Evaluation of the Sensitivity of the Falls Lake Nutrient Response Model

UNRBA Monitoring Program Development and Implementation

E213006400

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Executive Summary

The existing Falls Lake Nutrient Response model developed by the North Carolina Division of Water Resources (NCDWR) includes tributary inputs from 17 locations around Falls Lake. Cardno ENTRIX used the existing model to perform sensitivity analyses to determine the relative importance of each of the tributaries (i.e., is the model more sensitive to a particular lower lake tributary that would indicate that additional monitoring is needed in that area). It should be noted that the NCDWR model was used as calibrated and set up by the Division of Water Resources for the development of the Falls Lake requirements. The existing model was used as a tool to evaluate future monitoring needs for an updated model. This evaluation doesn’t attempt to make adjustments to the existing model to improve its sensitivity or recalibrate the model. The model is being used for reference purposes to determine the most critical model inputs to guide future monitoring objectives.

The sensitivity analyses described in this TM were developed to identify whether any specific tributary, or tributaries, have a particularly strong influence on lake water quality. A key question of the monitoring program is where to focus monitoring resources, so determining if particular tributaries are more influential than others will help the UNRBA allocate limited monitoring resources. This sensitivity analysis was conducted assuming 50 percent increases in tributary nutrient loading for two reasons. First, past sensitivity analyses evaluated the influence of reductions in nutrient and chlorophyll inputs on Falls Lake Nutrient Response model water quality model predictions (Cardno ENTRIX 2013a, Framework for a Re-examination of Stage II of the Falls Nutrient Strategy). The results of these simulated reductions in nutrients and chlorophyll *a* are presented again in this TM. Second, some of the tributaries have very low nutrient loads relative to the upper lake tributaries in the current version of the model. Testing the sensitivity of the model to reduced nutrient loads from one of these tributaries would be difficult to detect because the effects of their loads are already overwhelmed by the loading from the larger tributaries. The impacts from large nutrient increases on overall lake water quality are easier to detect in the model output.

Additional model sensitivity analyses on in-lake modeling parameters were outside of the scope of work for this project. However, in preparation for planning of future special studies to address issues such as benthic nutrient flux rates, sediment inflow partitioning, and algal growth rates which influence model predictions, the Fiscal Year 2015 Monitoring Program scope of work will include resources to refine this need and will look at modeling sensitivity prior to moving forward with special studies. For now, Cardno ENTRIX has identified specific monitoring studies for incorporation into the monitoring plan that will provide, as appropriate, the collection of data needed to refine the model inputs of these parameters. These will be described in more detail in the draft Monitoring Optimization TM.

For the most part, the sensitivity analyses (using both the State’s model and an empirical model developed by Cardno ENTRIX (2013a)) indicate that the lake is most responsive to changes in loading that occur from the five upper tributaries which drain the largest watershed areas, contribute the largest flow volumes, and receive discharges from the largest wastewater treatment plants in the basin. Based on the existing model, none of the tributaries in the middle or lower part of the watershed disproportionally impacted water quality in the vicinity of Highway 50 or the Raleigh water supply intake relative to any other tributary.

A separate set of analyses were conducted to determine how sensitive the Falls Lake Nutrient Response model (also referred to as Environmental Fluid Dynamics Code or EFDC model) was to the various methods available to generate daily tributary nutrient concentration input values for the model. The State’s method for developing EFDC model inputs uses interpolation between grab samples. The USGS has developed a series of regression models that estimate loads by correlating observed water quality concentrations with flow data. Cardno ENTRIX tested the sensitivity of the EFDC model to changes in input loading methods. These sensitivity analyses compare the baseline EFDC model inputs developed by NCDWR (using the linear interpolation method) to LOADEST inputs based on pairing water quality samples with either daily average flows or 15-minute flows, both of which are reported by USGS for the upper lake tributaries. While the LOADEST model performed better on Ellerbe Creek when 15-minute flows were used to develop the regressions, the LOADEST models developed for the other four upper lake tributaries were not very sensitive to the time increment of the flow measurements (Section 2).

The EFDC model was very sensitive to how the daily nutrient concentration and flow model inputs were calculated, particularly in the Ellerbe Creek arm of the lake (Section 3.4). The different LOADEST models and variations in flow estimation totals produce very different nutrient loading patterns to the lake, which have a strong effect on simulated lake water quality. These analyses indicate that when the UNRBA begins to revise the State's EFDC model based on the collection of new monitoring data, that the choice of tributary nutrient input estimation method will have a strong effect on the model's response. Targeted storm event monitoring with post storm event monitoring for 2 to 3 days afterward can be used to provide the data needed to determine which method most accurately estimates actual loading. This monitoring would need to be conducted during the UNRBA monitoring program period and prior to the time that the Falls Lake Nutrient Response model revisions are initiated.

In addition to these sensitivity analyses, Cardno ENTRIX (2013c) previously evaluated the EFDC model sensitivity to tributary chlorophyll *a* concentrations. The results of those analyses were presented in the Task 4 TM (from 2012 UNRBA project, Support of Long Term Planning and Regulatory Nutrient Activities in the Falls Lake Watershed, TM4 located at
http://unrba.org/sites/default/files/Task4TM_FINALJune18.pdf), and are repeated in this TM (Section 3.1) to present all of the existing model sensitivity analyses in one document. On the basis of this previous work the concentration level tributary inputs of chlorophyll *a* to Falls Lake likely affect the sensitivity of the model to changes in nutrient loads. During some times of the year, the model appears to be more sensitive to this assumption for tributary chlorophyll *a* inputs than to the methodology used to determine the flow and nutrient input relationships (Section 3.4). The monitoring program is being designed to collect chlorophyll *a* samples within the tributaries so that actual data can replace the use of assumed chlorophyll *a* concentrations.

Overall, the EFDC model water quality predictions make sense in general terms; chlorophyll *a* and nutrient concentrations within the lake increase along with increased nutrient inputs from the tributaries. Decreases in chlorophyll *a* and nutrient loading from the tributaries produce reductions in predicted chlorophyll a and nutrient concentrations throughout the lake. Also, the tributaries with the largest flows and wastewater treatment plants influence lake nutrient concentrations more than tributaries that contribute lower volumes of flow. Although the model predictions make sense, the model is not as responsive to changes in inputs as experience would lead us to expect. This may be due in part to the model's calibration that was based on chlorophyll *a* inputs from the tributaries that reflected values found in the tributary's arm instead of from the free-flowing section. The relatively small lake response to changes in nutrient inputs may have influenced the setting of the Stage II nutrient reduction targets. Therefore, therefore the accurate measurement of tributary input levels are values, particularly for chlorophyll *a,* is a high priority for the monitoring program.

General conclusions related to future UNRBA actions that result from this TM include:

> The UNRBA monitoring program should include collection of chlorophyll *a* data within the tributaries to allow future model inputs to reflect actual tributary conditions.

> Since the tributaries with the largest flows have the most influence on lake water quality, it is important that the loading from these tributaries be estimated as accurately as possible.

> We recommend that the UNRBA monitoring program includes regular water quality monitoring at tributary loading stations from the largest 5 tributaries and supports at least one USGS flow gage on

each of these tributaries. Monitoring should also occur at the mouths of the other smaller tributaries in the middle and lower lake, but this monitoring could occur less frequently.

> Water quality monitoring stations will also be established at jurisdictional boundaries.

> Monitoring frequency at all water quality monitoring locations will be determined using statistical assessments to identify the number of samples needed to characterize water quality with an agreed upon level of certainty. The appropriate level of certainty will be discussed with the UNRBA and described in the Water Quality Estimation Technical Memorandum (TM).

> Flow estimation models, described in the Flow Estimation TM will be used to estimate flows at most jurisdictional boundaries. Appropriate monitoring in the watersheds that reflect jurisdictional loading will also be undertaken in the final monitoring plan. However, for this TM monitoring recommendations relate to direct inputs to the lake response modeling.

> Cardno ENTRIX has proposed that the UNRBA use the USGS LOADEST program to generate daily nutrient concentrations for running the EFDC model.

> The USGS LOADEST model can be used to generate loadings at most tributary loading locations using a daily flow estimate paired with monthly water quality sampling. Daily loading estimates for some tributaries, particularly Ellerbe Creek and possibly Knap of Reeds Creek may be generated by pairing water quality measurements with 15-minute or hourly flow data.

> The UNRBA should request that the NCDWR provide the source code associated with the existing Falls Lake Nutrient Response model. Once this code is obtained the model file size limitations can be modified so that the model can be run on a less than daily timestep for a sufficient amount of time to predict annual or growing season conditions within Falls Lake.

1 Introduction

In 2010 the Environmental Management Commission (EMC) passed the Falls Lake Nutrient Management Strategy, requiring two stages of nutrient reductions (N.C. Rules Review Commission 2010). The basis used by the NC Division of Water Quality (NC DWQ)—now the Division of Water Resources (NCDWR) for setting the nutrient loading targets in the Falls Lake Nutrient Management Strategy is the Falls Lake Nutrient Response Model developed with the Environmental Fluid Dynamics Code (EFDC) model (NCDENR 2009). In 2011, the Upper Neuse River Basin Association (UNRBA) began a project to re-examine, under the adaptive management provisions of the Falls Lake Rules, the Falls Lake Nutrient Management Strategy. Cardno ENTRIX has developed and is evaluating additional tools and models for the UNRBA to support the re-examination process.

Cardno ENTRIX is currently assisting the UNRBA with the development of a monitoring design plan to support the re-examination process. Key questions in the design of the monitoring program are where in the watershed should monitoring occur and whether or not certain tributaries will require more frequent monitoring. In order to address specific questions regarding the design of the monitoring program, the sensitivity of the existing tools and models was tested against various input assumptions. Three existing tools were used for this assessment:

> The United States Geologic Survey's (USGS) LOADEST described previously in work products developed by Cardno ENTRIX through UNRBA funding (2013b).

> The Falls Lake Nutrient Response Model using the Environmental Fluid Dynamics Code (EFDC) developed by NCDENR (2009).

> The United States Army Corps of Engineers' (USACE) BATHTUB model adapted to Falls Lake by Cardno ENTRIX (2013c).

The USGS LOADEST model was used to test the sensitivity of predicted nutrient loading estimates to 15-minute versus daily mean flow rates measured by USGS (Section 2). The Falls Lake Nutrient Response Model and the Falls Lake BATHTUB model were used to assess the sensitivity of predicted lake chlorophyll *a* concentrations to variations in nutrient loading from tributaries around the lake (Section 3). Section 4 summarizes the findings of these analyses with respect to design of the monitoring program and future model revisions.

Figure 1-1 shows a map of the watershed and the tributaries that are included in the sensitivity analyses that were performed to help answer these questions. Table 1-1 lists the total drainage area for each tributary, the percent of the total drainage area, and the percentages of the total nitrogen and total phosphorus loads simulated in the State's EFDC lake response model for 2006 (the baseline year).

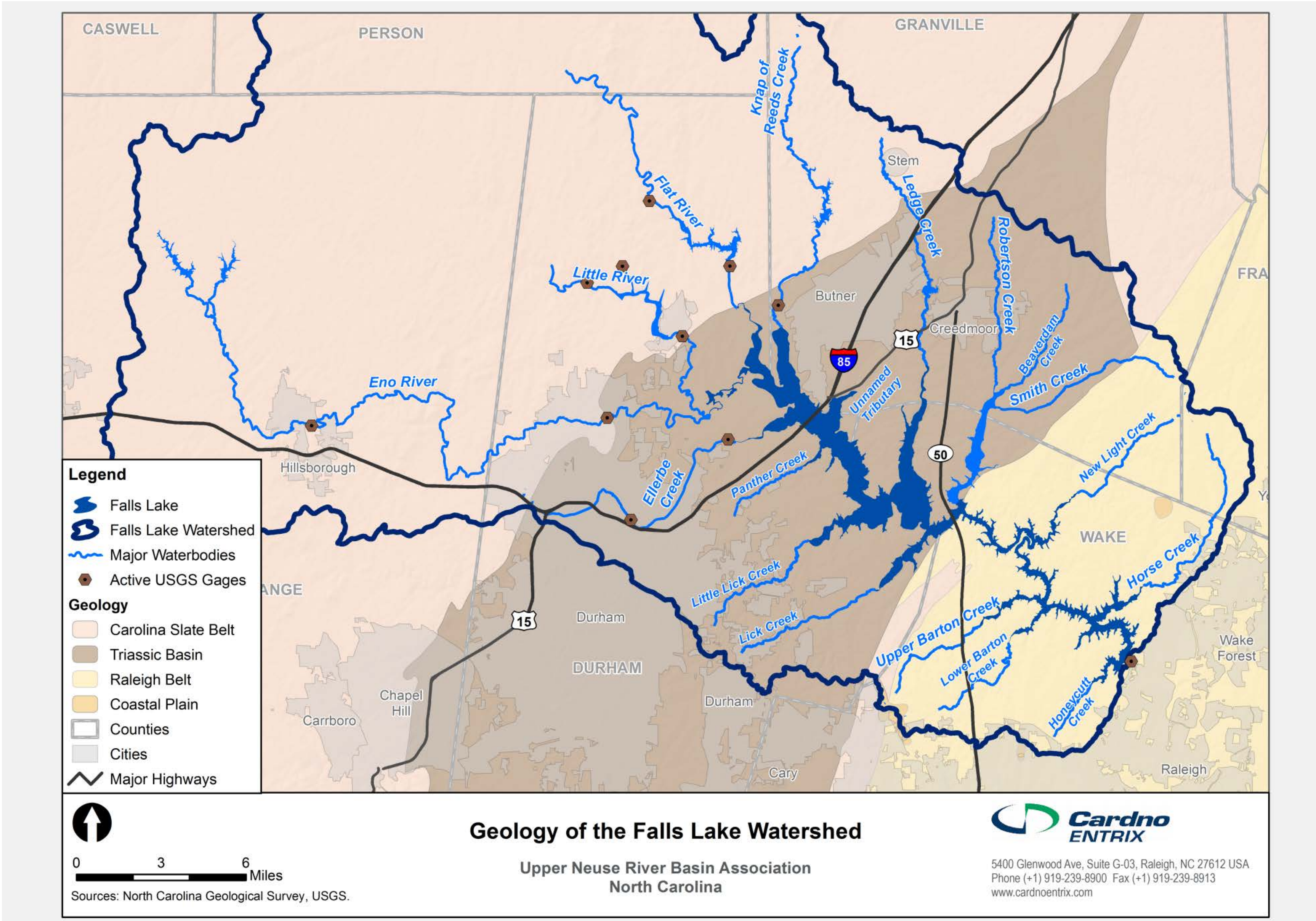

Figure 1-1 Tributaries in the Falls Lake Watershed. The "upper" watershed and its tributaries are those located upstream of I-85. The "middle" watershed is that area between I-85 and Highway 50 (Creedmoor Road). The "lower" watershed is the area between Highway 50 and the Falls Lake Dam.

Table 1-1 Relative Drainage Areas and Baseline Nutrient Loads for the Falls Lake Tributaries

Tributary	Drainage Area (ac)	Percent of Lake Drainage Area	Percent of Baseline Year Total Nitrogen Loads	Percent of Baseline Year Total Phosphorus Loads
Flat River	111,800	23.3%	7.0%	10.4%
Knap of Reeds Creek	29,778	6.2%	28.9%	13.5%
Eno and Little Rivers	167,019	34.8%	13.4%	18.8%
Ellerbe Creek	16,854	3.5%	28.4%	36.4%
Unnamed Creek	7,243	1.5%	1.2%	1.3%
Panther Creek	4,992	1.0%	1.7%	1.6%
Ledge Creek	21,460	4.5%	3.4%	3.6%
Little Lick Creek	14,263	3.0%	1.9%	1.7%
Lick Creek	13,895	2.9%	1.7%	1.1%
Beaverdam Creek (includes Smith, Robertson, and Beaverdam Creeks)	33,528	7.0%	4.7%	4.9%
New Light Creek	17,277	3.6%	2.2%	2.3%
Combined Upper and Lower Barton Creek	18,929	3.9%	3.8%	2.4%
Horse Creek	14,261	3.0%	1.1%	1.3%
Honeycutt Creek	9,231	1.9%	0.6%	0.7%

2 Sensitivity of Load Estimation Technique

The USGS LOADEST tool is a [statistical package developed by USGS that correlates nutrient concentrations and/or loads with flow at a given location. Several of the larger tributaries to Falls Lake have co-located flow and water quality data for which LOADEST model configurations were developed by Cardno ENTRIX. The USGS reports both 15-minute and daily average flows for these particular sites, and the key questions with respect to the monitoring program:

Are daily flows sufficient for developing the load regression equations, or does 15-min flow data significantly improve the regression model?

For those locations in the watershed where flow gages are not currently present or planned for the future monitoring study, will estimates of daily flow paired with water quality sampling likely generate a reasonably accurate load estimate?

Do we lose a significant amount of information by not having 15-minute flows in these ungaged areas?

The USGS LOADEST files were developed for the five upper lake tributaries to Falls Lake. The nine regression models included in the LOADEST package were tested by pairing observed water quality samples with either the daily average flow or the 15-minute flow that was recorded closest to the sample collection time. Results from each of the nine models included in the LOADEST package were generated, and the results are presented for each of the tributaries. A more complete description of LOADEST and the nine models (

Table 2-1) was previously summarized by Cardno ENTRIX in Technical Memos funded by the UNRBA (2013b). More information on the LOADEST program details and software can be found at the following location: http://water.usgs.gov/software/loadest/

When the Falls Lake Nutrient Response model is updated in the future, any loading calculations generated by LOADEST will be based on the most recent version of LOADEST available at that time. Model fit statistics such as the Nash-Sutcliffe Efficiency Index, and prediction bias indicators such as the partial load ratio and percent load bias will be calculated and reviewed as part of the process of selecting the most appropriate LOADEST model for use in estimating daily nutrient concentrations and flows at tributary loading locations.

Table 2-1 Nine Regression Models Included in 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	$a0 + a1 \ln Q + a2 \ln Q2 + a3 \sin(2\pi dtime) + a4 \cos(2\pi dtime) + a5 dtime + a6 dtime2$

[I, Integer; lnQ = ln(streamflow) - center of ln(streamflow); dtime = decimal time - center of decimal time]

Table 2-2 summarizes the flow and water quality data available for each of the five tributaries that was used to develop the LOADEST models. The number of samples less than the detection limit is also provided. The Eno and Little River subwatersheds have the highest percentages of samples less than the detection limit (up to 20 percent). A map of the flow and water quality monitoring stations is provided in Figure 2-1.

