Basic Evaluation of Model Performance Special Study SS.LR.8

UNRBA FY2016 Monitoring Program

August 2016

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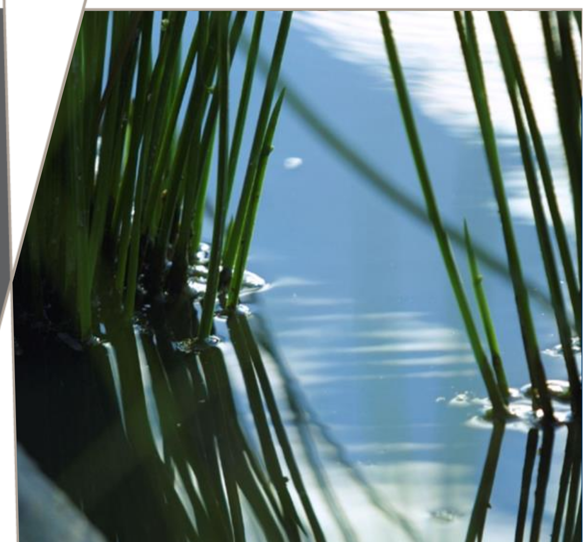

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Project Manager	Douglas J. Durbin, Ph.D.
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Prepared for:

Upper Neuse River Basin Association
P.O. Box 270, Butner, NC 27509

Prepared by:

5400 Glenwood Ave, Suite G03, Raleigh, NC, 27612

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Background

The member jurisdictions of the Upper Neuse River Basin Association (UNRBA) are faced with very strict nutrient load reduction requirements under the Falls Lake Nutrient Management Strategy. This Strategy was put into place by the State of NC to address elevated chlorophyll *a* levels in Falls Lake, some areas of the lake were exceeding the chlorophyll *a* water quality criterion of 40 µg/L. The NC General Assembly established the Strategy and the timeline for achieving the requirements. During the Strategy development process, the impacted local governments established a set of Consensus Principles that helped to guide the provisions of the Strategy. Those principles included a provision for adaptive reexamination of the Falls Lake Strategy.

Entities seeking to develop a reexamination are required to collect at least three years of monitoring data under a DWR-approved monitoring plan and quality assurance project plan. They are also required to obtain approval of a description of the modeling framework that will be used to conduct modeling associated with the reexamination. The UNRBA began the process of putting in place the plans and resources to perform a reexamination evaluation at the same time the rules were being adopted in 2011.

In 2014, the UNRBA gained agency approval of the three required documents and began collecting data under the UNRBA Monitoring Program. The UNRBA Monitoring Program is primarily composed of two categories of tasks. The first category is Routine Monitoring which is the repeated testing of water quality variables at fixed locations over many months. Routine Monitoring provides insight into the seasonal and annual variation of nitrogen, phosphorus, and other parameters over time. The second category is Special Studies, which are focused evaluations conducted in a time-limited effort to inform water quality model development and calibration so that baseline and management scenarios can be more accurately simulated. Together these two categories provide a scientific basis for the reexamination of the Falls Lake Nutrient Management Strategy.

Analyses Conducted for the Evaluation of Model Performance Special Study

The FY2016 UNRBA Monitoring Program included a Special Study (this report) to evaluate the existing agency lake response model, tributary loading methods, and a conceptual model for an empirical/probabilistic/ Bayesian model. The main objectives of this Special Study were to: 1) identify changes that should be made to the current monitoring program and 2) confirm that the UNRBA Monitoring Program is collecting the appropriate data and information needed to properly support the reexamination effort. Reviews of alternative lake response models and watershed models were not included in this Special Study but will be considered under the UNRBA's Modeling and Regulatory Support efforts. The results of the analyses conducted as part of this Model Performance evaluation were used to revise the FY2017 Monitoring Program which began in July 2016. The recommendations for revising the UNRBA Monitoring Program were summarized in the 2016 Annual Report and incorporated into the FY2017 Monitoring Plan. This document describes the analyses and results of the Basic Evaluation of Model Performance Special Study which formed the basis for many of the revisions to the Monitoring Program for FY 2017. The analyses that were conducted to support this evaluation are described briefly in this Executive Summary.

Estimation of Loading to Falls Lake

Accurate representation of nutrient loading to a waterbody is critical to the development of lake response models where chlorophyll *a* is a key parameter of concern. Previous work conducted by the UNRBA (UNRBA Monitoring Plan Model Sensitivity Technical Memorandum at https://www.unrba.org/monitoring-program) indicated that loading estimates could vary greatly depending on how water quality samples were paired with flows, and that the prediction of algal growth was sensitive to these inputs. However, at the time the previous work was conducted, frequent nutrient data collected during storm events was not available. As a result, in 2015 the UNRBA approved the Storm Event Sampling Special Study (http://www.unrba.org/monitoring-program) to collect water quality samples at a high frequency during storm events at two gaged tributaries in the Falls Lake Watershed. As intended, that Special Study has provided data that will allow the UNRBA's reexamination effort to better describe tributary loads generated during a storm.

As part of this Basic Evaluation of Model Performance Special Study, the measured tributary loads were compared to those predicted by several load estimation techniques to evaluate whether data collection efforts associated with the intensive storm event sampling have provided sufficient data and whether additional high flow sampling in the watershed could further improve loading estimates at other tributaries. This evaluation is described in Section 2.1, which demonstrates that the accuracy of load estimation is improved when load estimates incorporate flow as a predictor. In order to provide water quality across a range of flow conditions to build the flow-based statistical regression models, sufficient water quality data need to be collected across a wide range of flow regimes. The UNRBA Routine Monitoring typically represents relatively low-flow or baseline-type conditions during most sampling events. Because high flow conditions occur so rarely, routine sampling may not capture them.

To better represent flow conditions when loading to Falls Lake is high, the UNRBA approved an expanded High Flow Special Study for FY2017 targeting the five largest tributaries to allow for sample collection as close to the peak of a storm hydrograph as possible. When modeling efforts are initiated to support the reexamination, the Storm Event data from FY2015 and FY2016 and the High Flow data from FY2015, FY2016, and expanded in FY2017 will be available for refining loading estimates and further evaluating the accuracy of the different methods. The UNRBA's monitoring program for higher flow events will greatly improve the accuracy of tributary loading estimates. These modeling inputs are critically important in determining the lake's response to variations in flow and loading over the selected timeframe for analysis.

Environmental Fluid Dynamics Code (EFDC) Model Evaluations

One of the primary objectives of the UNRBA is to revise the lake response modeling originally conducted by DWR (DENR 2009) that was used to assign the nutrient load reduction targets set forth in the Falls Lake Nutrient Management Strategy. DWR originally used the Environmental Fluid Dynamics Code (EFDC) model (DENR 2009). The UNRBA Monitoring Program was established following work that identified a number of data gaps and unsupported modeling assumptions for which the collection of additional data could reduce the uncertainty associated with future modeling efforts that the UNRBA would conduct. (Task 4 Technical Memorandum: https://www.unrba.org/reexamination).

This report expands the assessment of the model needs by revising select model input files and evaluating changes in predicted lake response for key parameters. To support this effort, model sensitivity analyses and model input assessments were used to inform changes to the FY2017 Monitoring Program (Section 3). A comparison of the lake water quality model variables to existing monitoring programs indicates that key model variables for simulating and projecting algal response and the impacts to total organic carbon are currently being monitored in Falls Lake (nutrient species, algal composition, chlorophyll *a*, total and dissolved organic carbon).

Model Sensitivity

Model Sensitivity analyses involve changing an input value and determining how the model output changes in response. Previous model sensitivity analyses conducted in 2014 (UNRBA Monitoring Plan Model Sensitivity Technical Memorandum at https://www.unrba.org/monitoring-program) indicated that simulated algal growth in the lake was sensitive to the assumed tributary input concentrations of chlorophyll *a*. When DWR originally developed the lake model, tributary chlorophyll *a* concentrations were not available to provide this input. To inform future lake modeling, the UNRBA began collecting chlorophyll *a* data in tributaries as part of the Routine Monitoring in August 2014.

One of the main purposes of this Basic Evaluation of Model Performance Special Study is to evaluate some of the parameters currently monitored by the UNRBA. The data included in the UNRBA database which includes data from other entities was used to test the effect on model output when these inputs are varied. If the model is relatively insensitive to a parameter (e.g., prediction of algal growth does not vary significantly when the parameter is varied across a reasonable range), then further monitoring may not provide significant value to the monitoring effort. Monitoring efficiency can be achieved if existing data can be used to establish appropriate relationships that will result in realistic estimates for the model. Suspending collection of certain data under these circumstances allows the UNRBA to efficiently reallocate its resources to other higher priority purposes.

Sensitivity analyses conducted as part of this Basic Evaluation of Model Performance Special Study resulted in the following recommendations:

> Based on analyses on the labile and refractory fractions of particulate organic carbon, the UNRBA approved discontinuing analysis of CBOD5 at the lake loading stations in FY2017. The model is relatively insensitive to this parameter because very little of the organic carbon entering the lake is in the particulate form for which EFDC assigns lability (EFDC does not designate lability for the dissolved fraction which comprises approximately 95 percent of the organic carbon load from the tributaries).

> With respect to the light extinction data collected in Falls Lake, revisions to the modeling parameters are needed to provide a more accurate prediction of light attenuation, particularly with respect to background light extinction. While the current version of the model is relatively insensitive to changes to light extinction parameters, once the model is revised, the degree of impacts may change and additional data collection may be warranted. Given that the model response using the DWR version of the EFDC model is relatively insensitive to changes in light extinction parameters and that significant improvements can be made to light extinction parameterization simply based on existing data, the UNRBA has not funded collecting additional paired light penetration data in FY2017.

Model Grid

Falls Lake is a manmade reservoir in the Piedmont of NC that has varying topographic features from the upstream end, which is relatively shallow and wide, to the downstream end, which is deeper and much narrower. There are also several road crossings that form separate lake segments by restricting the width of the reservoir by 80 to 90 percent at these locations. These constrictions limit the movement of water and materials, particularly when flows into the lake are relatively low, and water quality in each segment can be quite different from one segment to the next.

Accurate representation of topographic features and flow restrictions is an important component of model development that often has significant ramifications for the ability of the model to accurately simulate water quality conditions across a range of flow regimes. Evaluation of the DWR model grid indicates that these hydraulic constrictions were not represented in the model. To preliminarily explore the potential effects of the constrictions, the model grid was adjusted at two of the bridge causeways in the upper lake to better simulate the flow and transport of materials (such as nutrients). Subsequent work on the model should incorporate all of the constrictions into the model grid to better simulate hydrodynamics in the lake. In addition to the bridge constrictions, additional revisions to the grids should consider including the simulation of wetting and drying in the shallow cells that comprise the upper lake and extension of the model grid into tributary arms that are often inundated by lake backwaters. In FY2017, the UNRBA will conduct a bathymetric survey of Falls Lake to provide additional data to support revisions to the modeling grid.

The UNRBA Monitoring Program also includes a Special Study to collect velocity and water quality data at constriction points in Falls Lake. One of these data collection events was conducted in FY2016 and one will occur in FY2017. When the lake model is redeveloped to support the reexamination, data from that study will also help to inform the grid revisions and model development.

Estimates of Nutrient Releases from Lake Sediments

This Model Evaluation also reviewed existing information about the release of nutrients from the Falls Lake bottom sediments. The DWR version of the EFDC model assumed that nutrient releases were constant regardless of location in the lake (upper lake, lower lake, floodplain, and historic river channel) and that sediment releases contribute approximately 20 percent of the nitrogen and phosphorus load to the lake water column. There were in situ benthic chamber measurements conducted in 2006 at three locations in the lake to inform this model parameter, but these results were not used directly. Rather, nutrient releases from lake sediments were used to calibrate the model, adjusting the release rates to improve model predictions of nutrients in the water column. There are other ways to account for nutrient releases from lake sediments including specifying loads as a time series or simulating loads using the EFDC sediment diagenesis module.

Given the potential contribution of lake sediments to nutrients available in the water column, and the lack of information about the spatial variability of these releases, the UNRBA conducted a Lake Sediment Evaluation Special Study in FY2015 that included sampling and analysis of nutrients and organic material in sediment cores collected at 12 locations in Falls Lake. This Basic Evaluation of Model Performance Special Study reviewed the data collected from the Lake Sediment Evaluation Special Study relative to the model input needs for the EFDC sediment diagenesis module. This module simulates the cycling of nutrients and organic material between the lake water column and lake bottom sediments (settling, decomposition, resuspension, and burial) and requires specification of particulate organic matter and porewater concentrations of inorganic nutrients. The Lake Sediment Evaluation Special Study collected the necessary data to define the initial conditions; these data are in the process of being reviewed and interpreted for inclusion in the FY2017 UNRBA Interim Monitoring Report.

On the basis of this analysis and the importance of the sediment nutrient release it was recommended and the UNRBA approved for FY2017 a sediment-mapping special study to generate estimates of unconsolidated sediments on the lake bottom. This sediment mapping data can be reviewed in light of the nutrient flux estimates generated as part of the Lake Sediment Evaluation Special Study. When the lake modeling is revised to support the reexamination, the modelers should have the data needed to evaluate the three methods for estimating nutrient releases from the sediments (constant values, time series, or sediment diagenesis modeling). After initial analyses of the sediment mapping and sediment data have occurred and recommendations for a technical approach have been discussed with the UNRBA, additional types of sediment data collection may be warranted.

The UNRBA monitoring program development process has consistently identified the importance of measuring sediment nutrient flux rates. In addition to the two studies noted, the UNRBA has included on its list of potential special studies in situ bottom sediment flux measurements. The EPA has resources to perform these types of studies, and the UNRBA continues to seek support from this agency to do this study. Based on the results of the Lake Sediment Evaluation Special Study, the UNRBA will need to reanalyze the importance of a new in situ flux study, and if still considered critical and if EPA will not provide this study, be prepared to consider funding an in situ study from UNRBA funds. The UNRBA Monitoring Program has identified the importance of this type monitoring and has identified it as a priority. The Program's current status in this area is consistent with the recognized need and provides sufficient flexibility for securing additional information, as appropriate, within the next two monitoring years.

