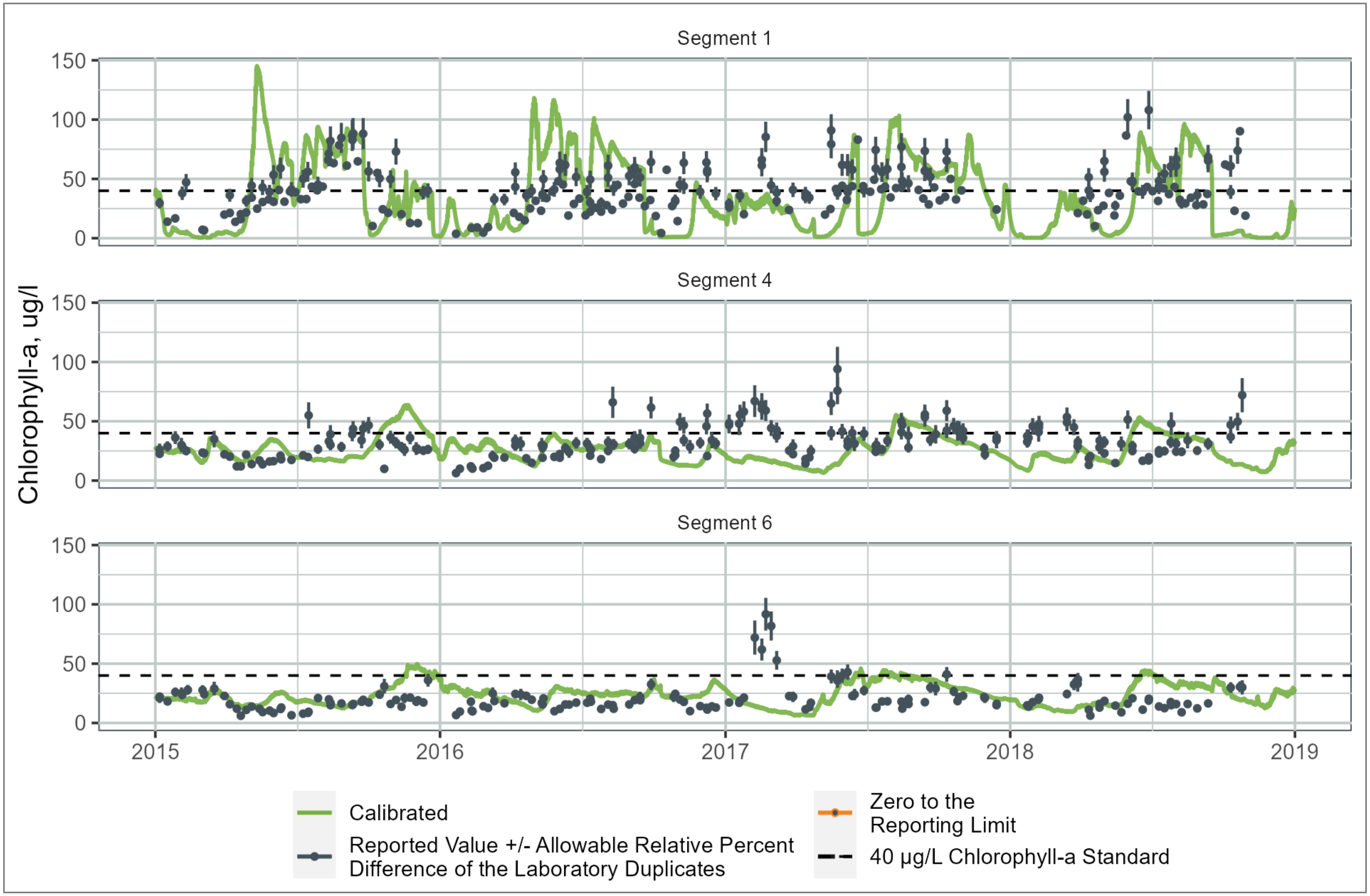

Figure 6-20. Comparison of WARMF Lake Simulated Chlorophyll-a Concentrations to Observations Collected at the Downstream End of Three Main Lake Segments in Falls Lake

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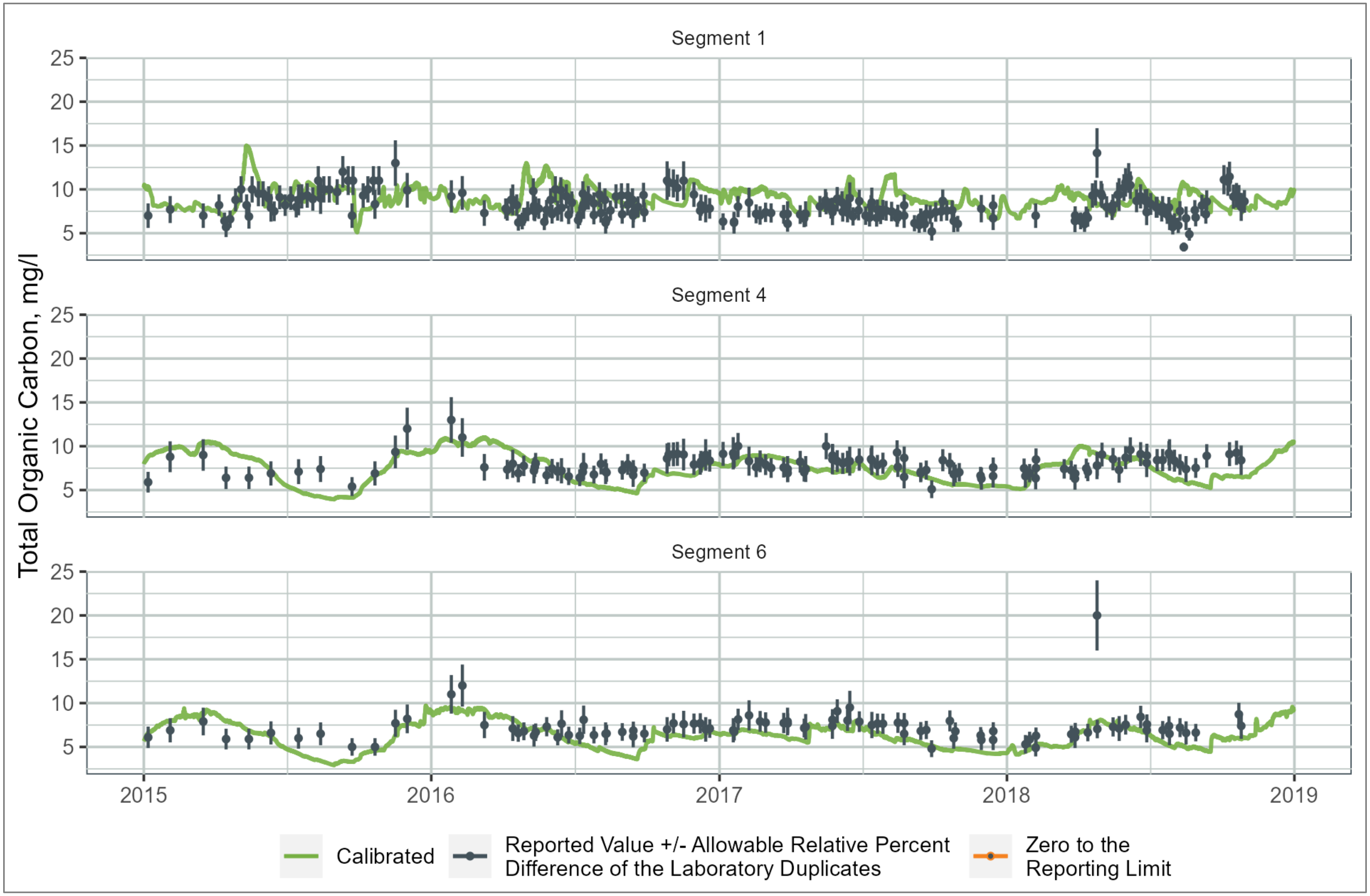

Figure 6-21. Comparison of WARMF Lake Simulated Total Organic Carbon (TOC) Concentrations to Observations Collected at the Downstream End of Three Main Lake Segments in Falls Lake

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Results for the WARMF Lake sediment-nutrient flux model are summarized in Section 55.2.

6.3 Falls Lake Statistical Bayesian Model

The Falls Lake Statistical Bayesian model is developed using the historic record of water quality data and observed conditions. It provides an interactive summary of all observed data and the probabilistic relationships among variables. Rather than adjust model coefficients, like EFDC or WARMF, to fit the observations, the observations are used to generate probability distributions that indicate how frequently something has occurred.

When the full record is evaluated with the model, this is the “default condition” or “default scenario.” For example, the default condition evaluates all data collected in the warm and cool seasons. If the user wants to see how the probability distributions change if warm season is selected, this would be a scenario. Section 9.3 summarizes how scenarios change the probability distributions of the key output variables.

Figure 6-22 through Figure 6-24 show the probability distributions for the default scenario for the upper, middle, and lower lake segments, respectively. The categorical bins (e.g., low, medium, high) are based on all data collected in Falls Lake. The models for each segment use the same bins but focus on data and conditions for that segment. The upper lake has higher probabilities of high nutrient and high chlorophyll-a concentrations. The lower lake has higher probabilities of low nutrient and low chlorophyll-a concentrations. The distributions of the data and the conditions under which they were collected, affect how responsive the outputs are to scenarios. For example, in the upper lake, chlorophyll-a concentrations are generally high, and high concentrations of chlorophyll-a have been observed across the range of seasons, nutrient loads, and precipitation regimes. Changing these model inputs does not have a significant impact on the probability distributions for chlorophyll-a because they are typically high regardless of the other conditions. In the lower lake, the impact of changing conditions has even less effect on chlorophyll-a because concentrations have been consistently low regardless of other conditions.

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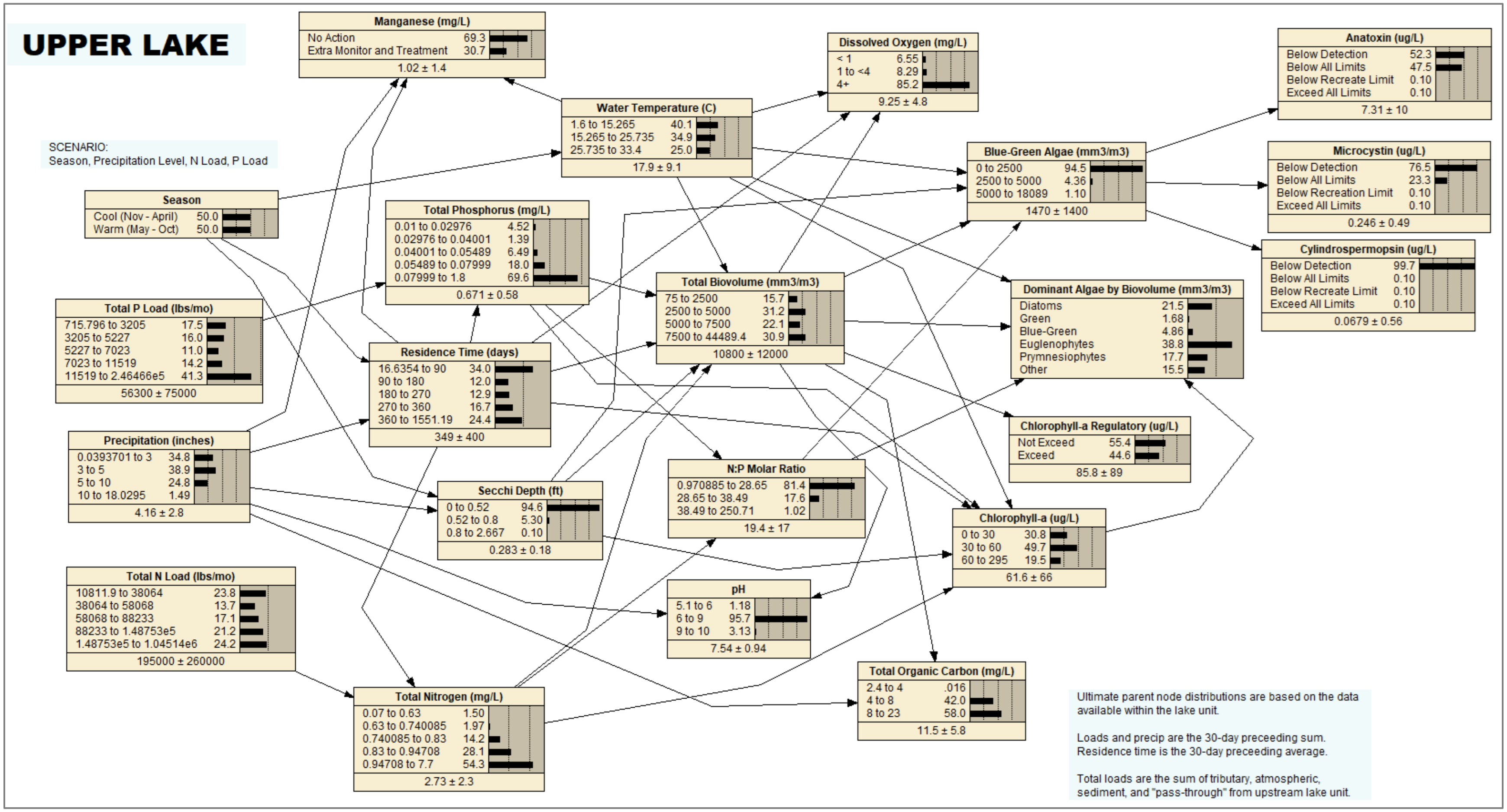

Figure 6-22. Default Probability Distributions for the Upper Lake Statistical Bayesian Model

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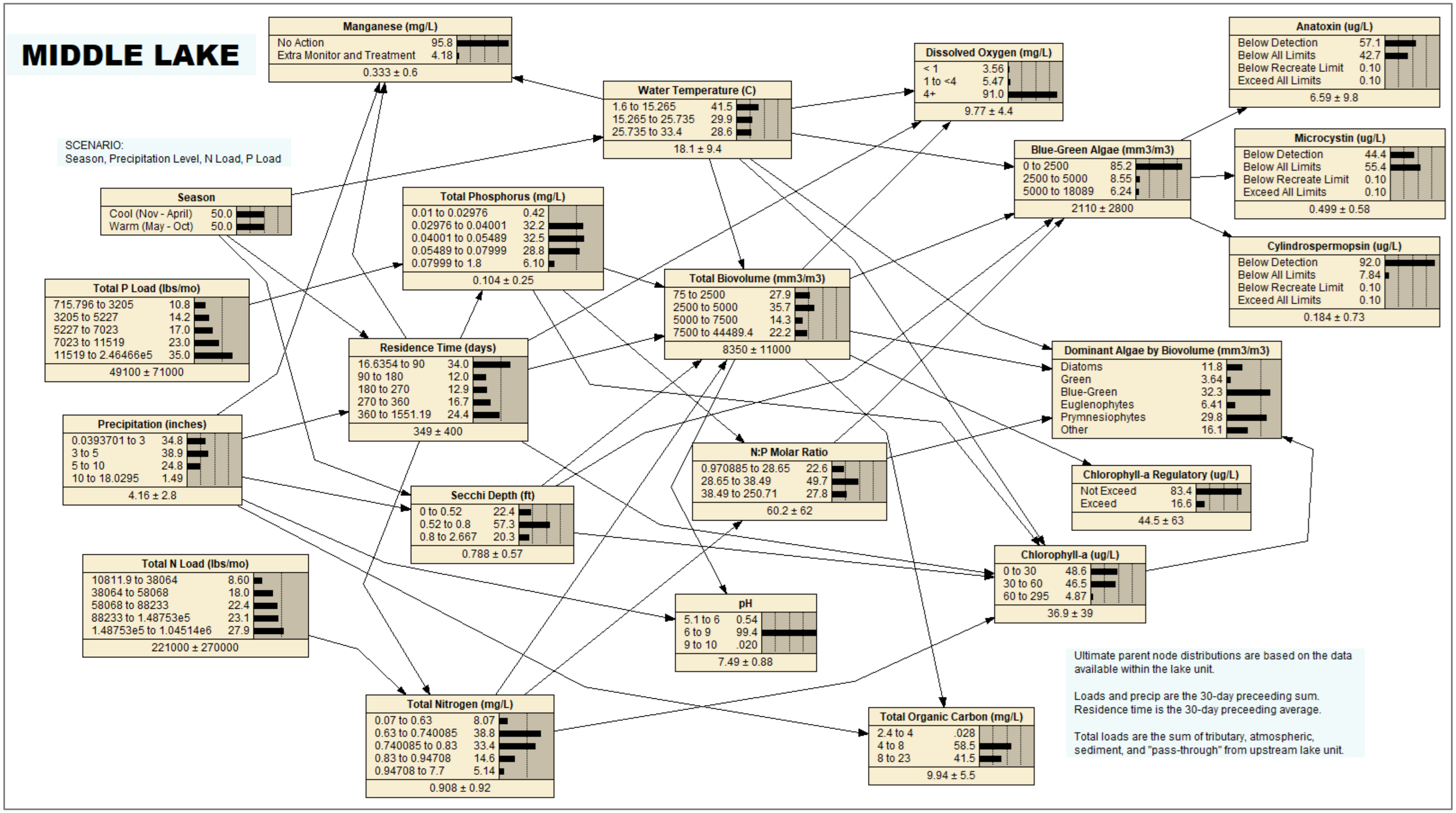

Figure 6-23. Default Probability Distributions for the Middle Lake Statistical Bayesian Model