Table 2-2 Flow and Water Quality Data for LOADEST Tributary Nutrient Loading Estimates

Subwatershed	USGS Gage	Co-located Water Quality Stations	No. TN samples	No. TP samples	No. TP <Limit	Date Range
Ellerbe Creek near Gorman	02086849	J1330000, EL1.9EC, 02086849	147	148	2	2006-2011
Eno River near Durham	02085070	EN8.9ER, 02085079, J0770000	123	131	26	2001-2011
Flat River at Lake Michie Dam	02086500	FR5.2FR, J1100000	94	129	4	2003-2011
Knap of Reeds Creek near Butner	02086624	J1210000, 02086624	77	77	0	2006-2011
Little River below Reservoir	0208524975	0208524950, 0208524975	207	207	35	1999-2011

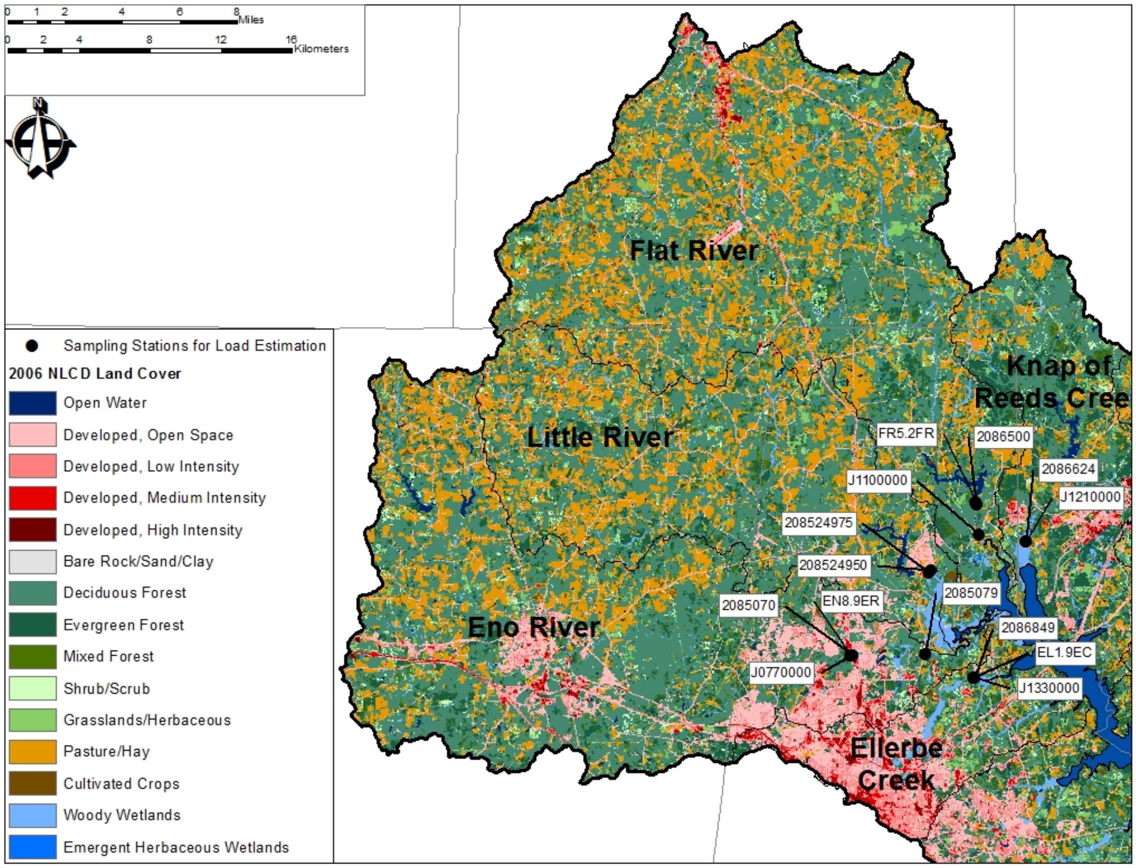

Figure 2-1 Water Quality Monitoring Stations used for the LOADEST Analysis

2.1 LOADEST Results for Ellerbe Creek near Gorman

The Ellerbe Creek LOADEST files were initially set up for the water quality monitoring station downstream of the North Durham WWTP using the full available flow and water quality data set for this station (2006 to 2011). The load regressions for total phosphorus and total nitrogen are provided below.

2.1.1 Total Phosphorus

Figure 2-2 shows the time series concentration predictions for total phosphorus when the water quality samples were paired with daily mean flow. Black circles on the figures are the measured water quality observations. The ability of the LOADEST models to predict the observed TP concentrations, as represented by the R^2 value for each model, ranges from 0.5 to 0.65. The models do not adequately predict the higher total phosphorus concentrations that were observed in 2006 and 2007.

Figure 2-3 shows the results when the water quality samples are paired with 15-minute flow data. For the 2006 to 2011 model, the R^2 increases from 0.64 to 0.74, which is a noticeable improvement over the daily flow model.

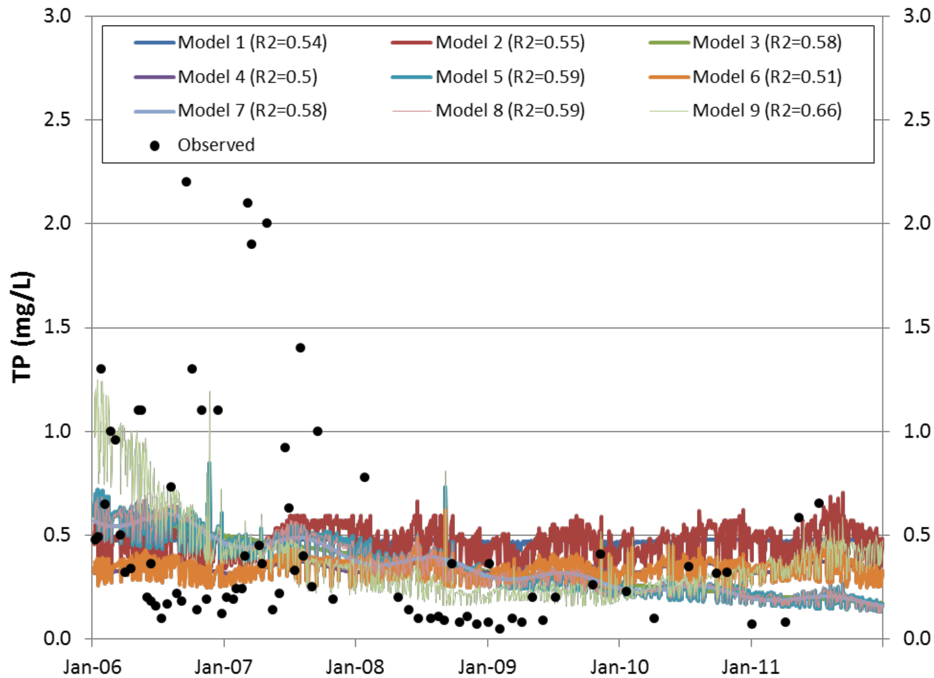

Figure 2-2 USGS LOADEST Predictions for TP (2006 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using Daily Flows

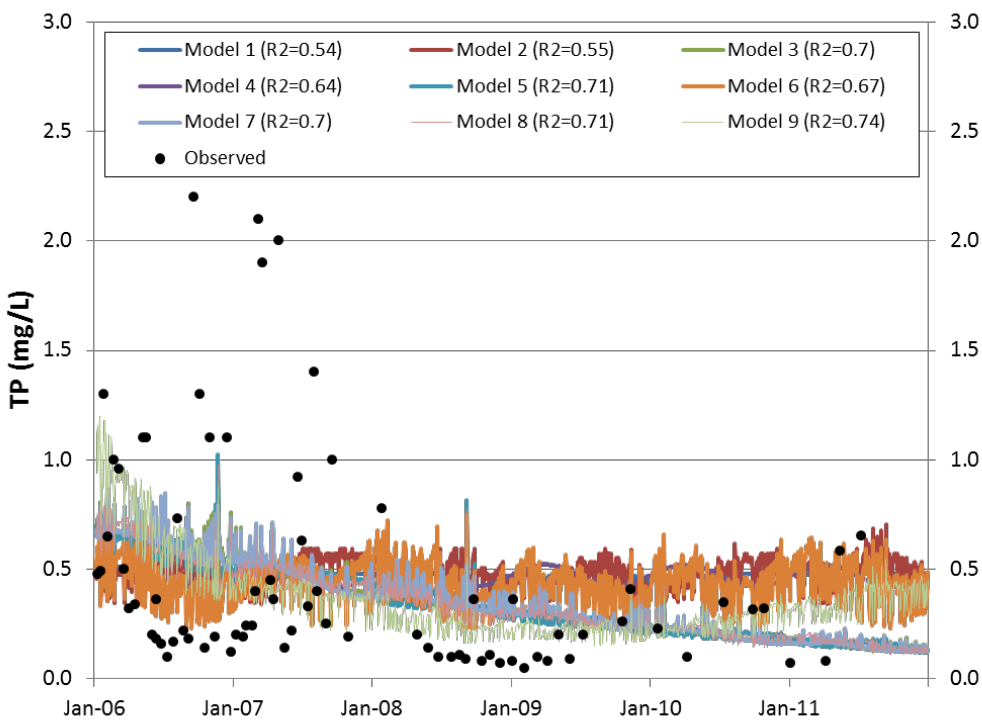

Figure 2-3 USGS LOADEST Predictions for TP (2006 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using 15-Minute Flows

While the use of the 15-minute flow data improves the R^2 in Ellerbe Creek for all nine models, it still is not able to estimate the higher TP concentrations observed in 2006 and 2007. The City of Durham made a significant investment in nutrient removal upgrades at this facility, which is reflected by the lower TP concentrations in Ellerbe Creek after the updates were completed in 2008. Because the LOADEST model is not able to address the disparity in the dataset, the Ellerbe Creek dataset was split into 2006 to 2007 and 2008 to 2011 and reanalyzed.

Figure 2-4 and Figure 2-5 present the results of the split Ellerbe Creek models using data collected in 2006 and 2007 using daily or 15-minute flows, respectively. When the data set is split, the R^2 values using daily flows decrease to about 0.2, and it appears that the model is not able to deal with the amount of variability observed in 2006 to 2007 in a way that can be correlated well to flow. The 15-minute flows result in R^2 up to 0.66. While this R^2value is less than that generated with the full period of record and 15-minute flows (Figure 2-3), the simulated concentrations are slightly higher, so this configuration was selected for generating total phosphorus inputs to the EFDC model (Section 3.3). It is likely that the R^2 values using the full data set are higher than the 2006 to 2007 dataset because there is less variability in the full data set, and there is more data from which to compare simulated and observed values.

The split model does a much better job at predicting total phosphorus concentration in 2008 to 2011 (Figure 2-6 and Figure 2-7). Using the 15-minute flows to develop the regressions results in a slightly higher R^2, and the 15-minute flow regressions do at a better job at predicting the extremes of the observed dataset (lowest and highest concentrations).

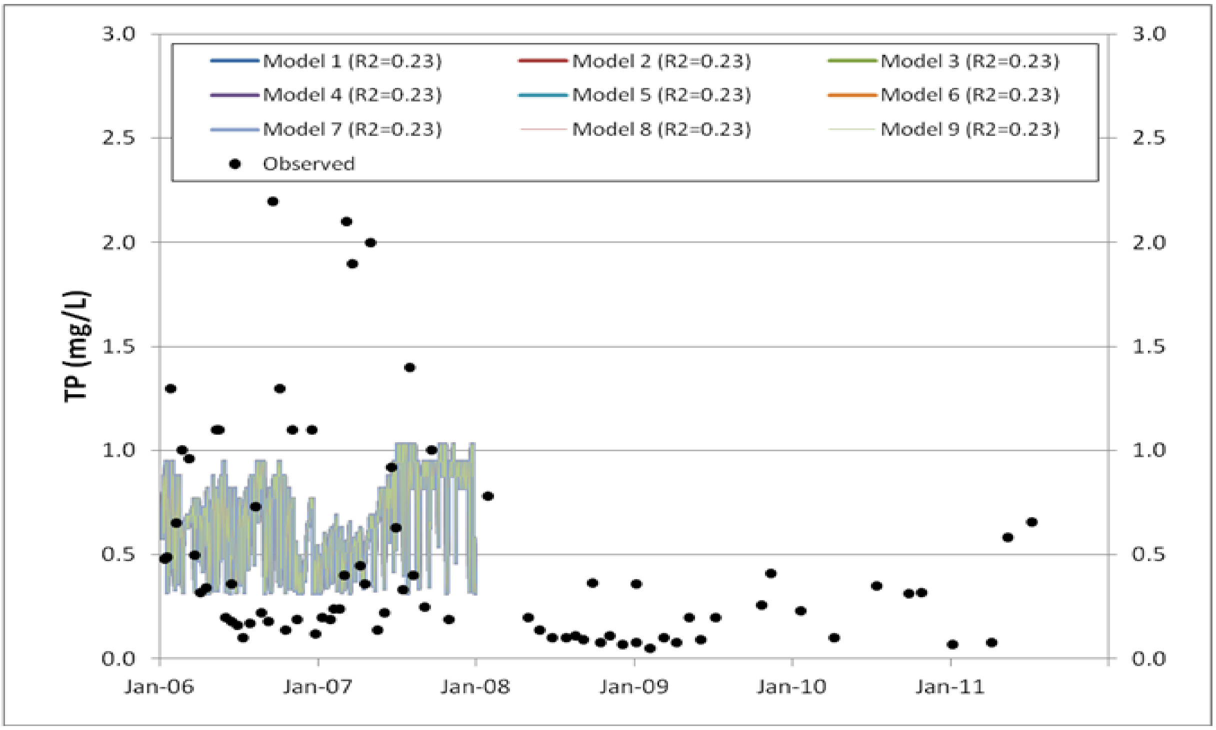

Figure 2-4 USGS LOADEST Predictions for TP (2006 to 2007) at Ellerbe Creek Downstream of the North Durham WWTP Using Daily Flows

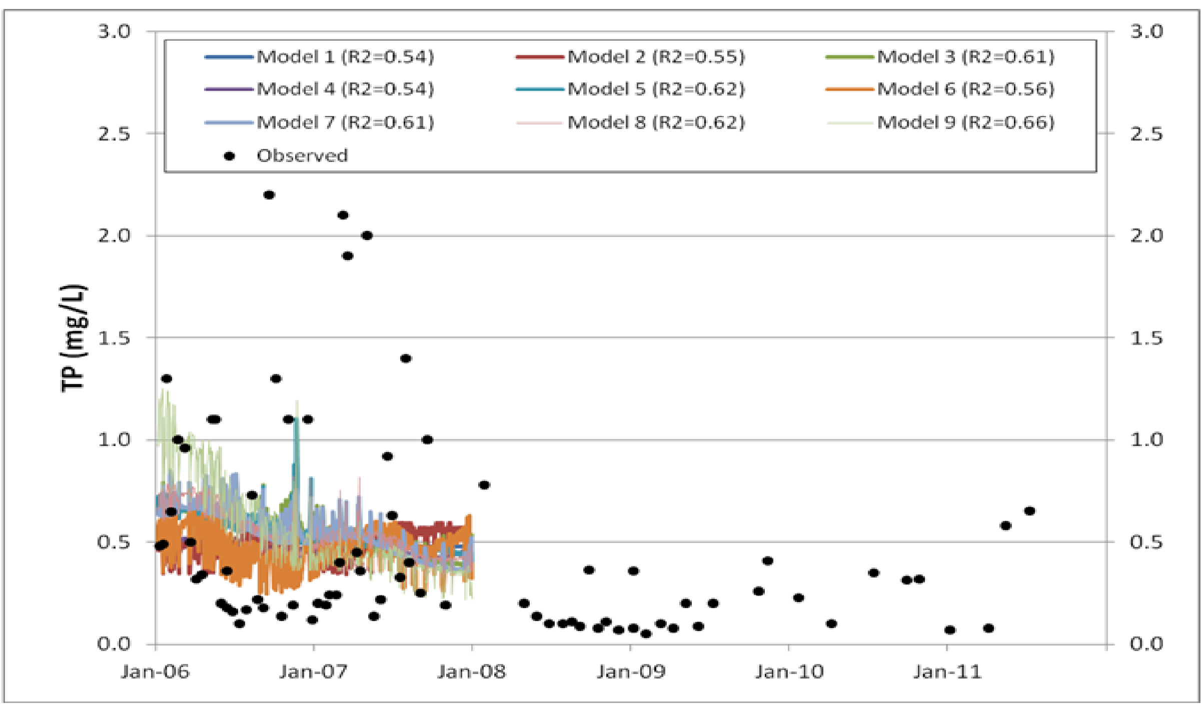

Figure 2-5 USGS LOADEST Predictions for TP (2006 to 2007) at Ellerbe Creek Downstream of the North Durham WWTP Using 15-Minute Flows

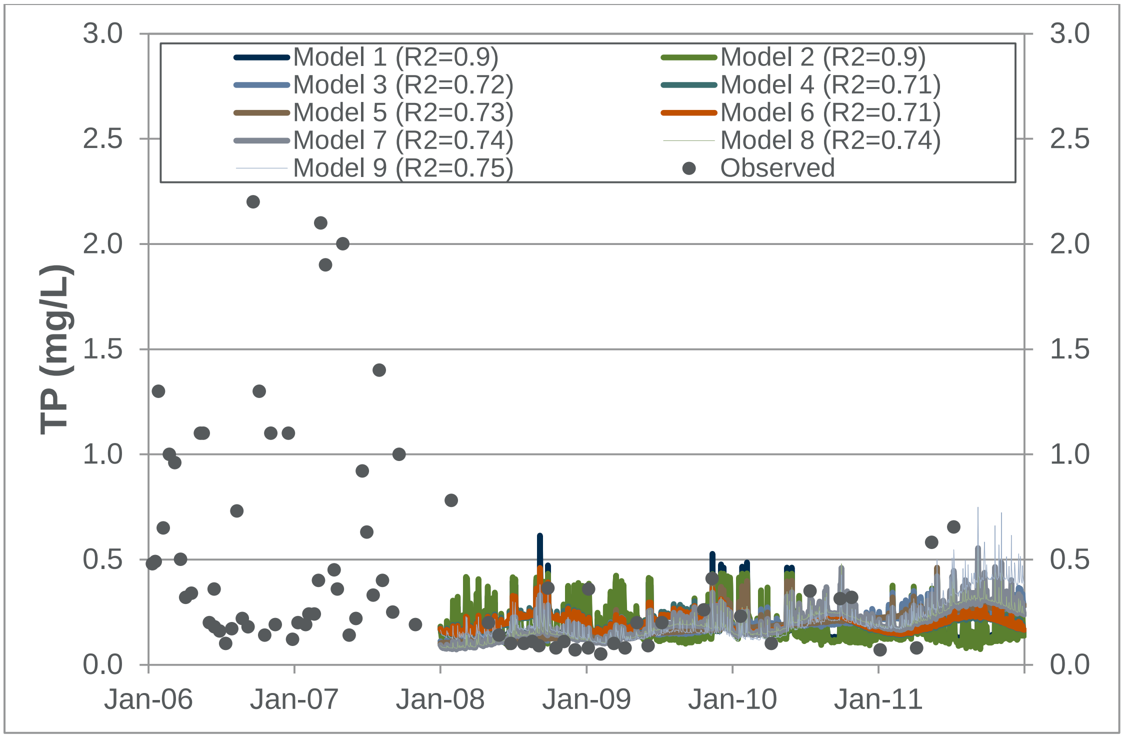

Figure 2-6 USGS LOADEST Predictions for TP (2008 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using Daily Flows

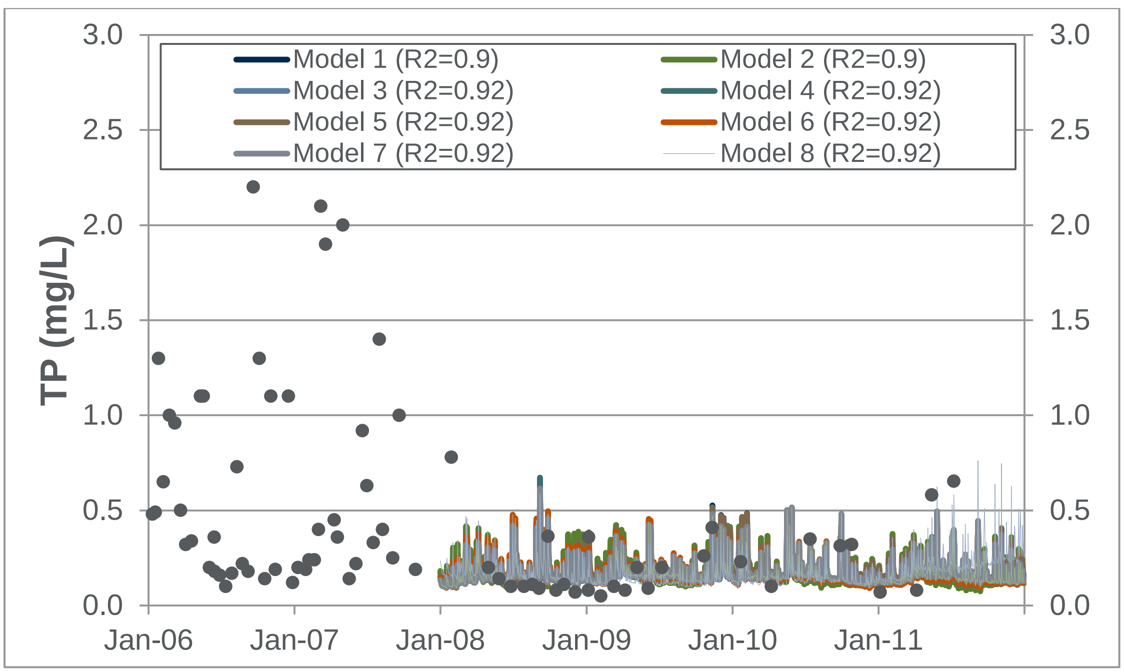

Figure 2-7 USGS LOADEST Predictions for TP (2008 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using 15-Minute Flows

2.1.2 Total Nitrogen

Total nitrogen regressions for Ellerbe Creek are shown in Figure 2-8 and Figure 2-9 using daily or 15-minute flows, respectively, for the full period of record (2006 to 2011). The 15 minute flows result in higher R^2 values compared to the daily flows. Split data set models were also developed for total nitrogen. Because total nitrogen concentrations did not have the same level decline relative to the total phosphorus concentrations, the R^2 values split models (2006 to 2007 and 2008 to 2011) are similar to the full period of record (Appendix A).