Evaluations of Empirical/Probabilistic Models

The EFDC model is a mechanistic model that uses a series of model formulations to describe the processes that affect lake water quality. While mechanistic models can be developed to predict water quality with a high degree of accuracy, they are not usually capable of predicting the impacts to designated uses. For example, EFDC predicts concentrations of total organic carbon (TOC) near the City of Raleigh's drinking water intake in Falls Lake, but it does not predict whether or not these concentrations will cause treatment difficulties or generate disinfection byproducts. Connecting lake water quality to the other designated uses in Falls Lake such as recreation and aquatic life use presents similar challenges.

The strategy developed by the UNRBA for the reexamination process includes development of an empirical/probabilistic/Bayesian model to link lake water quality to the designated uses of Falls Lake (see the technical memorandum Task 1 - Develop a Framework for a Reexamination of Stage II of the Falls Lake Nutrient Management Strategy available at http://www.unrba.org/reexamination). During earlier phases of work, a conceptual model for the empirical/probabilistic/Bayesian model was developed. This component of the Evaluation of Model Performance Special Study updated the conceptual model and evaluated whether or not the existing monitoring efforts (by the UNRBA and other organizations) were collecting the data necessary to build the model and define the linkages (Section 4). This evaluation indicated that several organizations collect data in and around Falls Lake that will provide the inputs needed to develop the empirical/probabilistic/Bayesian model. Once model development begins, analysis of the various relationships that may be used to establish the model linkages will be needed. If data gaps are identified as the model is developed, they may be filled by collecting additional data on Falls Lake, using data collected from similar waterbodies, or through expert elicitation (i.e., obtaining input from subject matter experts).

Recommendations for the UNRBA Monitoring Program

The recommendations derived from the modeling evaluation summarized in this report were also considered and incorporated in the FY2016 Annual Monitoring Report. The annual report recommendations have already been considered by the UNRBA and incorporated into modifications for the FY2017 Monitoring Year. With the exception of the recommended additional data collection efforts listed below, the evaluation of potential model types planned to support the reexamination indicates no apparent, fundamental data gaps that are not addressed or being considered as the UNRBA moves toward completion of its monitoring program period (four years with an additional year, if needed). This report has identified the changes that are planned for FY2017 and noted some areas of monitoring and special studies that will continue to be evaluated from year to year as the monitoring program proceeds. Additional data needs that may arise as the modeling and regulatory support component of the reexamination gets underway should be addressed through focused Special Studies in future years. The FY2017 Monitoring Program includes the following changes based on this Basic Evaluation of Model Performance Special Study:

- Expansion of the High Flow Sampling Special Study to include multiple storms at the five uppermost tributaries. Depending on the duration of the storms and timing of hydrographs, additional lake loading stations will also be targeted for high flow sampling.
- Discontinuation of analysis of CBOD5 at the lake loading stations.
- Discontinuation of paired light penetration measurements using a PAR meter in addition to routine Secchi depth measurements.
- A survey of Falls Lake to generate a bathymetric map to define the model domain and support revisions to the model grid.

> A sediment mapping study of Falls Lake to identify the presence, absence, and relative thickness of unconsolidated sediments throughout the lake for comparison to nutrient release estimates from the FY2015 Lake Sediment Evaluation Special Study.

In addition to helping support revisions to the FY2017 Monitoring Program, the Basic Evaluation of Model Performance Special Study also was aimed at determining whether or not the Monitoring Program is collecting the types of data needed to allow the development of updated and improved models that will be critical to support of the reexamination. The overall conclusion of this evaluation is that the current monitoring programs (UNRBA, NCDWR, local governments, and universities), with the revisions noted for the UNRBA's FY2017 Monitoring Program and the pending special studies already identified, will provide the types of data that the models need. As the empirical/probabilistic/Bayesian model is developed, data gaps may be identified. Additional data needs that may arise as models are revised and/or developed could be addressed by with focused Special Studies, using data collected from similar waterbodies, or expert elicitation.

1 Introduction

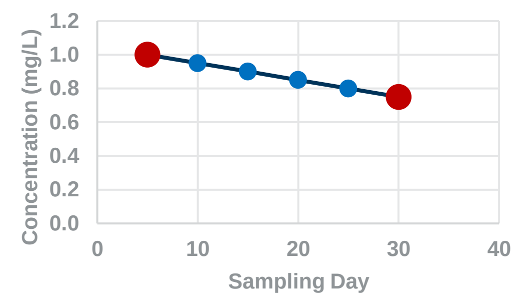
The UNRBA Monitoring Program is primarily composed of two categories of tasks. The first category is Routine Monitoring which is the repeated testing of water quality variables at fixed locations over many months. Routine Monitoring provides insight into the seasonal and annual variation of nitrogen, phosphorus, and other parameters over time. The second category is Special Studies, which are typically focused evaluations conducted in a time-limited effort to inform water quality model development and calibration so that baseline and management scenarios can be more accurately simulated. Together the analytical results from these two categories of monitoring provide a data-based scientific foundation for the reexamination of the Falls Lake Nutrient Management Strategy.

This document presents and discusses findings from the Basic Evaluation of Model Performance Special Study, one of the studies performed under the UNRBA's Monitoring Program in FY2016. This evaluation was designed to ensure that data collected is appropriate and sufficient for future modeling efforts. This evaluation includes a review of the resources allocated among existing or potential monitoring studies. The review utilizes targeted sensitivity analyses, analyses of monitoring data, and the data requirements of models that may be developed to support the reexamination effort. This review also offers the opportunity to consider future modeling decisions and scenarios for the reexamination of the Falls Lake Nutrient Management Strategy and to better compare more efficient alternatives for water quality management in Falls Lake.

This evaluation considered three independent facets of modeling. The first is a general investigation of relationships between tributary inflows and tributary water quality. This facet of the study evaluates several ways that nutrient loadings to the lake might be estimated statistically from routinely collected tributary data. Watershed models were not evaluated as part of this study but will be considered under the UNRBA's Modeling and Regulatory Support effort. The second facet is a review of the Environmental Fluid Dynamics Code (EFDC) model as used by the North Carolina Division of Water Resources (DWR). This review explored the sensitivity of the model to data inputs in an effort to ensure that suitable data are being collected by the Monitoring Program, and to determine where UNRBA resources could be conserved by reducing or eliminating further collection of redundant or nonessential data. A number of other lake response models could be used as part of the reexamination, however this document focuses on the EFDC model given the precedent of its use by DWR. The UNRBA's upcoming Modeling and Regulatory Support effort will evaluate the potential utility of alternate lake response models. The third facet was the consideration of a basic modeling framework appropriate for linking lake water quality to designated uses and incorporating the scientific uncertainty involved with making conclusions about water quality models. These factors are not usually well represented in mechanistic water quality models.

2 Estimation of Loading to Falls Lake

Accurate representation of nutrient loading to a waterbody is critical to the development of lake response models where chlorophyll *a* is a key parameter of concern. Tributary nutrient loading is calculated by multiplying flow by concentration and applying the appropriate conversion factors. In 2014, the UNRBA funded an Evaluation of the Sensitivity of the Falls Lake Nutrient Response Model (see the UNRBA Monitoring Plan Model Sensitivity Technical Memorandum at https://www.unrba.org/monitoring-program) which included an analysis of several methods to estimate nutrient loading to Falls Lake and an assessment of the sensitivity of the Falls Lake nutrient response model developed by DWR (DENR 2009). The results of the 2014 analysis indicated that loading estimates could vary greatly depending on how water quality concentrations were paired with flows, and that the prediction of algal growth was sensitive to these inputs.



Measurements of concentration (indicated by the two red points) may be interpolated to estimate values for days that were not sampled (indicated by the blue dots).

Various load estimation techniques are available to predict loading from flow and water quality concentration data. To develop the Falls Lake Nutrient Response Model, DWR used linear interpolation between water quality sample observations to pair with measured or estimated flow in their calculation of loads. This approach is similar to drawing a straight line between data values from samples collected only once or twice a month to estimate the water quality concentrations each day between two sampling events (see inset box). During relatively dry conditions when water quality pollutant concentrations tend to be less variable, and for water quality constituents that tend to have concentrations not dramatically affected by tributary flow variation, linear interpolation between monthly or twice monthly samples might provide reasonable estimates of parameter concentrations. However, when precipitation events occur, nutrient loading tends to be more variable as runoff from the watershed and increased discharge from shallow groundwater can result in sporadic high loading events. When storm events occur outside of the timing of routine sampling, linear interpolation may underestimate loading. Conversely, if the routine sampling occurs during storm events, then linear interpolation could result in an overestimate of loading once storm flows subside.

Fortunately, discharge is measured by the US Geological Survey (USGS) approximately every 15-minutes on each of the five largest tributaries to Falls Lake. This discharge monitoring data can be used to improve water quality estimates between field measurements for parameters where there is a demonstrable relationship between flow and concentration. The USGS developed the software package LOADEST to evaluate these relationships and to help identify the best of a series of statistical models that include terms for flow, seasonality, and long term trends (Runkel et al. 2004). LOADEST develops and tests nine regression models for calculating nutrient loading in tributaries (Table 2.1). The regression models are calibrated using paired observations of flow and concentration at a given location. After calibration of LOADEST is performed, mean load estimates, standard errors, and 95% confidence intervals are generated for monthly or seasonal time periods. Then a selected LOADEST model can be used to generate daily or sub-daily time series of loading from each tributary to provide inputs to the lake response model. The time increment input period selected can have a significant impact on model performance and accuracy.

Table 2.1 Regression Models Tested by USGS LOADEST

Method Number	Equation
1	$a0 + a1 \ln Q$
2	$a0 + a1 \ln Q + a2 \ln Q2$
3	$a0 + a1 \ln Q + a2 dtime$
4	$a0 + a1 \ln Q + a2 \sin(2\pi dtime) + a3 \cos(2\pi dtime)$
5	$a0 + a1 \ln Q + a2 \ln Q2 + a3 dtime$
6	$a0 + a1 \ln Q + a2 \ln Q2 + a3 \sin(2\pi dtime) + a4 \cos(2\pi dtime)$
7	$a0 + a1 \ln Q + a2 \sin(2\pi dtime) + a3 \cos(2\pi dtime) + a4 dtime$
8	$a0 + a1 \ln Q + a2 \ln Q2 + a3 \sin(2\pi dtime) + a4 \cos(2\pi dtime) + a5 dtime$
9	$a0 + a1 \ln Q + a2 \ln Q2 + a3 \sin(2\pi dtime) + a4 \cos(2\pi dtime) + a5 dtime + a6 dtime2$

The Evaluation of the Sensitivity of the Falls Lake Nutrient Response Model report demonstrated that a range of nutrient loads could be estimated depending on the method used (e.g., linear interpolation or LOADEST). However, frequent nutrient data collected during storm events was not available to calculate a "measured load" that could be used to compare the various estimation methods to select the most appropriate one. In 2015, the UNRBA approved the Storm Event Sampling Special Study (http://www.unrba.org/monitoring-program) to collect water quality samples at a high frequency during storm events at two gaged tributaries in the Falls Lake Watershed. Table 2.2 describes the characteristics of the storms that were sampled (some storms consisted of back to back precipitation events that resulted in elevated hydrographs for several days). As intended, that Special Study has provided data that will allow the UNRBA's reexamination effort to better describe tributary loads generated during a storm.

Table 2.2 Storm Event Characteristics Used to Calculate Measured Loads

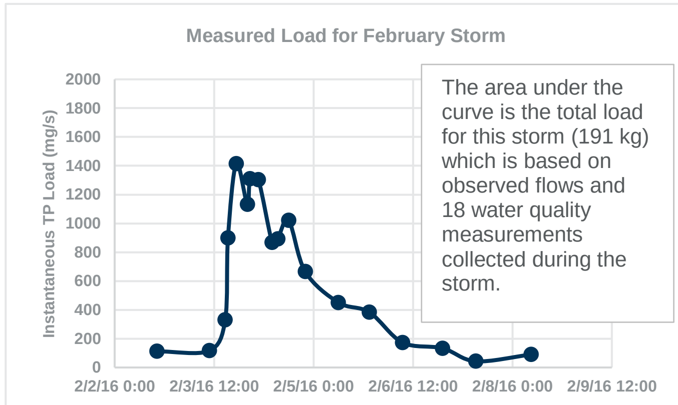
Storm	Storm Hydrograph Duration for Eno River (days)	Number of Water Quality Samples for Eno River	Storm Hydrograph Duration for Ellerbe Creek (days)	Number of Water Quality Samples for Ellerbe Creek
4/19/2015 – 4/23/2015	5	43	5	41
9/25/2015 – 9/30/2015	6	25	6	25
10/1/2015 – 10/5/2015	5	20	4	23
2/3/2016 – 2/8/2016	6	18	6	23
Total	**22**	**106**	**21**	**112**

As part of this Basic Evaluation of Model Performance Special Study, the sum of the tributary loads measured during Storm Event Sampling were compared to those predicted by several load estimation techniques to evaluate whether data collection efforts associated with the intensive Storm Event Sampling have provided sufficient data and whether additional high flow sampling in the watershed could further improve loading estimates at other tributaries. This evaluation is described in the following section of the report (2.1).

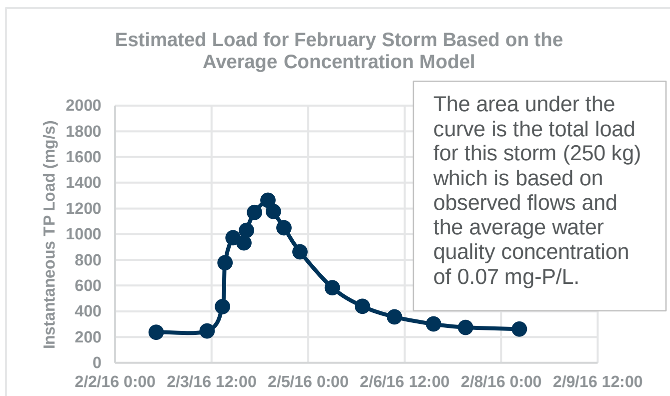
2.1 Comparison of Load Estimation Methods

To compare the accuracy of several load estimation techniques, total measured loads of nitrogen, phosphorus, and carbon were calculated using samples collected on Ellerbe Creek and Eno River as part of the Storm Event Sampling Special Study (Table 2.2). These measured loads were then compared to the loads calculated using each load estimation technique. Storm Event Sampling data collected during April, September, and October 2015 and February 2016 were used to calculate the total measured load. The following load estimation techniques were used for comparison to the measured load of each parameter (estimated loading was calculated for the same four periods as the measured load). For the methods below, each site (Eno and Ellerbe) was fit separately.