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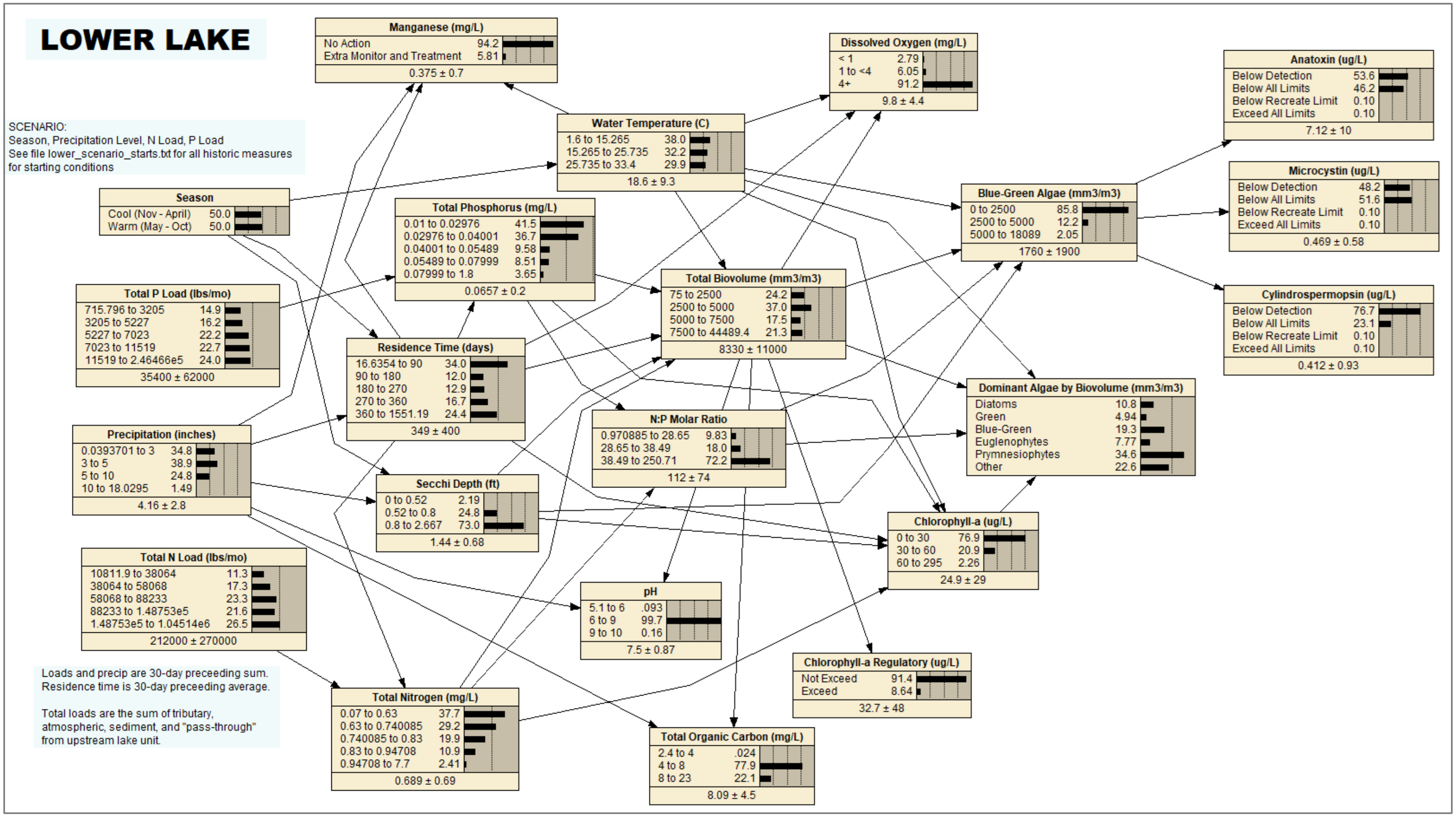

Figure 6-24. Default Probability Distributions for the Lower Lake Statistical Bayesian Model

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Section 7

Sensitivity Analyses of Falls Lake Models

Following calibration of the two mechanistic lake models, sensitivity analyses were conducted on a subset of model parameters to evaluate how changing model parameters would affect simulated water quality in Falls Lake. The purpose of the sensitivity analysis is to gain a better understanding of how changing a model input parameter affects modeling results. The sensitivity analysis provides useful information regarding the relative importance of the physical, chemical and biological processes represented in the model and identifies the most influential parameters for improving model accuracy. This information can also provide future insight to help identify research studies that would improve future modeling efforts under an adaptive management framework.

The modeling team worked with the MRSW, "third-party" model reviewers, and DWR modelers to determine the parameters and ranges for sensitivity analyses evaluation. As the regulatory driver for the project is chlorophyll-a, this output parameter in Falls Lake is the focus of the sensitivity analyses. Total organic carbon, total nitrogen, and total phosphorus were also evaluated for change as described in the model-specific appendices. As the focus of the reexamination is the impact of nutrient levels on algal production and chlorophyll-a, lake model parameters addressing algal kinetics and impacts on nutrient release rates from the lake sediments were the focus of the sensitivity analyses.

One product of the statistical/Bayesian model is a sensitivity analysis. This analysis summarizes how much the variability in the expected value of one variable is reduced given knowledge of each of the other variables in the model, individually. The output is expressed as a percent reduction in variability. A higher percent reduction in variability means the variable is more sensitive and there is a stronger relationship. Given the complexity of the system (hydrologic, seasonal, algal species shifts, changes in nutrient loading patterns, changes in nutrient availability), the sensitivities among the variables were relatively low. No variable in any segment caused even a ten percent reduction in variability for any other variable.

7.1 UNRBA Falls Lake EFDC

Sensitivity analyses were performed with the calibrated and validated Falls Lake EFDC water quality model. The main aim of the analyses was to evaluate the responses for chlorophyll-a, total organic carbon, total nitrogen, and total phosphorus under the different perturbation levels of four (4) model input parameters for the period of January 1, 2015, through December 31, 2018. The four (4) model input parameters evaluated include the carbon/chlorophyll -a ratios assigned to each algal group, the maximum algae growth rate for each group, algae settling velocity for each group, and the diffusion coefficient in pore water of the lake sediments.

Simulated chlorophyll-a, total organic carbon, total nitrogen, and total phosphorus are all most sensitive to the maximum algal growth rate. Simulated chlorophyll-a, total organic carbon, and total nitrogen were the least sensitive to the diffusion coefficient in the pore water of the lake sediments. TP was least sensitive to changes in the algae settling velocity.

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Appendix A provides more details about the sensitivity analyses and evaluations conducted on these model input parameters.

7.2 Falls Lake WARMF

Sensitivity analyses were conducted on algal growth, sediment bed diffusion, nitrification, and organic material decay rates using the calibrated WARMF Lake model. Ammonia, nitrate, TKN, and TOC were most sensitive to increases in bed diffusion rate. These parameters were also sensitive to organic matter decay rate. Ammonia and nitrate were also sensitive to the nitrification rate during parts of the simulation (conversion of ammonia to nitrate occurs through the nitrification process). Chlorophyll-a was sometimes sensitive to the bed diffusion rate, but generally concentrations were similar across the analyses. The algal growth rates sometimes shifted the peak chlorophyll-a concentration but usually did not affect the magnitude of the simulated values; an exception occurs in early to mid-2017 in Segment 1 when very high concentrations of chlorophyll-a (up to 400 µg/L) were simulated when growth rates were higher. Total phosphorus was generally not sensitive to these parameters with the exception of very high TP concentrations simulated with the high algal growth rate analysis. The high TP concentrations lagged the very high chlorophyll-a concentrations that were simulated in Segment 1 in early to mid-2017. The model assumes a constant amount of phosphorus is stored in algae cells. When the algae associated with the simulated bloom died and decayed, the assumed amount of phosphorus was released into the water column. The simulated and observed TP before and after this simulated bloom was approximately 0.1 mg/L. The simulated bloom and release of TP into the water column raised the TP concentration to over 0.8 mg/L. This very high TP concentration is an artifact of the sensitivity analyses and model assumptions and highly unlikely. This simulated bloom caused similar anomalous peaks in TKN, total nitrogen, and TOC. Additional information and figures associated with the WARMF Lake sensitivity analyses are provided in Appendix B.

7.3 Falls Lake Statistical/Bayesian

The Falls Lake statistical/Bayesian model includes 22 variables that are linked together in a network. Separate networks were developed for the upper, middle, and lower sections of Falls Lake. Figure 7-1 shows the variables that have at least a four percent reduction in variability for a target variable in the upper lake. The target variable is listed on the y-axis. For example, for chlorophyll-a regulatory (above or below 40 µg/L), knowing the category of total algal biovolume reduces the variability of the prediction by at least four percent. However, for chlorophyll-a ecological (less than 30 µg/L, 30 to 60 µg/L, greater than 60 µg/L), the variables with at least a four percent reduction in the variability of the prediction are total phosphorus concentration and dominant algal group. Figure 7-2 presents this information for the lower lake where for chlorophyll-a regulatory, no variable reduces the variability of the prediction by at least four percent. For chlorophyll-a ecological, knowing the category of the total nitrogen concentration reduces the variability in the prediction by at least four percent.

As noted above, no variable in any segment caused even a ten percent reduction in variability for any other variable. Such results support conclusions that (1) knowledge of one variable does not result in high certainty of the values of any other variables; and (2) a change in the value of one variable has not predictably changed values of other variables.

Additional sensitivity output tables and graphics for the statistical/Bayesian model are provided in Appendix C.

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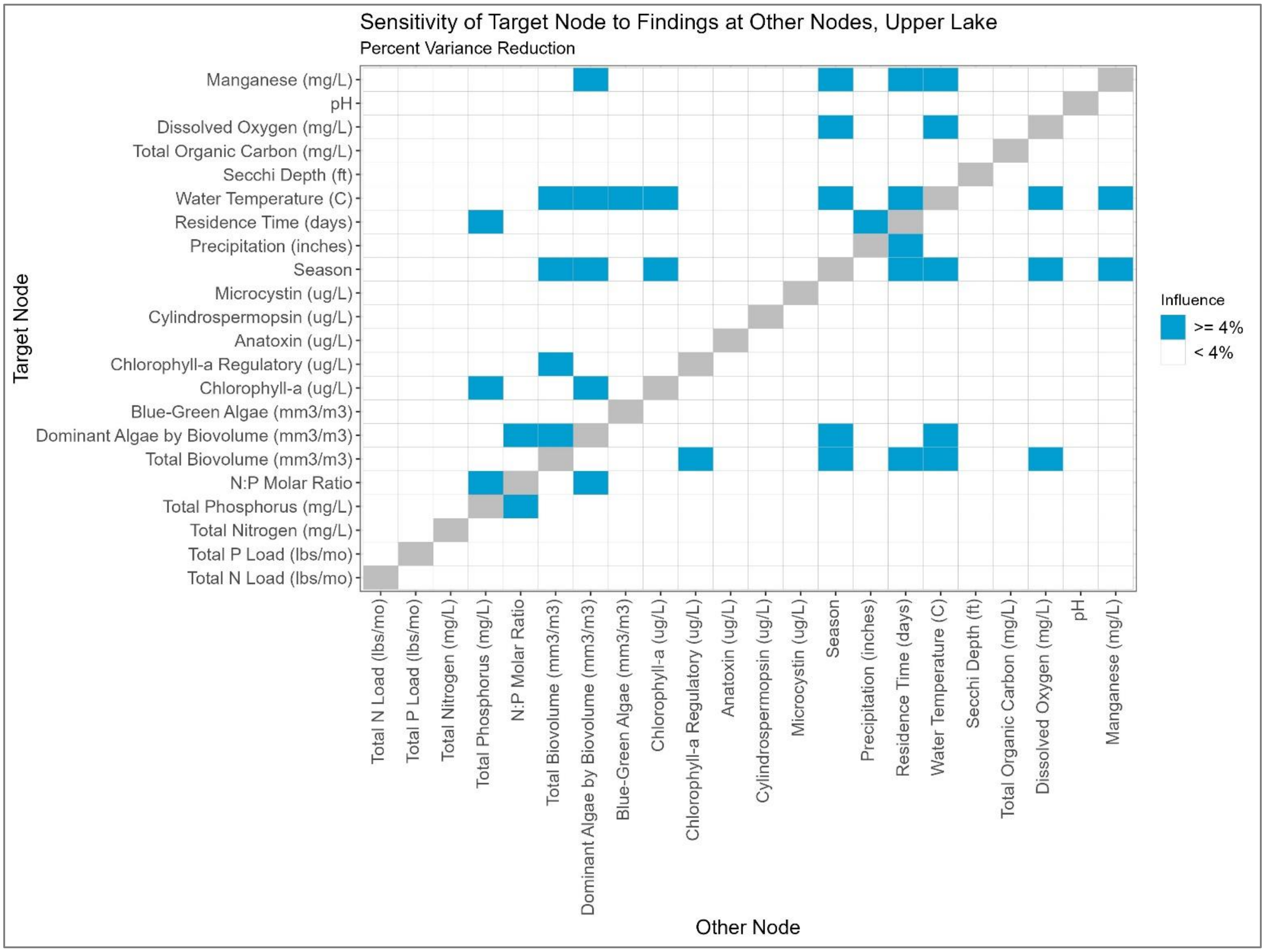

Figure 7-1. Sensitivity of Target Variable (y-axis) to Other Variables (x-axis) for the Upper Lake with at least 4 Percent Reduction in Variability

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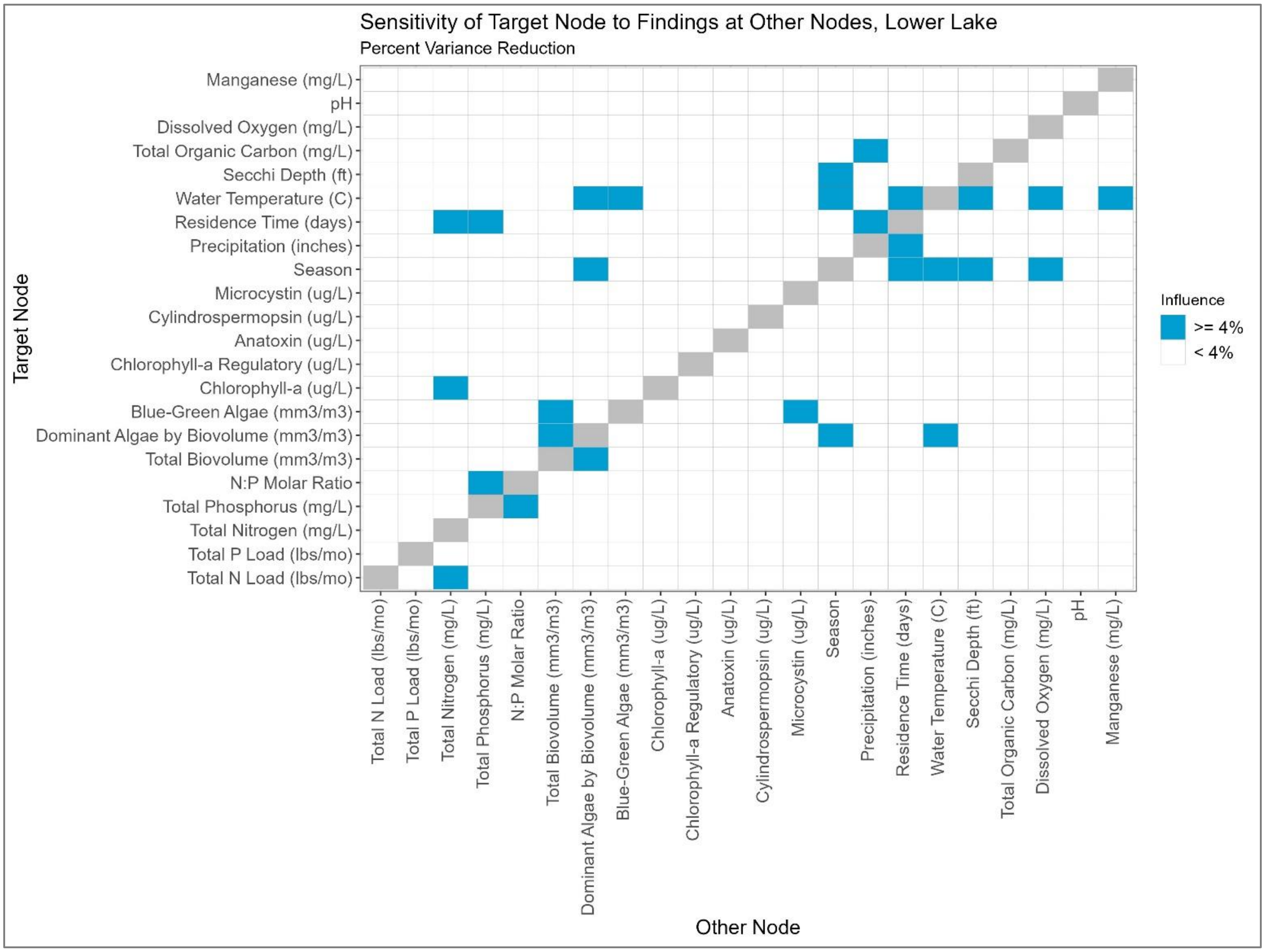

Figure 7-2. Sensitivity of Target Variable (y-axis) to Other Variables (x-axis) for the Lower Lake with at least 4 Percent Reduction in Variability

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Section 8

Model Uncertainty and Limitations in the Context of the UNRBA Recommendations

Several sections of the report as well as its appendices address uncertainty associated with model inputs, calibration data sets, and model configurations and calculations. This section summarizes that information in the context of the UNRBA recommendations for a revised nutrient management strategy.

8.1 Nutrient Balances and Sources

Estimates of ammonia and phosphate releases from Falls Lake sediments vary widely, indicating significant uncertainty. These releases represent a substantial portion of the total nitrogen (12 to 30 percent) and phosphorus loads (5 to 27 percent) to the lake. The uncertainty in these estimates is particularly pronounced for phosphate, as it is influenced by chemical conditions at the sediment-water interface. As a result, nutrient release rates from lake sediments will remain an important consideration in making management decisions. These continued releases impact how quickly the lake will respond to changes in nutrient loading from the watershed. Continued monitoring of this source in response to changes in watershed inputs will be important for adaptively managing the reservoir. Model simulations for internal nutrient loading should be considered a relative magnitude and not precise estimates. This source and its uncertainty was factored into the UNRBA recommendations for a revised nutrient management strategy as discussed in Section 8.8.