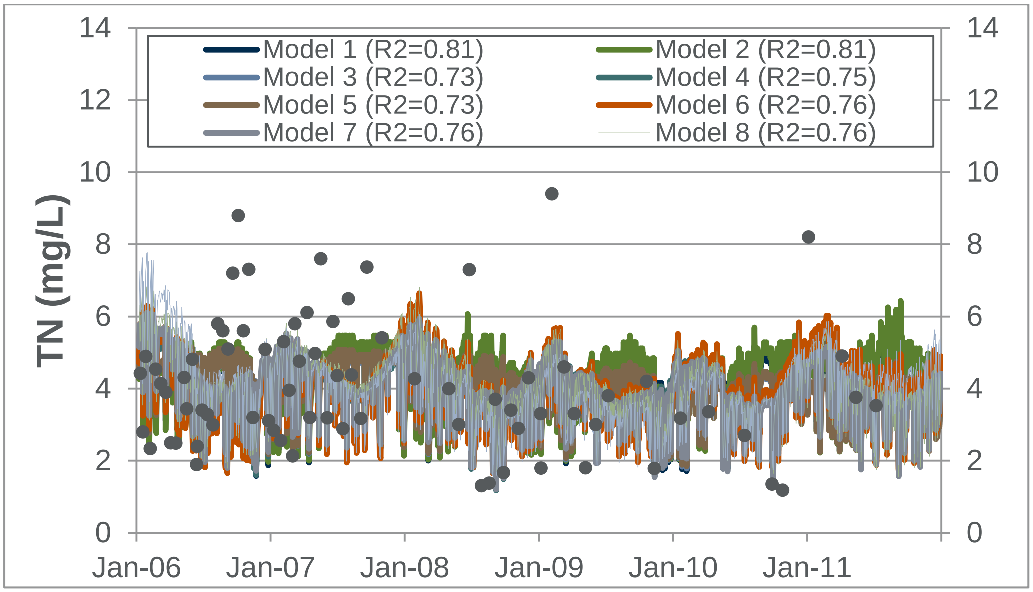

Figure 2-8 USGS LOADEST Predictions for TN (2006 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using Daily Flows

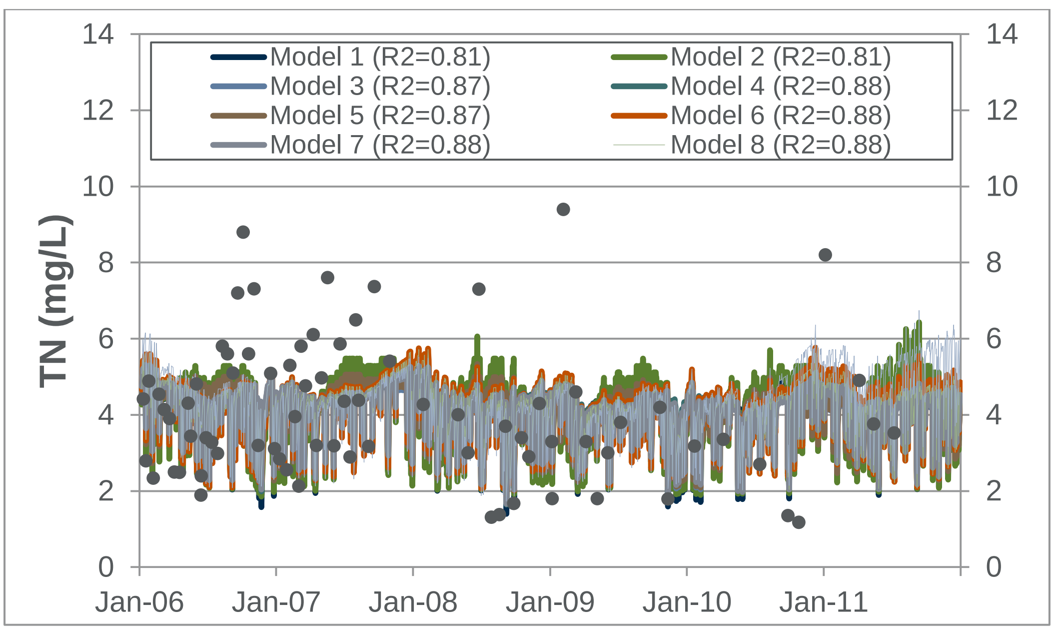

Figure 2-9 USGS LOADEST Predictions for TN (2006 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using 15-Minute Flows

2.2 LOADEST Results for the Other Upper Lake Tributaries

The LOADEST models were also developed for the other four upper lake tributaries to assess the impact of pairing observed water quality samples with either daily or 15-min flows. It is noted that the selection of the "best" LOADEST model involves multiple factors to reach a final decision. Since this effort is aimed at comparison of existing modeling and loading from the perspective of monitoring design, this is not a complete review of the application of the best LOADEST model configuration. As the UNRBA Re-Examination effort moves from monitoring program design into the application of the data for modeling and analysis work, new modeling based on LOADEST predictions should do a more complete evaluation of selecting the most appropriate configuration of the 9 LOADEST options. This should include generation and review of Nash-Sutcliffe coefficient, multiple bias indicators, and other adjustments that would improve ability to evaluate the best LOADEST equation to use for calculating daily model inputs.

Table 2-3 lists the highest R^2 values of the nine LOADEST models for the daily and 15-minute flow regressions. Using 15-minute flows for these tributaries did not significantly impact the model fit. Appendix A presents the results for each of the nine models as time series plots compared to observed values.

It is noted that the selection of the "best" LOADEST model involves multiple factors to reach a final decision. Since this effort is aimed at comparison of existing modeling and loading from the perspective of monitoring design, this is not a complete review of the application of the best LOADEST model configuration. As the UNRBA Re-Examination effort moves from monitoring program design into the application of the data for modeling and analysis work, new modeling based on LOADEST predictions should do a more complete evaluation of selecting the most appropriate configuration of the 9 LOADEST options. This should include generation and review of Nash-Sutcliffe coefficient, multiple bias indicators, and other adjustments that would improve ability to evaluate the best LOADEST equation to use for calculating daily model inputs.

Table 2-3 Comparison of LOADEST Regression Models Using Daily or 15-Minute Flows at Four Upper Lake Tributaries

Waterbody	Highest R^2 Value for Phosphorus Using Daily Flows	Highest R^2 Value for Phosphorus Using 15-minute Flows	Highest R^2 Value for Nitrogen Using Daily Flows	Highest R^2 Value for Nitrogen Using 15-minute Flows
Eno River	0.93	0.93	0.96	0.96
Flat River	0.99	0.99	0.99	0.99
Knap of Reeds Creek	NA	NA	0.48	0.46
Little River	0.9	0.9	0.98	0.98

NOTE: LOADEST did not generate reasonable results for total phosphorus at Knap of Reeds Creek, and further analysis will be required to determine if LOADEST can be used for this input, or if another method will be more accurate.

3 Sensitivity of Lake Response

Cardno ENTRIX obtained the Falls Lake Nutrient Response Model using the Environmental Fluid Dynamics Code (EFDC) model (NCDENR 2009). During previous work, Cardno ENTRIX identified several data gaps and assumptions that indicate that revisions to the lake model following collection of additional water quality data will likely support the re-examination process. To date, no revisions to the water quality simulations using the Falls Lake Nutrient Response Model have been conducted, and the model remains the best available tool to test the lake's response to variations in nutrient loading. After the model inputs are revised and the model is recalibrated, the lake will likely respond differently in terms of simulated lake water quality. To support the monitoring design plan, the existing version of the Falls Lake Nutrient Response Model was used to test the model sensitivity to various input configurations to help address the following questions:

How sensitive is the existing lake response model to inputs from the upper, middle and lower lake tributaries? Is the model particularly sensitive to inputs from specific tributaries that may require a greater frequency of water quality sampling in the UNRBA monitoring program?

Given the boundary conditions and input parameters used for the existing Falls Lake Nutrient Response Model, does the USACE BATHTUB model predict a similar degree of sensitivity to variations in tributary loading?

How sensitive is the Falls Lake Nutrient Response Model to the data input timestep (hourly versus daily)?

How sensitive is the Falls Lake Nutrient Response Model to the load estimation method (interpolation between samples versus LOADEST predictions)?

These questions are addressed with modeling scenarios in Sections 3.1 through 3.4, respectively. Figure 3-1 shows the EFDC modeling grid and the corresponding in lake monitoring stations, some of which are used as output locations for these sensitivity analyses.

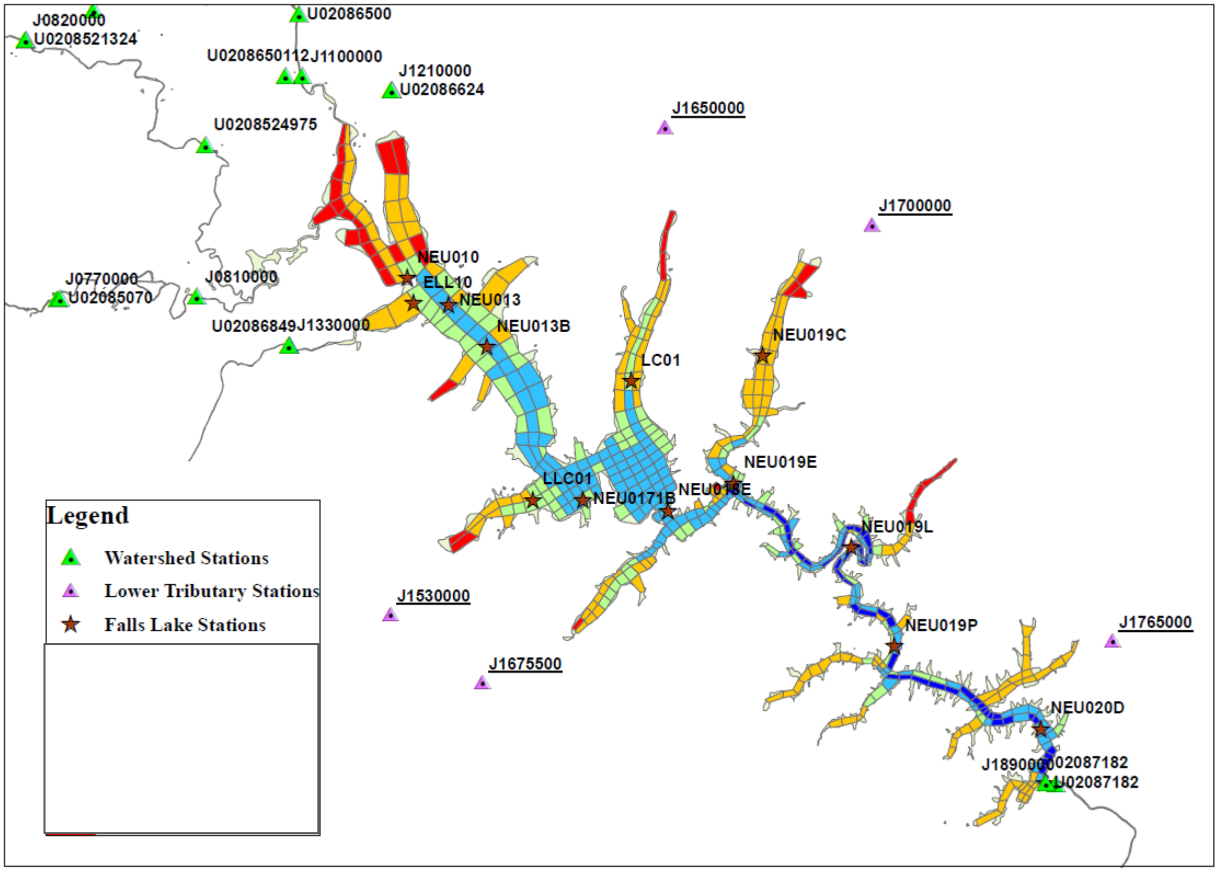

Figure 3-1 EFDC Modeling Grid and In Lake Monitoring Stations (From NCDENR 2009)

3.1 EFDC Model Sensitivity to Tributary Chlorophyll *a* Concentrations

Cardno ENTRIX previously evaluated the EFDC modeling sensitivity to tributary chlorophyll *a* concentrations. The results of those analyses were presented in the Task 4 TM (2013), and are repeated in this TM to present all of the existing model sensitivity analyses in one location.

As mentioned previously, when NCDWQ developed the lake response model using EFDC, there were no chlorophyll *a* data collected at the mouths of the tributaries. To provide an input for the time series for each tributary, NCDWQ assumed that the chlorophyll *a* concentration at the mouth of each tributary was equal to observations collected at the nearest lake station. For example, concentrations observed in the Ellerbe arm of the lake (ELL10) were used to represent tributary concentrations for Ellerbe Creek and values observed at the station near the dam (NEU020D) were used to represent tributary concentrations for Horse Creek and Honeycutt Creek. This assumption not only affects model development and calibration, but also the simulated response to nutrient reductions. Additionally, as nitrogen and phosphorus reductions were assumed in the watershed as a result of Stage I and Stage II implementation, the chlorophyll *a* inputs to the lake were not altered (neither were TOC or TSS). It is expected that nutrient reductions in the tributaries would also reduce chlorophyll *a* concentrations in the tributaries. In-Lake chlorophyll *a* concentrations predicted by the model are sensitive to tributary chlorophyll *a* levels. Maintaining the baseline tributary chlorophyll *a* concentrations results in higher lake chlorophyll *a* concentrations relative to what would be expected with reduced nutrient loading.

To compare the impacts of the tributary chlorophyll *a* concentrations on simulated chlorophyll *a* concentrations at the compliance point (NEU013B), Cardno ENTRIX ran four scenarios with the 2006 EFDC model: baseline, Stage I reductions, baseline with tributary chlorophyll *a* concentrations set to 10 µg/L continuously, and Stage I reductions with tributary chlorophyll *a* concentrations set to 10 µg/L continuously. The results are shown in Figure 3-2. The model shows that in 2006, there was a spring bloom in early May. Through the remainder of that year, chlorophyll *a* concentrations remained above the standard 40 µg/L until late December and were greater than that standard 52 percent of the time (baseline). With Stage 1 reductions, the concentrations would have been slightly less with concentrations greater than the standard one-third of the time. If chlorophyll *a* concentrations were held to a constant 10 µg/L throughout the year at year 2006 nutrient loading levels, the standard would be exceeded at NEU013B 35 percent of the time. A combination of Stage 1 reductions and chlorophyll *a* concentrations at 10 µg/L reduced the concentration during the spring bloom and throughout the summer with the standard only consistently being exceeded starting in October. Simulated percent exceedance at the compliance point is 20 percent of the time for this scenario. Thus the model is highly sensitive to the assumption regarding tributary chlorophyll *a* concentrations, and predicted exceedance varies by 15 percent for a given loading scenario.

In the following section, this TM focuses its attention on the effect of increasing nutrient loading from the tributary areas to determine how sensitive the existing model is to significant increases in nutrient loading. As just noted, the existing model predictions in the lake, with its current calibration, are very sensitive to chlorophyll *a* tributary input levels. Figure 3-2 shows that the model is responsive to reduced chlorophyll a inputs and reduced nutrient inputs. The model is most responsive to combined reductions in chlorophyll a and nutrient inputs (Figure 3-2). It is possible that a combination of both changes in chlorophyll inputs with increases or decreases in nutrients could affect the sensitivity of the existing model. Increased model sensitivity is a critical consideration and this TM emphases the need for better chlorophyll input data to support future UNRBA sponsored model updates. A newly calibrated, verified and confirmed EFDC model with better tributary input information should allow the UNRBA's Re-Examination effort to produce a more responsive and sensitive model. The importance of securing better chlorophyll *a* data for the free-flowing areas of the tributaries has been confirmed by the previous work done (TM 4, 2013) and must be a crucial component of the UNRBA's monitoring program and future modeling work.