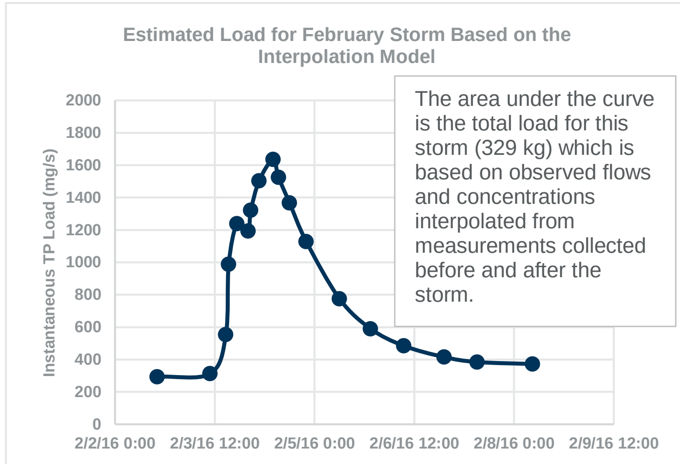
> **Measured:** Measured water quality concentrations from the Storm Event Sampling were time-matched with USGS 15-minute flow measurements to calculate instantaneous “measured” loads associated with each water quality parameter. The total load for the storm (i.e., the total area under the curve) was calculated by applying a trapezoidal integration between instantaneous loads across the duration of the storm. The total Measured Loads presented in Table 2.3 and Table 2.4 are the sum of the loads measured during the four storm events for each parameter.



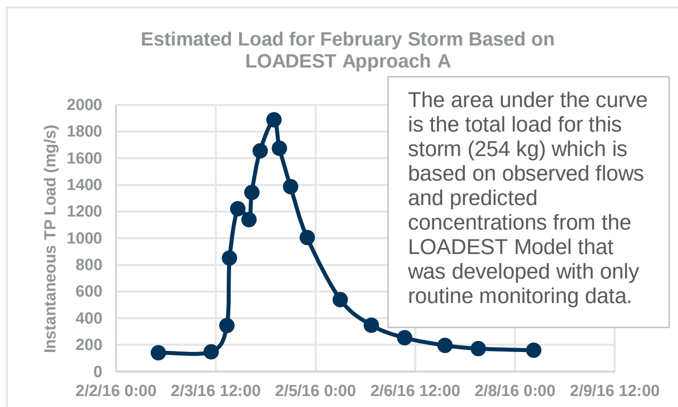
> **Average Concentration Model:** To be consistent with the approach used to calculate the Measured Loads, this approach estimates loads by pairing 15-minute USGS flow measurements corresponding to each Storm Event sample with the average concentration of each water quality parameter measured by the UNRBA Routine Monitoring program (from August 2014 to March 2016). If water quality is unrelated to flow and season, this estimation technique should approximate measured loads. For Ellerbe Creek, the average total nitrogen concentration is 3.08 mg/L and the average total phosphorus concentration is 0.08 mg/L; for Eno River, the concentrations are 0.72 mg/L and 0.07 mg/L, respectively. The load for each storm was calculated by integrating between estimated loads across the duration of the storm.



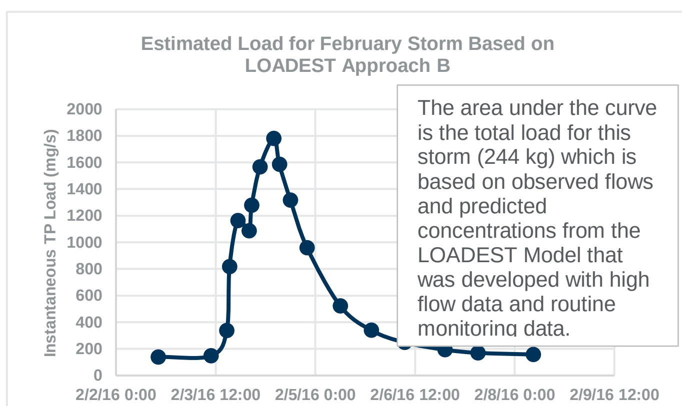
> **Interpolation Model:** This was the method used by DWR to set loading inputs for its 2006 version of the Falls Lake Nutrient Response Water Quality Model (DENR 2009). Water quality samples collected as part of the Routine Monitoring conducted by the UNRBA were linearly interpolated to estimate the concentrations over the course of each storm event. The interpolated concentrations were paired with USGS flow measurements to estimate loads. This method should improve upon the average concentration model if water quality exhibits a seasonal pattern; however, this method does not account for variability due to flow.



> **LOADEST Approach A:** This method uses the USGS LOADEST statistical package to estimate loads using the model that provided the best overall fit to the calibration data. For Approach A, each LOADEST model was calibrated using only <u>routine</u> water quality data collected by DWR and UNRBA paired with USGS flow measurements (samples collected under targeted high-flow conditions were not included in the calibration). For Eno River, the calibration dataset included routine measurements collected from January 1999 to March 2016, and the LOADEST method that provided the best fit incorporated both flow and season (Method 6 in Table 2.1). For Ellerbe Creek, the calibration dataset included routine measurements collected from January 2008 to March 2016, and the best-fit model incorporated only flow (Method 2 in Table 2.1). After the models were calibrated, flows observed during the storm periods were used to estimate loads for comparison to the Measured Loads.



> **LOADEST Approach B:** This method is the same as Approach A, with the exception that the data used to calibrate the model also included samples collected under targeted high flow conditions and a data point representing the highest flow conditions from each of the storm events monitored under the Storm Event Special Study. After the models were calibrated, flows observed during the storm periods were used to estimate loads for comparison to the Measured Loads. This approach generally performed better than Approach A because routine sampling does not adequately capture flow conditions necessary for estimating loads during storm events.



As mentioned above, the best fitting LOADEST regression equations were different for the two tributaries examined. For Eno River, the equation which included terms for both flow and seasonality was the most accurate whereas for Ellerbe Creek, the equation based only on flow was most accurate. Ellerbe Creek was not part of the High Flow Special Study and so monitoring results representing high flows from all seasons may not have been in the calibration data set. A key point from this comparison is that application of appropriate analytical approaches and the most representative data should provide the most robust modeling outcomes.

Table 2.3 and Table 2.4 compare the values of the measured and estimated loads as well as the relative percent difference (RPD) between the measured load and the estimates. For each parameter and tributary that was evaluated, assuming a single concentration based on the average of water quality measurements resulted in the highest RPDs which indicates that this method is the least accurate. The linear interpolation method provided better estimates than the average concentration, but it was not as accurate as either of the LOADEST approaches. The best model fit between estimated and measured loads for the majority of the parameters was the LOADEST Approach B, which included water quality measurements collected during high flow events that better characterize water quality conditions following rain events. Ultimately, with additional years of data collection, the best fitting models for the reexamination effort may be improved upon those identified here.

Table 2.3 Comparison of Total Measured Eno River Nutrient and Carbon Loadings During Four Storms to Four Different Modeling Approaches Using Relative Percent Differences (RPDs)

Parameter	Measured Load (kg)	Average Concentration Method: Estimated Load (RPD)	Interpolation Method: Estimated Load (RPD)	LOADEST Approach A: Estimated Load (RPD)	LOADEST Approach B: Estimated Load (RPD)
Total Nitrogen	26,463	12,382 (72%)	18,655 (35%)	22,756 (15%)	24,235 (9%)
Ammonia	1,673	934 (57%)	1,141 (38%)	1,277 (27%)	1,337 (22%)
Nitrate/Nitrite	4,735	3,446 (32%)	4,709 (1%)	4,483 (5%)	4,714 (0.4%)
Total Kjeldahl Nitrogen	21,622	9,107 (81%)	13,186 (48%)	21,193 (2%)	21,203 (2%)
Total Phosphorous	3,767	1,200 (103%)	1,859 (68%)	4,517 (18%)	4,049 (7%)
Total Organic Carbon	181,064	83,135 (74%)	137,474 (27%)	240,595 (28%)	180,437 (0.3%)
Average RPD		70%	36%	16%	7%

Table 2.4 Comparison of Total Measured Ellerbe Creek Nutrient and Carbon Loadings During Four Storms to Four Different Modeling Approaches Using Relative Percent Differences (RPDs)

Parameter	Measured Load (kg)	Average Concentration Method: Estimated Load (RPD)	Interpolation Method: Estimated Load (RPD)	LOADEST Approach A: Estimated Load (RPD)	LOADEST Approach B: Estimated Load (RPD)
Total Nitrogen	12,872	18,659 (37%)	14,403 (11%)	14,478 (12%)	14,980 (15%)
Ammonia	1,277	1,005 (24%)	298 (124%)	2,535 (66%)	1,331 (4%)
Nitrate/Nitrite	4,963	11,910 (82%)	8,618 (54%)	6,526 (27%)	6,025 (19%)
Total Kjeldahl Nitrogen	7,909	6,634 (18%)	5,786 (31%)	10,521 (28%)	8,920 (12%)
Total Phosphorous	1,321	510 (89%)	530 (85%)	1,648 (22%)	1,539 (15%)
Total Organic Carbon	57,425	42,552 (30%)	44,610 (25%)	72,184 (23%)	57,337 (0.2%)
Average RPD		47%	55%	30%	11%

2.2 Revisions to the FY2017 Monitoring Program to Collect Additional Sampling during High Flows

As described in the FY2016 Annual Report for the UNRBA Monitoring Program (https://www.unrba.org/monitoring-program), Routine Monitoring in the watershed represents relatively low-flow or baseline-type conditions during most sampling events, with only a small number of events capturing moderately high flows and very few capturing the highest flow conditions when the majority of flows (and therefore loads) are delivered to Falls Lake (Table 2.5). For the five largest tributaries, about 20 percent of the water delivered to Falls Lake comes from flows which occur during just one percent of the time, and 40 percent of the water is delivered during 5 percent of the time. The Flat, Eno, and Little Rivers and Knap of Reeds and Ellerbe Creeks together contributed nearly 80 percent of the water delivered to Falls Lake over the monitoring period. On these tributaries, between 50 and 75 percent of samples have been collected during flow conditions which represent just 20 percent of the water delivered to Falls Lake. Flow conditions representing the upper 20 percent of the load are either not represented by any samples or have been sampled only once. Because these high flow conditions occur so rarely, routine sampling may not capture them. As shown in Section 2.1, the best fitting models for estimating nutrient loads from the tributaries include flow and sometimes seasonality as predictors. Therefore, obtaining data from the tributaries during high flows across a range of seasonal conditions is desirable for optimal model calibration.

As noted, information from this evaluation was referenced in the FY2016 Annual Report which included recommendations for adjustments to the Monitoring Program. To better represent flow conditions when loading to Falls Lake is high, the UNRBA approved an augmented High Flow Special Study for FY2017 targeting the five largest tributaries to allow for sample collection as close to the peak of a storm hydrograph as possible. Additional portions of the hydrograph and other tributaries will also be sampled as time allows during high flow conditions.

When modeling efforts are initiated to support the reexamination, the Storm Event data from FY2015 and FY2016 and the High Flow data from FY2015, FY2016, and expanded in FY2017 will be available for refining loading estimates and further evaluating the accuracy of the different methods. The modelers can continue to evaluate these relationships as additional data become available. Overall, with the adjustments made for FY2017, the UNRBA's monitoring program for higher flow events will greatly improve the accuracy of tributary loading levels over any evaluation period selected. These modeling inputs are critically important in determining the lake's response to variations in flow and loading over the selected timeframe for analysis.

Table 2.5 Percent of Routine Monitoring Samples Collected during Five Ranges of Flow from August 2014 through December 2015

Tributary	Flow Range	Percent of Hydrologic Load	Percent of Time	Number of Samples	Percent of Samples
Ellerbe Creek	0 - 19 cfs	20%	53%	17	52%
	19 - 36 cfs	20%	30%	11	33%
	36 - 118 cfs	20%	12%	3	9%
	118 - 366 cfs	20%	4%	2	6%
	366 - 1420 cfs	20%	1%	0	0%
Flat River	0 - 88 cfs	20%	71%	23	66%
	88 - 181 cfs	20%	18%	5	14%
	181 - 462 cfs	20%	8%	5	14%
	462 - 1290 cfs	20%	3%	2	6%
	1290 - 5300 cfs	20%	1%	0	0%
Knap of Reeds	0 - 24 cfs	20%	70%	23	72%
	24 - 42 cfs	20%	16%	5	16%
	42 - 98 cfs	20%	9%	3	9%
	98 - 273 cfs	20%	4%	1	3%
	273 - 581 cfs	20%	1%	0	0%
Eno River	0 - 76 cfs	20%	69%	22	63%
	76 - 133 cfs	20%	18%	5	14%
	133 - 357 cfs	20%	9%	4	11%
	357 - 847 cfs	20%	3%	3	9%
	847 - 3630 cfs	20%	1%	1	3%
Little River	0 - 43 cfs	20%	75%	23	66%
	43 - 79 cfs	20%	13%	5	14%
	79 - 153 cfs	20%	7%	4	11%
	153 - 330 cfs	20%	3%	2	6%
	330 - 2480 cfs	20%	1%	1	3%

3 EFDC Model Evaluations

One of the primary objectives of the UNRBA Monitoring Program is the collection of data through Routine Monitoring and Special Studies to revise the lake response modeling originally conducted by DWR (DENR 2009) which was used to assign the nutrient load reduction targets set forth in the Falls Lake Nutrient Management Strategy. The adaptive UNRBA Monitoring Program was originally established following work that identified a number of data gaps and modeling assumptions for which the collection of additional data would reduce the uncertainty associated with the model inputs and outputs (Task 4 Technical Memorandum: https://www.unrba.org/reexamination). This Basic Evaluation of Model Performance Special Study expands the assessment of the model needs by revising select model input files and evaluating changes in predicted lake response for key parameters. This section describes the model evaluations conducted as part of this special study to answer the following questions:

1. Considering the data input requirements for the EFDC water quality simulations, are the monitoring organizations collecting water quality data in Falls Lake that appropriately represents the need for producing an improved modeling approach to regulatory decision making? If not, is historic information sufficient to develop the model?
2. What types of improvements may be necessary for the EFDC model grid to better represent the topographic and manmade features of Falls Lake? What types of additional data would improve this representation?
3. Considering the data input requirements for the EFDC sediment diagenesis module, was the sediment core data collected as part of the FY2015 Lake Sediment Evaluation Special Study sufficient to parameterize this module? Is additional data (cores, sediment mapping, etc.) needed for this component?