Data used for simulating nutrient processing in Falls Lake models like EFDC and WARMF suggests that nitrogen fixation plays a minor role, comprising only around 1 percent of the lake's nitrogen balance (Hall et al. 2023). The researchers funded by the NC Collaboratory indicate that omitting this source of nitrogen from the models does not introduce notable uncertainty. For the calibrated lake models, this uncertainty does not significantly affect model results. For model scenarios that greatly reduce nitrogen inputs to the lake, nitrogen fixation could become an important process to sustain algal growth. The models are not capable of simulating nitrogen fixation. For example, the nutrient load reduction scenario that simulated a reduction in watershed inputs of total nitrogen by 50 percent to meet the chlorophyll-a standard 90 percent of the time is uncertain because algal species capable of nitrogen fixation may “import” additional nitrogen from the atmosphere. Nitrogen fixation is beyond the control of the regulated entities in the watershed. The UNRBA recommendations for a revised nutrient management strategy include flexibility and adaptive management to address changing conditions. If watershed loads of total nitrogen decrease significantly in the future, monitoring of this potential source will be important for adaptively managing the reservoir.

Annual loads from atmospheric deposition contribute relatively small amounts to Falls Lake compared to other sources, comprising around 6 percent of the average annual total nitrogen load and 1 percent of the average annual total phosphorus and total organic carbon loads during the UNRBA Study Period. Therefore, despite simplifying assumptions and uncertainties in historic estimates, these are not expected to significantly affect total loading estimates for the lake. These estimates were used to develop the total loading input for the UNRBA statistical/Bayesian model. Loading inputs are categorized as very low, low,

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moderate, high, and very high. The uncertainties in the historic estimates of atmospheric deposition will not greatly affect these loading categories which are dominated by loading from the tributaries.

8.2 Simulation of Algae Using Three Simulation Groups

Both EFDC and WARMF Lake can simulate three groups of algae. Parameter ranges for certain algal groups like diatoms, blue-green, and green algae are well-documented in literature (e.g., USEPA publications from 1985 and 2019). Other algal groups lack such comprehensive data, and these other groups often dominate the algal biovolume measured in Falls Lake. Green algae is a very small component of the algae. Both EFDC and WARMF Lake applications for Falls Lake retained the algal groups for diatoms and blue-greens. The third algal group was used to simulate all other types of algae. Only one parameter set can be applied to a group, so algal kinetics are adjusted to simulate these algal groups as a unit. However, different algae groups have different kinetic rates and temperature preferences. This approach introduces uncertainty into the model, particularly when simulating blooms of Prymnesiophytes and Euglenoids which can result in highly variable chlorophyll-a concentrations. Focused research on the algae groups present in Falls Lake would be helpful for adaptive management in the future. Potential research topics include the quality of algal groups as a food source, carbon to chlorophyll-a ratios under various stressors, growth rates, and nutrient preferences.

Algal biovolume, a measure of algae volume within water, is determined through microscopic counts and empirical equations for different algal groups. However, these estimates are subject to uncertainty compared to other data collected in Falls Lake. Therefore, discussions focus on relative rather than absolute magnitudes and trends across algal groups. The North Carolina Division of Water Resources (DWR) uses a biovolume threshold of 5,000 mm3/m3 to signal an algal "bloom," although this doesn't necessarily indicate specific use impairments. Higher biovolumes can lead to temporal and spatial changes in dominant algal groups, with Pymnesiophytes and Euglenoids frequently exceeding the bloom threshold in Falls Lake. Notably, these groups are not among the three default groups simulated by the models but are lumped into the "other" algae group, represented by a single set of algal parameters. Algal biovolume data were not used directly to calibrate the models but were used to identify the most prominent algae growing at certain times of the year or during particularly high observations of chlorophyll-a. These data provided useful context for discussing model results and performance with DWR modeling staff and subject matter experts.

Both the EFDC and WARMF Lake models have better performance for the two calibration years (2015 to 2016) compared to the validation years (2017 to 2018). This is particularly true for the simulation of chlorophyll-a concentrations. Prymnesiophytes were a dominant algae group in the validation years, and this group was lumped in with other algal groups. In addition, this group does not have consistent patterns in terms of biovolume and chlorophyll-a concentrations. Sometimes high biovolumes of Prymnesiophytes would correspond to low chlorophyll-a concentrations and sometimes high biovolumes would correspond to high chlorophyll-a concentrations.

8.3 Conversion of Simulated Algae to Chlorophyll-a Concentrations

Both WARMF Lake and EFDC simulate the growth of algae as carbon. A ratio is then applied to convert the amount of carbon in each of three simulated algae groups to chlorophyll-a. For the step to develop EFDC tributary inputs from WARMF watershed model outputs, the conversions used the ratios applied by WARMF (Appendix A).

Other than the simulated watershed inputs, WARMF Lake and EFDC were developed and calibrated independently. Carbon to chlorophyll-a ratios for both models were initially set to ratios reported in the literature (Geider et al. 1997, Llewellyn and Gibb 2000, Bowie et al. 1985). To improve simulated chlorophyll-a concentrations for the EFDC model calibration compared to observations, the chlorophyll-a to carbon ratios for the three algal groups were increased approximately ten times higher than those used in

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the WARMF Lake model. As demonstrated by the UNRBA 2019 Monitoring Report, chlorophyll-a inputs from tributaries to Falls Lake are much lower than chlorophyll-a concentrations observed in Falls Lake. This difference in the ratios applied to tributary inputs versus lake simulations for EFDC does not introduce significant uncertainty in the model because tributary inputs of algae and chlorophyll-a are relatively minor.

8.4 Comparison of Simulated Water Quality to Observations

Time series of simulated water quality serve as a basis for comparison with observations to visualize various aspects like magnitudes and seasonal patterns. The Falls Lake EFDC model in general performs better during model calibration period than the validation period. The RSR target was not met for many of the parameters and stations. Meeting the RSR target is very difficult when the water quality concentrations in the lake do not exhibit significant variability or are frequently less than the reporting limit. The percent bias statistics for most parameters were “good” to “very good” including TN, TOC, and DOC during the calibration and validation periods. The model underpredicts TSS at many of the deeper, lower lake stations. In the upper, more shallow part of the lake, TSS predictions generally ranked “fair” to “very good.” During model calibration, the settling rates for organic material and algae were increased to add more organic material to the sediment bed. This change was made to simulate larger releases of inorganic nutrients from the lake sediments to better match the range observations recorded by some researchers, particularly in the deeper parts of the lake where most of the settling occurs. Total phosphorus concentrations were generally overpredicted in the upper part of the lake and underpredicted in the lower part of the lake, in part due to the settling rates used to drive organic material into the lake sediments. For ammonia, the model overpredicted concentrations in the upper lake sometimes by two and half times. However, the concentrations of ammonia in this part of the lake are relatively low, and 65 percent of observations from 2015 to 2018 were less than the reporting limit. The model also over-predicts nitrate concentrations in the upper lake; approximately 35 percent of observations are less than the reporting limit. The upper part of the lake is relatively shallow and wide, and experiences more wetting and drying than the lower part of the lake. This cycling is more conducive to denitrification in the absence of dissolved oxygen. In the upper and middle part of the lake, simulated dissolved oxygen concentrations are not low enough to trigger denitrification. In reality, small zones of denitrification may occur in this part of the lake, but not at the size of an EFDC model grid cell. This model limitation may explain why nitrate is over-predicted in the upper lake. Researchers from the NC Collaboratory indicate that denitrification is a significant component of the nitrogen balance in Falls Lake. Nitrate is an available form of nitrogen, and so over-estimating this parameter would not result in under-prediction of algal growth and chlorophyll-a concentrations. Percent bias for simulated chlorophyll-a concentrations is ranked “good” to “very good” in the calibration period. The model underpredicts chlorophyll-a throughout the lake in the validation period as explained in Section 8.2. For this reason, scenarios evaluated with the EFDC model were evaluated only for the calibration period (2015 to 2016).

The WARMF Lake model faced similar challenges to model calibration. Ammonia and nitrate concentrations are generally overpredicted in the segments upstream of Highway 50, “very good” downstream of Highway 50, and underpredicted closer to the dam. Throughout the lake, most of the total nitrogen is in the organic nitrogen form (TKN minus ammonia) because the inorganic forms (ammonia and nitrate plus nitrite) are quickly consumed by algae and the relatively large input of organic material from the watershed is slowly converted to inorganic forms. Both TKN and total nitrogen have “very good” percent bias in all segments/periods except one that is just over the threshold and ranked as “good.” TSS percent bias is “very good” in segments 3, 5, and 6 and “very good” to “fair” in segments 1 and 2; segment 4 ranks “fair” or predicts an average TSS concentration that is more than 35 percent higher than observed. Total phosphorus percent bias is “very good” in Segments 3, 4, 5, and 6; “good” to “very good” in segment 2, and “fair” to “good” in segment 1. Total organic carbon model bias is “very good” in all segments/periods except one that is just below the threshold and ranked as “good.” Model bias for chlorophyll-a is generally “good” to very good” except in two segments in the validation period when the model underpredicts chlorophyll-a by

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more than 35 percent. As documented in Appendix D, chlorophyll-a concentrations were generally higher in the validation period compared to the calibration period due to blooms of Prymnesiophytes. Earlier versions of the model calibration performed better than the final version because reaction rates were calibrated for each model segment. Subject matter experts suggested the model would be more robust for evaluating scenarios if reaction rates were uniform throughout the lake. The modeling team adjusted the rates to be uniform with the exception of the net settling rates which are very different throughout the lake and the diffusion rates which are distinct based on accumulated depth of sediment.

The average of the chlorophyll-a concentrations during the validation period is 45% higher than the average of the chlorophyll-a concentrations during the calibration period. However, nutrient concentrations and Secchi depth were not drastically different during these periods. For mechanistic models like EFDC and WARMF Lake, nutrients and light availability are key factors in the amount of simulated algae, and the equations and kinetic parameters are fixed for the calibration and validation periods. If the nutrient-algae-chlorophyll-a relationships are drastically different for the calibration and validation periods, one set of kinetic parameters cannot meet the targets for both periods.

Similar to the UNRBA Watershed Model Report, the UNRBA emphasizes the importance of incorporating uncertainty around laboratory measurements when assessing model output. Discussions among UNRBA MRSW, DWR, and third-party model reviewers revolved around methods to represent the potential range of "observed" values, considering relative percent differences allowed by each laboratory during the evaluation of field duplicates. Strategies for dealing with observations below the reporting limit were also deliberated. Accuracy statements of field meters were utilized for field measurements. The ranges showing the relative percent differences allowed by each laboratory were not used to calibrate the models or calculate performance statistics. They are included only as visual representations that reported values are not precise measurements and there is some uncertainty in the value.

8.5 Adjustment of Water Level and Flow Balancing

The initial step in model calibration involves hydrodynamics, encompassing water movement, level, evaporation, and thermal stratification. Calibration of lake water level is conducted using observations near the dam and Beaverdam impoundment. Stream flows are calibrated against data from five major tributaries to Falls Lake, as outlined in the UNRBA Watershed Modeling Report. Uncertainty arises concerning simulated stream flows due to discrepancies in model time steps versus recorded flows, uncertainties within recorded flows, and the absence of stream flow gauges in approximately 35 percent of the watershed, particularly in tributary or near-lake drainage areas. Given the uncertainties inherent in the modeling process, it is standard practice to adjust water levels to match observations. In the UNRBA Falls Lake EFDC model, simulated water levels were calibrated using a flow balancing method near tributary mouths. This balancing corrects for uncertainties related to stream flow calibration, ungaged tributaries, lake surface evaporation, and direct precipitation. Discussions with the MRSW and DWR led to the approval of this approach, with input from both parties and “third-party” reviewers considered in meetings and email communications. Similarly, the WARMF Lake model simulates hydrologic parameters such as water elevation and segment volume. WARMF Lake incorporates inputs from tributaries, adjacent watershed modeling catchments, and precipitation. Evaporation from the lake surface is also accounted for using meteorological data specified in the WARMF watershed model. Time series inputs include withdrawals and dam releases, with withdrawal rates provided by the City of Raleigh Public Utility Department and dam releases based on reported streamflow data. To address uncertainties related to tributary inputs, evaporation rates, etc., the WARMF model sets the water level at or below the recorded level.

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8.6 Uncertainties Associated with Bi-Directional Flow

The WARMF Lake model was selected by the UNRBA as a computationally simpler (when compared to the EFDC model), segment-based model which, in concept, allows for shorter model run times. The water column for each segment is dynamically divided by the model (the user does not specify the number or the depth of layers) into a maximum of 40 layers, with fewer layers utilized when the lake level falls, or in shallow regions. In the Falls Lake model, each layer is approximately 0.75 meters thick. Water can move from one segment into adjacent segments via advection in either direction but cannot move in different directions within a model segment in a timestep.

Luettich et al. (2023) observed that “The surface flow often moves in the same direction as the wind and can be either towards or away from the dam. Currents at mid-depth or below may flow in the direction opposing the surface flow causing the current direction to reverse with depth and creating a wind-driven exchange flow.” As WARMF Lake is simulating the net flow magnitude and direction, directional transport of algae at specific time steps may not be accurate. This aspect of the model may result in missed timing of simulated chlorophyll-a concentrations compared to point-in-time measurements and introduces some uncertainty into the model results.

During discussions with the UNRBA modeling team, the “third-party” reviewers and DWR modelers expressed that they do not expect that the mechanistic models of Falls Lake would simulate isolated peaks in chlorophyll-a concentrations, especially when such peaks do not correspond to clear physical drivers. They noted that mechanistic models are not capable of simulating all peaks because of their limitations in accounting for the physical, chemical, and biological processes and their inability to simulate anomalous events. The reviewers indicated that they expect the models to predict the general trends in nutrient and chlorophyll-a concentrations (e.g., trends associated with seasonality and varying hydrologic inputs) and that the performance results should be evaluated in the context of the model limitations.

8.7 Uncertainties Associated with the Watershed Model

Uncertainties associated with tributary inputs of sediment, nutrients, and total organic carbon also have the potential to affect the EFDC and WARMF Lake models. Table 8-1 summarizes the performance rankings provided in the UNRBA Watershed Modeling Report for inputs from the largest five tributaries to Falls Lake. These tributaries include water quality monitoring stations and USGS stream flow gages. Simulated values for TSS from the tributaries are generally on the low side with only the Little River having a “good” model performance ranking. Underpredicting TSS would allow more simulated light to penetrate the water column and grow algae. Total phosphorus bound to sediment is mostly unavailable for algal growth, and observations of total phosphorus concentrations in the lake are relatively low. Simulated available nitrogen from the watershed in the form of ammonia or nitrate ranges from too low to too high. In the upper lake which receives most of the inputs from the watershed, approximately 65 percent of the ammonia observations and 35 percent of the nitrogen observations were less than the reporting limit. Calibrating a model and achieving performance targets when much of the data is less than the reporting limit is very challenging. Approximately 90 percent of the of the total nitrogen delivered from the watershed is organic, and the watershed model is ranked “very good” for four tributaries and “fair” for Ellerbe Creek. Simulated total nitrogen, total phosphorus, and total organic carbon are ranked “good” to “very good” at four of the five largest tributaries to Falls Lake. Total phosphorus concentrations from Knap of Reeds creek were underpredicted due to a lack of model input data for an extended period. The lake model underpredicts concentrations of total phosphorus in late 2015 to early 2016 as a result. This lack of input data was discussed with DWR modelers and “third-party” model reviewers during model development. The group decided not to artificially adjust the Knap of Reeds Creek total phosphorus inputs. This anomalous period has been resolved and the model provides a good representation of nutrient loading to Falls Lake under more recent conditions.

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Table 8-1 . Water Quality Performance Rankings for the UNRBA Study Period (2015-2018) for the Five Largest Tributaries

Parameter	Ellerbe	Eno	Flat	Little	Knap
Temperature	Very good	Good	Good	Good	Good
TSS	Low[1]	Fair	Low	Good	Fair
Ammonia	Good	High[2]	Good	Low	Good
Nitrate	Very good	Good	Low	Low	Low
TKN	Fair	Very good	Very good	Very good	Very Good
TN	Good	Very good	Very good	Very good	Good
TP	Very good	Good	Good	Very good	Low
TOC	Very good	Very good	Very good	Very good	Good
Chlorophyll-a	Low	Low	Low	Fair	Low

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

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

8.8 Uncertainties Associated with the Statistical/Bayesian Model

The statistical/Bayesian model relies on data collected in Falls Lake since it was filled in the 1980s. Uncertainties associated with the statistical/Bayesian model arise from the following aspects of the modeling:

- In some cases, data matches by segment and date used to develop the conditional probability tables require supplementing spatially (using upstream segments) and temporally (up to one month). This expanded data matching can smooth relationships among variables but is needed to ensure that every possible combination of variable values has a reasonable estimate of likelihood.
- Most of the data matches occur in the more recent period (since 2005). Earlier years often cannot support data matches across the range of observed values of the variables in the network. With most of the data matches occurring after 2005, the statistical model may not fully reflect the earlier conditions.
- Nutrient availability has changed over time with reductions in inorganic loading from atmospheric deposition and wastewater treatment plants. Data is not available to characterize the historic nutrient loading to Falls Lake as inorganic (more available) or organic (less available). With most of the data matches occurring after 2005, the statistical model may not fully reflect conditions when nutrients were more available for algal growth. Rather the model reflects current ratios of available nutrients based on the technologies and practices used over the past 20 years.