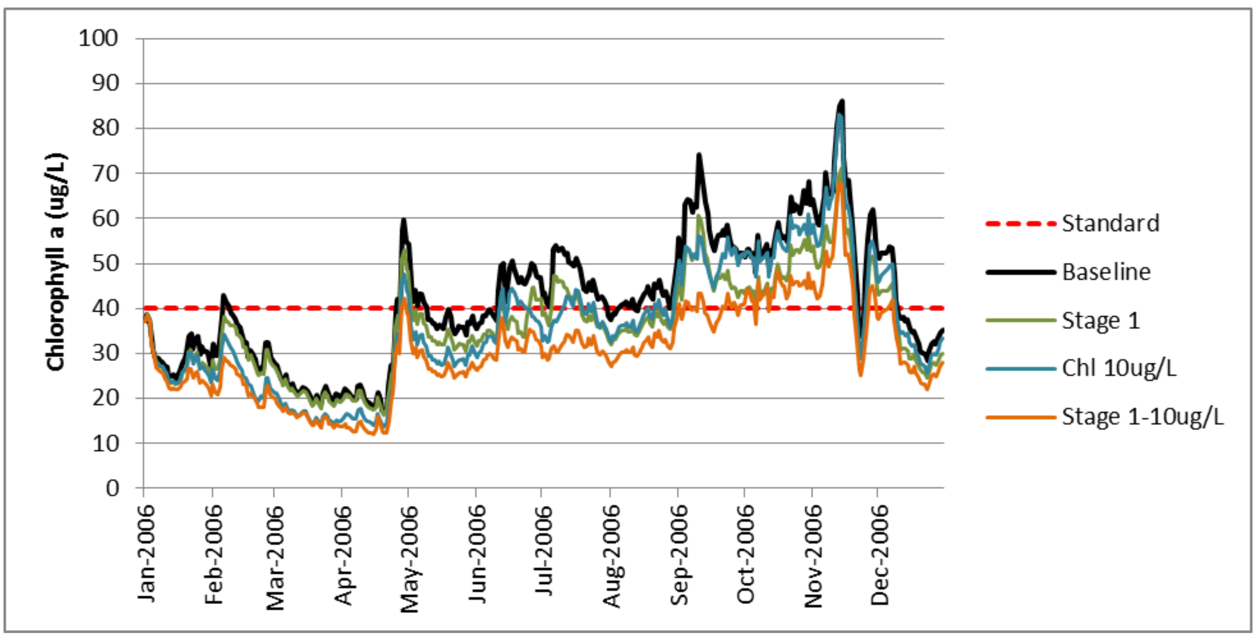

Figure 3-2 Sensitivity of the EFDC Model to Tributary Chlorophyll *a* Assumptions for Baseline and Stage I Scenarios (at NEU013B)

3.2 EFDC Model Sensitivity to Tributary Nutrient Loading

The five upper lake tributaries to Falls Lake are well represented in terms of flow and water quality monitoring data. The middle and lower lake tributaries have less water quality data and no existing USGS flow gages (Cardno ENTRIX 2012). A key question with respect to the monitoring program is whether or not the lake response model is sensitive to loading inputs from these smaller tributaries that have less data. To assess this sensitivity, the concentrations of nitrogen and phosphorus species in the EFDC model input files were multiplied by 1.5 to effectively increase nutrient loading by 50 percent without altering the water balance of the lake. For this assessment, each tributary input was increased individually and the other tributaries maintained at the baseline model values. Three additional scenarios were run where all of the upper lake tributaries were increased by 50 percent, all middle lake tributaries were increased by 50 percent, and all lower lake tributaries were increased by 50 percent.

The model was configured to output daily average concentrations at three stations in the lake using the 2006 modeling files: near I-85, Highway 50, and the dam. Concentrations of TOC, TN, and TP, were averaged over the water column. For chlorophyll *a*, concentrations were output for the top layer only. Appendix B presents the distribution of daily average concentrations as box plots and tables of summary statistics. The TOC results are presented because it is an important water quality parameter that influences water treatment performance, but since there is so little TOC data the uncertainties in the predictions are much higher than for other parameters where we have more data. The accuracy of TOC predictions and loading estimates will improve over time as the UNRBA monitoring program collects TOC data within the Falls Lake watershed.

The results for chlorophyll *a* at the three assessment points are included in this section. The various tributaries are ordered upstream to downstream (left to right), with the baseline version of the model (using the NCDWQ year 2006 input files) shown at the far left. On the boxplots, endcaps or whiskers represent the minimum and maximum simulated daily average concentrations with the 25th, 50th, and 75th percentiles shown as the lower end, the solid black line, and upper end of the box, respectively. The mean is marked by a green dot, and the 90th percentile is shown as a red line. The chlorophyll *a* discussion focuses on the 90th percentile concentration because this statistic is comparable to the State water quality standard for chlorophyll *a*. For this parameter, the predicted number of days exceeding the chlorophyll *a* standard is also presented for each assessment point.

3.2.1 <u>Model Sensitivity Downstream of I-85</u>

Figure 3-3 is a boxplot of predicted chlorophyll *a* concentrations downstream of I-85 (at NCDWR monitoring station NEUSE 013B). Under baseline conditions, the simulated 90th percentile chlorophyll *a* concentration is 61 µg/L (Table 3-1). Increases in loading of 50 percent from Ellerbe Creek and Knap of Reeds Creek cause the greatest increase in the simulated 90th percent concentration (73 µg/L and 64 µg/L, respectively). These two tributaries also cause the greatest increase in the number of days that the model predicts that the chlorophyll *a* concentration to exceed 40 µg/L (Figure 3-4). As expected, increases in loading of 50 percent at other individual tributaries, particularly those downstream of I-85, do not significantly affect simulated concentrations at this assessment point. Only in a hydrodynamic situation where flow was moving back upstream (such as in a tidal environment) would you expect downstream loading to influence upstream water quality.

To test the sensitivity of the model to cumulative increases in nutrient loading, model runs were also performed where all tributaries in the upper, middle, or lower part of the lake are increased by 50 percent. This analysis is more relevant at the middle and lower lake assessment points, but results are presented for the upper lake assessment point as well. Increasing nutrient loading from all five upper lake tributaries results in a predicted 90th percentile concentration of 81 µg/L.

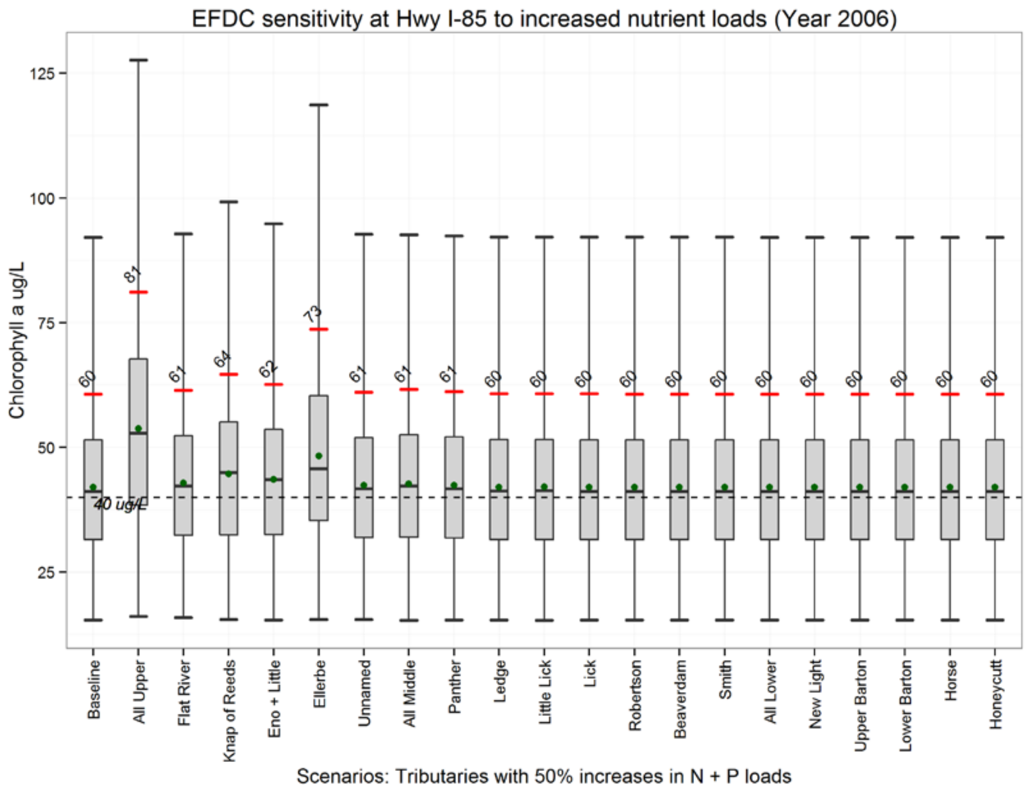

Figure 3-3 Box Plots of Predicted Chlorophyll a Concentrations downstream of I-85 Under Various Tributary Loading Scenarios

Table 3-1 Summary Statistics for Predicted Daily Average Chlorophyll *a* in the Top Layer downstream of I-85

Scenario	Minimum	25th percentile	Median	75th percentile	90th percentile	Maximum
Baseline	15.4	31.5	41.1	51.5	60.7	92.1
All Upper	16.1	38.4	52.8	67.7	81.1	127.6
Flat River	15.8	32.3	42.2	52.4	61.5	92.7
Knap of Reeds	15.5	32.5	44.9	55.1	64.7	99.2
Eno + Little	15.4	32.6	43.5	53.6	62.6	94.8
Ellerbe	15.5	35.4	45.7	60.3	73.6	118.6
Unnamed	15.5	31.9	41.7	51.9	61.1	92.7
All Middle	15.3	32.0	42.2	52.5	61.6	92.6
Panther	15.4	31.8	41.7	52.1	61.1	92.4
Ledge	15.4	31.5	41.2	51.6	60.7	92.1
Little Lick	15.3	31.5	41.3	51.6	60.7	92.1
Lick	15.4	31.5	41.2	51.5	60.7	92.1
Robertson	15.4	31.5	41.1	51.5	60.7	92.1
Beaverdam	15.4	31.5	41.1	51.5	60.7	92.1
Smith	15.4	31.5	41.1	51.5	60.7	92.1
All Lower	15.4	31.5	41.1	51.5	60.7	92.1
New Light	15.4	31.5	41.1	51.5	60.7	92.1
Upper Barton	15.4	31.5	41.1	51.5	60.7	92.1
Lower Barton	15.4	31.5	41.1	51.5	60.7	92.1
Horse	15.4	31.5	41.1	51.5	60.7	92.1
Honeycutt	15.4	31.5	41.1	51.5	60.7	92.1

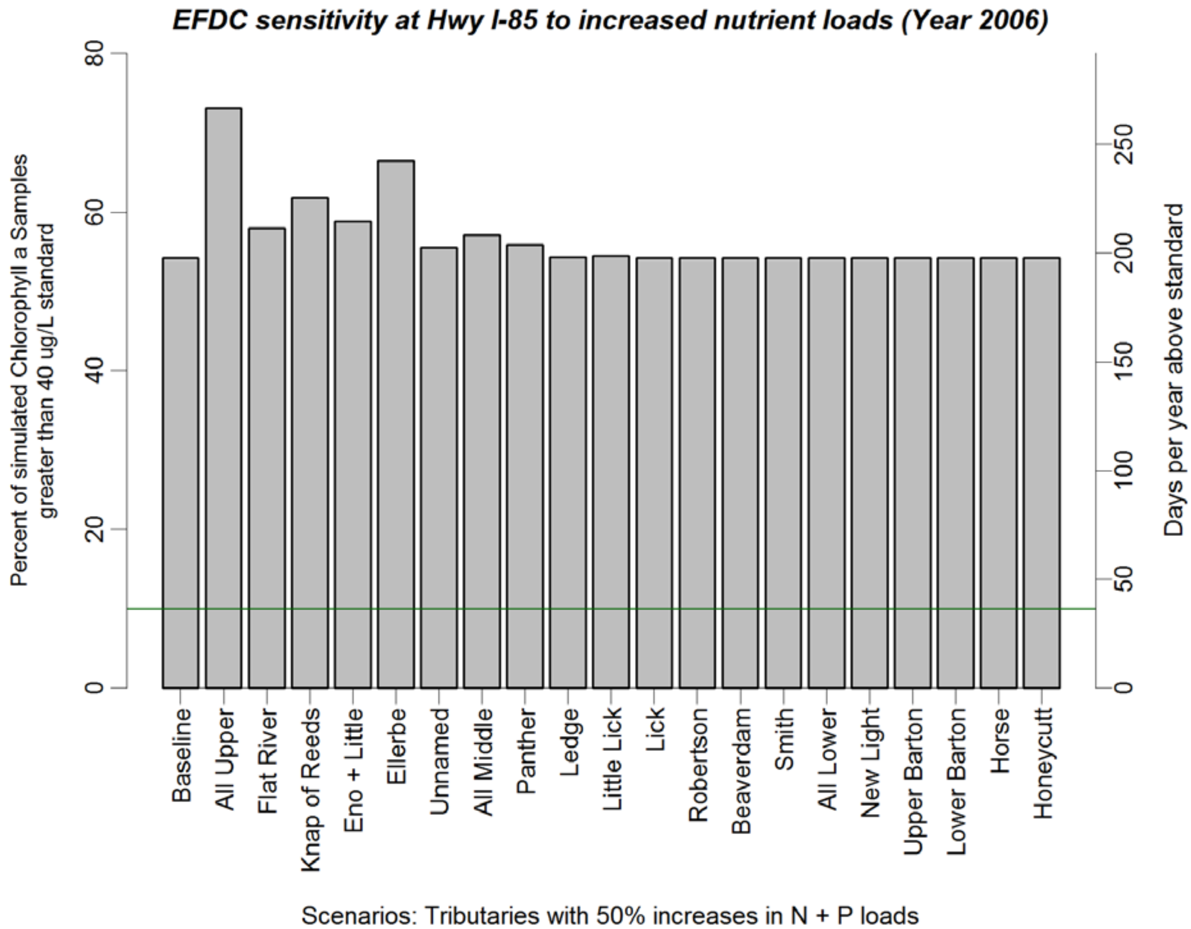

Figure 3-4 Number of Days and Percent of Days When Predicted Chlorophyll a Concentrations downstream of I-85 Exceeds the Water Quality Criterion Under Various Tributary Loading Scenarios

3.2.2 Model Sensitivity at Highway 50

Under the baseline scenario where nutrient loads from all tributaries were held at 2006 levels, the simulated 90th percentile concentration at Highway 50 is 34 µg/L (Figure 3-5 and Table 3-2). The individual tributary with the greatest impact on simulated chlorophyll *a* at this assessment point is Ellerbe Creek where an increase in loading of 50 percent results in a 90th concentration of 38 µg/L and results in the greatest increase in number of non-compliant days (Figure 3-6).

The only scenario that caused a compliance issue relative to the 90th concentration was increasing nutrient loading by 50 percent in all of the upper lake tributaries (42 µg/L). Even increasing all of the middle lake tributaries by 50 percent only raised the 90th percentile relative to baseline levels by 1 µg/L. This indicates that having a larger degree of uncertainty with respect to the loading from the middle lake tributaries compared to the upper lake tributaries is likely acceptable, at least with the current version of the lake response model.

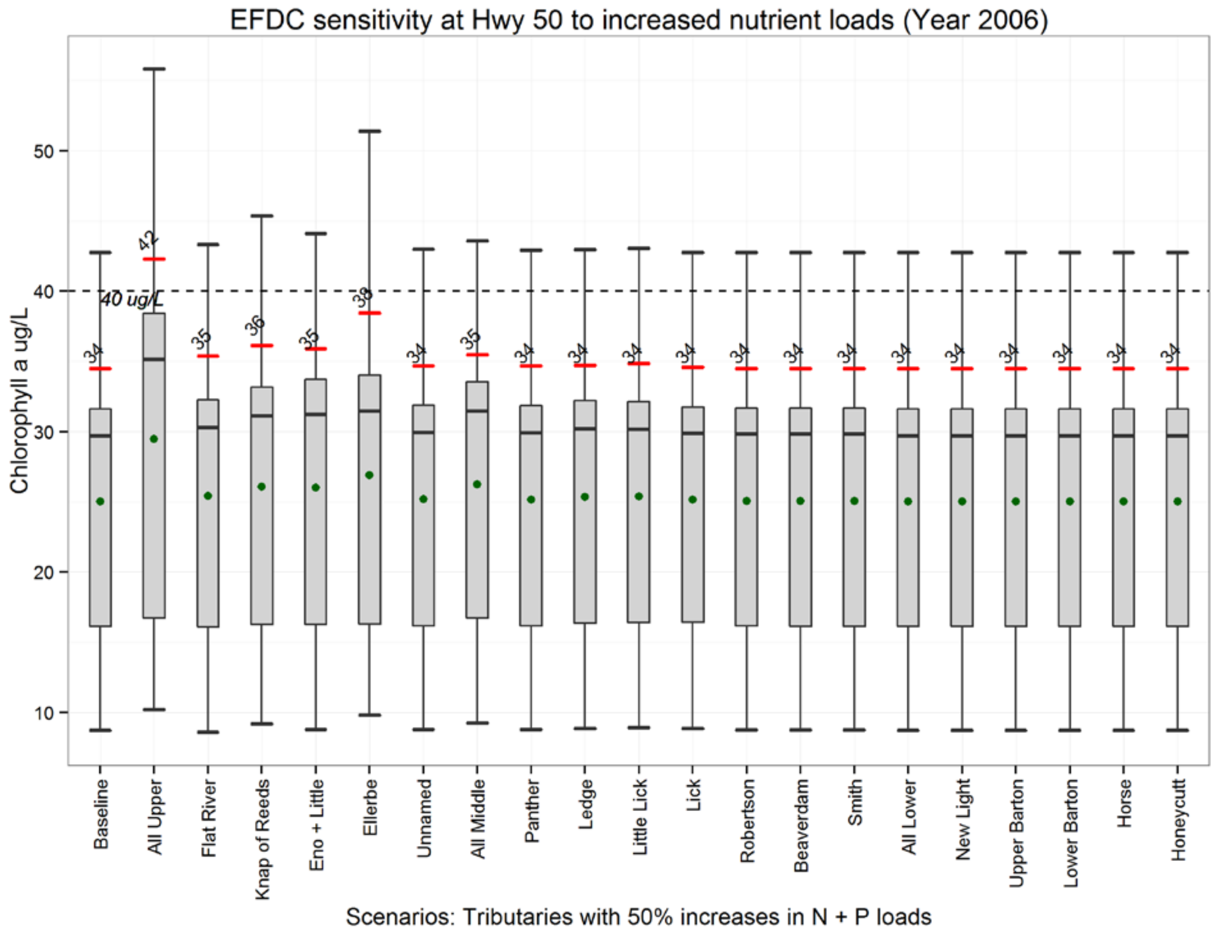

Figure 3-5 Box Plots of Predicted Chlorophyll a Concentrations at Highway 50 Under Various Tributary Loading Scenarios

Table 3-2 Summary Statistics for Predicted Daily Average Chlorophyll *a* in the Top Layer at Highway 50