3.1 EFDC Nutrient Response Water Quality Model

3.1.1 Model Variables

The EFDC model developed by DWR for Falls Lake simulates the response to lake water quality (nutrients, carbon, algal growth, etc.) using 16 variables. The model formulations utilize a range of different forms of water chemistry and biologic constituents to simulate the resultant concentrations of nitrogen (five fractions), phosphorus (four fractions), dissolved and particulate organic carbon (three fractions), and suspended algae (three groups). The modeled forms of some of these constituents do not always correspond to a laboratory measurement for direct comparison. Matching the modeled forms of the constituents with the parameters that are typically measured requires a number of assumptions regarding the relationships between the different forms of water quality parameters.

Table 3.1 lists the water quality variables included in the Falls Lake EFDC Model and provides the relationships and laboratory parameters that correlate to the modeled constituents based on the assumptions applied by the agency. Some of these relationships may be refined when the Falls Lake model is redeveloped by the UNRBA, depending on the availability of additional data and the suite of models selected to support the reexamination. The key model variables for simulating algal response in the lake and the impacts to total organic carbon are currently monitored in Falls Lake (nutrient species, algal composition, chlorophyll *a*, total and dissolved organic carbon). Other model variables, such as determining the difference between the portion of organic material that is readily broken down by biological and chemical processes (labile), versus the portion that is unavailable or more difficult to metabolize (refractory) must rely on assumptions or information developed from similar ecological systems because measuring these values in the environment through sampling is analytically difficult, impractical or impossible. Such variables may be derived from related parameters or otherwise determined through a combination of literature review and quantitative sensitivity analyses.

3.1.2 Model Sensitivity

In 2014, the UNRBA funded an Evaluation of the Sensitivity of the Falls Lake Nutrient Response Model (listed as the UNRBA Monitoring Plan Model Sensitivity Technical Memorandum at https://www.unrba.org/monitoring-program). In addition to preliminary evaluations of tributary nutrient loading using LOADEST (conducted prior to the collection of storm event data by the UNRBA and referenced in Section 2), this evaluation conducted a sensitivity analysis of the assumed tributary chlorophyll *a* concentrations that were used to develop the EFDC lake response model. When DWR developed the model, there were no chlorophyll *a* data collected at the mouths of the tributaries. To provide the required inputs for the lake model, DWR assumed that the chlorophyll *a* concentration entering the lake from each tributary was equal to observations collected at the nearest lake station. The sensitivity analyses conducted in 2014 by the UNRBA indicated that simulated algal growth in the lake was sensitive to the assumed tributary input concentrations. To inform future lake modeling, the UNRBA began collecting chlorophyll *a* data in tributaries as part of the Routine Monitoring in August 2014.

One of the main purposes of this Basic Evaluation of Model Performance Special Study is to evaluate some of the parameters currently monitored by the UNRBA (and the data included in the database from other entities) and test the effect on model output when these inputs are varied. If the model is relatively insensitive to a parameter (e.g., prediction of algal growth does not vary significantly when the parameter is varied across a reasonable range), then further monitoring may not provide significant value to the monitoring effort, especially if existing data can be used to establish appropriate relationships that will result in realistic estimates for the model. Suspending collection of certain data under these circumstances allows the UNRBA to efficiently reallocate its resources to other higher priority purposes.

For example, the UNRBA currently measures carbonaceous biochemical oxygen demand exerted over a five day period ($CBOD_5$) at the Lake Loading stations to provide information regarding the lability (potential for biochemical conversion in the water column) of particulate organic carbon (POC) entering Falls Lake from its tributaries. 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). Routine Monitoring has since shown that POC accounts for only about 5 percent of the organic carbon entering Falls Lake. The model developed by DWR (DENR 2009) was used to test the sensitivity of EFDC model predictions to assumptions about tributary POC lability and found that because POC makes up only 5 percent of the incoming organic carbon, its lability has a negligible effect on modeled carbon and chlorophyll concentrations. When the percentage of POC in tributary loads is reduced to the recently-documented 5 percent of organic carbon, the model's ability to reasonably simulate total organic carbon (TOC) is affected (Figure 3-1), but chlorophyll *a* is not (Figure 3-2). The dotted purple line visible in Figure 3-1 shows the model prediction based on the State's assumption that 50 percent of the total organic carbon is in particulate form, and the green line shows the model prediction based on 5 percent of TOC being POC. Note that the orange, green, and blue lines are effectively stacked on top of one another in Figure 3-1 and Figure 3-2, indicating the insensitivity of the model to differences in carbon lability at such low concentrations. In Figure 3-2, all four lines are stacked together, showing the lack of effect of POC levels or lability on chlorophyll *a* prediction. Furthermore, most samples show $CBOD_5$ at levels below the laboratory reporting limit which reduces the utility of $CBOD_5$ for resolving differences in lability among samples. Therefore, it was recommended and the UNRBA approved discontinuing analysis of $CBOD_5$ at the lake loading stations for FY2017 because sufficient data have been collected to characterize the model inputs.

Table 3.1 EFDC Model Water Quality Variables for the DWR Falls Lake Nutrient Response Model (DENR 2009)

No.	Variable Code	Variable Name	Available Information and Relationships Assumed by DENR	Organizations Collecting Relevant Data
1	Bc	cyanobacteria	Algal species composition;	DWR;
2	Bd	diatom algae	Chlorophyll *a*	DWR, City of Durham, City of Raleigh, CAAE
3	Bg	green algae		
4	RPOC	refractory particulate organic carbon	(TOC–DOC)*0.5 The existing model assumes ½ of particulate organic carbon (POC) is refractory and the other half is labile.	DWR, City of Durham, City of Raleigh, CAAE
5	LPOC	labile particulate organic carbon		
6	DOC	dissolved organic carbon	DOC	DWR
7	RPOP	refractory particulate organic phosphorus	(TP-TDP)*0.5 The existing model assumes that ½ of the particulate organic phosphorus (POP) is refractory and the other half is labile. POP is calculated as the difference between filtered and unfiltered samples of TP.	DWR collects TP in Falls Lake, but does not filter samples to estimate TDP because historic measurements in the lake indicate the dissolved fraction is negligible City of Durham analyzes both (5 months per year)
8	LPOP	labile particulate organic phosphorus		
9	DOP	dissolved organic phosphorus	TDP*0.5 The existing model assumes that ½ of the total dissolved phosphorus (TDP) is organic and the other half is inorganic	City of Durham analyzes TDP at 2 stations during 5 months per year
10	PO4	total phosphate		
11	RPON	refractory particulate organic nitrogen	(TKN-NH3)*0.3 The existing model assumes that 30 percent of the organic nitrogen is in the particulate form and is refractory.	DWR, City of Durham, City of Raleigh, CAAE
12	LPON	labile particulate organic nitrogen	(TKN- NH3)*0.3 The existing model assumes that 30 percent of the organic nitrogen is in the particulate form and is labile.	
13	DON	dissolved organic nitrogen	(TKN- NH3)*0.4 The existing model assumes that 40 percent of the organic nitrogen is in the dissolved form.	
14	NH4	ammonia nitrogen	NH4	
15	NO3	nitrate nitrogen	NO3	
16	DO	dissolved oxygen	DO	DWR, City of Durham, City of Raleigh, CAAE

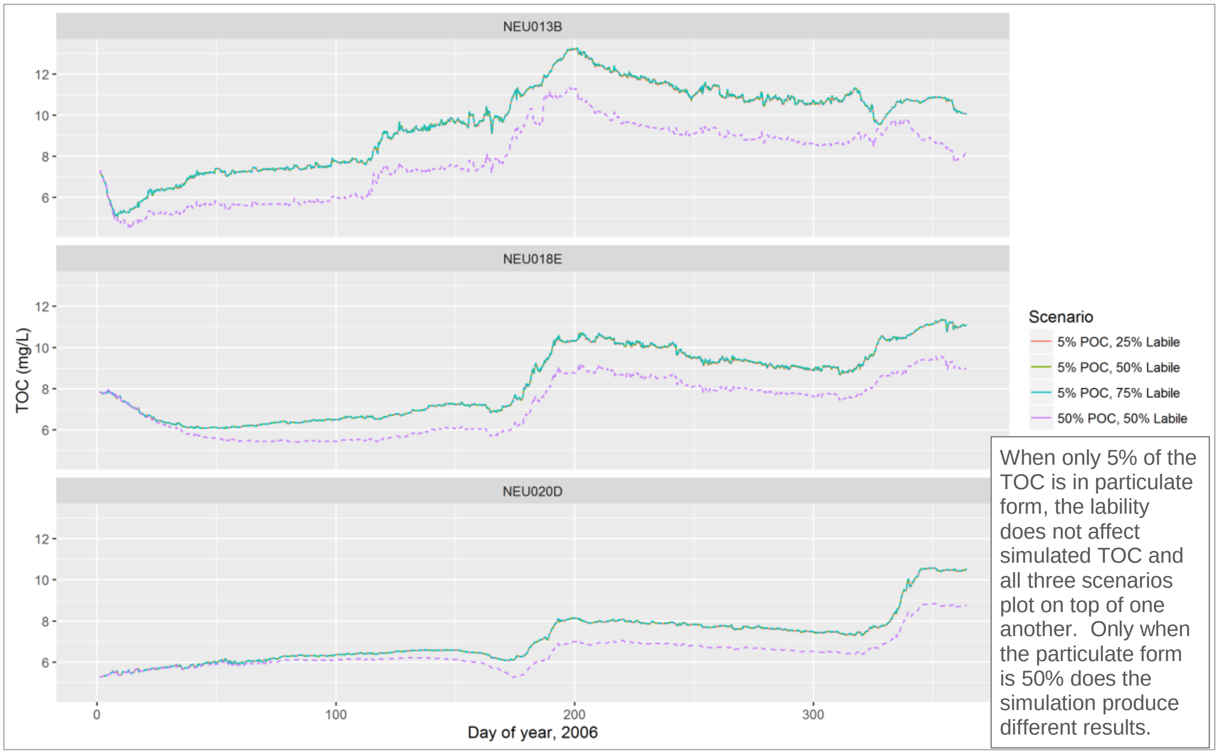


Figure 3-1 Sensitivity of Simulated TOC to Proportion and Lability of POC

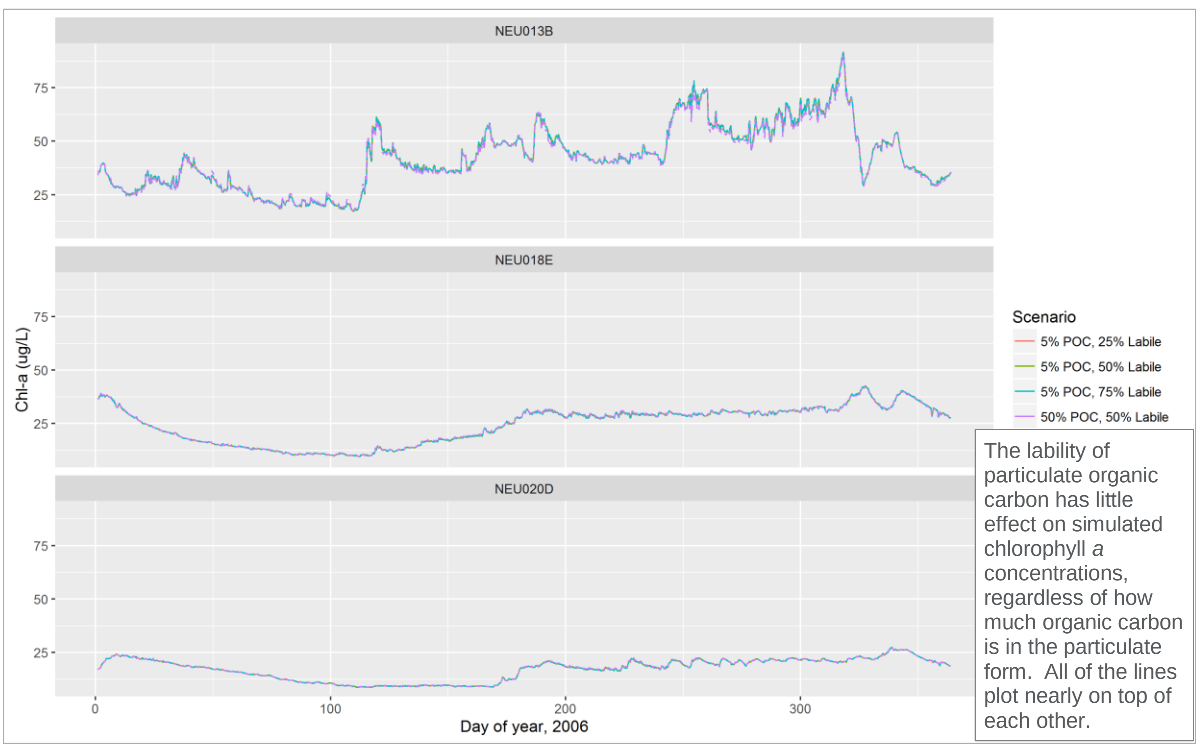


Figure 3-2 Sensitivity of Simulated Chlorophyll *a* to Proportion and Lability of POC

3.1.3 Light Extinction and Algal Response

Lake and reservoir response models often predict the growth of algae based on a number of conditions including the amount of light available in the water column. Incorrect estimates of light availability can have large impacts on model predictions of algal production.

DWR routinely collects Secchi depth measurements (lowering a black and white disk below the water surface and recording the depth at which it is no longer visible as observed by the sampling personnel) to approximate the photic depth. It is established convention to consider twice the Secchi depth as equivalent to the photic depth, which is defined as the depth where 99 percent of the light has been attenuated. A photosynthetically active radiation (PAR) meter provides a more accurate measurement of photic depth, but this technique is much more time intensive to apply, so it is not used routinely on most waterbodies.

In the mid-1980s and early 1990s, DWR conducted paired Secchi depth and PAR measurements on Falls Lake to correlate the measurements. In October 2015, DWR conducted an additional paired measurement study on Falls Lake at the request of the UNRBA. An analysis of the historical and current measured relationships between Secchi depth and depth of 99 percent light attenuation was presented in the FY2016 UNRBA Monitoring Program Annual Report. That analysis showed that a statistical relationship could predict photic depth from Secchi depth with a 95 percent prediction interval of plus or minus 0.7 meters, and that the relationship between Secchi depth and PAR measurements was similar in the historic and recent datasets.