8.9 Discussion of Model Uncertainty and Considerations for UNRBA Recommendations

None of the uncertainties and limitations of the UNRBA watershed or lake models change the outcome of the key findings of the modeling or the resulting recommendations by the UNRBA to revise the nutrient management strategy for Falls Lake. The recommendations do not rely on simulated quantities of nutrients delivered to Falls Lake and are not a conventional approach to attainment of water quality standards. The

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recommendations rely on a broader understanding of the system that is supported by the long-term monitoring record and the UNRBA models:

- Significant reductions in available nutrients to Falls Lake have occurred since the State started tracking in 2006
  - The acreage in agricultural production has decreased by nearly half
  - Wastewater treatment plants have reduced total phosphorus loads by 80 percent and total nitrogen loads by nearly 40 percent
  - Deposition of nitrogen from atmosphere has decreased by 20 to 25 percent
- Most of the nutrient loading to Falls Lake is not in an easily available form. Ninety percent of total nitrogen is organic and total phosphorus is mostly in particulate form (organic or bound to sediment). Eighty percent of total phosphorus concentrations observed in Falls Lake for the full record are less than 0.08 mg-P/L and twenty percent are less than 0.03 mg-P/L.
- Concentrations of nutrients, chlorophyll-a, and total organic carbon have decreased and stabilized since the lake was filled based on the long-term monitoring record.
- Seventy-five percent of the watershed area is forested or other unmanaged land. It is very difficult to reduce nutrient loading from these areas, particularly during wet periods than saturate soils and increase nutrient export to Falls Lake. These are vitally important areas to the health of the watershed and Falls Lake and must be protected in order to maintain the stable water quality and attainment of designated uses.

The UNRBA proposes a long-term, adaptive approach to improve and protect water quality in Falls Lake. This watershed-health approach is vital to the long-term protection of Falls Lake as it faces continued development pressure and larger, more frequent storms.

The UNRBA submitted two documents to NC regulators and lawmakers in November 2023. These products are the culmination of the 12-year UNRBA study. These recommendations were unanimously approved by the UNRBA and each of its members:

- UNRBA Concepts and Principles for Revised Falls Lake Rules describes an updated approach to nutrient management for the watershed. It addresses the history and background of the lake. It also summarizes the underlying technical information for the recommendations.
- The Consensus Principles II provide a focused summary.

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Section 9

Scenario Analysis

The UNRBA modeling tools were primarily developed to evaluate nutrient management actions and support regulatory decisions. The UNRBA formed a Scenario Screening Workgroup to prioritize and select scenarios to evaluate with each model including management and boundary-type conditions. This workgroup included UNRBA members as well as representatives from DWR, agriculture, DOT, and environmental advocacy groups. The MRSW and PFC also provided review of and input on the scenarios considered. The scenarios evaluated by the UNRBA provide important information for understanding the system and making regulatory decisions. The model selected for each scenario was determined based on the particular aspects of the models. Because chlorophyll-a is the regulatory driver for the Falls Lake Rules, this section compares simulated chlorophyll-a concentrations for the model scenarios to the calibrated model. Additional details about the methods and results from these scenarios are provided in Appendix A for the EFDC model, Appendix B for WARMF Lake, and Appendix C for the statistical/Bayesian decision support tool.

9.1 UNRBA Falls Lake EFDC

The calibrated EFDC water quality model was applied to simulate the in-lake response for several types of scenarios. The purpose of these scenarios was to understand how lake water quality would change if study-period (2014 to 2018) watershed loading persisted into the future or changed over time. The UNRBA EFDC model was selected for these scenarios because it includes the sediment diagenesis model that simulates how nutrient releases from lake sediments change over time. Sediment release is a critical factor in determining nutrient balance and potential changes in lake water quality relative to a specific management scenario.

Another set of EFDC model scenarios was developed to determine the combination of nitrogen and phosphorus load reductions that would be needed to meet the chlorophyll-a standard near Fish Dam/Cheek Road where observed concentrations are typically highest (station NEU013B). This station was selected because it is in the upper, shallow part of the lake where chlorophyll-a is usually the highest. DWR did a similar evaluation at this station which they referred to as the compliance point in their lake modeling report (DWR 2009). The UNRBA EFDC model was selected for this evaluation for two reasons. First, DWR used the EFDC model to perform their evaluation in support of the Falls Lake Rules, and the UNRBA wanted to use a consistent approach. Second, the EFDC model uses time series to represent flow and nutrient concentrations discharged to Falls Lake from the tributaries. These nutrient concentrations were more easily scaled using a multiplier to increase or decrease the nutrient loading to Falls Lake.

EFDC scenario evaluations compare simulated values for the calibration period (2015 to 2016) because the model performance was better for these years compared to the validation period (2017 to 2018). The validation period included fast-acting blooms of Prymnesiophytes that were beyond the scope of the EFDC model framework. Appendix D discusses the challenges associated with simulating blooms of Prymnesiophytes and associated chlorophyll-a concentrations.

9.1.1 EFDC Simulation of Long-Term Impacts Using Study-Period Watershed Loads

One of the scenarios selected for evaluation with the EFDC model included running long-term simulations using the study-period watershed loads (2014 to 2018) to the lake. These long-term simulations were run for 25 and 50 years. As described in the UNRBA Watershed Model Report, significant reductions in delivered

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loading to Falls Lake have occurred since the baseline period. The purpose of this model scenario was to see if chlorophyll-a concentrations would decrease over time due reduced nutrient releases from the sediments. It was assumed that reduced loading from the watershed would reduce lake cycling of nutrients over time and reduce algal growth and chlorophyll-a concentrations.

While the EFDC model does show some reductions in nitrogen and phosphorus releases from lake sediments, the chlorophyll-a concentrations were not significantly affected and not visibly discernible when displayed graphically (i.e., the lines are on top of each other). While significant reductions in nutrient loading have occurred since the baseline period (e.g., 38 percent reduction in total nitrogen and 81 percent reduction in total phosphorus from wastewater treatment plants when comparing 2018 to 2006), there are still 1.65 million pounds of total nitrogen and 183,000 pounds of total phosphorus entering the lake each year, on average, during the study period. These amounts of nutrients are sufficient sustain the algal population in the reservoir and cycling of nutrients to and from the lake sediments. This long-term model evaluation scenario further supports the finding that chlorophyll-a concentrations in Falls Lake are stable and that sufficient nutrients to sustain chlorophyll-a levels are present even with the reductions documented from the baseline year. Figures displaying the results of this scenario are available in Appendix A.

This long-term model evaluation further supports the finding that chlorophyll-a concentrations in Falls Lake are stable.

9.1.2 EFDC Simulation of Nutrient Load Reduction Curves

The EFDC model was selected to evaluate combinations of total nitrogen and total phosphorus load reductions from all tributaries to Falls Lake and the effect on the percent of time the chlorophyll-a standard (40 µg/L) would be exceeded. Combinations of nutrient load reductions were evaluated to determine the level of load reduction needed from 2015-2016 levels to achieve the chlorophyll-a standard everywhere in the lake at least 90 percent of the time. Note that meeting chlorophyll-a at least 90 percent of the time (exceeding 10 percent of the time) would not necessarily result in attainment of DWR's standard for chlorophyll-a based on NC's current Clean Water Act Section 303(d) assessment methodology (Section 1.3). Models are not used for assessment, but rather to predict future changes and likely outcomes. Assessment requires collection of data. Attainment would essentially require a simulated percent exceedance of 0 percent because two or more exceedances of the standard would maintain the non-attainment status.

These load reduction curves are an approximation of potential conditions if watershed nutrient loads were decreased instantly. Sediment quality and potential nutrient releases from lake sediments are not altered for these scenarios. These scenarios do not reflect the long-term changes to sediment quality and nutrient releases from lake sediments following significant, sustained reductions from the watershed. Alperin (2018) reports that changes to the nutrient releases from Falls Lake would take decades to occur. It is beyond the scope of this project to run the long-term simulations described in Section 9.1.1 for each of the load reduction combinations.

9.1.2.1 Individual DWR Stations

The simulated values were compared for DWR stations NEU013B, NEU018E, and NEU020D. Station NEU012B is near Fish Dam/Cheek Road. This station is in the shallow part of the lake where chlorophyll-a concentrations are typically highest. This evaluation was also conducted for this station by DWR using their EFDC model (DWR 2009). NC still applied a simple 90 percent compliance threshold when DWR developed their models (not including 90 percent confidence in the assessment).

Figure 9-1 shows the percent exceedance of the 40 µg/L chlorophyll-a standard at DWR Station NEU013B for combinations of total nitrogen and total phosphorus load reductions. With no reduction in loading from

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2015 to 2016 levels (i.e., the calibrated model), the EFDC model simulates exceedances of the chlorophyll-a standard approximately 40 percent of the time. To achieve simulated 10 percent exceedance of the chlorophyll-a standard, a 50 percent reduction in total nitrogen relative to 2015 to 2016 levels would be needed. Under current loading conditions, approximately 90 percent of the total nitrogen delivered to Falls Lake is organic. This reduction in total nitrogen load would be in addition to those already achieved in the watershed since the baseline period. Under this scenario, chlorophyll-a is still predicted to exceed the standard 10 percent of the time, so the lake would not attain the standard as currently applied. A 50 percent reduction from 2015 to 2016 levels is approximately 825,000 pounds of total nitrogen per year, on average. As explained in the UNRBA Watershed Model Report, there are no scenarios where 50 percent of the nitrogen load to Falls Lake could be reduced. Seventy-five percent of the watershed is forest, wetlands, scrubland, non-pasture grassland, open water, or land in forest succession. These unmanaged lands do not receive nutrient application and do not contain onsite wastewater treatment systems. Significant reductions in nutrient loading have been achieved on agricultural lands and from wastewater treatment plants. Medium to high intensity development comprises less than two percent of the watershed area, and more 350 stormwater retrofits have been installed to treat these areas. The current composition of loading sources to Falls Lake does not lend itself to a reduction in nitrogen loading of 50 percent. Even the hypothetical land conversion to forests with removal of nutrient application to land surfaces, wastewater treatment plant discharges, and onsite wastewater treatment systems did not reduce nitrogen loading by 50 percent.

At station NEU013B, the UNRBA EFDC model indicates that total phosphorus reductions of 50 percent would achieve the standard 65 percent of the time. At total nitrogen reductions of 50 percent, the reductions in total phosphorus are not predicted to significantly affect the percent of time chlorophyll-a exceeds the standard. This location is in the upper part of Falls Lake just downstream of tributaries that receive discharges from three major wastewater treatment plants (discharging more than 1 million gallons of water per day). Since 2006, these plants have reduced discharges of total phosphorus by 81 percent. These reductions at wastewater treatment plants shift the relative amount of delivered phosphorus to sediment- or organic matter-bound forms. Wastewater treatment plants discharge mostly dissolved phosphorus which is more accessible to algae than particulate-bound forms.

Phosphorus that is bound to sediment is not immediately available for algal growth, and sediment does not remain in the upper part of the lake because it is moved downstream by tributary inflows and resuspended by wind action. Dr. Marc Alperin described the upper part of Falls Lake as a “conveyor” for sediment until it reaches deeper waters near Highway 50 (Alperin 2018). Because most of the phosphorus is bound to sediment or contained in organic matter, and because settling rates are low in this part of the lake, 50 percent reductions in delivered total phosphorus load are predicted to have less impact at this location than reductions in delivered total nitrogen load. Researchers in Norway have noted similar trends there with nitrogen limitation becoming more common than co-limitation (nitrogen and phosphorus) due to declining levels of nitrogen deposition from the atmosphere (Deininger et al. 2020).

Figure 9-2 and Figure 9-3 show the percent exceedance of 40 µg/L chlorophyll-a concentrations at DWR Stations NEU018E and NEU020D, respectively, for combinations of total nitrogen and total phosphorus load reductions. These stations already have an exceedance frequency of 40 µg/L less than 10 percent.

The results of the simulated reduction curves is similar to findings by Hall and Paerl (2023) which indicate algal growth in Falls Lake is nitrogen limited. Note the EFDC model does not include nitrogen fixation by blue-green algae as a source of nitrogen. While Hall and Paerl (2023) found nitrogen fixation to be a small component of the nitrogen balance for Falls Lake under current conditions, significant reductions in nitrogen loading to Falls Lake could increase rates of fixation by algae. These load reduction curves do not reflect a potential increase in nitrogen fixation, so simulations of significant total nitrogen reductions from the watershed are uncertain, and chlorophyll-a concentrations could be higher than predicted under this scenario.

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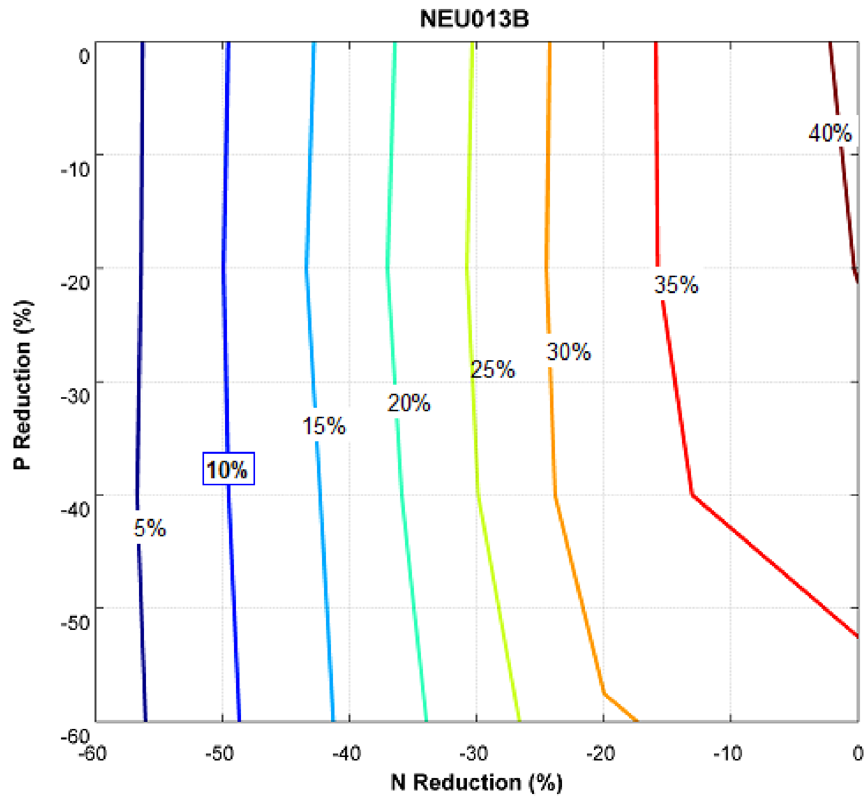

Figure 9-1. Percent Exceedance of 40 µg/L Chlorophyll-a Concentrations at DWR Station NEU013B for Combinations of Total Nitrogen (N) and Total Phosphorus (P) Load Reductions

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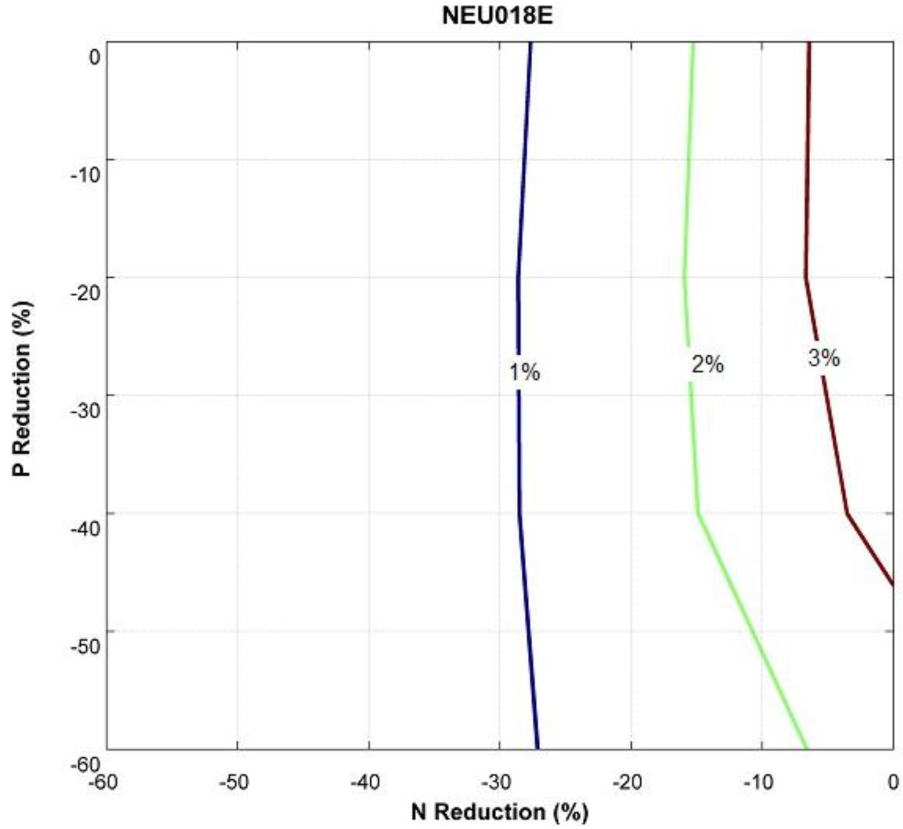

Figure 9-2. Percent Exceedance of 40 µg/L Chlorophyll-a Concentrations at DWR Station NEU018E for Combinations of Total Nitrogen (N) and Total Phosphorus (P) Load Reductions