Scenario	Minimum	25th percentile	Median	75th percentile	90th percentile	Maximum
Baseline	8.7	16.1	29.7	31.6	34.5	42.8
All Upper	10.2	16.7	35.1	38.4	42.3	55.8
Flat River	8.6	16.1	30.3	32.3	35.4	43.3
Knap of Reeds	9.2	16.3	31.1	33.2	36.1	45.4
Eno + Little	8.8	16.3	31.2	33.7	35.9	44.1
Ellerbe	9.8	16.3	31.4	34.0	38.4	51.4
Unnamed	8.8	16.2	29.9	31.9	34.7	43.0
All Middle	9.2	16.7	31.4	33.6	35.5	43.6
Panther	8.8	16.1	29.9	31.8	34.7	42.9
Ledge	8.8	16.4	30.2	32.2	34.7	43.0
Little Lick	8.9	16.4	30.2	32.1	34.8	43.0
Lick	8.9	16.4	29.9	31.7	34.6	42.8
Robertson	8.7	16.1	29.8	31.7	34.5	42.8
Beaverdam	8.7	16.1	29.8	31.7	34.5	42.8
Smith	8.7	16.1	29.8	31.7	34.5	42.8
All Lower	8.7	16.1	29.7	31.6	34.5	42.8
New Light	8.7	16.1	29.7	31.6	34.5	42.8
Upper Barton	8.7	16.1	29.7	31.6	34.5	42.8
Lower Barton	8.7	16.1	29.7	31.6	34.5	42.8
Horse	8.7	16.1	29.7	31.6	34.5	42.8
Honeycutt	8.7	16.1	29.7	31.6	34.5	42.8

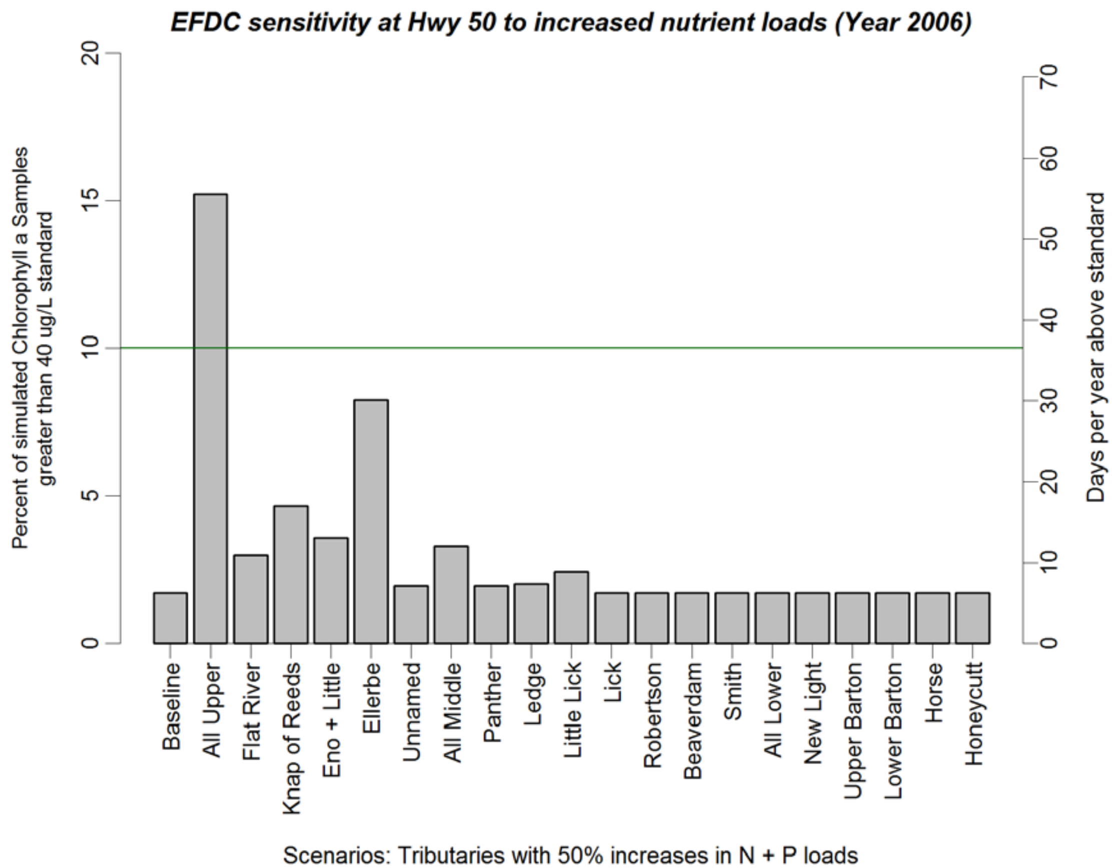

Figure 3-6 Number of Days and Percent of Days When Predicted Chlorophyll a Concentrations at Highway 50 Exceeds the Water Quality Criterion Under Various Tributary Loading Scenarios

3.2.3 Model Sensitivity at the Falls Lake Dam

The model results at the dam are rather insensitive to increased upstream nutrient loading (Figure 3-7, Table 3-3, and Figure 3-8). This result is not surprising considering that biological activity occurs from the time the tributary flow enters the lake until it reaches the lower lake results in conversion of nitrogen and phosphorus. The farther a drainage area and entrance point of a drainage area is from the lower lake the more likely that biological and chemical action as flow moves through the lake would reduce the potential of the nutrient inputs to affect the lower lake, at least during that real-time period (cycling of nutrients can result in ongoing impacts). Under baseline conditions, the 90th percentile concentration is 28 µg/L. Increasing nutrient loading from all upper, middle, or lower tributaries only increases the 90th percentile value to 30 µg/L or 31 µg/L. The model is likely less sensitive to increases in loading at this assessment point for the following reasons:

> The majority of the nutrient loading entering the lake originates from the five upper lake tributaries. By the time these loads travel to the lower end of the lake, they have been largely removed from the water column by sedimentation and uptake in the upper and middle sections of the lake. Even when loads from these tributaries are increased by 50 percent, the processes that occur along the length of the lake mitigate those simulated increases.

> The nutrient loading from the lower tributaries is relatively small compared to the pool of water that is present in the lower section of the lake.

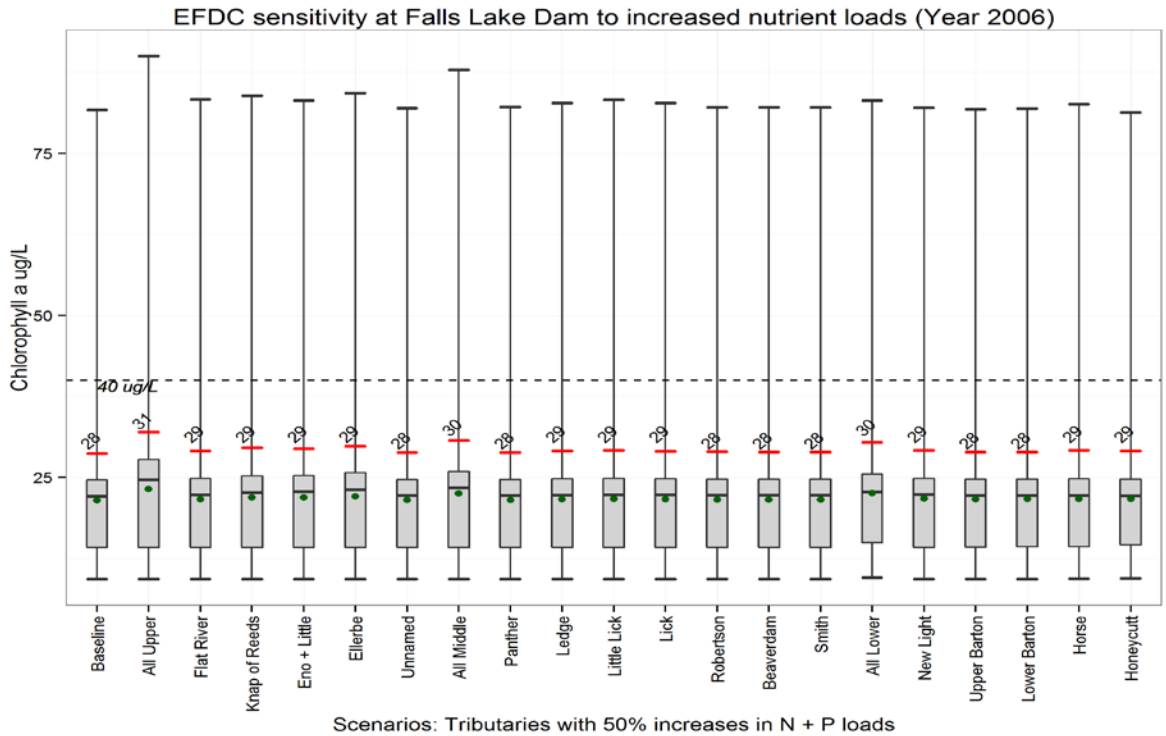

Figure 3-7 Box Plots of Predicted Chlorophyll a Concentrations at the Falls Lake Dam Under Various Tributary Loading Scenarios

It is important to note that simulated maximum daily concentrations at the dam are greater than simulated maximum concentrations observed at Highway 50 This is likely an issue with the lake response model and not a condition that is evident based on review of the water quality data collected in the lake. These questionable maximums could be a function of the hydrodynamics of the model (e.g., thermal stratification) as currently represented, the deeper waters present near the dam that result in a thicker surface layer, or the increased clarity of the water at the dam due to settling that has occurred throughout the lake. While the simulated maximums are likely erroneous, the majority of the simulated chlorophyll *a* concentrations at the dam are less than those simulated at Highway 50, and the existing tool still provides a reasonable framework for assessing lake response to increased nutrient loading for the purposes of monitoring program design.

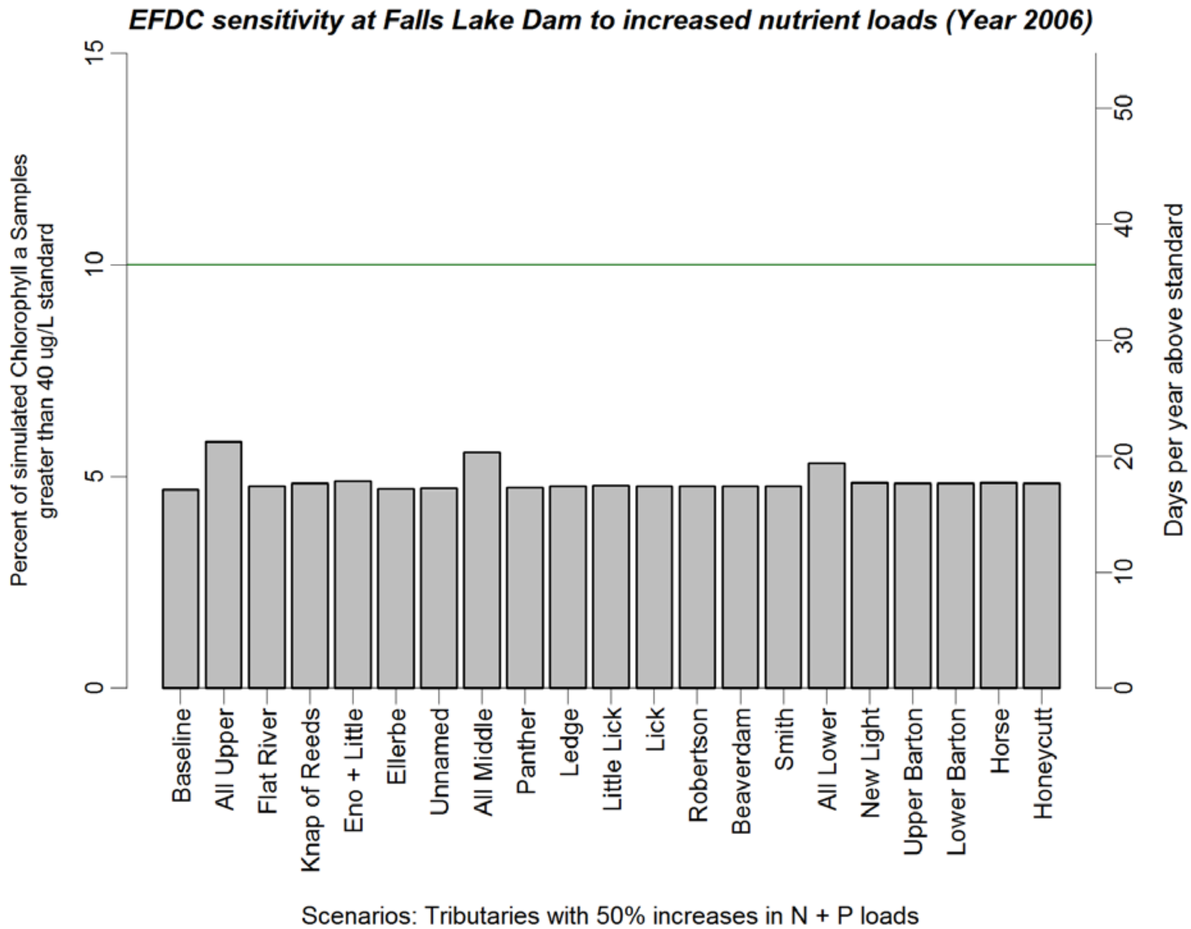

Figure 3-8 Number of Days and Percent of Days When Predicted Chlorophyll a Concentrations at Falls Lake Dam Exceeds the Water Quality Criterion Under Various Tributary Loading Scenarios

Table 3-3 Summary Statistics for Predicted Daily Average Chlorophyll *a* in the Top Layer at the Falls Lake Dam

Scenario	Minimum	25th percentile	Median	75th percentile	90th percentile	Maximum
Baseline	9.3	14.2	22.1	24.6	28.7	81.7
All Upper	9.3	14.2	24.6	27.8	32.0	90.0
Flat River	9.3	14.2	22.3	24.8	29.0	83.3
Knap of Reeds	9.3	14.2	22.6	25.2	29.5	83.9
Eno + Little	9.3	14.2	22.8	25.3	29.4	83.1
Ellerbe	9.3	14.2	23.1	25.7	29.8	84.3
Unnamed	9.3	14.2	22.2	24.7	28.8	81.9
All Middle	9.3	14.2	23.4	25.9	30.7	87.9
Panther	9.3	14.2	22.2	24.7	28.8	82.2
Ledge	9.3	14.2	22.3	24.8	29.0	82.7
Little Lick	9.3	14.2	22.3	24.8	29.1	83.3
Lick	9.3	14.2	22.3	24.8	29.0	82.7
Robertson	9.3	14.2	22.3	24.7	28.9	82.1
Beaverdam	9.3	14.2	22.3	24.7	28.9	82.1
Smith	9.3	14.2	22.3	24.7	28.9	82.1
All Lower	9.5	14.9	22.8	25.5	30.4	83.1
New Light	9.3	14.2	22.4	24.9	29.2	82.0
Upper Barton	9.3	14.2	22.2	24.7	28.9	81.8
Lower Barton	9.3	14.3	22.2	24.7	28.9	81.9
Horse	9.4	14.3	22.2	24.8	29.2	82.6
Honeycutt	9.4	14.6	22.1	24.7	29.1	81.3

3.3 BATHTUB Model Sensitivity to Tributary Nutrient Loading

Given the reservations regarding the existing Falls Lake Nutrient Response Model and the way it was set up and calibrated to very high assumed tributary chlorophyll *a* concentrations, Cardno ENTRIX used the USACE BATHTUB (Cardno ENTRIX 2013c) to provide a corroboration of the sensitivity analyses using the existing Falls Lake Nutrient Response Model described in Section 3.1. Because BATHTUB is a steady state model developed with three segments for Falls Lake, many of the tributaries were grouped together within a segment.

The USACE BATHTUB model predicts growing season average chlorophyll *a* concentrations and the percent of time during the growing season that each assessment point would exceed the 40 µg/L chlorophyll *a* standard (Table 3-4). While these numbers are not directly comparable to the sensitivity analyses using Falls Lake Nutrient Response Model, the general trends with respect to sensitivity are similar:

> Increases in nutrient loading at Ellerbe Creek have the greatest impact on simulated chlorophyll *a* values at I-85 and Highway 50 when loads from only one tributary are increased by 50 percent.

> Increasing loading from all upper lake tributaries has a greater impact on simulated chlorophyll *a* values at Highway 50 than increasing loading from all middle lake tributaries, which are closer to the Highway 50 assessment point and undergo less trapping in the lake.

> Increasing loading from any single tributary around the lake, or group of tributaries (upper, middle, and lower), has a similar impact on simulated chlorophyll a values at the dam.

> For the tributaries in the middle and lower part of the lake where relatively less data is currently collected, there is no single tributary that appears to influence simulated chlorophyll a values at Highway 50 or the dam more than any other.

Table 3-4 Predicted Growing Season Average Chlorophyll *a* Concentrations and Percent Exceedance of the Chlorophyll *a* Standard at Three Assessment Points When Nutrient Loads from Specific Tributaries are Increased by 50 Percent

Scenario	Average Chl a at I-85	Percent Exceedance at I-85	Average Chl a at Highway 50	Percent Exceedance at Highway 50	Average Chl a at Dam	Percent Exceedance at Dam
Baseline	60.5	63	30.8	19	21.1	10
All Upper	88.6	79	37.1	35	23.4	13
Flat River	65.3	67	32.0	22	21.5	11
Knap of Reeds	65.7	68	32.1	22	21.6	11
Eno + Little	67.9	69	32.6	23	21.8	11
Ellerbe	71.5	71	33.4	25	22.1	12
All Middle	60.5	63	34.0	27	22.9	13
Panther/Little Lick/Lick	60.5	63	32.9	24	21.9	11
Unnamed/Ledge/Robertson/ Beaverdam/Smith	60.5	63	31.9	22	22.1	12
All Lower	60.5	63	30.8	19	23.4	13
New Light/Horse	60.5	63	30.8	19	21.8	11
Upper Barton/Lower Barton/ Honeycutt	60.5	63	30.8	19	22.6	12

3.4 EFDC Model Sensitivity to Data Input Time step and Nutrient Concentration Estimation Method

As described in Section 2, many of the USGS gages in the watershed report both daily mean and 15-minute flows. The existing Falls Lake Nutrient Response Model uses daily mean flow and interpolated water quality concentrations between monitoring events to generate daily inputs for flow and nutrient concentrations from each tributary. To test the model sensitivity to the input format, the existing Falls Lake Nutrient Response Model was modified with inputs at a smaller time step using various methods to estimate nutrient concentrations.

The source code for the existing lake model limits the amount of data that the user can input to around 3300 time series records for flow and water quality. Thus, the current configuration could not be used to input flow and water quality at 15-minute increments for a length of time sufficient to test the model's sensitivity to input time step. To test the model sensitivity to a smaller input time step, hourly values for flow and water quality were developed and the model run for approximately 125 days.

The existing Falls Lake Nutrient Response Model was also used to test the model's response to various methods of estimating tributary nutrient concentrations. The baseline model, which linearly interpolates water quality concentrations between grab samples, was compared to three LOADEST-based predictions for Ellerbe Creek (Section 2.1). Each of the LOADEST methods relied on the same set of LOADEST regressions which were developed by pairing observed water quality with 15-minute flows. The difference in these models is in how the regression equations were used to generate the tributary concentrations (e.g., were daily flows or hourly flows input into the regression equation to generate output).

Table 3-5 summarizes the methods used to develop the flow and nutrient concentration inputs for the various model runs. The resulting year 2006 nitrogen and phosphorus loads entering the lake from Ellerbe Creek for each method are provided as well. The "Hourly LoadEst" scenario results in the smallest amount of estimated nitrogen and phosphorus loading from Ellerbe Creek, partly because the total flow volume is approximately 25 percent lower than the other scenarios. Because the other scenarios use daily flow inputs, the flow time series from the baseline model was used for each of these scenarios, and only the nutrient concentrations were altered based on the LOADEST regressions. There is a two week period in November 2006 where the flow inputs for the baseline model were much higher than the USGS estimated flows. Because the "Hourly LoadEst" scenario relies on 15-minute flows reported at the gage, the USGS flow estimates are used for that scenario, albeit averaged to hourly values. The flows and associated nutrient loads are therefore smaller for this scenario relative to the others. Among the other scenarios, the difference in loading is due to the changes in predicted nutrient concentrations only. The largest loads are estimated by the "Flow Weighted" method for total nitrogen and the "Daily LoadEst" for total phosphorus. Given the range in delivered load resulting from these various methods, it is clear that selecting the most accurate method will be an important component of the revised modeling.