The EFDC model does not explicitly use inputs of photic depth, but rather uses parameters to define light penetration based on background light extinction (i.e., the color of the water), suspended sediment, and algae (self-shading), and the DWR version of the EFDC model (DENR 2009) used literature values to define these parameters. While it is difficult to measure each of these model parameters directly, the predicted photic depth can be compared to measured photic depth to ensure a reasonable prediction of light penetration. The predicted photic depths from the DWR parameters are approximately two times higher than those measured in Falls Lake. Predictions of photic depth can be improved by adjusting the model parameters related to background light extinction, suspended sediment, and algae.

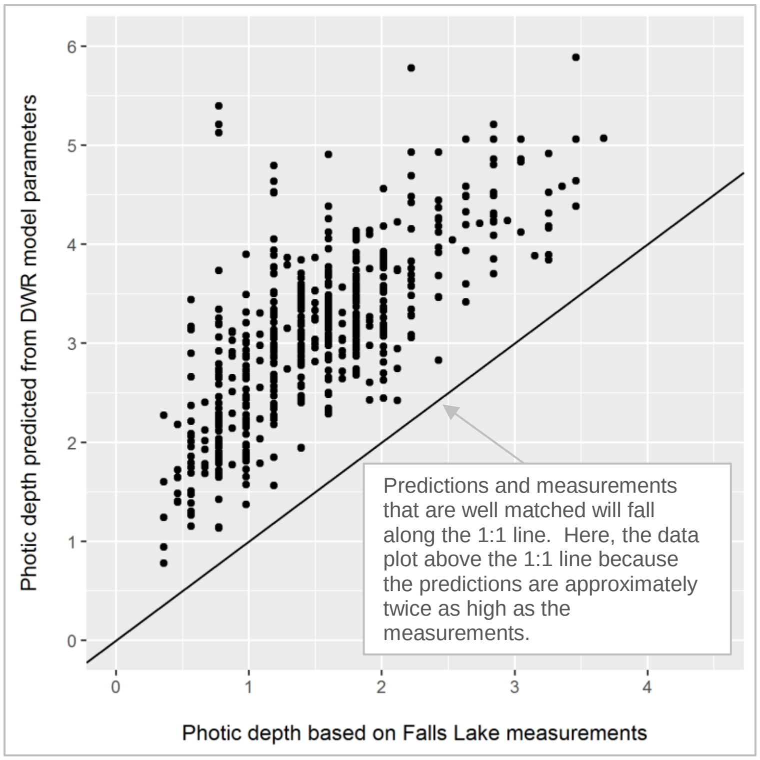
Figure 3-3 compares predicted photic depth (gray lines) to measured photic depth (black dots) for two sets of model parameters. The top pane shows the predicted photic depth compared to measurements when the DWR model parameters are used. The diagonal line on each figure is the 1:1 line, and a good fit between predictions and measurements results in data that coincide with this line. For the top pane, the data are always plotted below the line because the predictions are twice as high as the measurements. The bottom pane shows the comparison when the model parameters are adjusted. This improvement results in predictions and measurements that are similar, and the data coincides better with the 1:1 line.

Figure 3-3 shows that the model parameters for light extinction could be improved. However, it is not clear whether or not an improvement in predicted light extinction would significantly affect the simulation of algal growth in the lake using the DWR version of the EFDC model. To test the sensitivity of predicted algal concentrations, simulated chlorophyll *a* concentrations were compared using the existing and improved model parameters. Figure 3-4 reflects minimal change in simulated chlorophyll *a* concentrations between the DWR model and a model using revised light extinction parameters.

Given that the model response using the DWR version of the EFDC model is relatively insensitive to changes in light extinction parameters and that significant improvements can be made to light extinction parameterization simply based on existing data, the UNRBA has not funded collecting additional paired light penetration data in FY2017. However, the DWR model assumed chlorophyll *a* levels in tributary inflows that are generally, and in some situations significantly, higher than those measured by Routine Monitoring. The calibration of some algal parameters (growth rates, nutrient preferences, etc.) is constrained by the assumed tributary chlorophyll *a* loads. Therefore, when the UNRBA revises the lake modeling and the assumed tributary chlorophyll *a* inputs, recalibration of these parameters may change the model sensitivity to these light extinction parameters. The UNRBA modeling team will need to evaluate these relationships early in the modeling effort, in case supplemental data or analysis is needed to better characterize light extinction characteristics.

The UNRBA is preparing for the reexamination of the requirements of Stage II of the Falls Lake Nutrient Management Strategy and the regulatory framework that underlies this Strategy, and has identified several lake models that may be used effectively to support this effort. The UNRBA will likely develop two or three independent lake models to ensure model predictions are accurate and robust. The USACE BATHTUB model (Walker 1999) is one that is being considered. This model was previously incorporated into the Falls Lake Framework Tool to link changes in nutrient loading to changes in lake water quality and attainment of designated uses (see the technical memorandum Task 1 - Develop a Framework for a Reexamination of Stage II of the Falls Lake Nutrient Management Strategy available at http://www.unrba.org/reexamination).

The light attenuation model in the USACE BATHTUB model was also evaluated as part of the Basic Evaluation of Model Performance Special Study to ensure that existing monitoring data are sufficient to support model development if this model is selected as an independent lake model for Falls Lake. BATHTUB provides the user with five options for the simulation of chlorophyll *a* concentrations based on varying combinations of phosphorus concentration, nitrogen concentration, light availability, and hydraulic flushing rate. The model takes user-supplied values of Secchi depth and chlorophyll *a* values to parameterize light availability. For Falls Lake, there is adequate data to characterize these inputs and evaluate deviation from the mean, and thus the uncertainty associated with this parameter.



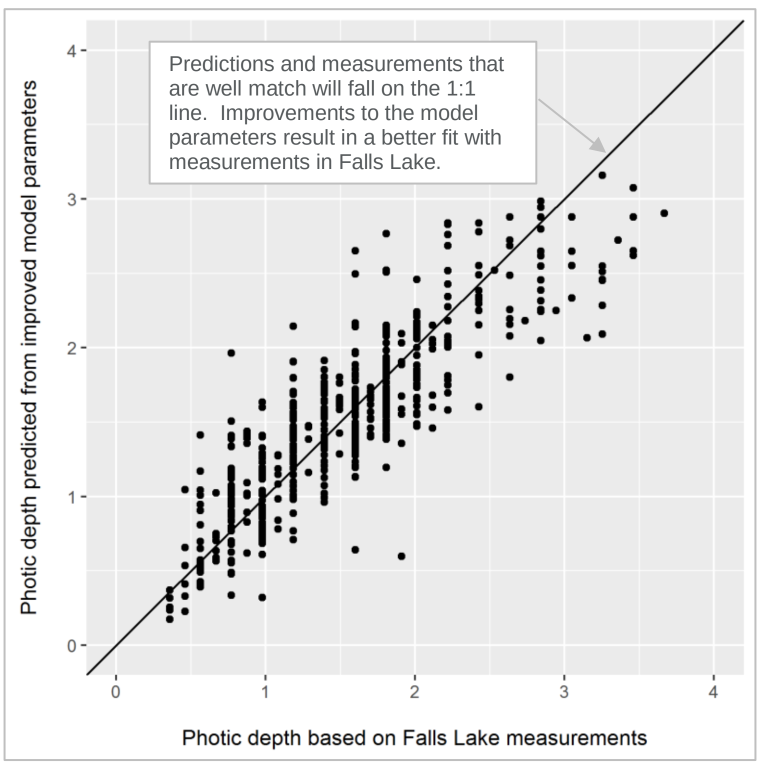


Figure 3-3 Improvement in Predicted Photic Zone Depth Using Revised Light Extinction Parameters (bottom pane) Relative to the DWR Model Parameters (top pane)

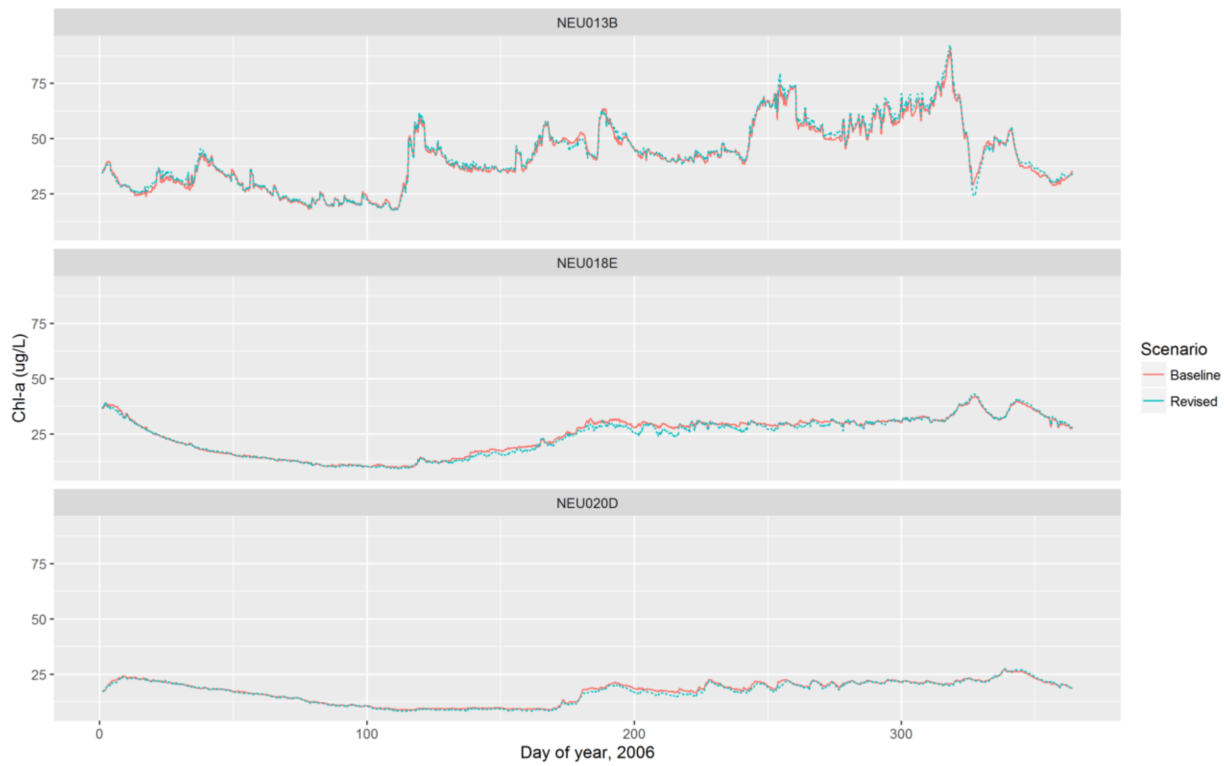


Figure 3-4 Sensitivity of Simulated Chlorophyll *a* to Revised Light Extinction Parameters

3.1.4 Evaluation of the Model Grid

Falls Lake is a manmade reservoir in the Piedmont of NC that has varying topographic features from the upstream end, which is relatively shallow and wide, to the downstream end, which is deeper and much narrower. There are also several road crossings that essentially form separate lake segments by restricting the width of the reservoir by 80 to 90 percent at these locations. These constrictions limit the movement of water and materials, particularly when flows into the lake are relatively low, resulting in water quality in each segment that can be quite different from one segment to the next. These constrictions may also result in wind driven currents localized within each segment that may affect the exchange and mixing of water and material between segments. Because the current version of the model does not account for these constrictions, the segmented nature of Falls Lake is likely not well represented by the model, and the simulated water quality between the segments may appear to be more constant throughout the lake than the data indicates. Calibration of the model to the 12 water quality monitoring stations in Falls Lake is expected to be improved when these constrictions are accounted for and the movement of water is more accurately simulated. Improvements to model calibration will reduce the uncertainty of the model predictions and increase the confidence in the model scenario predictions that evaluate lake operational changes, nutrient management strategies, etc.

Accurate representation of topographic features and flow restrictions is an important initial component of model development that often has significant ramifications for the ability of the model to accurately simulate water quality conditions across a range of flow regimes. Evaluation of the DWR model grid indicates that the hydraulic constrictions caused by road crossings were not represented in the model. DWR generally represented the width of the lake with three grid cells. Because the DWR grid cells are large, it is not possible to restrict flows using the existing model grid (modelers sometimes block flows leaving an entire grid cell to represent small dams or other restrictions). Blocking flows from two of the three grid cells across the lake would only restrict flow by 66 percent, and some of these restrictions cover

80 to 90 percent of the lake width. Figure 3-5 shows two of the bridge causeways in the upper part of the lake; yellow arrows illustrate the degree of constriction at these two locations.

To preliminarily explore the potential effects of the constrictions, the model grid was adjusted at two of the bridge causeways in the upper lake to better simulate the flow and transport of materials (such as nutrients). Subsequent work on the model should incorporate all of the constrictions into the model grid to better simulate hydrodynamics in the lake.

The transport between the two upper most segments with and without revisions to the existing model grid was evaluated. Model simulations were performed using the original DWR EFDC model input files (DENR 2009) to determine the impact of modeling the constrictions. The daily average and hourly flows through the Railroad Bridge constriction using the DWR version of the model grid were compared to the revised model grid for a period of high flows observed in June 2006. Mean daily flows through the constriction were insensitive to the grid change, but the hourly flows through the bridge were significantly different, with the constriction reducing the hourly variability. Given that the EFDC model operates at a very small time step (i.e., minutes), it is important to accurately simulate the hydrodynamics of the system through these physical constrictions. Hence the UNRBA Monitoring Program includes a Special Study to collect velocity and water quality data at constriction points in Falls Lake. One of these data collection events was conducted in FY2016 and one will occur in FY2017. When the lake model is redeveloped, data from that study will help inform the grid revisions and development of the model.

When the lake models are revised to support the reexamination, modeling of Falls Lake should include configuration of the model grid at each constriction to allow for better simulation of the transport of nutrients, carbon, and chlorophyll through the lake. The coarseness of the model grid and number of grid layers should also be evaluated to optimize model run times and model accuracy in terms of temperature, thermal stratification, etc. Additional revisions to the grid should consider including the simulation of wetting and drying in the shallow cells that comprise the upper lake and extension of the model grid into tributary arms that are often inundated by lake backwaters. In FY2017, the UNRBA will conduct a bathymetric survey of Falls Lake to provide additional data to support revisions to the modeling grid.