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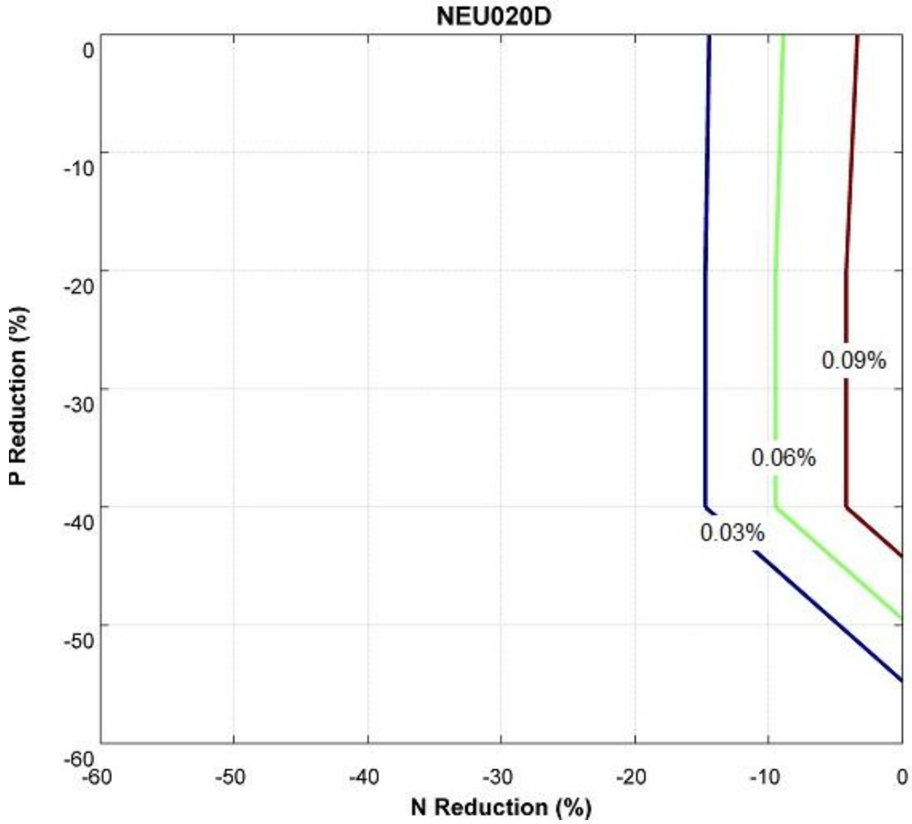

Figure 9-3. Percent Exceedance of 40 µg/L Chlorophyll-a Concentrations at DWR Station NEU020D for Combinations of Total Nitrogen (N) and Total Phosphorus (P) Load Reductions

9.1.2.2 Grouped Stations Upstream and Downstream of Highway 50

The combinations of nitrogen and phosphorus reductions were also evaluated for groups of stations to see the effect on meeting a compliance threshold of 90 percent with the chlorophyll-a standard. The two groups of stations evaluated were either all stations upstream or all stations downstream of Highway 50. Upstream of Highway 50, the lake is relatively wide and shallow. Downstream of Highway 50, the lake is relatively narrow and deep. Highway 50 also divides the lake into the two segments described as “upper lake” and “lower lake” by the current Falls Lake Rules.

Figure 9-4 shows the percent exceedance curves for all stations upstream of Highway 50. The gray line shows the 40 µg/L chlorophyll-a standard. Extending a vertical line from where each curve crosses the gray line indicates the percent of time the standard is exceeded on the x axis. For the calibrated model (red line), the chlorophyll-a standard is exceeded 15 percent of the time when stations are grouped upstream of Highway 50. When delivered loads of total nitrogen and total phosphorus are both reduced by 20 percent, the chlorophyll-a standard is exceeded 10 percent of the time. When both nutrients are reduced by 40 percent, the chlorophyll-a standard is exceeded 5 percent of the time, and when both nutrients are reduced by 60 percent, the chlorophyll-a standard is not exceeded for this group of stations.

Figure 9-5 shows the percent exceedance curves and calibrated model for all stations downstream of Highway 50. For these stations, the calibrated model only exceeds the chlorophyll-a standard 1 percent of the time. All of the combinations of total nitrogen and total phosphorus reductions that were simulated result in no exceedances of the chlorophyll-a standard.

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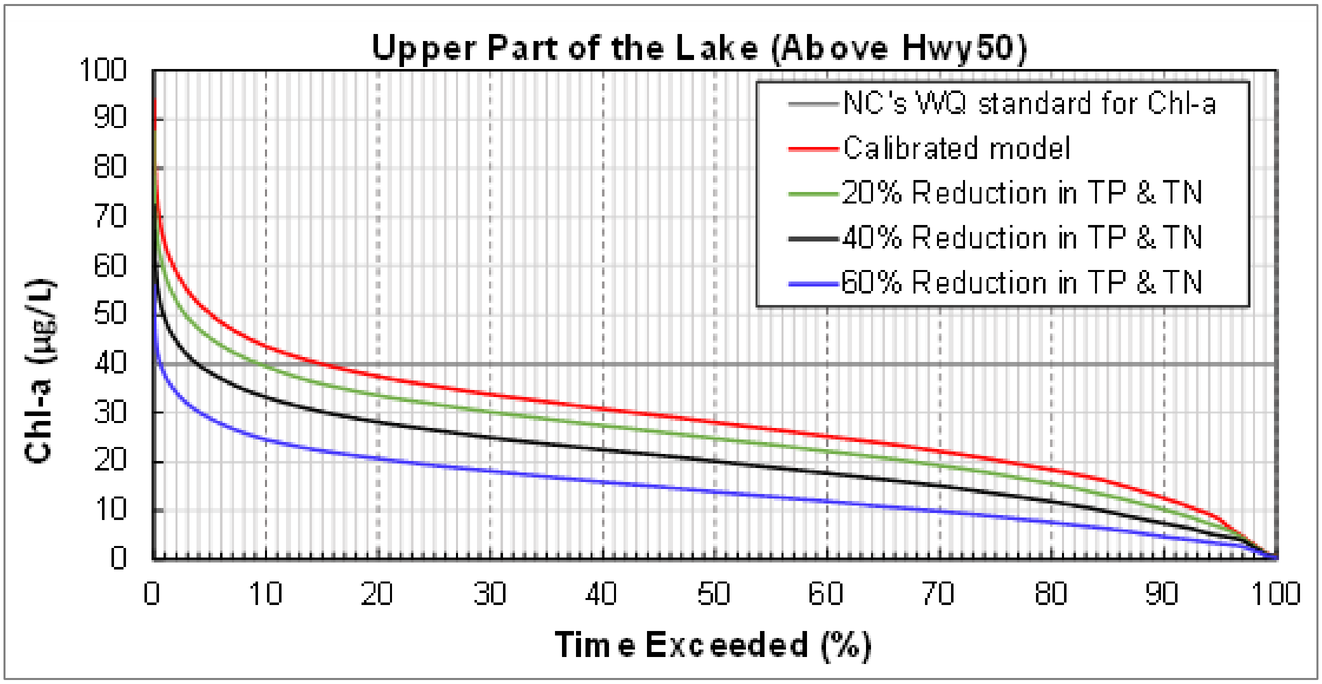

Figure 9-4. EFDC-Simulated Percent of Time the Chlorophyll-a Standard is Exceeded for All Stations Upstream of Highway 50 for Three Nutrient Load Reduction Scenarios Compared to the Calibrated Model

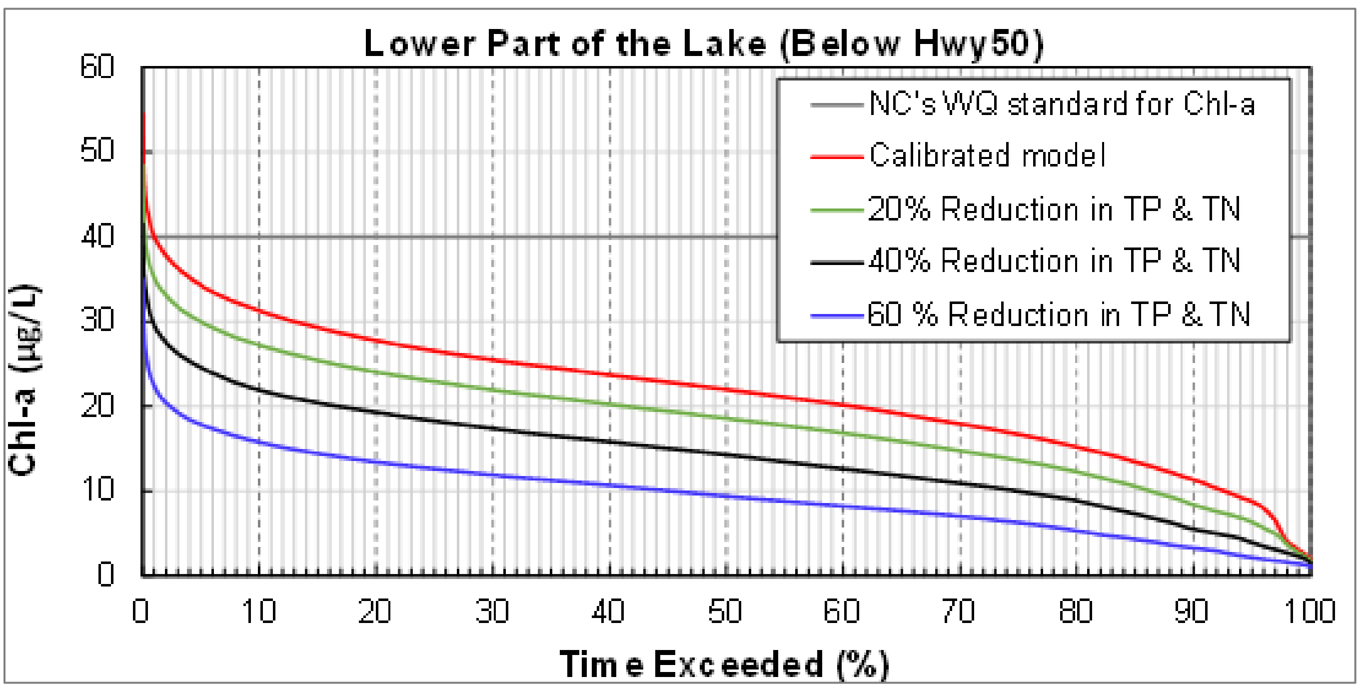

Figure 9-5. EFDC-Simulated Percent of Time the Chlorophyll-a Standard is Exceeded for All Stations Downstream of Highway 50 for Three Nutrient Load Reduction Scenarios Compared to the Calibrated Model

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9.1.3 EFDC Simulation of Nutrient Load Increases

The EFDC model was also used to simulate the impacts of increased nutrient loading from all lake tributaries by 20 percent. This simulated increase was used to understand the potential impacts of further land use changes and/or increased nutrient loading to Falls Lake.

Two stations were evaluated to determine the impact to percent exceedance of the chlorophyll-a standard. At DWR station NEU013B near Fish Dam/Cheek Road, a 20 percent increase in both delivered nutrients increased the percent of time the chlorophyll-a standard was exceeded from 40 percent (for the calibrated model) to 45 percent. At DWR station NEU020D near the dam, both the calibrated model and the 20 percent increase in delivered nutrients scenario have percent exceedances of approximately 1 percent. This load-increase scenario further supports the stability of chlorophyll-a concentrations in Falls Lake, particularly near the dam where most of the nutrient processing has already occurred in upstream portions of the lake. Historically, water quality near the dam has been stable even under higher nutrient loading conditions (Table 4-7).

This load-increase scenario further supports the finding that chlorophyll-a concentrations in Falls Lake are stable.

9.2 Falls Lake WARMF

The MRSW chose to apply the WARMF Lake model for scenarios dealing with changes in the watershed because the WARMF watershed and lake models are directly linked. All watershed-based scenarios evaluated with WARMF Lake were run for five iterations (25 years) as described in the UNRBA Watershed Modeling Report (BC and Systech Water Resources 2023). To reflect the correct starting conditions for the lake sediments for the study period, the Falls Lake sediments were set to initial conditions at the beginning of each model iteration. The initial conditions for the Falls Lake sediments are based on sediment quality data collected in 2016, so resetting them each time the model is run provides a better representation of conditions during the study period (2014 to 2018).

As with the calibration figures provided in Section 6.2.3, the scenario figures display simulation results for three example WARMF Lake segments:

- Segment 1 upstream of Interstate 85
- Segment 4 between Rolling View marina and Highway 50
- Segment 6 between Highway 98 and the dam

The scenario figures for chlorophyll-a concentrations are provided in this section. Similar figures for nutrient species and total organic carbon are provided in Appendix B.

9.2.1 WARMF Lake Simulation of Land Conversion to Forests and Removal of Nutrient Application and Wastewater-Related Discharges

One of the WARMF scenarios evaluated was a land conversion to “all forest” and wetlands with removal of wastewater treatment plant discharges, onsite wastewater treatment systems, and nutrient application to land surfaces. Atmospheric deposition was not changed from the calibrated model. This scenario establishes the lowest potential loading to Falls Lake and the resulting lake water quality if conditions on the ground were to change instantaneously (assuming atmospheric deposition rates remain at current levels). This “all forest” scenario is further described in the UNRBA Watershed Modeling Report (BC and Systech Water Resources 2023).

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Figure 9-6 shows the simulated and observed chlorophyll-a concentrations for this scenario (light green line) and the calibrated WARMF Lake model (dark green line). The modeling shows similar distributions of chlorophyll-a as the chlorophyll-a data by year and segment shown in Table 4-7. For both the “all forest” scenario and the calibrated model, the upper lake has higher and more variable chlorophyll-a concentrations than the lower lake. While the “all forest” scenario resulted in lower chlorophyll-a concentrations than the calibrated model, these levels still exceed the 40 µg/L chlorophyll-a standard (dashed line) in the upper lake approximately 31 percent of the time. For the calibrated model (2015 to 2018 conditions), 37 percent of the simulated chlorophyll-a values exceed 40 µg/L at this location. Therefore, while the percent exceedance decreases, not even this hypothetical scenario results in simulated attainment of the chlorophyll-a standard everywhere, all the time in Falls Lake.

The impacts of this scenario are less pronounced in the middle and lower lake segments where the simulated chlorophyll-a concentrations for the “all forest” scenario are similar to the calibration scenario. However, the “all forest” scenario reduces the frequency of exceedances from 11 percent to 8 percent in Segment 4 and from 6 percent to 0.6 percent in Segment 6. The “all forest” scenario could theoretically result in attainment of the standard near the dam, but it would not result in attainment at other lake stations.

These results are not presented to imply that forests are bad for water quality. On the contrary, forests are the best possible land use for watershed health. If the Falls Lake dam were not present, this scenario would attain the chlorophyll-a standard. Current watershed conditions would also likely achieve the chlorophyll-a standard if the dam were not present. However, the Falls Lake reservoir provides irreplaceable benefits to society. Expecting water quality in the reservoir, even under an “all forest” condition, to mimic the water quality of a system without a dam, is not realistic. In other words, it is not possible to achieve the current chlorophyll-a standard in Falls Lake under any watershed conditions due to hydraulic alteration of the system.

The “all forest” scenario is not intended to represent a feasible solution to meeting the chlorophyll-a standard as removal of residents from the watershed is not being proposed. It is rather used to illustrate the infeasibility of meeting the 40 µg/L chlorophyll-a standard as it is currently applied in Falls Lake.

Not even this hypothetical “all forest” scenario can meet the chlorophyll-a standard everywhere, all the time in Falls Lake.

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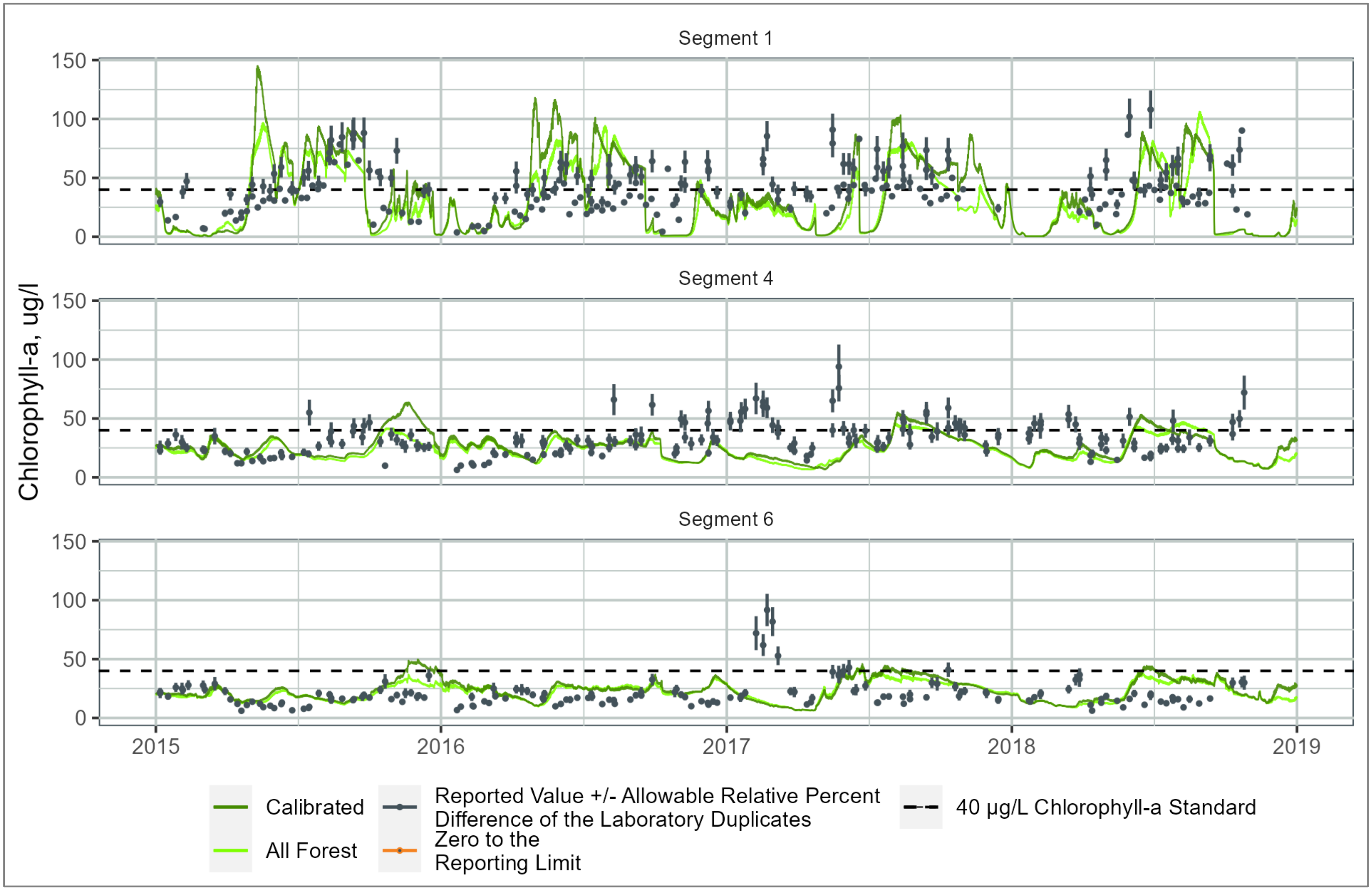

Figure 9-6. WARMF Lake Simulated Chlorophyll-a Concentrations for the Calibrated Model Compared to the Instantaneous Land Conversion to All Forest with Elimination of Onsite and Centralized Wastewater Treatment Discharges and Nutrient Application to Land Surfaces (Atmospheric Deposition is not Altered from the Calibrated Model) in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

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9.2.2 WARMF Lake Simulation with Changes to Rates of Atmospheric Deposition

Another scenario that was previously evaluated with the UNRBA WARMF watershed model (BC and Systech Water Resources 2023) either increased or decreased rates of atmospheric deposition by 25 percent for total nitrogen, total phosphorus, and total organic carbon. This amount is similar to the reduction in total nitrogen deposition that has occurred since 2006 in the watershed. To simulate these changes, the study period deposition rates were multiplied by 0.75 and 1.25 to reflect 25 percent less and more atmospheric deposition, respectively.