Table 3-5 Summary of Methods for Ellerbe Creek EFDC Model Sensitivity Analyses and Resulting Nutrient Loading for 2006

Scenario	Flow Input	Water Quality Concentration	Volume (ac-ft/yr)	Total Nitrogen Load (lb/yr)	Total Phosphorus Load (lb/yr)
Baseline	Daily time step using USGS daily flows (with two weeks of estimated flows in November)	Daily time step based on linear interpolation between weekly to monthly grab samples	39,667	432,293	42,731
Daily LOADEST	Daily time step using USGS daily flows (with two weeks of estimated flows in November)	Daily time step based on daily flows input to the LOADEST regressions*	39,667	317,213	77,861
Hourly LOADESTt	Hourly time step calculated by averaging USGS 15-min flows	Hourly time step based on hourly flows input to the LOADEST regressions *	29,550	256,429	69,403
Flow Weighted	Daily time step using USGS daily flows (with two weeks of estimated flows in November)	Daily time step based on flow weighting the hourly time step values (see row above)*	39,667	556,062	67,300
*The LOADEST regressions for these analyses were developed by pairing observed 15-min flow data with observed water quality concentrations.					

*The LOADEST regressions for these analyses were developed by pairing observed 15-min flow data with observed water quality concentrations.

Because of the level of effort associated with these analyses, the revised inputs and evaluation of model output were only performed for the Ellerbe Creek tributary inputs and simulated concentrations in the Ellerbe arm of Falls Lake, downstream of I-85 at NEU013B, and just upstream of I-85 at NEU013. All other tributary inputs were based on the “Baseline” scenario. Based on the limitations on input data, the model can be run for approximately four months with hourly inputs; thus the “Hourly LoadEst” scenario in the graphs below stop at the end of April.

When reviewing these figures, it is important to remember that the existing version of the model was calibrated using the baseline methods (daily input time step and interpolated water quality concentrations), and no effort was made during this sensitivity analysis to recalibrate the model. This comparison is only to demonstrate how sensitive the model is to input data time step and nutrient concentration estimation method.

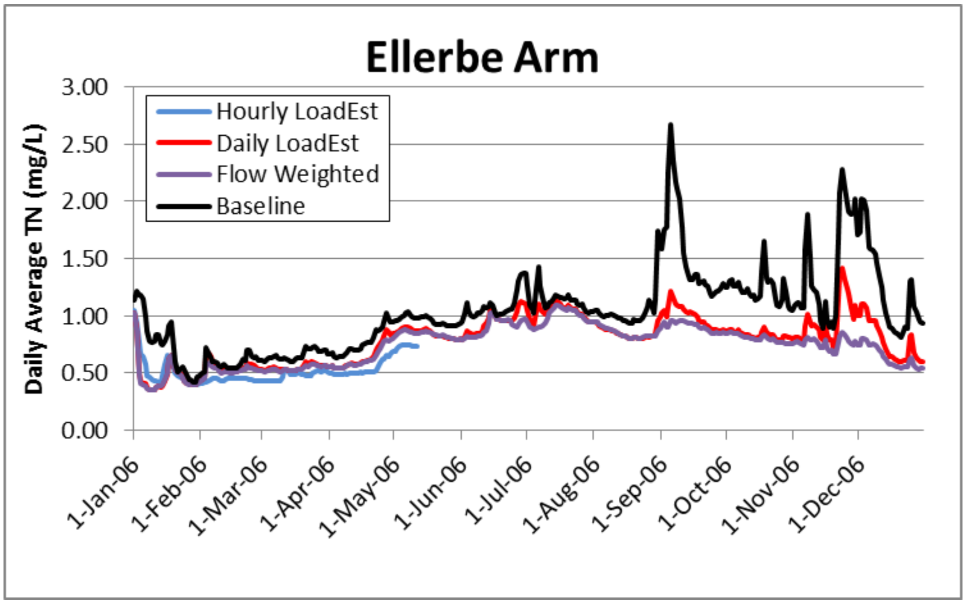

Figure 3-9 Simulated Total Nitrogen Concentrations in the Ellerbe Arm of Falls Lake Under Various EFDC Input Scenarios

Figure 3-9 through Figure 3-18 show the results of the sensitivity analyses in the Ellerbe Cove and downstream and upstream of I-85. Nitrogen and phosphorus concentrations at each assessment point are averaged over the four model layers. Chlorophyll *a* results are presented for the top layer only. The greatest differences with respect to simulated water quality occur with the baseline run. For total nitrogen and chlorophyll *a*, the baseline input methodology result in much higher concentrations in the Ellerbe arm and downstream. For total phosphorus, the simulated concentrations using the baseline methods are much lower than the other input methods. Among the LOADEST driven input scenarios, there is no consistent pattern in the simulated concentrations: during some periods for a given parameter one of the LOADEST scenarios is higher than the others and for other periods it is lower.

Given the constraints on the model runs, using either the Daily LoadEst or Flow Weighted approach would be less resource intensive when the revised model is developed. These two approaches typically yield similar results. The greatest divergence occurs in November 2006, which had a very large storm event. These two options could be considered together during preliminary model calibrations (following collection of at least one year of monitoring data) to determine which method produces the best model fit.

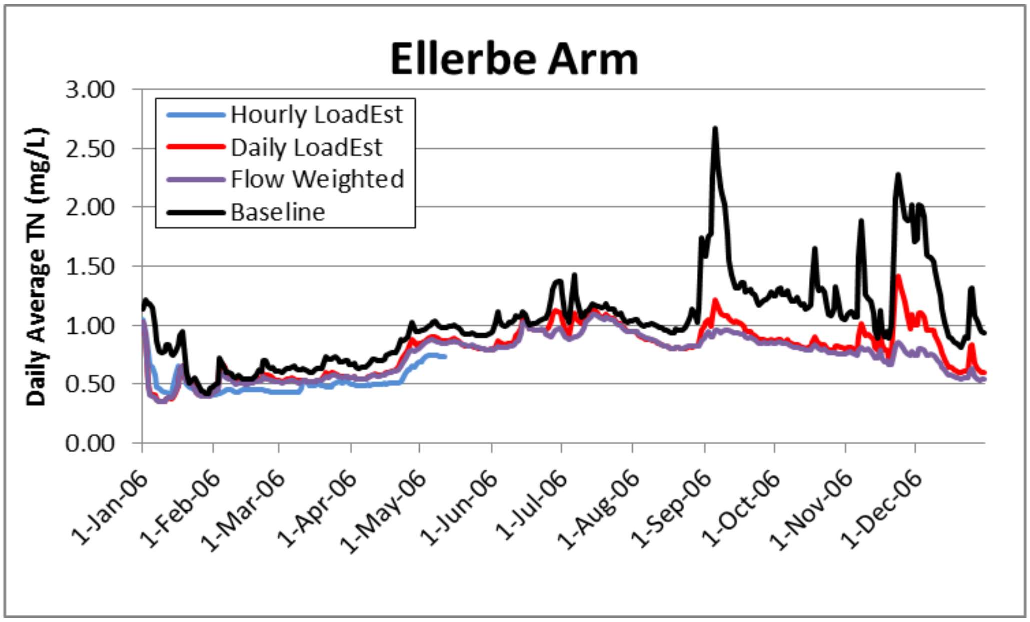

Figure 3-10 Simulated Total Nitrogen Concentrations in the Ellerbe Arm of Falls Lake Under Various EFDC Input Scenarios

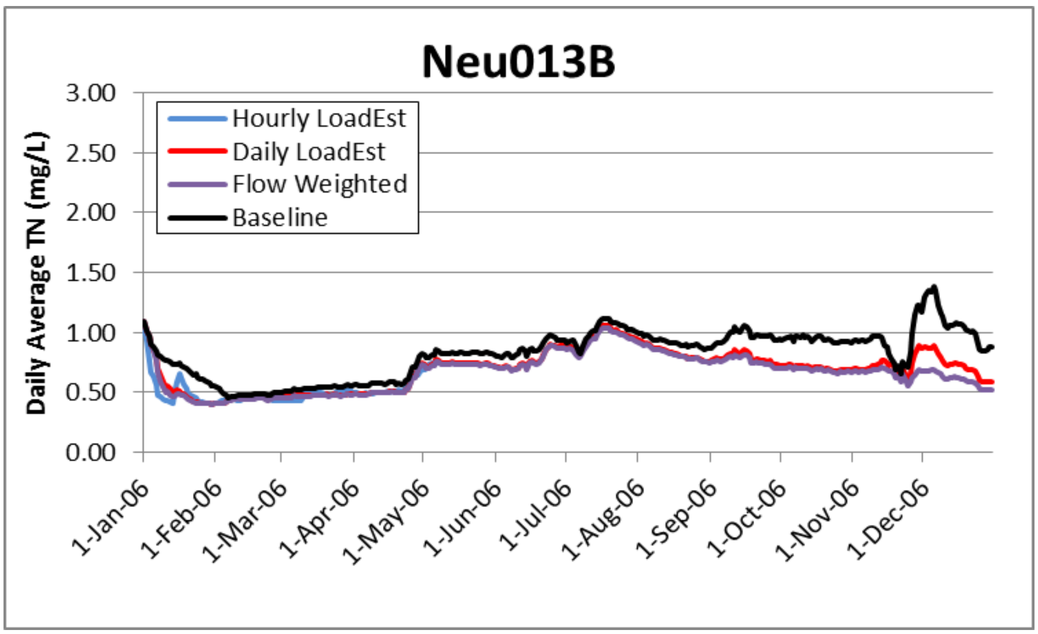

Figure 3-11 Simulated Total Nitrogen Concentrations Downstream of I-85 Under Various EFDC Input Scenarios

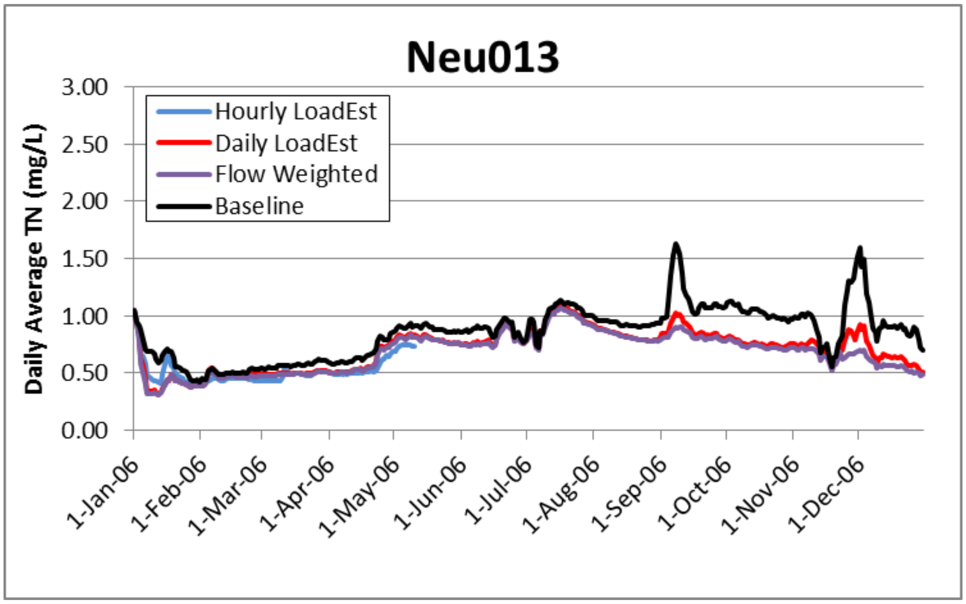

Figure 3-12 Simulated Total Nitrogen Concentrations Just Upstream of I-85 Under Various EFDC Input Scenarios

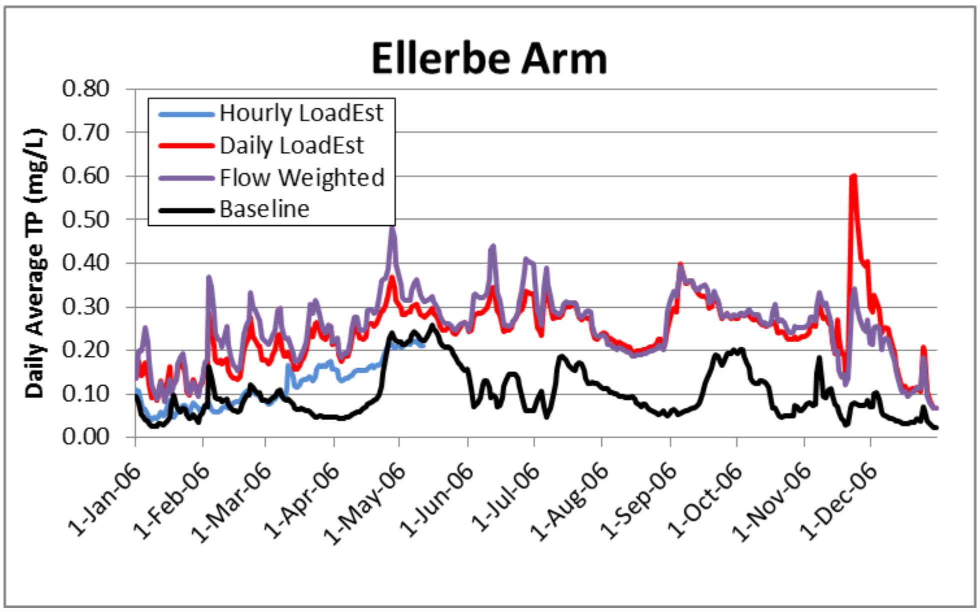

Figure 3-13 Simulated Total Phosphorus Concentrations in the Ellerbe Arm of Falls Lake Under Various EFDC Input Scenarios

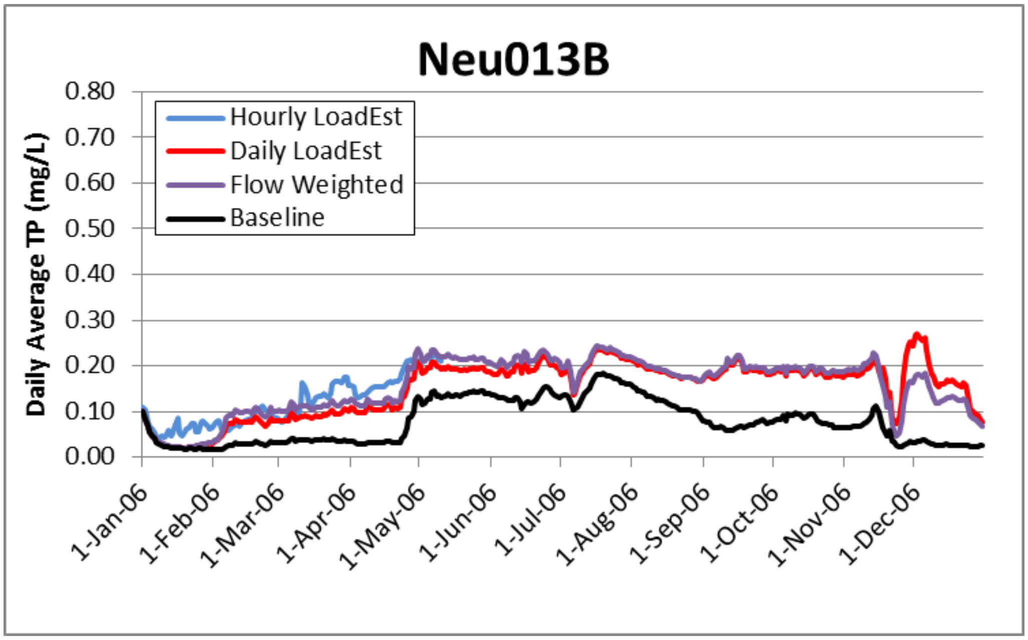

Figure 3-14 Simulated Total Phosphorus Concentrations Downstream of I-85 Under Various EFDC Input Scenarios

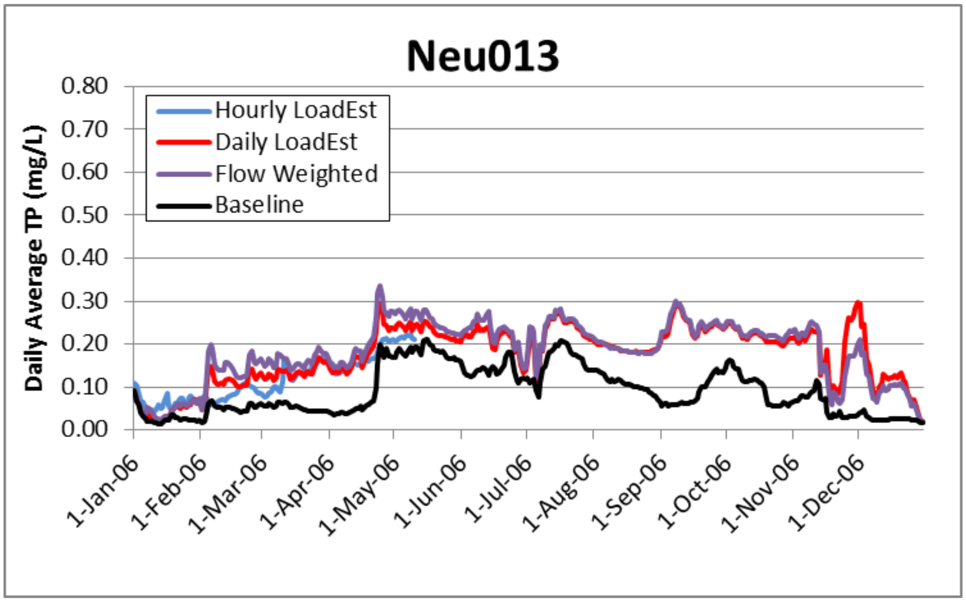

Figure 3-15 Simulated Total Phosphorus Concentrations Just Upstream of I-85 Under Various EFDC Input Scenarios