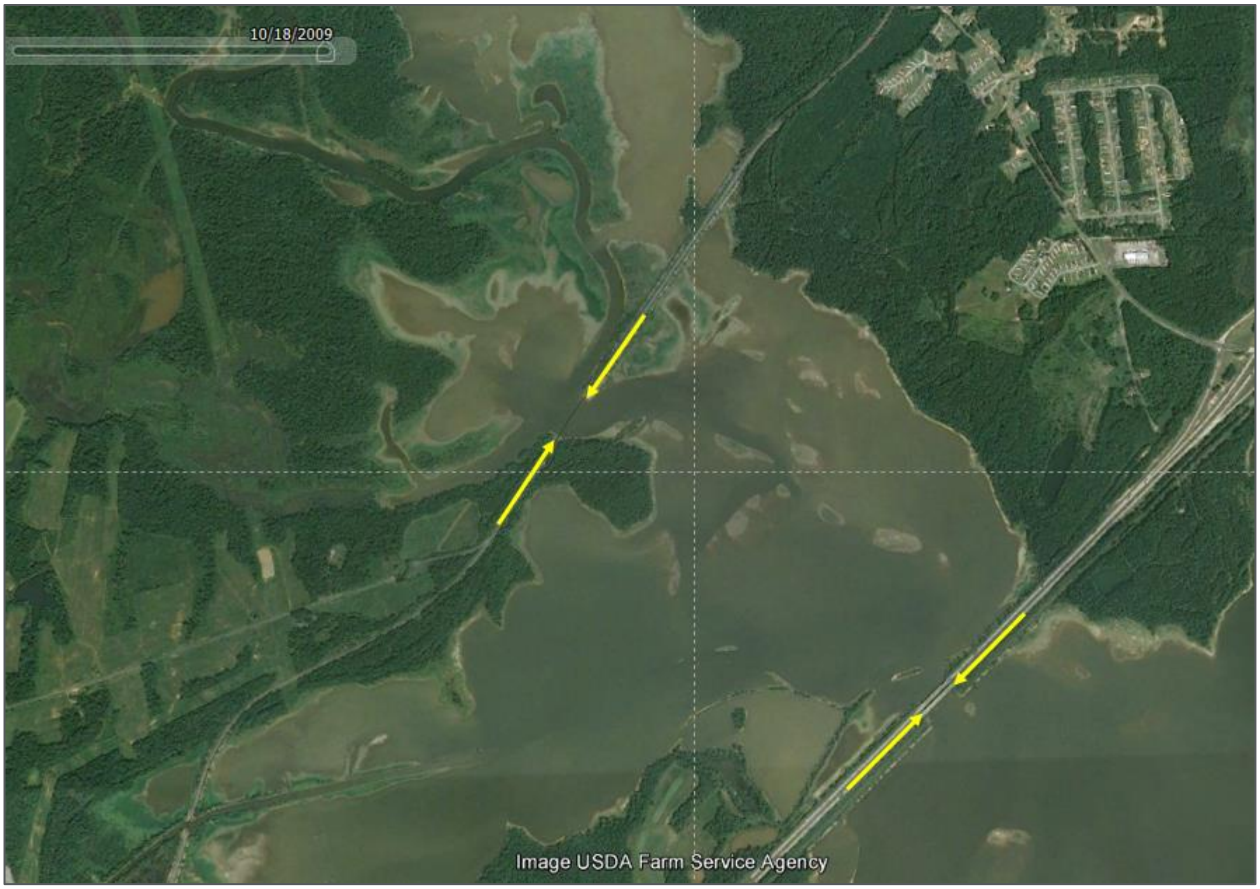


Figure 3-5 Two Flow Restrictions Caused by Bridge Causeways in Upper Falls Lake

3.2 EFDC Sediment Diagenesis Module

Algal production and resulting biomass (as measured by chlorophyll concentration) are influenced by a number of factors including nutrient availability, temperature, stratification, retention time, and light availability. The availability of nutrients in the water column is a function of the loading to the lake (from the tributaries, atmosphere, and sediment releases) as well as model parameters that represent lake processes (settling of particulate fractions of nutrients, algal preferences for various nutrient forms, cycling of nutrients between the water and sediments, etc.) In a previous evaluation of the State's EFDC model for Falls Lake, Tetra Tech (2010) summarized the modeled loads from the tributaries, sediment releases, and wet and dry atmospheric deposition (Table 3.2). For both nitrogen and phosphorus, given the models assumptions, loading from the tributaries was the dominant source of loading and releases from the sediment contributed approximately 20 percent of the loads for both nitrogen and phosphorus.

Table 3.2 Summary of Loads from the Existing 2006 Falls Lake EFDC Model (from Tetra Tech 2010)

Source	Nitrogen Load (lb/yr), (%)	Phosphorus Load (lb/yr), (%)
Tributaries	1,219,142 (72%)	155,536 (80%)
Atmospheric Deposition	102,324 (6%)	0 (0%)
Sediment releases	381,678 (22%)	38,168 (20%)
Total	**1,703,146 (100%)**	**193,704 (100%)**

While nutrient releases from the sediments may not contribute the largest source of loading to the water column, 20 percent is still a significant fraction of the load, and accounting for this source accurately in the model is important for the evaluation of nutrient management strategies and certain regulatory options. The importance of the sediment release factor is likely increased during drought or low flow periods when tributary loading is significantly reduced. These low flow/high detention time periods typically occur at critical times of the year for excessive algae growth. The ability of the model to accurately project algal conditions and other pollutant levels in the lake on a very short time increment and during critical environmental conditions will be strongly linked to the model's ability to accurately reflect variations in sediment release.

There are several ways to simulate the release of nutrients from lake sediments. The option used in the DWR version of the EFDC model assumed that releases of nutrients were constant across the lake bottom and temperature-dependent coefficients result in variable loads through time. A second option is to use empirical relationships which may vary spatially and specify these exchanges as time series inputs to the model. A third option is to use the EFDC sediment diagenesis module that simulates the settling of organic material to the lake bottom as well as burial, decomposition, and releases of nutrients to the water column (Figure 3-6). This module can be used to evaluate the long term effects on sediment releases that occur as a result of changing nutrient loading to the lake. This capability provides additional information regarding the lake's response to nutrient management and the amount of time that stored nutrients in the sediments will continue to be released and recycled back into the water column.

Initial conditions for the sediment diagenesis module require specification of particulate organic matter and porewater concentrations of inorganic nutrients. In FY2015, the UNRBA initiated the Lake Sediment Evaluation Special Study that included collection of sediment cores in Falls Lake at locations corresponding to the 12 DWR ambient monitoring locations. This work is under contract through Dr. Marc Alperin at UNC-Chapel Hill. Water quality samples were also collected from the water column above the lake bottom. The sediment samples were analyzed for carbon and nitrogen. Porewater and bottom water samples are being analyzed for ammonium, phosphate, and nitrate plus nitrite. These data are in the process of being reviewed and interpreted by Dr. Alperin to estimate the release of nutrients from lake sediments, and his technical memorandum is forthcoming. This information is anticipated to be summarized in the FY2017 UNRBA Monitoring Program Interim Report.

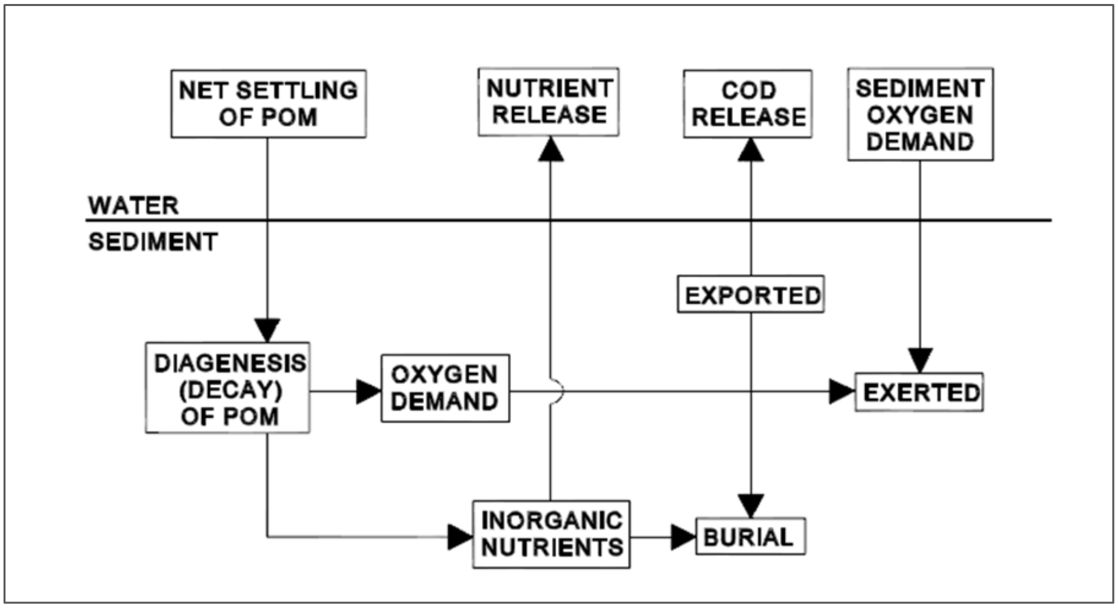


Figure 3-6 Schematic Overview of Sediment Diagenesis Model Processes (from Park et al, 1995)

On the basis of this analysis and the importance of the sediment nutrient release it was recommended and the UNRBA approved for FY2017 a sediment-mapping special study to generate estimates of unconsolidated sediments on the lake bottom. This sediment mapping data can be reviewed in light of the nutrient flux estimates generated as part of the Lake Sediment Evaluation Special Study. The modelers should therefore have the data needed to evaluate the three methods for estimating nutrient releases from the sediments (constant values, time series, or sediment diagenesis modeling). After initial analyses of the sediment mapping and sediment data have occurred and recommendations for a technical approach have been discussed with the Modeling Subcommittee, additional types of sediment data collection may be warranted.

The UNRBA Monitoring Program development process has consistently identified the importance of measuring sediment nutrient flux rates. In addition to the two studies noted above, the UNRBA has included on its list of potential special studies in situ bottom sediment flux measurements. The EPA has the resources to perform these types of studies, and the UNRBA continues to seek support from the agency to do this study. Based on the results of the Lake Sediment Evaluation Special Study, the UNRBA will need to reanalyze the importance of a new in situ flux study, and if still considered critical and if EPA will not provide this study, be prepared to consider funding an in situ study from UNRBA funds. The UNRBA Monitoring Program has identified the importance of this type monitoring and has identified it as a priority. The Program’s current status in this area is consistent with the recognized need and provides sufficient flexibility for securing additional information, as appropriate, within the next two monitoring years.

4 Evaluations of Empirical/Probabilistic Models including the Falls Lake Framework Tool and Bayesian Models

The EFDC model discussed in Section 3 is a mechanistic model that uses a series of model formulations to describe the processes that affect lake water quality. While mechanistic models can be developed to predict water quality with a high degree of accuracy, they are not usually capable of predicting the impacts to designated uses. For example, EFDC predicts concentrations of total organic carbon (TOC) near the City of Raleigh's drinking water intake in Falls Lake, but it does not predict whether or not these concentrations will cause treatment difficulties or generate disinfection byproducts. Connecting lake water quality to the other designated uses in Falls Lake presents similar challenges. EFDC may predict changes in chlorophyll *a* concentrations and total suspended solids, but it cannot predict how recreational users will perceive these changes and whether or not visitation to Falls Lake may be affected.

Empirical models use data (and sometimes expert opinion in the case of a Bayesian model) to define linkages between different types of data and to predict the likelihood of various outcomes. The mathematical expressions that define these linkages may be 1) mechanistic descriptions such as chemical reaction kinetics, 2) empirical relationships such as linear regression models, or 3) relationships derived from expert judgment, depending on how much information there is about the relationships characterizing a particular linkage. The possible outcomes are expressed probabilistically and describe a set of likely system responses. The ability to incorporate mechanistic, empirical, and judgmental information makes the empirical/probabilistic/Bayesian approach extremely flexible and facilitates an extension to non-traditional model endpoints of public concern (e.g., increase in number of recreational trips to Falls Lake).

The strategy developed by the UNRBA for the reexamination process includes development of an empirical/probabilistic/Bayesian model to link lake water quality to the designated uses of Falls Lake (see the technical memorandum Task 1 - Develop a Framework for a Reexamination of Stage II of the Falls Lake Nutrient Management Strategy available at http://www.unrba.org/reexamination). During earlier phases of work, a conceptual model for the empirical/probabilistic/Bayesian model was developed. This component of the Evaluation of Model Performance Special Study updated the conceptual model and evaluated whether or not the existing monitoring efforts (by the UNRBA and other organizations) are collecting the data necessary to build the model and define the linkages. The updated conceptual model is provided in Figure 4-1. The model is driven by nutrient and carbon loading from the watershed and uses a number of descriptors of lake conditions (e.g., depth and residence time) to predict lake water quality (nutrient concentrations, chlorophyll *a* concentrations, dissolved oxygen concentration, etc.) and biological response (algal species composition, fish type and size, etc.).

The final step in the empirical/probabilistic/Bayesian modeling is to link the in-lake conditions to the designated uses. Each designated use has a different set of available data and information that may be used to define these linkages. Given the complexities associated with each set of linkages between water quality and designated uses, it is important to incorporate subject matter experts in each field to ensure that the best available science and information are utilized. For example, there is a large body of literature that evaluates recreational user response to changing conditions that may include water quality, facility access, weather patterns, economic indicators, etc. In the previously developed Falls Lake Framework Tool (see the Task 1 - Develop a Framework for a Reexamination of Stage II of the Falls Lake Nutrient Management Strategy available at http://www.unrba.org/reexamination), a recreational model developed by researchers at North Carolina State University (Phaneuf et al. 2008) was used predict how changes in lake water quality would affect the value of recreation to the lake. This model uses total phosphorus, turbidity, and ambient dissolved oxygen as water quality indicators to predict the impact of water quality on the value of local recreation trips. As another example, there is a separate body of research regarding how raw water quality and water treatment operations affect the formation of disinfection byproducts. Including an evaluation of how water quality affects designated uses provides additional information to weigh the cost associated with various management strategies. If a load reduction of 20 percent, for example, has a significant reduction in water treatment costs or provides an increase in local revenue due to increased recreation, but a load reduction of 30 percent does not, the diminishing returns may be factored into the final management strategy to utilize resources in the most productive manner.