Figure 9-7 shows the simulated chlorophyll-a concentrations for these two scenarios (light and dark orange lines) as well as for the calibrated model (green line). There is little discernable difference among these three scenarios when viewed as time series. In terms of percent exceedance of the chlorophyll-a standard, 25 percent less atmospheric deposition results in an exceedance of 36.1 percent in Segment 1 while 25 percent more atmospheric deposition results in an exceedance of 36.9 percent. In Segment 4, these two scenarios result in percent exceedances of 10.5 percent and 11.2 percent, respectively. In Segment 6, these two scenarios result in percent exceedances of 3.4 percent and 8.0 percent, respectively.

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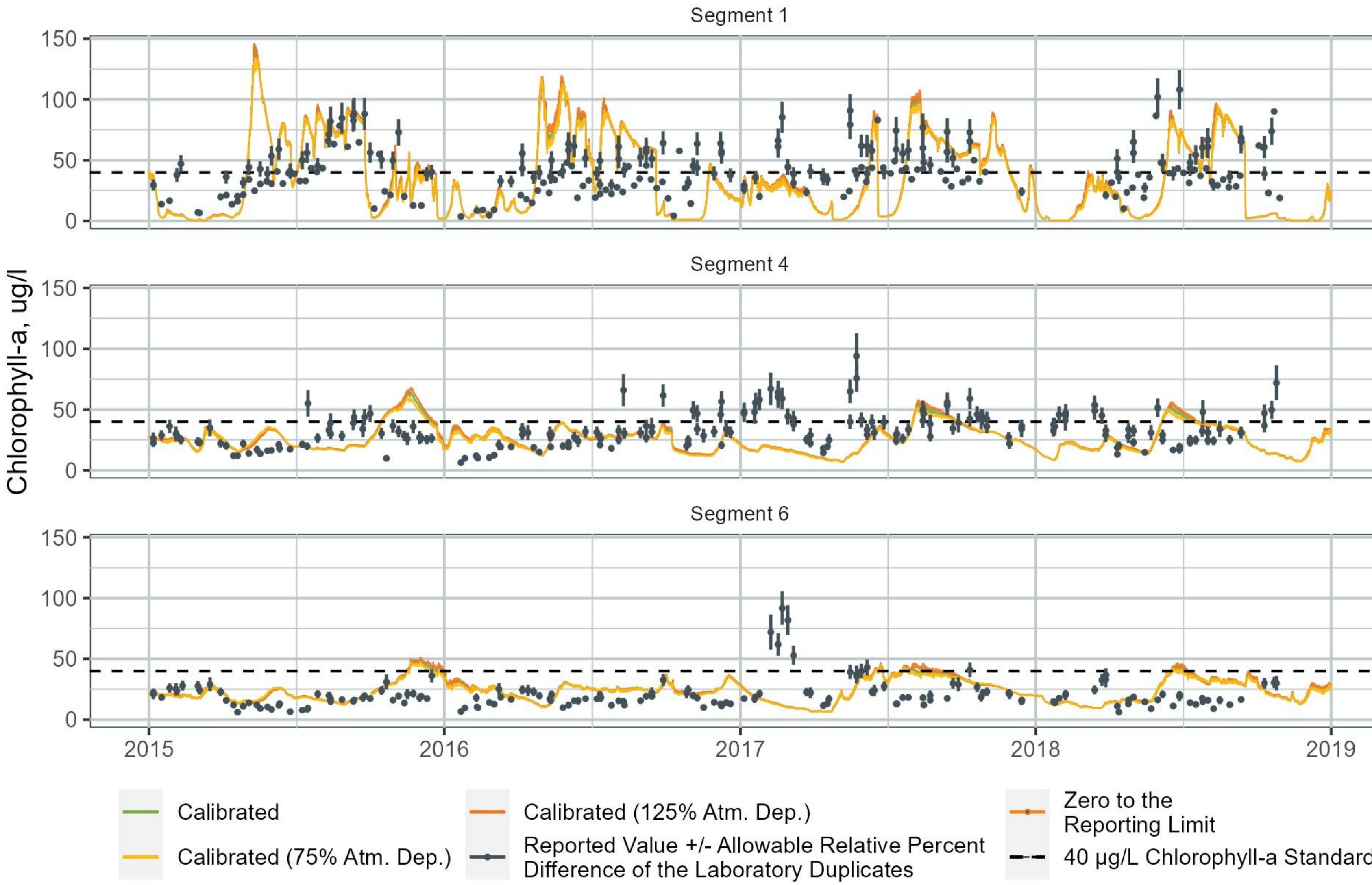

Figure 9-7. WARMF Lake Simulated Chlorophyll-a Concentrations for the Calibrated Model Compared to 25 Percent Increase or Decrease in Atmospheric Deposition of Total Nitrogen, Total Phosphorus, and Total Organic Carbon in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

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9.2.3 WARMF Lake Simulation with Changes to Precipitation Amounts

Watershed modeling demonstrates that precipitation amount is the determining factor for the amount of nutrient loading delivered to Falls Lake (BC and Systech Water Resources 2023). The average annual rainfall for the area is approximately 45 inches per year. The UNRBA study period represents an average to wet hydrologic condition with annual precipitation at the Raleigh Durham International Airport (RDU) ranging from 45.6 inches in 2017 up to 60.3 inches in 2018. The average rainfall over the UNRBA study period was 53.9 inches.

Two precipitation scenarios were developed for the WARMF watershed-lake model. One modeling scenario decreased precipitation amount by 20 percent to represent rainfall amounts that occurred during the DWR baseline modeling period for the Falls Lake Rules and the monitoring studies conducted by the US Forest Service in the Falls Lake watershed. This scenario was developed by multiplying each precipitation input by a factor of 0.8 (every 6-hour precipitation value for the 78 precipitation stations represented in the watershed model). This factor reduced simulated annual precipitation at RDU airport to a range of 36.5 to 48.2 inches per year with an average of 43.1 inches. Conversely, each precipitation value in the watershed model was multiplied by 1.2 to represent a 20 percent increase in rainfall amount. This modeling scenario was conducted to evaluate larger, more frequent storm events to represent a “climate change” scenario as requested by UNRBA stakeholders at technical workshops as well as PFC and Board members (though temperature and other factors predicted to change under future climate conditions were not altered).

Figure 9-8 compares simulated values for 20 percent less precipitation (light blue line), 20 percent more precipitation (dark blue line), and the calibrated model (green line). For most of the simulation period, the three scenarios track relatively closely in terms of chlorophyll-a concentrations. The most dramatic differences occur in Segment 1 where the 20 percent less precipitation scenario results in higher concentrations of chlorophyll-a than the calibrated model or the 20 percent more precipitation scenario, particularly in the first half of 2017. This increase in simulated chlorophyll-a concentration is likely because less rainfall results in stagnation of the lake water allowing more time for algae to grow. This lower rainfall scenario results in 35 percent <u>less</u> total nitrogen delivered to Falls Lake and 42 percent <u>less</u> total phosphorus delivered to Falls Lake.

These precipitation scenarios illustrate that delivered nutrient loading is not the only determinant of algal growth and chlorophyll-a concentrations in Falls Lake.

With less simulated precipitation, the model predicts concentrations in Segment 1 that are higher than any observed in the lake. Algal growth rates in the model had to be set high to capture the magnitude of chlorophyll-a observations from 2014 to 2018. Some of the observations were as high as 100 µg/L, but the lower rainfall scenario predicts concentrations up to 400 µg/L. The combination of less precipitation and slower water movement in this shallow segment likely results in these very high simulated values. Because some of the simulated values are higher than any ever observed in Falls Lake, they are likely an artifact of the modeling and not a realistic representation of potential outcomes. Simulation of values in Segments 3 and 6 are within observed ranges and appear reasonable.

On the other hand, a 20 percent increase in rainfall increases delivered total nitrogen and total phosphorus loads by 36 percent and 60 percent, respectively, but these load increases do not translate to increases in simulated chlorophyll-a concentrations. While the nutrient loads increase under the higher precipitation scenario, stream flows also increase and water moves through the lake more quickly, reducing the potential for algal growth. These precipitation scenarios illustrate that delivered nutrient loading is not the single determining factor for algal growth and chlorophyll-a concentrations in Falls Lake. Hydrologic conditions are also important. This scenario further confirms that algal levels are relatively stable in the lake and that

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sufficient nutrients are available to sustain current algal levels, despite substantial reductions or increases in loading to the lake.

Simulated percent exceedance of the chlorophyll-a standard in Segment 1 is 52 percent under the 20 percent less rainfall scenario and 29 percent under the 20 percent more rainfall scenario. In Segment 4, 20 percent less rainfall results in a percent exceedance of 12 percent, and 20 percent more rainfall results in a percent exceedance of 15 percent (opposite trend compared to Segment 1). In Segment 6, both scenarios result in approximately 5 percent exceedance of the chlorophyll-a standard, further demonstrating the stability of chlorophyll-a concentrations in this part of the lake.

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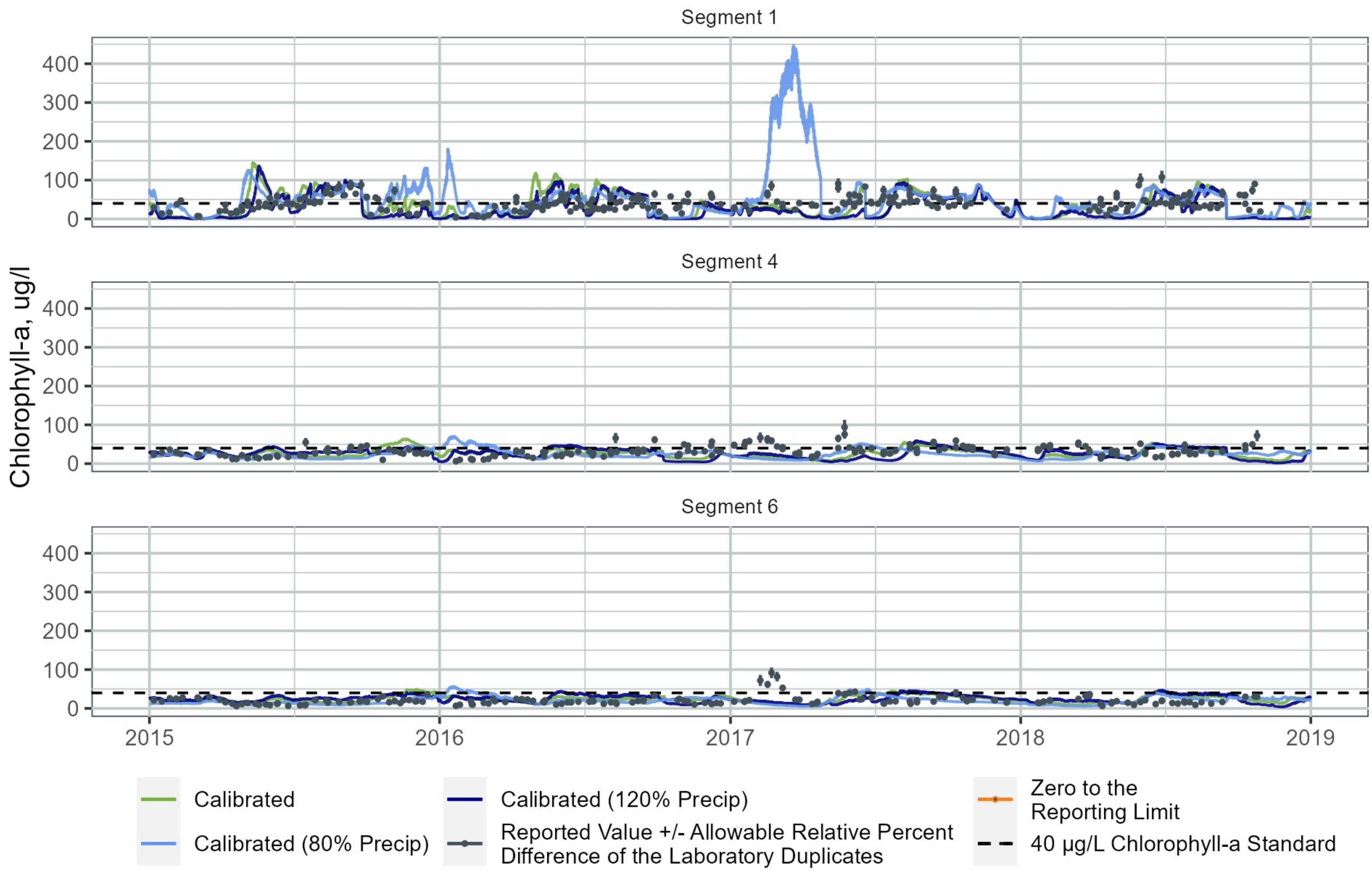

Figure 9-8. WARMF Lake Simulated Chlorophyll-a Concentrations for the Calibrated Model Compared to 20 Percent Increase or Decrease in Rainfall Amount in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

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9.2.4 WARMF Lake Simulation with Changes to Lake Operations

One WARMF Lake model scenario was designed to address a question frequently asked by stakeholders regarding the impact of USACE lake operations on nutrient cycling, algal growth, and chlorophyll-a concentrations in Falls Lake. A scenario was evaluated that simulates an open outflow structure (weir) at the normal pool elevation (251.5 feet above mean sea level). Under current operations, following a large rain event, the USACE stores water in the lake to minimize downstream flooding. The USACE closes the flow release gates to store the water, and the lake water level rises. Once the risk of downstream flooding has passed, the USACE releases water from Falls Lake. These releases continue until the target elevation is met. If a large event has not occurred, the USACE balances releases with inflows to maintain normal pool. Because large rain events are relatively infrequent, the USACE is usually able to maintain normal pool except during drought periods. Therefore, most of the time, the water level is 251.5 feet.

Under this scenario, and open weir is simulated at normal pool. This simulation removes the operation of the lake through flow release gates. Because the USACE already targets normal pool elevation in their operation of Falls Lake, this scenario did not significantly affect simulated water quality in Falls Lake (Figure 9-9). Maximum values of chlorophyll-a simulated for this change to lake operations increased, decreased, or shifted in time depending on when and where the simulation is compared to the calibrated model. However, the percentage of simulated chlorophyll-a concentrations for Segment 1 near Interstate 85 exceeding the standard was similar under both conditions (35 percent for the lake operation scenario and 37 percent for the calibrated model). In Segment 4, the percent exceedance is 11 percent for both scenarios. In Segment 6, the percent exceedance is 5.9 percent of the calibrated model and 5.5 percent for the lake operation scenario. While lake operation by the USACE may impact the timing of peak chlorophyll-a concentrations in Falls Lake, it does not dictate whether or not Falls Lake would be compliant with the chlorophyll-a standard.