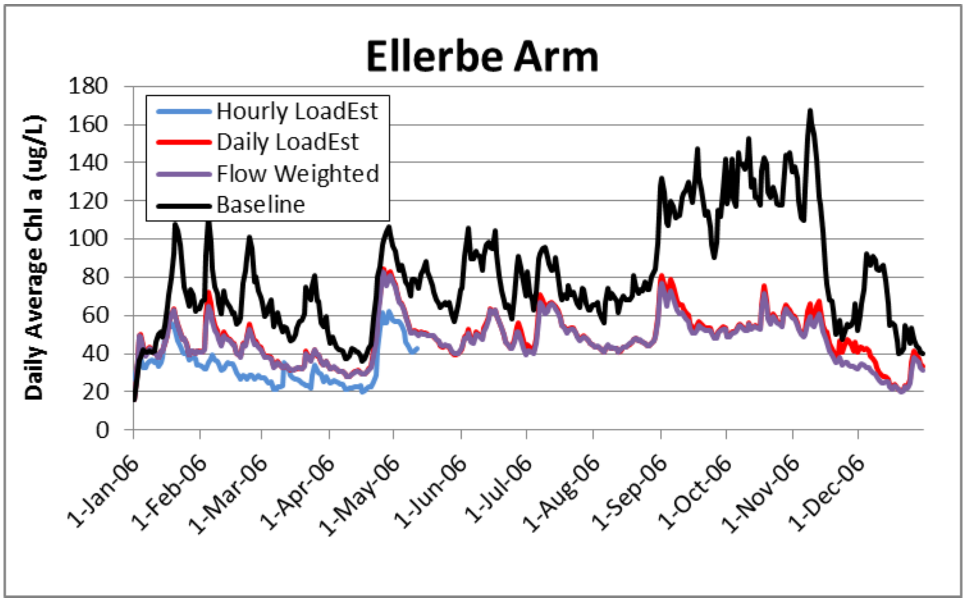

Figure 3-16 Simulated Chlorophyll a Concentrations in the Ellerbe Arm of Falls Lake Under Various EFDC Input Scenarios

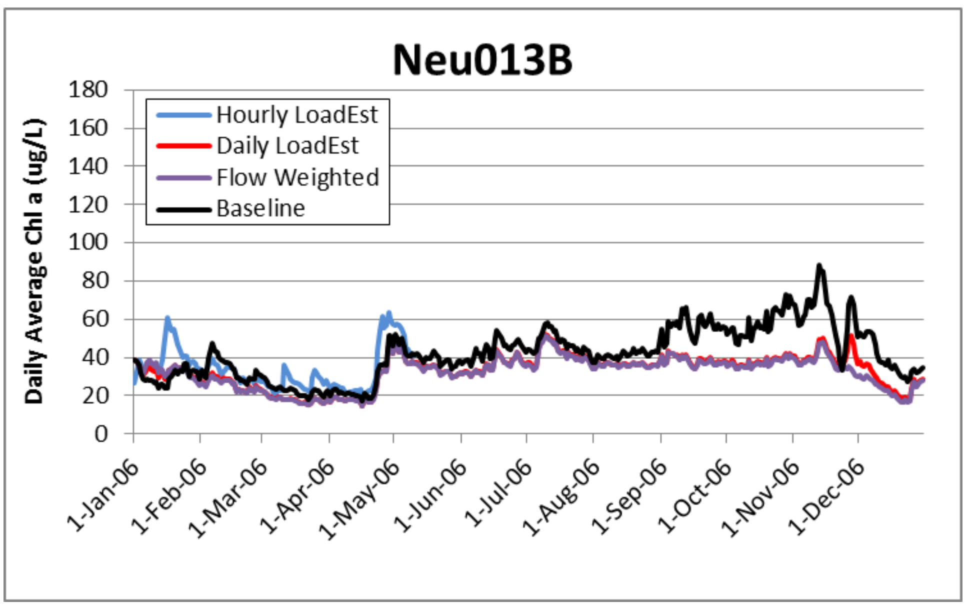

Figure 3-17 Simulated Chlorophyll a Concentrations Downstream of I-85 Under Various EFDC Input Scenarios

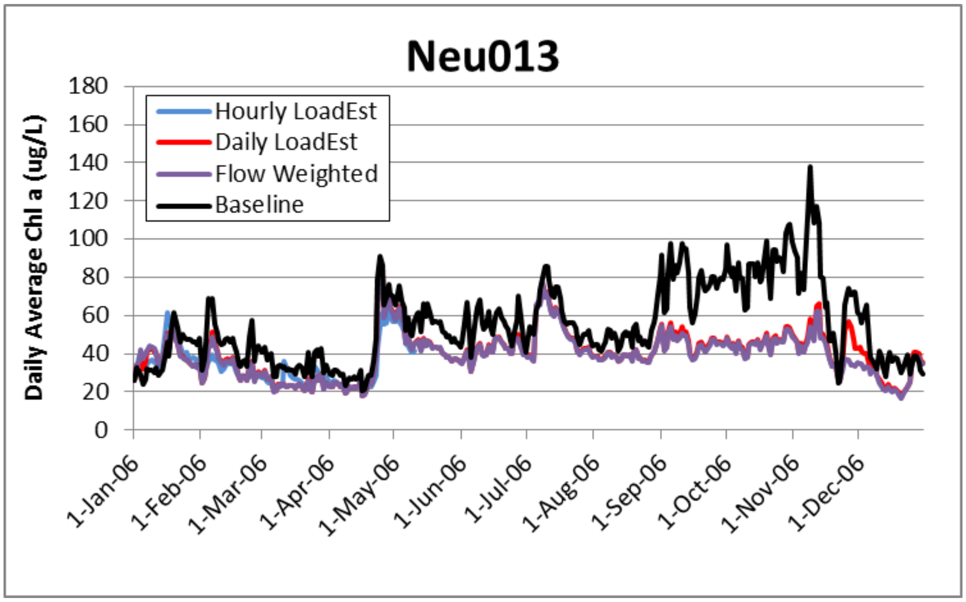

Figure 3-18 Simulated Chlorophyll a Concentrations Just Upstream of I-85 Under Various EFDC Input Scenarios

4 Summary

4.1 Implications for the Monitoring Program

This memorandum summarizes several sensitivity analyses that were conducted to answer key questions regarding the design of the monitoring program and future revisions to the lake response model. These questions are answered below.

1. **How sensitive is the model to changes in nutrient loading?**
   When nutrient loads from the upper five tributaries are increased by 50 percent, there is a measurable indicated response at the monitoring station downstream of I-85, but it is not as significant as expected from this level of load increase. The greatest impact from any single tributary results from an increase in loading at Ellerbe Creek by 50 percent. This scenario caused percent exceedance of simulated chlorophyll *a* to go from approximately 55 percent under the baseline scenario to approximately 65 percent for this scenario. Simulated reductions equivalent to Stage I requirements (20 percent for nitrogen and 40 percent for phosphorus) had a slightly greater impact with simulated percent exceedances decreasing to approximately 30 percent of the time. Because the existing model assumes that tributary chlorophyll *a* concentrations are equal to in lake observations, and these observations are sometimes very high relative to what would likely be observed in a free-flowing tributary, the existing model may not be as sensitive to changes in nutrient loading as a newly calibrated revised model may be. Further downstream in the lake, the model becomes less and less sensitive to the change in nutrient loads.

2. **Are daily flows sufficient for developing the load regression equations, or does 15-min flow data significantly improve the regression models?**

   For four of the upper lake tributaries, using 15-minute flow data does not significantly impact the LOADEST regressions (additional analyses are needed for total phosphorus in Knap of Reeds Creek as the models did not generate reasonable results). For Ellerbe Creek, however, using 15-minute flow data paired with observed water quality observations tended to increase R^2.

3. **For those locations in the watershed where flow gages are not currently present or planned for the future monitoring study, will estimates of daily flow paired with water quality sampling likely generate a reasonable load estimate? Do we lose a significant amount of information by not having 15-minute flows in these ungaged areas?**

   It is likely that correlating water quality observations with relatively accurate predictions of daily flow will generate loading estimates within the degree of sensitivity of the model to ungaged tributaries (i.e., the lake response model is not very sensitive to inputs in this section of the lake, so building regressions with daily flow values is likely sufficient and the Ellerbe Creek regressions were the only ones that were relatively sensitive to the time increment of flows). The USGS flow gage at Gorman should continue to be supported so that 15-minute data is available at this location.

4. **How sensitive is the existing lake response model to inputs from the middle and lower lake tributaries? Is the model particularly sensitive to inputs from specific tributaries that may require a greater frequency of water quality sampling in the UNRBA monitoring program?**

   The existing lake response model does not appear to be sensitive to nutrient inputs from the middle or lower lake tributaries, and no particular middle or lower lake tributary stands out in terms of its impact on simulated lake water quality. Additionally, even with significant changes in loading from tributaries shown by the current model to have the most influence in changing water quality, water quality changes are relatively small in the middle and lower sections of the lake. Simulated increases in nutrient loading from each tributary tended to have a similar impact on simulated lake water quality.

5. **Does the USACE BATHTUB model predict a similar degree of sensitivity to variations in tributary loading?**

   Yes, the USACE BATHTUB model produced similar results with respect to increased nutrient loading from various tributaries

6. **How sensitive is the Falls Lake Nutrient Response Model to the data input time step (hourly versus daily)?**

   The hourly time step for flow and nutrient concentration inputs did not significantly impact simulated chlorophyll *a* concentrations using the existing lake response model. Given the level of effort associated with setting up and running hourly inputs, one of the daily input methods is likely the best approach for future model revisions for most tributaries. Due to the variation in and quantity of loading observed at Ellerbe Creek, a shorter timestep should be used to generate loads from this tributary.

7. **How sensitive is the Falls Lake Nutrient Response Model to the concentration estimation method (interpolation between samples versus LOADEST predictions)?**

   Predicted chlorophyll *a* concentrations in the lake are fairly sensitive to the estimation method for nutrient concentrations. The baseline method tended to produce the highest simulated.

4.2 General Conclusions

4.2.1 Falls Lake EFDC Model Responsiveness and Tributary Input Characterization

Overall, the EFDC model water quality predictions make sense in general terms; chlorophyll *a* and nutrient concentrations within the lake increase along with increased nutrient inputs from the tributaries. Decreases in chlorophyll *a* and nutrient loading from the tributaries produce reductions in predicted chlorophyll a and nutrient concentrations throughout the lake. Also, the tributaries with the largest flows and wastewater treatment plants influence lake nutrient concentrations more than tributaries that contribute lower volumes of flow. Although the model predictions make sense, the model is not as responsive to changes in inputs as experience would lead us to expect. This may be due in part to the model's calibration that was based on chlorophyll *a* inputs from the tributaries that reflected values found in the tributary's arm instead of from the free-flowing section. The relatively small lake response to changes in nutrient inputs may have influenced the setting of the Stage II nutrient reduction targets. Therefore, the tributary input levels are a high priority in the monitoring objectives, particularly chlorophyll *a*.

The UNRBA monitoring program should include collection of chlorophyll *a* data within the tributaries to allow future model inputs to reflect actual tributary conditions instead of those observed at nearby lake stations. Future model updates conducted for the UNRNBA will include model recalibration with actual chlorophyll *a* and total organic carbon (TOC) data collected within the tributaries.

Since the tributaries with the largest flows have the most influence on lake water quality, it is important that the loading from these tributaries be estimated as accurately as possible. We recommend that the UNRBA monitoring program includes regular water quality monitoring at tributary loading stations from the largest 5 tributaries and supports at least one USGS flow gage on each of these tributaries. Monitoring should also occur at the mouths of the other smaller tributaries in the middle and lower lake, but this monitoring could occur less frequently. Two USGS gages should be installed (one in a middle lake tributary and one in a lower lake tributary) if appropriate locations can be identified to better characterize flows in these tributaries. Water quality monitoring stations will also be established at jurisdictional boundaries. Monitoring frequency at all of these locations will be determined using statistical assessments to identify the number of samples needed to characterize water quality with an agreed upon level of certainty. The appropriate level of certainty will be discussed with the UNRBA and described in the Water Quality Estimation Technical Memorandum (TM). Flow estimation models, described in the Flow Estimation TM will be used to estimate flows at most jurisdictional boundaries. Appropriate monitoring in the watersheds that reflect jurisdictional loading will also be undertaken in the final monitoring plan. However, for this TM monitoring recommendations relate to direct inputs to the lake response modeling.

4.2.2 Daily Load Estimation Method

Because the EFDC model requires daily loading inputs to the lake, this memorandum has identified methods that can be used to improve the accuracy of daily tributary and jurisdictional loading calculations. The different methods used to calculate loads generate a wide range in annual loading to the lake by tributary. Since the lake water quality predictions are sensitive to the total loading, it is important for the UNRBA to estimate these loads as accurately as is financially feasible.

The tributary inputs to the NCDWR's existing EFDC model were developed using a basic extrapolation technique. Cardno ENTRIX has proposed that the UNRBA use the USGS LOADEST program to generate daily nutrient concentrations for running the EFDC model. The LOADEST predictions use the relationship between flow and water quality to predict loading estimates. The USGS LOADEST model can be used to generate loadings at most tributary loading locations using a daily flow estimate paired with monthly water quality sampling. Daily loading estimates for some tributaries, particularly Ellerbe Creek and possibly Knap of Reeds Creek may be generated by pairing water quality measurements with 15-minute or hourly flow data. The flow estimates for tributaries influenced by treatment plants can also be improved by obtaining daily wastewater flows from the treatment plants.

The UNRBA monitoring program should include stormwater monitoring to provide data that can be used to determine which flow timestep should be used in the LOADEST program to generate the most accurate loading estimates. In addition statistical water quality prediction models can be used to determine what locations are expected to behave similarly in terms of flow and water quality concentrations. This information can be used to reduce water quality monitoring frequency at some locations, while still supporting the generation of accurate loading estimates. These statistical models are described and their use discussed in the Water Quality Estimation TM.

The UNRBA should request that the NCDWR provide the source code associated with the existing Falls Lake Nutrient Response model. Once this code is obtained the model file size limitations can be modified so that the model can be run on a less than daily timestep for a sufficient amount of time to predict annual or growing season conditions within Falls Lake.

5 References

NCDENR. 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.

Cardno ENTRIX. 2012. Task 2: Review Existing Data and Reports for Falls Lake and the Watershed Support of Long Term Planning and Regulatory Nutrient Activities in the Falls Lake Watershed. Prepared for the Upper Neuse River Basin Association.

Cardno ENTRIX. 2013a. Task 1: Framework for a Re-examination of Stage II of the Falls Nutrient Strategy Support of Long Term Planning and Regulatory Nutrient Activities in the Falls Lake Watershed. Prepared for the Upper Neuse River Basin Association.

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

Cardno ENTRIX. 2013c. Task 4: Review of Existing Models and Recommendations for Future Studies Support of Long Term Planning and Regulatory Nutrient Activities in the Falls Lake Watershed. Prepared for the Upper Neuse River Basin Association.

Cardno ENTRIX. 2014. Model Sensitivity Technical Memorandum. Prepared for the Upper Neuse River Basin Association.

R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna Austria. URL http://www.R-project.org/.

UNRBA Monitoring Program
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APPENDIX

A

USGS LOADEST RESULTS

Appendix A

A.1 LOADEST Results for Ellerbe Creek near Gorman

A.1.1 <u>Ellerbe Creek Total Phosphorus Results</u>

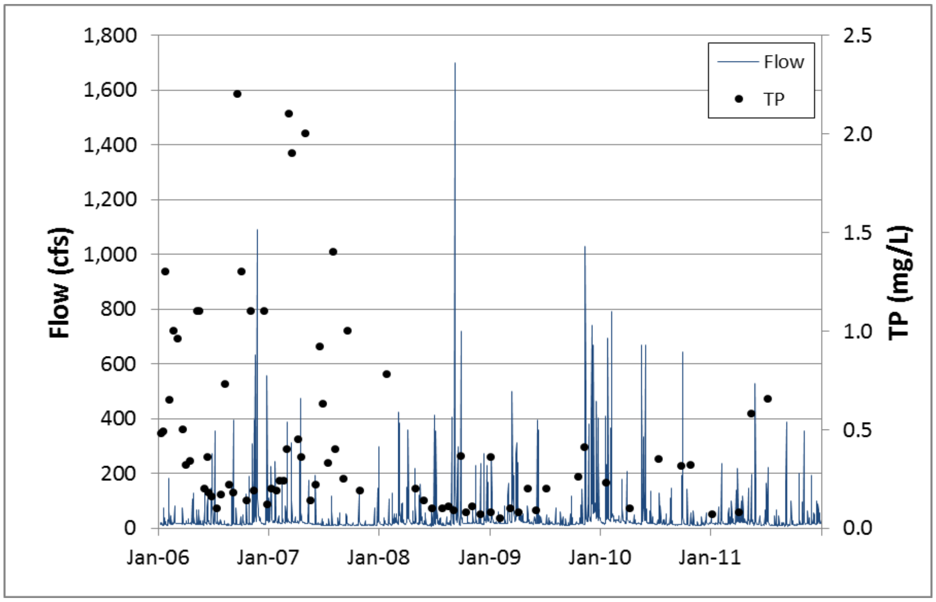

Figure A- 1 Relationship between Total Phosphorus and Flow at Ellerbe Creek downstream of North Durham WWTP

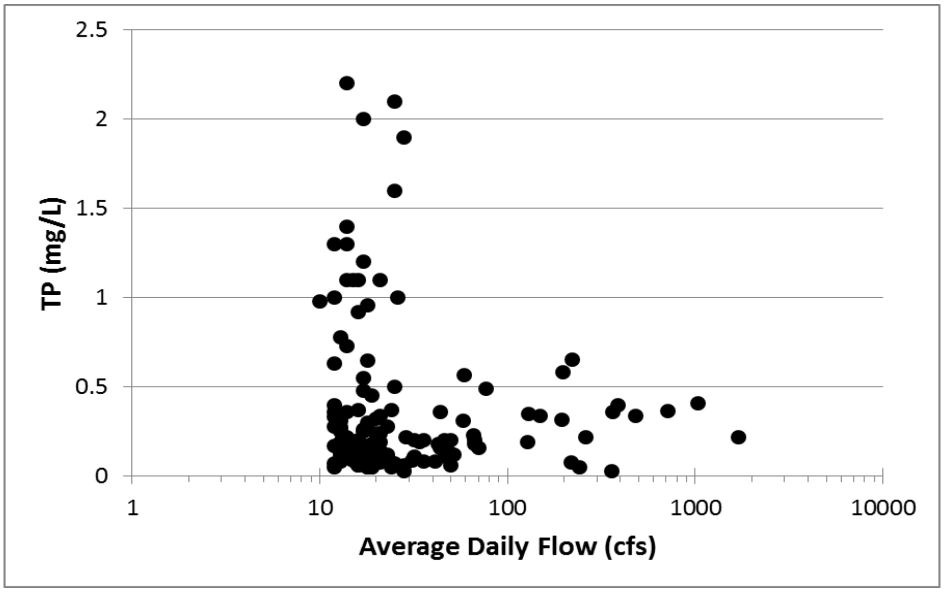

Figure A- 2 Relationship between Total Phosphorus and Average Daily Flow (log scale) at Ellerbe Creek downstream of North Durham WWTP