Table 4.1 lists the data sources that are available to populate the boxes of the empirical/probabilistic/ Bayesian model for Falls Lake. Several organizations collect data in and around Falls Lake that will provide the inputs needed to develop the empirical/probabilistic/Bayesian model. The model will use empirical formulas, probabilities, and/or expert elicitation to link the boxes in the model. Table 4.2 list the potential analyses that may be used to build these model linkages. Once the model development begins, these methods will be evaluated further and adapted as necessary. The methods selected for the empirical/probabilistic/Bayesian model will also depend on the models that are selected by the UNRBA as part of the multi-modeling approach to the reexamination strategy.

The Falls Lake Nutrient Management Strategy was primarily based on a single mechanistic lake model (the EFDC model described in Section 3), and as identified on a number of occasions, there is a relatively high degree of uncertainty around some of the modeling assumptions and data inputs that were used to develop the model and the regulatory framework for reducing chlorophyll *a* in the lake to the standard level. Fiscal analyses (NCDWQ 2010) indicate that the cost to comply with the Strategy ranges from $1 billion to $2 billion. In light of the very high cost estimates and the dependency on results from a single lake model, the UNRBA has indicated a preference for two to three independent lake models to support the reexamination. The use of multiple models for analysis is becoming a common practice in applied science to overcome weaknesses associated with model bias, lack of information, etc. The number of independent models selected by the UNRBA will dictate what relationships may be used to build the linkages in the empirical/probabilistic/Bayesian model. For example, if the UNRBA decides that three independent models are needed and that the empirical/probabilistic/Bayesian model is one of the three, then its model linkages should be developed using relationships that are independent from the other models (i.e., model equations and coefficients should not be replicated in an independent model). If two independent models are desired and the empirical modeling is used primarily to link water quality to designated uses (not as an independent predictor of water quality), then the relationships that predict water quality from one of the two independent models may be used to develop some of the model linkages in the empirical model.

Once model development begins, analysis of the various relationships that may be used to establish the model linkages will be needed (Table 4.2). If data gaps are identified as the model is developed, they may be filled by collecting additional data on Falls Lake, using data collected from similar waterbodies, or through expert elicitation.

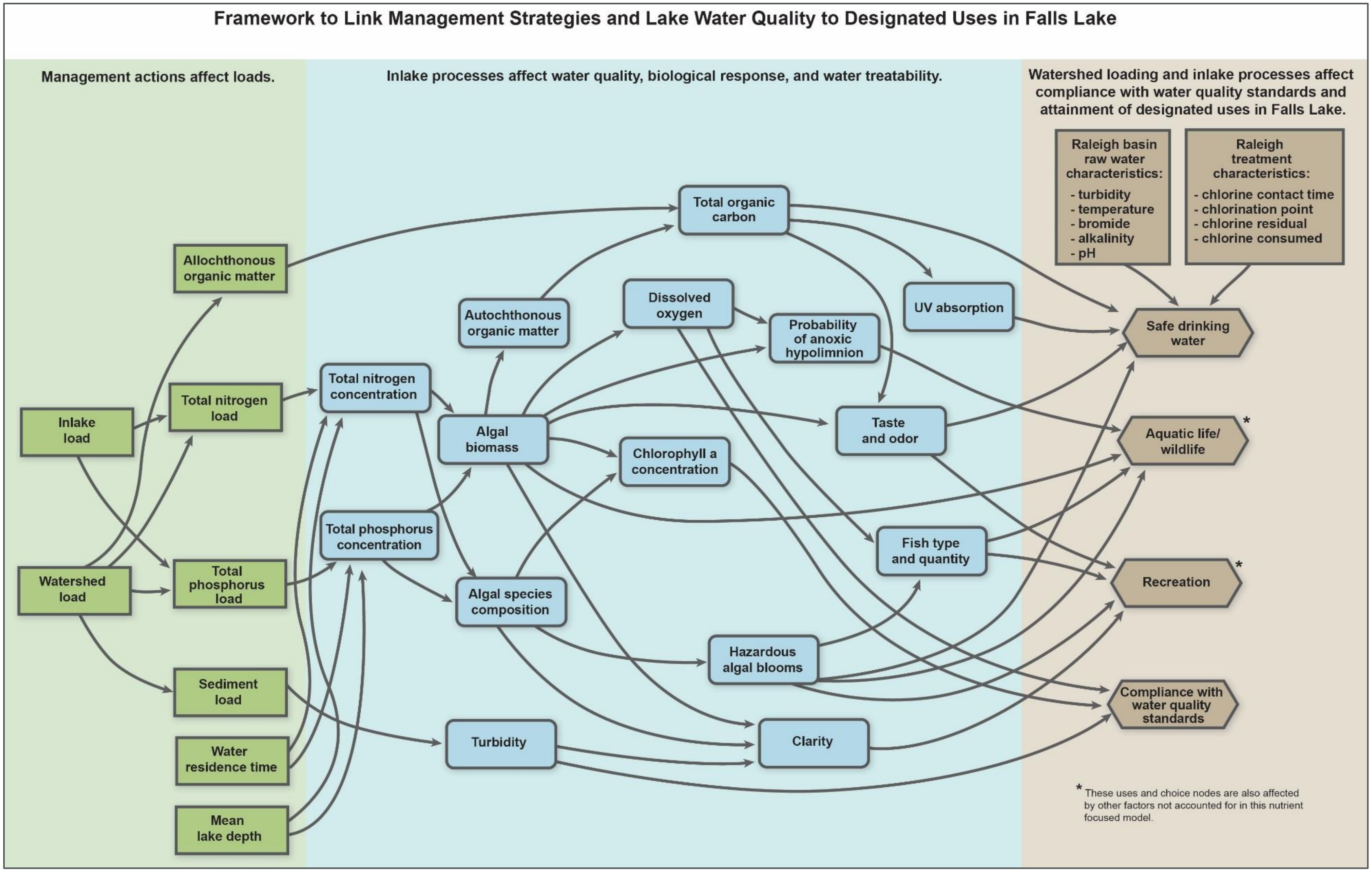


Figure 4-1 Conceptual Diagram for the Empirical/Bayesian Falls Lake Model

Table 4.1 Assessment of Data Availability for the Probabilistic Modeling

Node	Summary of Available Data	Assessment
Tributary organic matter loads (TOC concentrations and stream flows)	UNRBA – minimum monthly sampling – 18 LL stations - August 2014 to present DWR – monthly sampling – 6 Locations – February 2001 USGS – stream flows and monthly sampling - 13 locations – varying date ranges City of Durham – twice yearly sampling - 4 locations – 2009 - 2011	Flow and TOC concentration data are available to estimate these loads to the lake; will rely on basin proration to extrapolate flows; loads will likely rely on LOADEST
Tributary nitrogen loads (calculate TN concentrations and stream flows)	UNRBA - minimum monthly sampling – 18 LL stations - August 2014 to present DWR – monthly sampling – 8 locations – January 1999 – April 2011 USGS – stream flows and monthly sampling - 20 locations – varying date ranges City of Durham - monthly sampling - 26 locations – January 2005 – December 2011 Orange County – twice monthly sampling – 7 locations – April 2010 – March 2011 Wake County– twice monthly sampling – 9 locations – July 2008 – October 2009	Flow and TN concentration data are available to estimate these loads to the lake; will rely on basin proration to extrapolate flows; loads will likely rely on LOADEST
Tributary phosphorus loads (TP concentrations and stream flows)	UNRBA - monthly sampling – 18 LL stations - August 2014 to present DWR – monthly sampling – 8 locations – January 1999 – April 2011 USGS – stream flows and twice monthly sampling - 30 locations – varying date ranges City of Durham - monthly sampling - 27 locations – January 2005 – December 2011 Orange County – twice monthly sampling – 7 locations – April 2010 – March 2011 Wake County– twice monthly sampling – 7 locations – July 2008 – October 2009	Flow and TP concentration data are available to estimate these loads to the lake; will rely on basin proration to extrapolate flows; loads will likely rely on LOADEST
Tributary sediment loads (TSS concentrations and stream flows)	UNRBA - monthly sampling – 18 LL stations - August 2014 to present DWR – monthly sampling – 8 locations – January 1999 – April 2011 USGS – stream flows and monthly sampling - 20 locations – varying date ranges City of Durham – monthly sampling - 26 locations – January 2005 – December 2011 Orange County – twice monthly sampling – 7 locations – April 2010 – March 2011 Wake County– twice monthly sampling – 9 locations – July 2008 – October 2009	Flow and TSS concentration data are available to estimate these loads to the lake; will rely on basin proration to extrapolate flows; loads will likely rely on LOADEST
Average lake depth	Specify by lake segment based on published volume and surface area at normal pool (USACE)	Current data is sufficient to characterize mean depth and variability
Average lake residence time	Specify by lake segment based on published volume (USACE) and average inflows (USGS gaged flows and basin-prorated flows)	Current data is sufficient to characterize mean residence time and variability

Node	Summary of Available Data	Assessment
Inlake Secchi depth	DWR – monthly sampling – 12 locations – 2005 to present (with gaps) USGS – 4 to 6 samples per year – 5 locations – 2005 to 2011 City of Durham – weekly sampling generally from April to October - 2 locations – 2002 to present	Current data is sufficient to characterize mean Secchi depth and variability
Internal lake nitrogen loads (flux from lake sediments)	DWR – benthic flux measurements in April 2006 at three locations UNRBA – sediment cores from 12 locations with estimates of nutrient flux rates; may also use sediment diagenesis module in EFDC or other relationship to define time series USEPA – may conduct additional chamber work under summer conditions	Current UNRBA monitoring plans will collect sufficient data to estimate these loads; USEPA monitoring may supplement if benthic chamber studies are conducted
Internal lake phosphorus loads (flux from lake sediments)	DWR – benthic flux measurements in April 2006 at three locations UNRBA – sediment cores from 12 locations with estimates of nutrient flux rates; may also use sediment diagenesis module in EFDC or other relationship to define time series USEPA – may conduct additional chamber work under summer conditions	Current UNRBA monitoring plans will collect sufficient data to estimate these loads; USEPA monitoring may supplement if benthic chamber studies are conducted
Inlake algal biomass (biovolume)	DWR – monthly sampling – 3 locations – 2011 to present	Current monitoring is sufficient to characterize conditions in the lake
Inlake algal species composition	DWR – monthly sampling – 3 locations – 2011 to present	Current monitoring is sufficient to characterize conditions in the lake
Inlake hazardous algal blooms	DWR – monthly sampling – 3 locations – 2011 to present	Current monitoring is sufficient to characterize conditions in the lake
Inlake total nitrogen concentrations	DWR – monthly sampling – 12 locations – 2005 to present (with gaps) CAAE – monthly sampling – 2 locations – 2007 to 2010 USGS – 4 to 6 samples per year – 5 locations – 2005 to 2011 City of Durham – weekly sampling generally from April to October - 2 locations – 2002 to 2012 Wake County – 1 sample in 2009 – 3 locations	Current and historic monitoring are sufficient to characterize conditions in the lake
Inlake total phosphorus concentrations	DWR – monthly sampling – 12 locations – 2005 to present (with gaps) CAAE – monthly sampling – 2 locations – 2007 to 2010 USGS – 4 to 6 samples per year – 5 locations – 2005 to 2011 City of Durham – weekly sampling generally from April to October - 2 locations – 2002 to 2012	Current and historic monitoring are sufficient to characterize conditions in the lake

Node	Summary of Available Data	Assessment
Inlake chlorophyll *a* concentrations	DWR – monthly sampling – 12 locations – 2005 to present (with gaps) CAAE – monthly sampling – 2 locations – 2007 to 2010, less than monthly 2002 - 2006 USGS – 4 to 6 samples per year – 5 locations – 2005 to 2011 City of Durham – weekly sampling generally from April to October - 2 locations – 2002 to 2012 City of Raleigh – twice monthly sampling – 8 locations – 2009 to 2011	Current and historic monitoring are sufficient to characterize conditions in the lake
Inlake turbidity	DWR – monthly sampling – 12 locations – 2005 to present (with gaps) City of Raleigh – twice monthly sampling – 8 locations – 2007 to 2011, less than monthly 2005 – 2006 CAAE – every 3 hours – 3 locations – 2011 to present (profiler data at multiple depths) Wake County – 2 samples in 2009 – 3 locations	Current and historic monitoring are sufficient to characterize conditions in the lake
Inlake total organic carbon	DWR – monthly sampling – 12 locations – 2005 to present (with gaps) CAAE – monthly sampling – 2 locations – July 2007 to 2010 City of Raleigh – monthly sampling – 7 locations – 2000 to 2011, less than monthly 2005 – 2006 City of Durham – five samples in April - 1 location – 2012 USGS – twice monthly sampling – 5 locations – 2005 to 2011	Current and historic monitoring are sufficient to characterize conditions in the lake
Inlake dissolved oxygen, temperature, and pH	DWR – monthly sampling – 12 locations – 2005 to present (with gaps) CAAE – monthly sampling – 2 locations – July 2007 to 2010 CAAE – every 3 hours – 3 locations – 2011 to present (profiler data at multiple depths) City of Raleigh – twice monthly sampling – 8 locations – 2000 to 2011 City of Durham – weekly sampling generally from April to October - 2 locations – 2002 to 2012 USGS – twice monthly sampling – 5 locations – 2005 to 2011 Wake County – 2 samples in 2009 – 3 locations	Current and historic monitoring are sufficient to characterize conditions in the lake including probability of anoxia
Inlake clarity	DWR – monthly sampling – 12 locations – 2005 to present (with gaps) [Secchi depth] DWR – monthly sampling – 12 locations – October 2015 to present [PAR data] City of Durham – weekly sampling generally from April to October - 1 location – 2010 to 2011 [Secchi depth] USGS – twice monthly sampling – 5 locations – 2005 to 2011 [Secchi depth]	Current and historic monitoring are sufficient to characterize conditions in the lake
Inlake UV absorption	DWR/UNRBA - monthly sampling – 12 locations – October 2014 to present	Current monitoring is sufficient to characterize conditions in the lake
Taste and odor complaints	City of Raleigh – complaint records and analysis by UL Laboratories	Confirm with Raleigh that current monitoring is sufficient to characterize conditions in the lake