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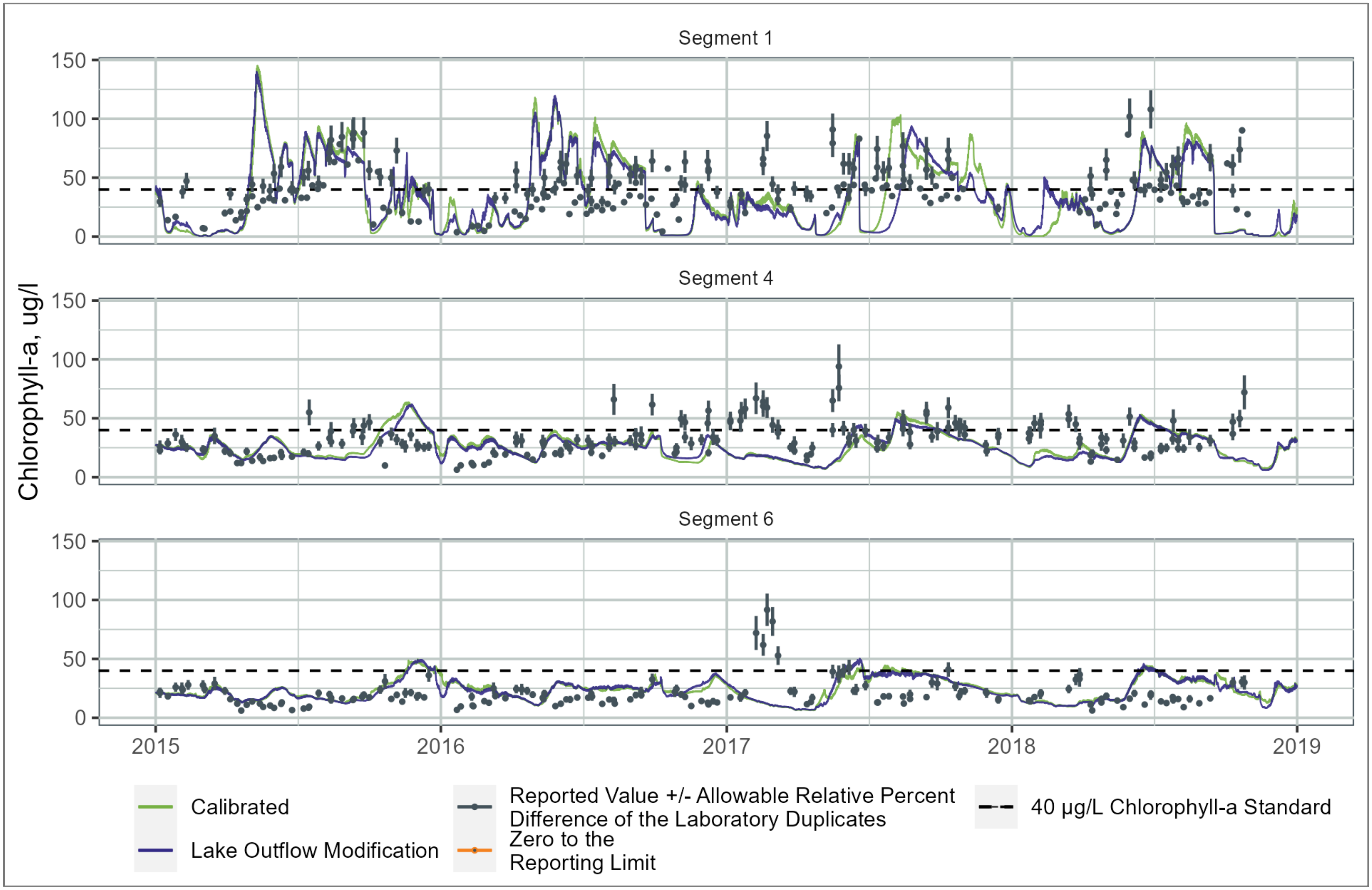

Figure 9-9. WARMF Lake Simulated Chlorophyll-a Concentrations for the Calibrated Model Compared to Modifying the Lake Operations in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

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9.2.5 Comparison of Chlorophyll-a Standard Exceedances for the WARMF Lake Scenarios

Chlorophyll-a is the regulatory driver for the Falls Lake Rules. Comparison of simulated chlorophyll-a across model scenarios informs the reexamination of the Falls Lake Nutrient Management Strategy and revisions to the Falls Lake Rules by placing bounds on what is reasonably achievable for this system. Figure 9-10 and Table 9-1 provide the simulated percent exceedance of the chlorophyll-a standard for each main lake segment and scenario. Annual and growing season means and geometric means are provided in Appendix B. The percent exceedances for the calibrated model are based on the calibration and validation years (2015 to 2018). The statistics for the scenarios are also evaluated for the four-year period. Each scenario was run five times in the WARMF watershed model to provide tributary inputs for the scenario. The initial conditions of the sediments in Falls Lake were reset for each iteration.

The percent exceedances of the chlorophyll-a standard decrease from the upstream to downstream direction in Falls Lake. The upper end of the lake is wider and shallower and receives most of the nutrient loading from the watershed. None of the scenarios evaluated achieve the chlorophyll-a standard at least 90 percent of the time in Segments 1 through 3. In Segment 4, only the "all forest" scenario could meet the standard at least 90 percent of the time. However, even this hypothetical scenario would not result in attainment of DWR's standard in this part of the lake under the current NC assessment methodology. Moving a water from non-attainment to attainment status essentially requires a simulated percent exceedance of 0 percent because two or more exceedances of the standard at any station in a segment would maintain the non-attainment status. **Therefore, it is not possible to achieve the chlorophyll-a standard in Falls Lake as currently applied.**

Segments 5 and 6 are located downstream of Highway 50 in the deeper, narrow part of the lake. Both of these segments are predicted to meet the chlorophyll-a standard at least 90 percent of the time under every scenario, including the calibrated model.

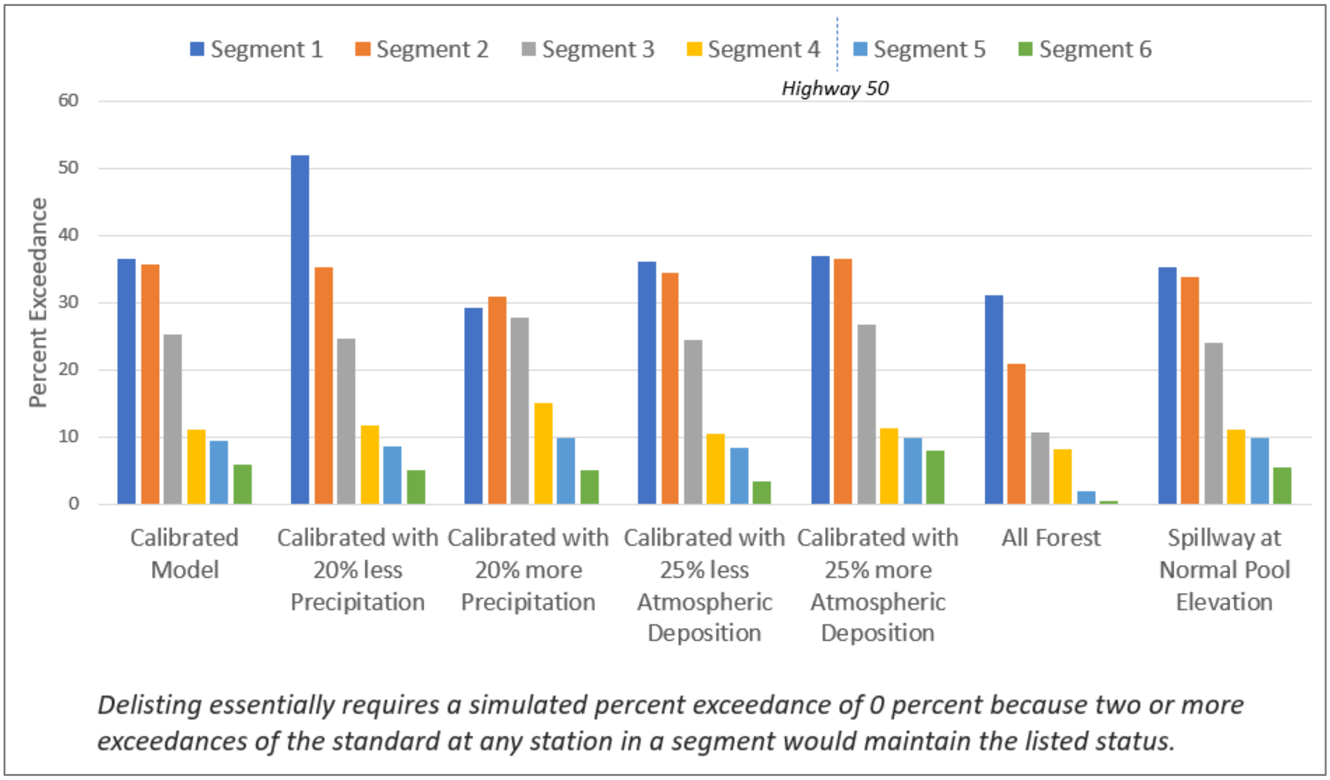

Figure 9-10. Simulated Percent Exceedances of the Chlorophyll-a Standard for the WARMF Lake Scenarios

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Table 9-1. Simulated Percent Exceedance of the 40 µg/L Chlorophyll-a Standard by Lake Segment for WARMF Lake Model Scenarios		
WARMF Lake Segment	Scenario	Percent Exceedance of 40 µg/L
1	All Forest	31.2
1	Calibrated Model	36.5
1	Calibrated with 20% more Precipitation	29.2
1	Calibrated with 25% more Atmospheric Deposition	36.9
1	Calibrated with 25% less Atmospheric Deposition	36.1
1	Calibrated with 20% less Precipitation	51.9
1	Spillway at Normal Pool Elevation	35.2
2	All Forest	20.9
2	Calibrated Model	35.7
2	Calibrated with 20% more Precipitation	30.9
2	Calibrated with 25% more Atmospheric Deposition	36.5
2	Calibrated with 25% less Atmospheric Deposition	34.4
2	Calibrated with 20% less Precipitation	35.3
2	Spillway at Normal Pool Elevation	33.7
3	All Forest	10.7
3	Calibrated Model	25.3
3	Calibrated with 20% more Precipitation	27.8
3	Calibrated with 25% more Atmospheric Deposition	26.7
3	Calibrated with 25% less Atmospheric Deposition	24.4
3	Calibrated with 20% less Precipitation	24.6
3	Spillway at Normal Pool Elevation	24.0
4	All Forest	8.1
4	Calibrated Model	11.1
4	Calibrated with 20% more Precipitation	15.0
4	Calibrated with 25% more Atmospheric Deposition	11.2
4	Calibrated with 25% less Atmospheric Deposition	10.5
4	Calibrated with 20% less Precipitation	11.7
4	Spillway at Normal Pool Elevation	11.0
5	All Forest	1.9
5	Calibrated Model	9.4

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Table 9-1. Simulated Percent Exceedance of the 40 µg/L Chlorophyll-a Standard by Lake Segment for WARMF Lake Model Scenarios		
WARMF Lake Segment	Scenario	Percent Exceedance of 40 µg/L
5	Calibrated with 20% more Precipitation	9.9
5	Calibrated with 25% more Atmospheric Deposition	9.8
5	Calibrated with 25% less Atmospheric Deposition	8.3
5	Calibrated with 20% less Precipitation	8.6
5	Spillway at Normal Pool Elevation	9.8
6	All Forest	0.6
6	Calibrated Model	5.9
6	Calibrated with 20% more Precipitation	5.1
6	Calibrated with 25% more Atmospheric Deposition	8.0
6	Calibrated with 25% less Atmospheric Deposition	3.4
6	Calibrated with 20% less Precipitation	5.0
6	Spillway at Normal Pool Elevation	5.5

9.3 Falls Lake Statistical/Bayesian Model

Scenarios for the statistical/Bayesian model were evaluated to determine if changing one or more system inputs would significantly change the model outputs for either regulatory variables (dissolved oxygen, pH, chlorophyll-a regulatory) or use-related variables (manganese, TOC, and algal toxin levels). The "default scenario" is based on all data collected in a lake segment, without selecting a specific condition like season. A scenario is created when one or more inputs are selected like warm or cool season, very low or very high nutrient loads, or dry or wet rainfall condition. Selecting specific inputs rather than the default can change the probability distribution of one or more output variables.

Table 9-2 summarizes the scenarios that most impact each of the output variables compared to the default scenario. The table focuses on specific outcomes for each variable that are of the most interest or concern, like dissolved oxygen concentrations less than the instantaneous standard of 4 mg/L. An increase in the percent probability for a specified outcome means that for the historic record, the scenario more frequently generated this outcome than the default scenario. A lower percent probability means that scenario was less likely to generate the specified outcome. Because of the variability in the historic record, with nearly every outcome observed at least once under nearly every condition, the model scenarios do not have a strong impact on the probabilities. Scenarios can also have a different impact on the upper versus lower lake. The warm season and rainfall condition (either dry or wet depending on the lake segment) have the greatest effect on outcomes and are part of each scenario identified in Table 9-2 as one with the greatest impact for a specified outcome.

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Table 9-2. Scenarios Evaluated with the Falls Lake Statistical/Bayesian Model that Have the Greatest Impact on Model Output Variables within the Photic Zone				
Specific Outcome for the Output Variable	Scenario	Upper Lake Probability (%)	Middle Lake Probability (%)	Lower Lake Probability (%)
Dissolved oxygen (DO) concentrations (profile measurements) less than the instantaneous standard (4 mg/L)	Default scenario	14.8	9.0	8.8
	Warm season, dry	25.5	16.5	16.5
	Warm season, dry, very high nutrient loads	25.5	16.5	17.0
pH below 6, pH above 9	Default scenario	3.1, 1.2	<1,<1	<1,<1
	Warm season, dry	<1, 8.2	<1,<1	<1,<1
	Warm season, wet	1.7, <1	<1,<1	<1,<1
Chlorophyll-a greater than the standard (40 µg/L)	Default scenario	44.6	16.6	8.6
	Warm season, dry	50.6	18.4	10.1
	Warm season, dry, very high nutrient loads	50.7	18.4	10.7
Manganese greater than the City of Raleigh's threshold for additional monitoring (0.45 mg/L)	Default scenario	30.7	4.18	5.81
	Warm season	51.5	8.14	10.3
	Warm season, dry	53.4	21	10.6
Total Organic Carbon Greater than 8 mg/L	Default scenario	58.0	41.5	22.1
	Warm season, dry	45.4	22.9	11.8
	Warm season, wet	75.0	57.5	27.8
Algal Toxin Levels Above Drinking Water or Recreational Use Thresholds	There have been no observations of algal toxin concentrations greater than the drinking water or recreational use health guidelines. The observations have been collected across decades, by multiple organizations, under varying seasons, precipitation conditions, and nutrient loading. Therefore, none of the model scenarios result in even a small probability of exceeding algal toxin thresholds.			

Another way to visualize the scenario output is by evaluating the mean, median, and standard deviation of a variable's probability distribution when model inputs are selected. Figure 9-11 shows chlorophyll-a values change very little in the upper lake (left) and lower lake (right). The “X”s are the mean, circles are the median, and the lines extend one standard deviation to either side of the mean. There is a strong left skew with most data to the left of the mean, and a long tail of rare values stretched out to the right. The wide standard deviation line indicates that many values are possible and have been observed under all conditions. In other words, there is high variability in chlorophyll-a under all scenarios. As expected, based on the box plots shown in Section 4.12, the mean and median values of chlorophyll-a are higher in the upper lake than the lower lake, and the standard deviations are larger.

In the upper lake, season has the highest impact on expectations, but the effects are weak. No scenario has much effect in the lower lake, and all medians and means are below the 40 ug/L limit. This is another indication of the stability of the distribution of chlorophyll-a concentrations in the lower lake. For both the upper and lower lake segments, switching from Very High to Very Low nitrogen or phosphorus load seems to have no measurable effect on expectations - all values are possible and have been observed under both extremes.

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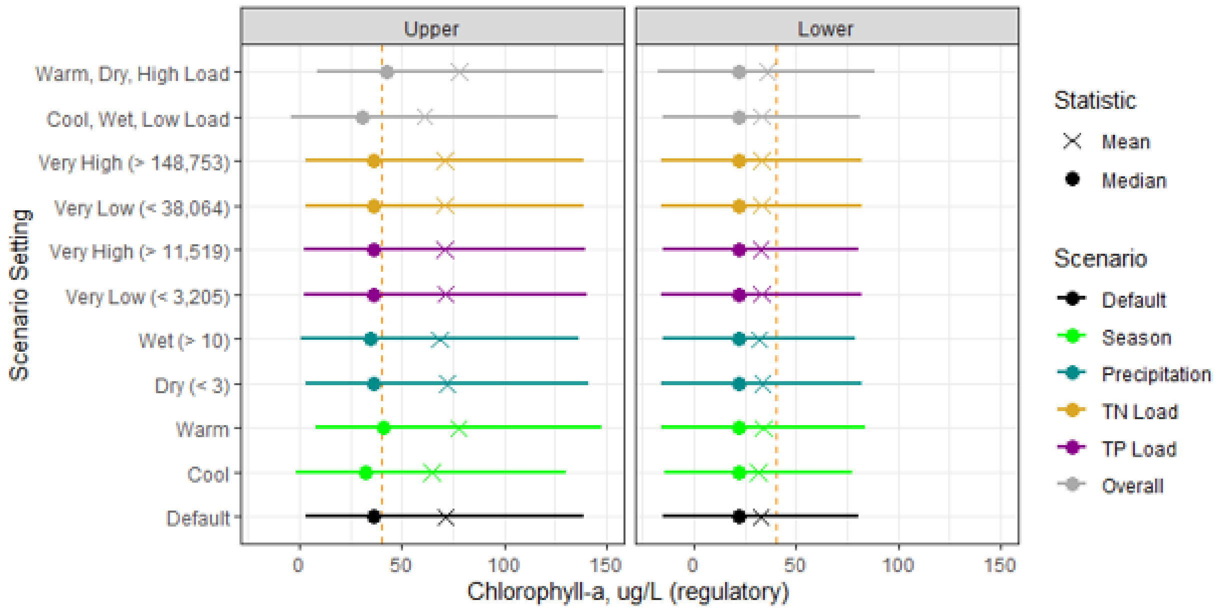

Figure 9-11. Impacts of Statistical/Bayesian Model Scenarios on Chlorophyll-a Concentrations

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Section 10

Key Findings

The UNRBA has invested over ten years and eleven million dollars in a comprehensive study and evaluation of Falls Lake. Several other organizations have studied Falls Lake with some data extending back to the 1980s. The UNRBA effort also has looked at these studies. The data collection efforts over the entire period encompass not only water quality data but water level and movement; lake sediment depth, quality, and nutrient releases; physical, chemical, and biological processes; light availability; algal types; and algal toxins. Additional data sets relate to satisfaction with the designated uses of Falls Lake including aquatic life, recreation, and drinking water supply. Several of these studies were summarized previously in the UNRBA 2019 Monitoring Report. Compared to similar studies and modeling efforts, the amount of data, level of information available, and number of researchers involved in this study is extraordinary.