Node	Summary of Available Data	Assessment
Inlake fish type and quantity	WRC – collects data on black crappie and largemouth bass every other year, alternating spring and fall depending on the species	WRC will be used to confirm presence of a healthy fish population, but will likely not be sufficient to link water quality to designated uses; we will likely rely on expert elicitation to inform these linkages
Additional raw water characteristics (turbidity, pH, bromide, alkalinity, temperature)	City of Raleigh – alkalinity and pH are collected daily, and bromide is analyzed quarterly DWR – evaluates turbidity near the raw water intake at Station NEU020D.	The City of Raleigh and DWR collect the data necessary to populate these inputs
Description of chlorination processes	City of Raleigh collects data on chlorine contact time, chlorination point, chlorine residuals, and chlorine consumed	The City of Raleigh collect the data necessary to populate these inputs

Table 4.2 Assessment of Potential Linkages for the Probabilistic Modeling

Linkage	Potential Assessment Methodologies	Notes
Total nitrogen loads (watershed and inlake), mean depth, and mean residence time to inlake TN concentrations	Current version of FLFT uses the default equation from the USACE BATHTUB model: Second order available N; other BATHTUB equations are available EUTROMOD empirical equations Develop an empirical relationship using Falls Lake watershed and lake data	Prediction capabilities and uncertainty of existing empirical relationships will be evaluated when the empirical modeling begins; the need for development of lake specific relationships will be determined at this time.
Total phosphorus loads (watershed and inlake), mean depth, and mean residence time to inlake TP concentrations	Current version of FLFT uses the default equation from the USACE BATHTUB model: Second order decay rate model; other BATHTUB equations are available EUTROMOD empirical equations Develop an empirical relationship using Falls Lake watershed and lake data	Prediction capabilities and uncertainty of existing empirical relationships will be evaluated when the empirical modeling begins; the need for development of lake specific relationships will be determined at this time.
Inlake TN and TP concentrations, mean depth, mean residence time, and clarity to algal biomass	Current version of FLFT predicts growing season average chlorophyll *a* concentrations using the Jones and Bachman model from the USACE BATHTUB model; other BATHTUB equations are available EUTROMOD empirical equations Develop an empirical relationship using Falls Lake TN, TP, clarity, and chlorophyll *a* data	Prediction capabilities and uncertainty of existing empirical relationships will be evaluated when the empirical modeling begins; the need for development of lake specific relationships will be determined at this time.
Inlake TN and TP concentrations to algal species composition	Assess EFDC model and literature for predefined relationships Develop an empirical relationship using Falls Lake data	Prediction capabilities and uncertainty of existing empirical relationships will be evaluated when the empirical modeling begins; the need for development of lake specific relationships will be determined at this time.
Watershed loading of organic material to inlake TOC concentrations (allochthonous)	Current version of FLFT predicts inlake TOC using a regression on inlake TSS concentrations with an R2 of 0.94 (correlation was based on the means of six lake basins) Develop an empirical relationship between tributary TOC loads and allochthonous TOC inlake concentrations partitioned from information on color and UV absorption or use tributary TOC loads and lake morphometry to estimate allochthonous TOC using a mass balance approach	Linkages will be explored in more detail before modeling begins.
Algal biomass to inlake organic material (authochthonous)	Use published relationships to convert algal biomass to carbon	Linkages will be explored in more detail before modeling begins.
Autochthonous organic material to inlake TOC concentrations	Add to watershed carbon to calculate TOC	Linkages will be explored in more detail before modeling begins.

Linkage	Potential Assessment Methodologies	Notes
Algal biomass to dissolved oxygen and frequency of anoxic hypolimnion	Use pre-existing relationships (e.g., BATHTUB or EUTROMOD frequency of anoxia) Develop an empirical relationship using Falls Lake chlorophyll *a* and dissolved oxygen data	Linkages will be explored in more detail before modeling begins.
Algal biomass to chlorophyll a	Develop an empirical relationship using Falls Lake DWR algal biovolume data and chlorophyll *a* concentrations Use published values to convert	Linkages will be explored in more detail before modeling begins.
Algal species composition to chlorophyll a	Use percent composition and biovolume data and correlate to chlorophyll *a* concentrations using Falls Lake data	Linkages will be explored in more detail before modeling begins.
Algal biomass to clarity	Use published relationships that relate turbidity and chlorophyll *a* to clarity Develop an empirical relationship using Falls Lake chlorophyll a, turbidity, Secchi depth, and light extinction data	Linkages will be explored in more detail before modeling begins.
Algal species composition to clarity	Use percent composition and biovolume data and correlate to clarity using Falls Lake data Use published information on species composition and effects on clarity	Linkages will be explored in more detail before modeling begins.
Sediment loading to turbidity	Use Falls Lake data or EFDC model to develop relationship	Linkages will be explored in more detail before modeling begins.
Turbidity to clarity	Use published relationships that relate turbidity and chlorophyll *a* to clarity Develop an empirical relationship using Falls Lake chlorophyll *a*, turbidity, Secchi depth, and light extinction data	Linkages will be explored in more detail before modeling begins.
Algal species composition to hazardous algal blooms	Use published information on algal species composition and biomass to hazardous algal blooms Use Falls Lake data to develop relationship	Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
TOC to UV absorption	Use published information on TOC/UV absorption relationships including the Information Collection Rule dataset Use Falls Lake data to develop relationship	Linkages will be explored in more detail before modeling begins.
TOC to taste and odor	Correlate TOC levels in Falls Lake with City of Raleigh Taste and odor data	Linkages will be explored in more detail before modeling begins.

Linkage	Potential Assessment Methodologies	Notes
Dissolved oxygen to fish type and quantity	Use published stress levels for fish for various dissolved oxygen concentrations and durations	Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
Algal biomass to taste and odor	Correlate algal biomass in Falls Lake with City of Raleigh Taste and odor data	Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
Hazardous algal blooms to fish type and quantity	Use published information on hazardous algal bloom levels and duration that stress fish	Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
TOC to Safe drinking water use	Use published information including the Information Collection Rule dataset to develop this linkage Use Falls Lake and City of Raleigh data to develop lake-specific relationships between TOC concentrations and SDWA triggers Current version of the FLFT incorporates City of Raleigh historic use of ferric sulfate to estimate changes in treatment costs (assumes no change to treatment process)	Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
UV absorption to Safe drinking water use	Use published information including the Information Collection Rule dataset to develop this linkage Use Falls Lake and City of Raleigh data to develop lake-specific relationships between UV absorption and SDWA triggers	Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
Taste and odor to Safe drinking water use	Discuss with Raleigh what number or frequency of taste and odor complaints is considered problematic	Consult with City of Raleigh/Hazen and Sawyer Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues

Linkage	Potential Assessment Methodologies	Notes
Raw water characteristics to Safe drinking water use	Use published information including the Information Collection Rule dataset to develop this linkage Use Falls Lake and City of Raleigh data to develop lake-specific relationships between raw water characteristics and SDWA triggers	Consult with City of Raleigh/Hazen and Sawyer Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
Treatment processes to Safe drinking water use	Use published information including the Information Collection Rule dataset to develop this linkage Use Falls Lake and City of Raleigh data to develop lake-specific relationships between treatment processes and SDWA triggers	Consult with City of Raleigh/Hazen and Sawyer Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
Hazardous algal blooms to Safe drinking water use	Use published literature to correlate hazardous algal blooms (level and duration) to drinking water treatment issues	Consult with CAAE Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
Dissolved oxygen to aquatic life use	Use published literature to correlate DO concentrations (concentrations and duration) to stress on aquatic organisms	Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
Algal biomass to aquatic life use	Use published literature and/or expert elicitation to link algal biomass to aquatic life use (food source, DO swings, etc.)	Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues

Linkage	Potential Assessment Methodologies	Notes
Hazardous algal blooms to aquatic life use	Use published literature and/or expert elicitation to link hazardous algal blooms to aquatic life use (food source, DO swings, etc.)	Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
Taste and odor to recreation use	Use published literature, expert elicitation, or human use surveys to correlate taste and odor to recreational use	Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
Fish type and quantity to recreation use	Obtain data from sources including bass fishing tournaments, WRC Or use creel surveys, catch effort data, Kenney data, etc. to correlate fish type and quantity to recreational use in Falls Lake Or conduct human use surveys to correlate fish type and quantity to recreational use	Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
Hazardous algal blooms to recreation use	Use published literature and/or expert elicitation to correlate hazardous algal blooms to recreational use	Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
Clarity to recreation use	Use published literature and/or expert elicitation or human use surveys to correlate water clarity to recreational use (safety issues, aesthetic quality, etc.); example literature includes the Phaneuf, Kenney, Reckhow model that was used to develop the current version of the FLFT	Linkages will be explored in more detail before modeling begins. Track NC NNC SAC process as they are considering these issues
Turbidity to meeting water quality standards	Compare inlake water quality data and model predictions to water quality standards	
Dissolved oxygen to meeting water quality standards	Compare inlake water quality data and model predictions to water quality standards	
Chlorophyll *a* to meeting water quality standards	Compare inlake water quality data and model predictions to water quality standards	

5 Summary of Recommendations

The recommendations derived from the modeling evaluation summarized in this report were also considered and incorporated in the FY2016 Annual Monitoring Report. The annual report recommendations have already been considered by the UNRBA and incorporated into modifications for the FY2017 Monitoring Year. With the exception of the recommended additional data collection efforts listed below, the evaluation of potential model types planned to support the reexamination indicates no apparent, fundamental data gaps that are not addressed or being considered as the UNRBA moves toward completion of its monitoring program period (four years with an additional year, if needed). This report has identified the changes that are planned for FY2017 and noted some areas of monitoring and special studies that will continue to be evaluated from year to year as the monitoring program proceeds. Additional data needs that may arise as the modeling and regulatory support component of the reexamination gets underway should be addressed through focused Special Studies in future years.

- Based on an evaluation of predicted and measured loads during storm events, estimated nutrient loading to Falls Lake is likely underestimated during storm events because there are insufficient water quality samples collected during high flow events. For FY2017, the UNRBA approved modifications of the High Flow Sampling Special Study to include multiple storms at the five uppermost tributaries. Depending on the duration of the storms and timing of hydrographs, additional lake loading stations will also be targeted for high flow sampling.
- Based on model sensitivity analyses on the labile and refractory fractions of particulate organic carbon, the UNRBA approved discontinuing analysis of $CBOD_5$ at the lake loading stations in FY2017. The model is relatively insensitive to this parameter because very little of the organic carbon entering the lake is in the particulate form for which EFDC assigns lability (EFDC does not designate lability for the dissolved fraction which comprises approximately 95 percent of the organic carbon load from the tributaries).
- With respect to the light extinction data collected in Falls Lake, revisions to the modeling parameters are needed to provide a more accurate prediction of light attenuation, particularly with respect to background light extinction. While the current version of the model is relatively insensitive to changes to light extinction parameters, once the model is revised, the degree of impacts may change and additional data collection may be warranted. Given that the model response using the DWR version of the EFDC model is relatively insensitive to changes in light extinction parameters and that significant improvements can be made to light extinction parameterization simply based on existing data, the UNRBA has not funded collecting additional paired light penetration data in FY2017.
- Evaluations of the USACE BATHTUB model indicate that it could serve either as an independent model of Falls Lake or as a means to supply regression equations for the empirical modeling. In either case, the model predicts inlake concentrations of total nitrogen, total phosphorus, and chlorophyll *a* as a growing season average and predicts the percent of time that specific chlorophyll *a* concentrations will be exceeded for individual basins in the lake. The model accounts for light attenuation using an algal and non-algal component. For the purposes of using the BATHTUB model, existing monitoring programs adequately characterize the inputs required by the model: flows to the lake, organic and inorganic nutrient loads to the lake, Secchi depth, and average bathymetric characteristics.

- Evaluations of the EFDC model grid indicate that improvements to the DWR version may be beneficial for future modeling efforts. For FY2017, the UNRBA approved a survey of Falls Lake to generate a bathymetric map to define the model domain and support revisions to the model grid.
  - Revisions to the model grid at lake constriction points are needed to better characterize the hydrodynamics and transport of material from one lake segment to the next.
  - Improvements to the simulation of wetting and drying and extension of the model grid into areas that are often flooded by lake backwaters may also improve water quality simulations.
- Based on the collection of sediment cores from Falls Lake as part of the Lake Sediment Evaluation Special Study and evaluation of the EFDC sediment diagenesis module, a sediment mapping study would provide information to inform the modeling of internal nutrient loading from lake sediments. For FY2017, the UNRBA approved a sediment mapping study of Falls Lake to identify the presence, absence, and relative thickness of unconsolidated sediments throughout the lake. The need for a new in situ nutrient flux study is still included as a priority. EPA assistance continues to be sought. If this need continues to represent a high priority (based on additional evaluation and the final results of the sediment cores study and EPA assistance cannot be secured, the UNRBA may want to allocate resources for this work in FY2018.
- Based on the evaluation of the empirical/probabilistic/Bayesian model framework, existing monitoring programs are collecting the data and information needed to build this model. If data gaps are identified as the model is developed, they may be filled by collecting supplemental data on Falls Lake, using data collected from similar waterbodies, or expert elicitation.

6 References

DENR (2009). *Falls Lake Nutrient Response Model Final Report*. Prepared by N.C. Department of Environment and Natural Resources, Division of Water Quality Planning Section, Modeling/TMDL Unit November 2009.

NCDWQ. 2010. Fiscal Analysis for Proposed Nutrient Strategy for Falls of Neuse Reservoir.

Park, K., Kuo, A.Y., Shen, J., Hamrick, J.M., A Three-Dimensional Hydrodynamic-Eutrophication Model (HEM-3D): Description of Water Quality and Sediment Process Submodels, Applied Marine Science and Ocean Engineering No. 327, 1995.

Phaneuf, Dan, V. Kerry Smith, Raymond Palmquist, Jaren Pope. 2008. "Integrating Property Value and Local Recreation Models to Value Ecosystem Services in Urban Watersheds." Land Economics 84(3): 361-381.

Runkel, R.L., Crawford, C.G., and Cohn, T.A., 2004, Load Estimator (LOADEST): A FORTRAN Program for Estimating Constituent Loads in Streams and Rivers: U.S. Geological Survey Techniques and Methods Book 4, Chapter A5, 69 p.

Tetra Tech. 2010. Falls Lake Nutrient Response Model Reduction Curves. Memorandum to Michelle Woolfolk, City of Durham. June 29, 2010.

Walker, William W. 1999. Simplified Procedures for Eutrophication Assessment and Prediction: User Manual. Prepared for Headquarters, U.S. Army Corps of Engineers.