10.1 Falls Lake Water Quality and Algae Data

The calibrated UNRBA lake water quality models, long-term monitoring data, and research studies show that concentrations of nutrients in Falls Lake were relatively low for the UNRBA study period (2014 to 2018). Research funded by the NC Collaboratory confirms nutrients in Falls Lake are not at excessive levels. While water quality in the upper part of the lake has been highly variable over time, it has stabilized in the past decade based on measurements of total nitrogen, total phosphorus, chlorophyll-a, and total organic carbon (see box plots by year in Table 4-7). Appendix C shows similar box plots for additional water quality parameters. Water quality in the lower part of the lake has been stable since the lake was filled. The middle part of the lake has more variability than the lower part, but data distributions look more like the lower than upper part of the lake.

The algae in Falls Lake are resilient. Chlorophyll-a can reach high concentrations even when nutrient concentrations, nutrient loading, and algal biovolume remain low. Species shifts are evident in the DEQ algae data collected in Falls Lake (Appendix D). These shifts and inconsistent patterns between algal biovolume measurements and chlorophyll-a concentrations complicate model calibration because the models are designed to predict more chlorophyll-a when more algae are present. Because WARMF Lake and EFDC simulate three groups of algae, it is not possible to simulate rapidly changing algal patterns and species shifts. It is also not possible to simulate varying chlorophyll-a production rates within a simulated algal group.

Algae are a resilient organism. They are also essential as the base of the food chain. Algal species can modify the amount of chlorophyll-a they produce in response to environmental stressors. Additional study on the predominant algal groups present in Falls Lake and their ability to change the amount of chlorophyll-a in their cells would improve understanding of this system. Chlorophyll-a values alone do not definitively define overall water quality trophic condition. Additional research on why and when chlorophyll-a concentrations are elevated when nutrients and algal biovolume are low would be helpful. In the meantime, four decades of water quality data have been collected in Falls Lake. Distributions of measured total nitrogen, total phosphorus, chlorophyll-a, and total organic carbon have decreased and stabilized since the lake was filled. Nutrient loads have decreased over this time with significant reductions in available forms. Most of the total nitrogen and total organic carbon are now in organic form. Most of the total phosphorus is particulate and either bound to sediment or in organic material. DEQ stopped monitoring dissolved phosphorus and ortho-phosphate in Falls Lake because the concentrations were nearly always below reporting levels.

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10.2 Internal Releases of Nutrients from Lake Sediments

The sediments in Falls Lake store and slowly release nutrients back to the water column. Estimates of ammonia releases from Falls Lake sediments range from 200,000 to 500,000 pounds per year, roughly 12 to 30 percent of what enters from the watershed and atmospheric deposition to the lake surface (1.65 million pounds of total nitrogen per year on average during the study period, 2014 to 2018). Ammonia releases from lake sediments are higher in the deeper areas of the lake where sediment accumulates. Estimates of phosphate releases from the lake sediments range from 10,000 to 50,000 pounds per year, roughly 5 to 27 percent of the load from the watershed (183,000 pounds of total phosphorus per year on average, 2014-2018). The significant variation in ranges indicate a great deal of uncertainty relative to specific releases, particularly for phosphate where releases are controlled by the chemical composition of the sediment and the redox conditions present. However, the studies show that nutrient release rates in Falls Lake are an extremely important factor in evaluating lake response to management actions. Nutrient release rates from lake sediments will remain an important consideration in making management decisions.

Based on long-term simulations at recent nutrient input levels (2014 to 2018), nutrient releases from Falls Lake sediments are stable. Nutrient inputs to the lake have significantly declined due to improvements at wastewater treatment plants, reduction of agricultural productions areas and nutrient application on crops, as well as reduction in atmospheric deposition of nitrogen.

Releases of ammonia from lake sediments are mitigated by denitrification which removes nitrogen from the system as nitrogen gas. NC Collaboratory researchers estimate the amount of denitrification as equivalent to the amount of ammonia released from the lake sediments on an annual basis. Phosphorus releases tend to occur in the deeper parts of the lake during warm stratified conditions. These releases are usually “trapped” near the lake bottom but are moved to the surface layers when the lake destratifies and “turns over” in the fall months when higher concentrations of total phosphorus are sometimes observed in the photic zone.

10.3 Project Goals and Applicable Models and Input

The historic data, Falls Lake watershed model, three lake models, and input from the TAW provide a complete assessment of this watershed-lake system. These evaluations meet the project goals from the UNRBA Modeling QAPP listed in Table 2-1. Each of these goals and the information applied are described below.

10.3.1 Estimating nutrient, carbon, sediment, and chlorophyll-a loading to Falls Lake and Evaluating the impacts of management strategies on water quality

The WARMF Watershed model simulates stream flows and loading of these parameters to Falls Lake. These inputs are directly linked to WARMF Lake, which runs simultaneously with WARMF Watershed. This direct linkage has two advantages. First, the watershed and lake models run at the same time, so additional model run time is not needed to simulate the lake response. Second, changes simulated using the watershed model (land use, nutrient application, etc.) are evaluated directly in the model.

The EFDC model also uses output from the WARMF Watershed model in terms of stream flows and nutrient loading. To link these models, the time series output from WARMF Watershed is post-processed into the correct formats to provide EFDC time series inputs. EFDC has different benefits and applications than WARMF Lake. First, EFDC simulates output at over 800 horizontal grid cells in Falls Lake. These grid cells are spatially matched to water quality monitoring stations in Falls Lake. This fine spatial resolution allows for predicted values that are directly compared to observations at a single monitoring station. EFDC was also used by DWR for their lake modeling. Second, the EFDC model allows for generation of the load reduction curves where combinations of percent reductions in nitrogen and phosphorus loading from the watershed are evaluated for impacts on lake water quality. Because EFDC uses time series inputs of stream flow and

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nutrient concentrations, applying a percent reduction is easy. Numerically applied percent reductions to lake inputs cannot be easily simulated for WARMF Lake which requires a specific change to the watershed or nutrient input.

The historic record of stream flows and tributary monitoring was also evaluated to estimate historic nutrient loads to Falls Lake. These estimates are summarized in Section 4.5. These historic loads provide a visual representation of how conditions in the watershed have changed and provide inputs to the UNRBA Statistical/Bayesian model.

10.3.2 Revising the lake response and watershed models using data that was not available at the time DWR conducted their modeling to develop the Falls Lake Nutrient Management Strategy

Conditions in the Falls Lake system have changed since the DWR watershed and lake models were developed. The acreage of land in agricultural production has decreased by almost half. The cost of fertilizer and improved crop science have resulted in lower nutrient application rates for most crops. Development continues in the watershed but is mitigated by the Falls Lake New Development Rules and Stage I Existing Development Interim Alternative Implementation Plan (IAIA). Before IAIA, over 350 projects had been implemented to reduce nutrient loading from existing development. Wastewater treatment plants have reduced total nitrogen loading by approximately 40 percent and total phosphorus loading by approximately 80 percent. Deposition of total nitrogen from the atmosphere has decreased by 20 to 25 percent. The data used to develop the previous models was collected during a historic drought (2005 to 2007) that exposed the old river channel in much of the upper lake. The UNRBA model period (2015 to 2018) reflects a wetter hydrologic condition for the calibrated model. From 2019 to 2022, annual rainfall was closer to average. Concentrations of nutrients, total organic carbon, and chlorophyll-a have declined and stabilized in the past decade (Table 4-7) due to these hydrologic and nutrient loading changes.

A tremendous amount of additional data has also been collected by DWR, UNRBA, USGS, US Forest Service, and researchers funded by the NC Collaboratory. The UNRBA watershed and three lake models have the benefit of this additional data and information to improve the models and build tools that reflect more recent conditions.

10.3.3 Understanding how changes in lake water quality affect the designated uses of the lake

The UNRBA Statistical/Bayesian model was developed specifically for this purpose. Evaluation of the long-term water quality monitoring record in Falls Lake was also a critical component of this evaluation. The modeling and long-term data record demonstrate the complexity and stability of the system. Input from the TAW provided critical insight into the uses and management of the lake. Together, the long-term record, statistical/Bayesian modeling, and input from the TAW indicate the following:

- Nutrient-related water quality concerns are not affecting the recreational uses of Falls Lake (fishing, swimming, etc.). User complaints focus on crowded conditions, trash, and park staff. Beach closures due to fecal coliform have occurred. Toxin levels in Falls Lake are relatively low compared to those in national datasets. Adverse effects from algal toxins in Falls Lake have not been documented by the State, and algal toxin levels have never resulted in a beach closure at Falls Lake. Additional data on food web accumulation of algal toxins would be helpful to evaluate this potential exposure pathway to subsistence fishers.
- With respect to the aquatic life use, staff from NC Wildlife Resources Commission noted the quality of fisheries in Falls Lake is generally above average for the Piedmont and not highly variable. Staff also noted that fisheries benefit from being eutrophic (more food) to a degree; there is a “sweet spot” level of eutrophication to provide a great fishery without detrimental impacts to the fishery or other uses. Their

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2015 report on the Falls Lake Largemouth Bass Fishery (2007–2015) states that "Falls Lake supports an excellent Largemouth Bass fishery," "is being appropriately regulated," and "the size structure of the fishery has been relatively stable." The long-term data record for both dissolved oxygen and pH show stability in these parameters as well. Nutrient or algae-related fish kills have not been reported since 1988 relatively soon after the lake was filled. Triangle Fly Fishers are frequently on Falls Lake. If a fish kill was noticed, they would notify their members and DWR, but the group has not seen fish kills on Falls Lake.

- To protect the drinking water supply, the City of Raleigh has monitored water quality in Falls Lake for the past two decades. Staff indicate that over this period, the type and timing of algal blooms has become more stable. Drought/flood cycle tends to increase total organic carbon in the lake. Staff are hopeful that research studies will increase the knowledge about how the lake bottom serves as a nutrient and sediment trap and whether dam releases stir up these materials. Staff noted manganese is the most difficult and expensive to treat. Staff observed that manganese concentrations can become high in Falls Lake when bottom material is stirred up. The statistical/Bayesian model shows that manganese concentrations are most sensitive to residence time. City of Raleigh drinking water staff also track algal toxin levels. Monitoring to date has not shown a concern in Falls Lake. Results show consistently low levels. Diatoms can clog filters at the drinking water plant. The City has two terminal ponds between Falls Lake and the treatment plant that are used for treatment of diatoms when needed. The City noted that they have had only one issue several years ago that required treatment in the terminal ponds. The City does not have issues with taste and odor or disinfection byproducts at Falls Lake. In 2023, the American Water Works Association ranked the City of Raleigh 3rd in its international "'Best of the Best' Water Taste Test"

10.3.4 Evaluating management strategies in the lake and watershed to determine the impacts to lake water quality and designated uses

This project goal relies on all of the available data, modeling, and input from the TAW and other stakeholders. The long-term data record shows that nutrient, total organic carbon, and chlorophyll-a concentrations have stabilized in the last two decades, even in the upper lake which tends to be more variable. The EFDC model indicates that in order to meet the chlorophyll-a criteria 90 percent of the time in the upper lake, a 50 percent reduction in total nitrogen loading from all sources would be needed. The watershed characterization data and the WARMF watershed model demonstrate that a 50 percent reduction is not achievable. Most of the area in the watershed is forest or other unmanaged land. Wastewater treatment plants in the Falls Lake watershed have already reduced nutrient loading significantly. There is not an additional 50 percent reduction in nitrogen load to be had, even if all urban and agricultural land use was removed. The WARMF Lake model shows that converting all of the land to forests and removing nutrient application and treated wastewater inputs would not meet the chlorophyll-a criteria 90 percent of the time in the upper lake. The magnitude of chlorophyll-a would decrease, but the standard would not be met. Therefore, the data and modeling show that significant changes to lake water quality cannot be made as a result of additional, achievable nutrient reductions. This is in part due to the storage and slow release of nutrients from sediments in the watershed and Falls Lake. Nutrients and algae are naturally occurring. In Falls Lake, they are stable due to reductions in nutrient loading over the past two decades and the mostly unmanaged lands in the basin. The lake data, statistical Bayesian model, and input from the TAW also indicate that the designated uses of Falls Lake are being met.

During the modeling process, the Scenario Screening Group for the watershed model selected and evaluated several management strategies. Because of the progress already made and the type of land use in the watershed (75 percent unmanaged), there are not management strategies that would significantly reduce nutrient loading to Falls Lake. Even removing all nutrient application to land surfaces, removing centralized and onsite treated wastewater discharges, and converting land to forests would not achieve the

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required reductions. For these reasons, the UNRBA has recommended an investment-based, adaptive approach to nutrient management. This approach is not focused on nutrient loading targets or implementing projects that reduce a specified amount of nutrients. Rather, the recommendations encourage activities throughout the watershed that provide multiple benefits: water quality, habitat, climate resilience, improved air quality, etc. These recommendations are summarized in the Concepts and Principles for the UNRBA Recommendations for a Revised Falls Lake Nutrient Management Strategy. The Consensus Principles provide a focused summary of the recommendations.

10.3.5 Examining alternative chlorophyll-a criteria that include duration, frequency, spatial, and temporal components consistent with the chlorophyll-a criteria approved by EPA for states with more recent standards (North Carolina's standard was developed in the 1970s).

The UNRBA's primary focus is the readoption of the Falls Lake Rules. The Association aims to support DWR in this process and to ensure the UNRBA's recommendations and updated scientific information are the basis of the revised rules.

The goal of the 2011 Falls Lake Rules is to meet the NC chlorophyll-a standard everywhere in Falls Lake. The State set the chlorophyll-a standard in the 1970s as an indicator for algae. The current standard is not applicable to Falls Lake which is meeting its designated uses and has had a stable distribution of chlorophyll-a for many years. However, the shallow areas of Falls Lake cannot meet this standard. These areas are not indicative of the health of the lake. The lake meets its intended uses despite not meeting the standard in some areas. The UNRBA is evaluating whether a site-specific chlorophyll-a standard would be more appropriate for Falls Lake. Other parameters like dissolved oxygen and pH are also being evaluated (presentation by Martin Lebo at the February 2024 PFC meeting). A site-specific standard would have to be approved by the State of North Carolina.

10.4 Model Scenarios

Modeling scenarios further validate the information from the monitoring data, research studies, and calibrated Falls Lake models. Water quality monitoring data collected in Falls Lake, including chlorophyll-a, has stabilized in the past decade. Simulating an increase in nutrient loading of 20 percent relative to the study period (2014 to 2018) does not significantly change chlorophyll-a concentrations especially near the dam. Similarly, changing the nutrient loading categories in the statistical/Bayesian model to the highest levels did not significantly change the chlorophyll-a predictions in any segment. When nutrient loading to Falls Lake is high, stream flows are also high and the residence time in the lake is shortened. These conditions do not allow sufficient time for algae to grow. These modeling results are consistent with long-term monitoring of chlorophyll-a concentrations in the three lake segments. Particularly in the lower lake, chlorophyll-a concentrations have always been relatively low even in the 1980s when nutrient loading to the lake was higher and chlorophyll-a concentrations in the upper lake were high. Decreasing nutrient loads by even 50 percent in addition to the load reductions already achieved will not result in attainment of the chlorophyll-a standard as currently applied in all parts of Falls Lake.

Decreasing nutrient loads by even 50 percent in addition to the load reductions already achieved will not result in attainment of DWR's standard for chlorophyll-a.

The information developed during this evaluation process shows a reservoir that has been eutrophic since it was constructed, but that it is meeting its designated uses. While water quality and chlorophyll-a concentrations are stable, the evaluation shows a lake that is likely subject to increases in nutrient loading

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due to changing weather patterns and ongoing development in the watershed. Therefore, ongoing management is needed. This includes investment in water improvement projects in the watershed that address existing land use (land under active human management), land conservation, and continued implementation of the new development rule. These actions are essential components of an effective, ongoing strategy. Actions to improve watershed health and address current nutrient loading will provide protection of this important water resource.

10.5 Development of Recommendations for a Revised Nutrient Management Strategy for Falls Lake

To summarize the findings of the modeling effort and address future challenges to ensure protection of Falls Lake into the future, the UNRBA has developed a set of recommendations for a revised nutrient management strategy called Concepts and Principles for the UNRBA Recommendations for a Revised Falls Lake Nutrient Management Strategy. The UNRBA Board of Directors unanimously approved this document and a focused set of revised consensus principles (Consensus Principles II) on September 20, 2023. The UNRBA hopes to work collaboratively with DWR as the Falls Lake rules are readopted using these two documents as guides.

The successful completion of the UNRBA modeling efforts and development of the guiding documents for the revised rules would not have been successful without direct input from the organizations and stakeholders operating in the watershed. The UNRBA sincerely thanks everyone who has participated in this project as a provider of data and information, reviewer of models and reporting, facilitator of external discussions, and active participant in discussing the challenges and path forward for this unique system. The next phase of work will include additional opportunities for discussion and feedback as the State moves through its rules readoption process. The UNRBA is hopeful the process will remain open and collaborative, engaging a broad range of stakeholders to identify issues and concerns before rule language is drafted.

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Appendix A: 3-Dimensional Hydrodynamic and Water Quality Model of Falls Lake, North Carolina

Appendix A (EFDC modeling report) is available online at https://unrba.org/resource-library.

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Appendix B: WARMF Lake

Appendix B is available online at https://unrba.org/resource-library.

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Appendix C: Statistical/Bayesian Lake Model

Appendix C is available online at https://unrba.org/resource-library.

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Appendix D: Extended Lake Data Evaluation

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