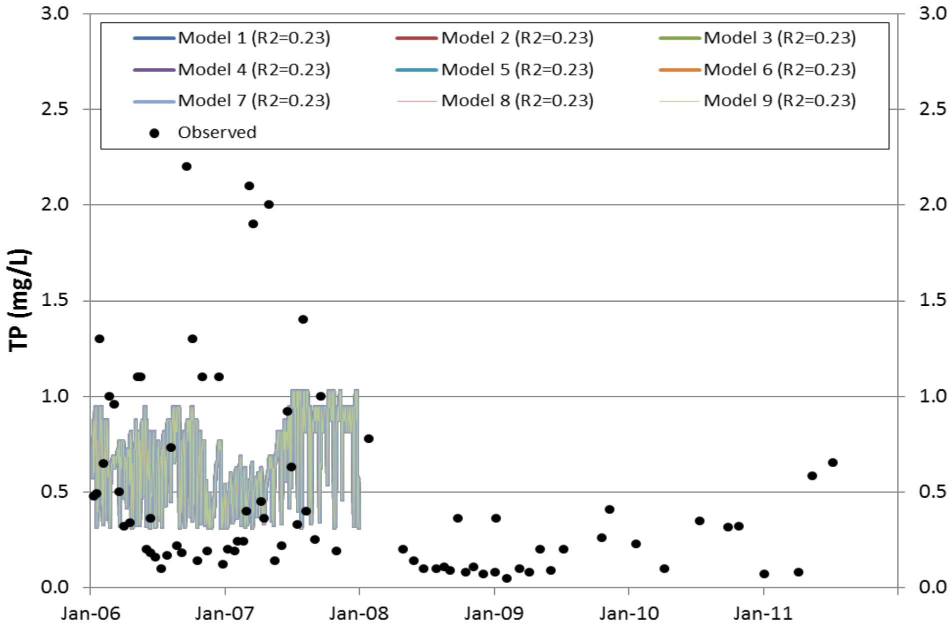

Figure A- 3 **USGS LOADEST Predictions for TP (2006 to 2007) at Ellerbe Creek Downstream of the North Durham WWTP Using Daily Flows**

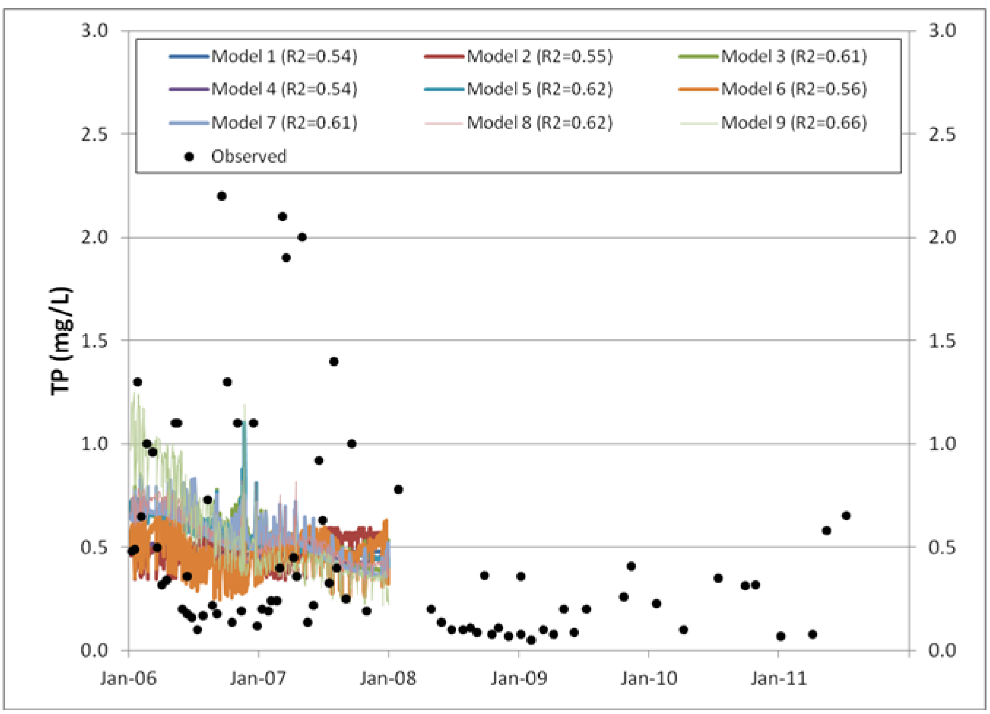

Figure A- 4 **USGS LOADEST Predictions for TP (2006 to 2007) at Ellerbe Creek Downstream of the North Durham WWTP Using 15 Minute Flows**

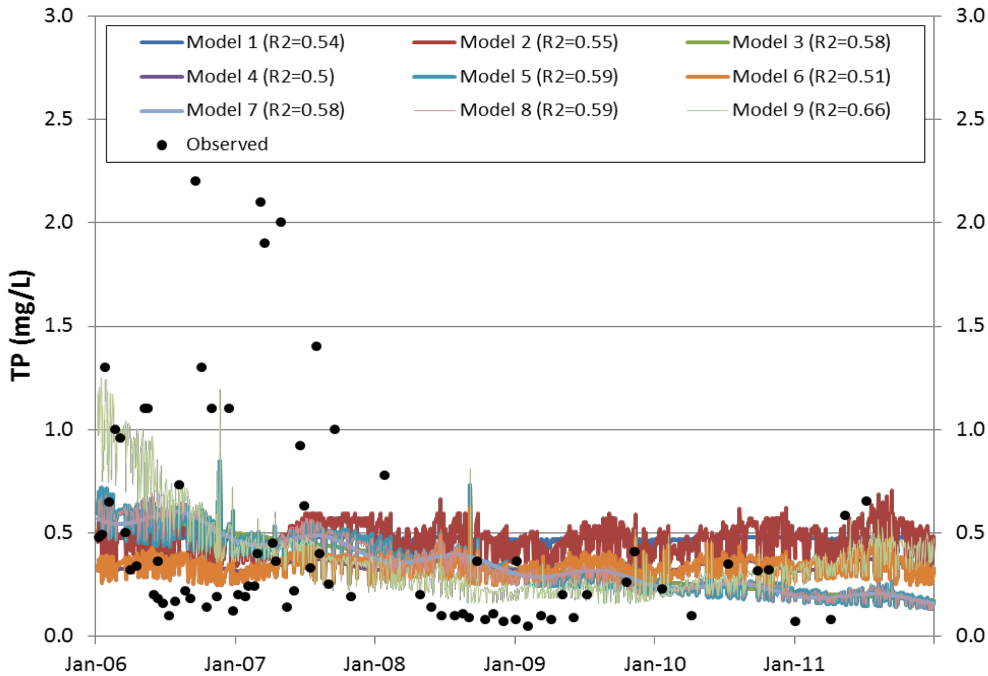

Figure A- 5 USGS LOADEST Predictions for TP (2006 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using Daily Flows

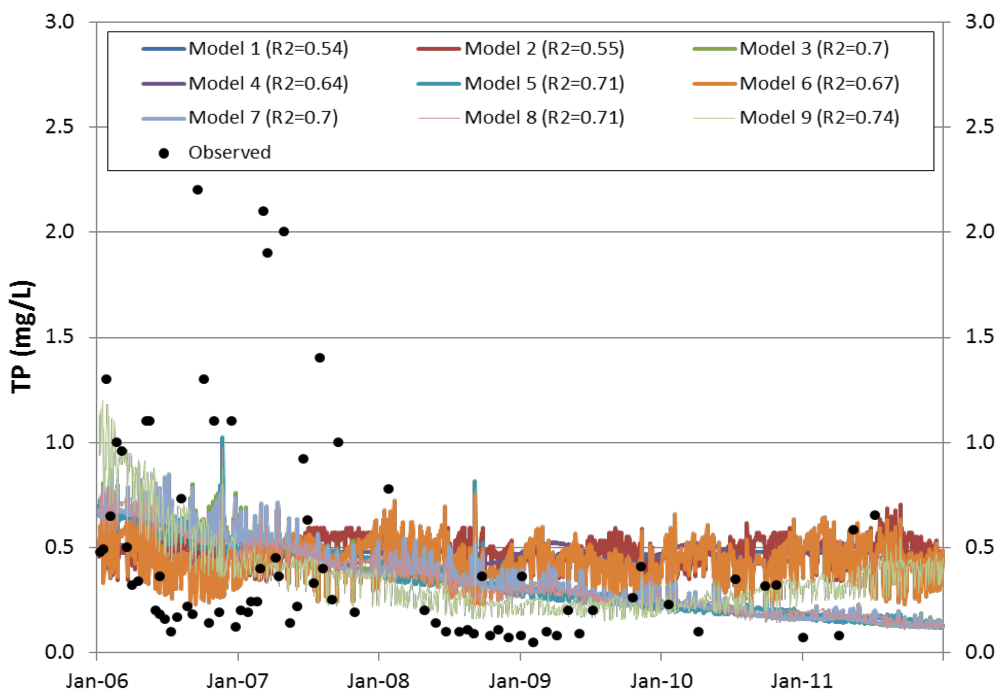

Figure A- 6 USGS LOADEST Predictions for TP (2006 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using 15 minute Flows

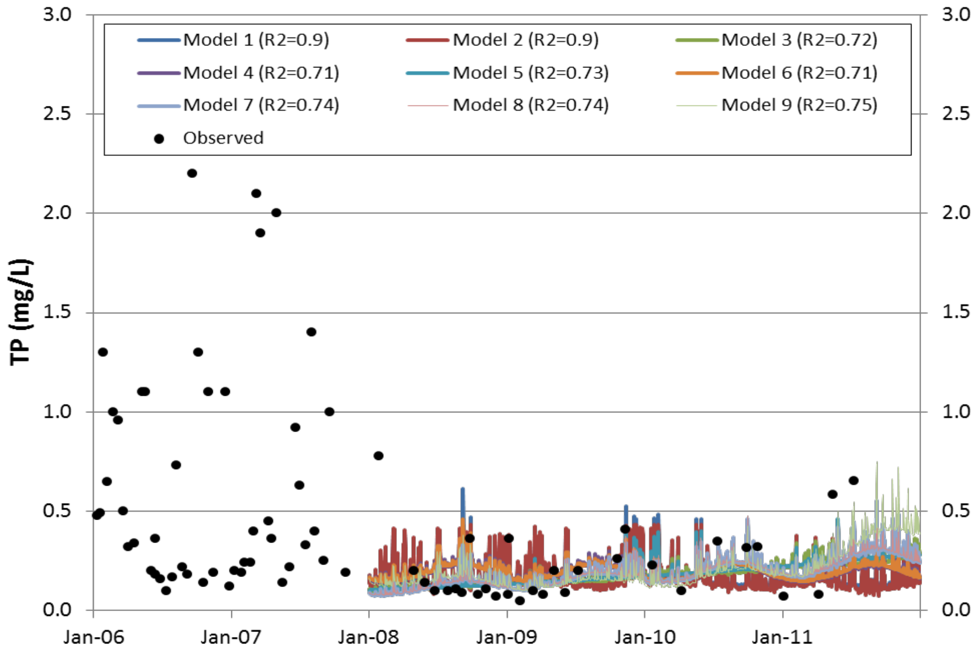

Figure A- 7 USGS LOADEST Predictions for TP (2008 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using Daily Flows

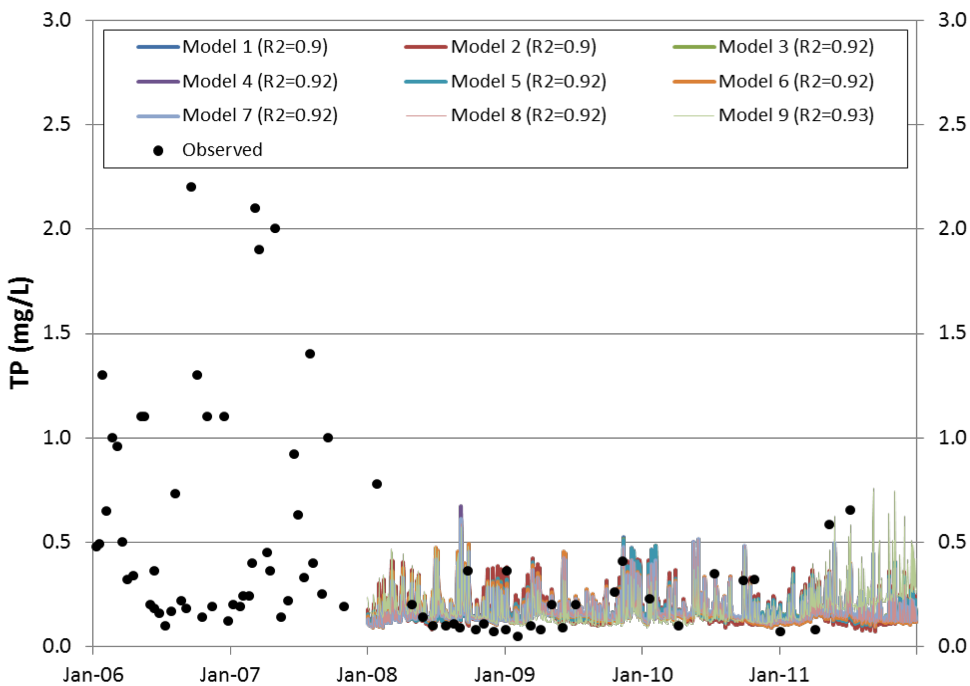

Figure A- 8 USGS LOADEST Predictions for TP (2008 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using 15 Minute Flows

A.1.2 Ellerbe Creek Total Nitrogen Results

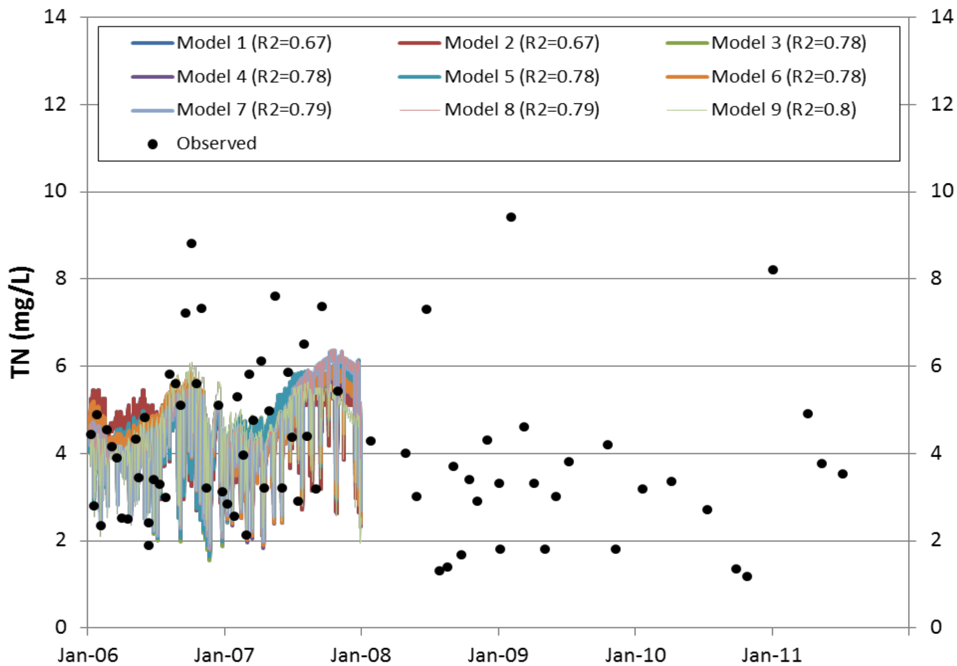

Figure A- 9 USGS LOADEST Predictions for TN (2006 to 2007) at Ellerbe Creek Downstream of the North Durham WWTP Using Daily Flows

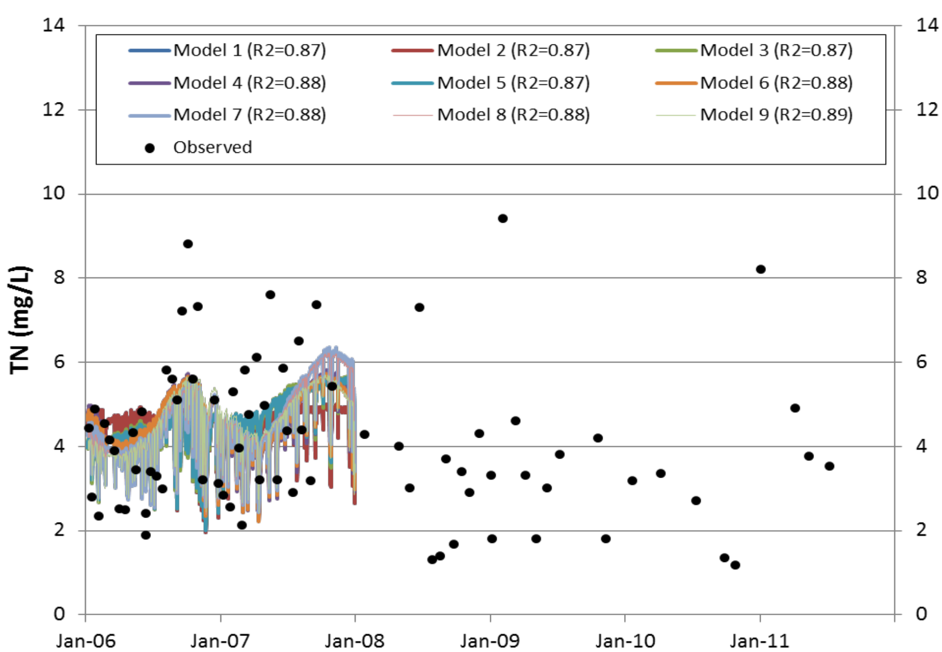

Figure A- 10 USGS LOADEST Predictions for TN (2006 to 2007) at Ellerbe Creek Downstream of the North Durham WWTP Using 15 Minute Flows

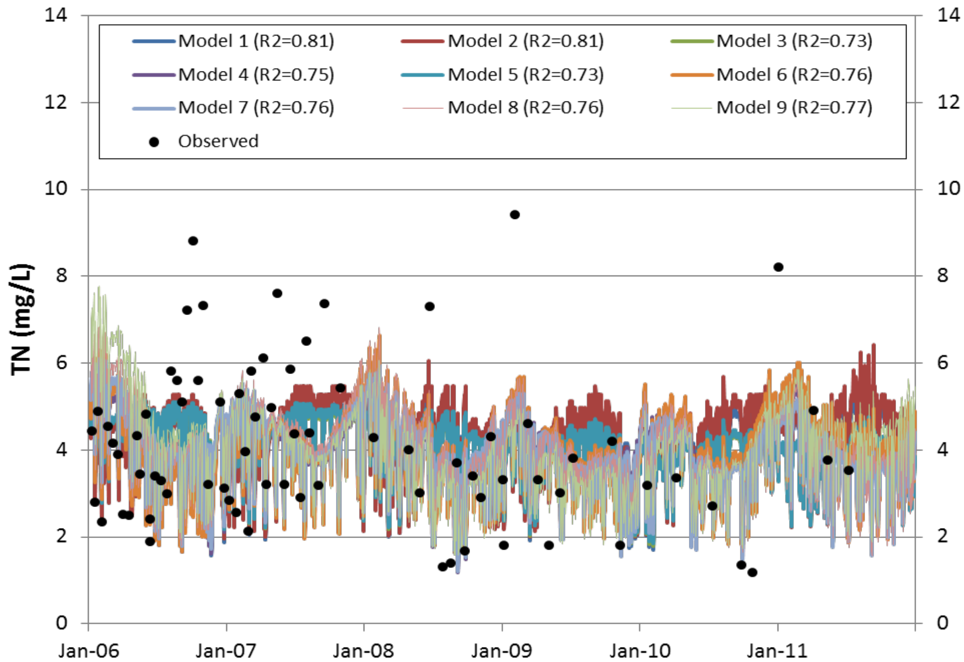

Figure A- 11 USGS LOADEST Predictions for TN (2006 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using Daily Flows

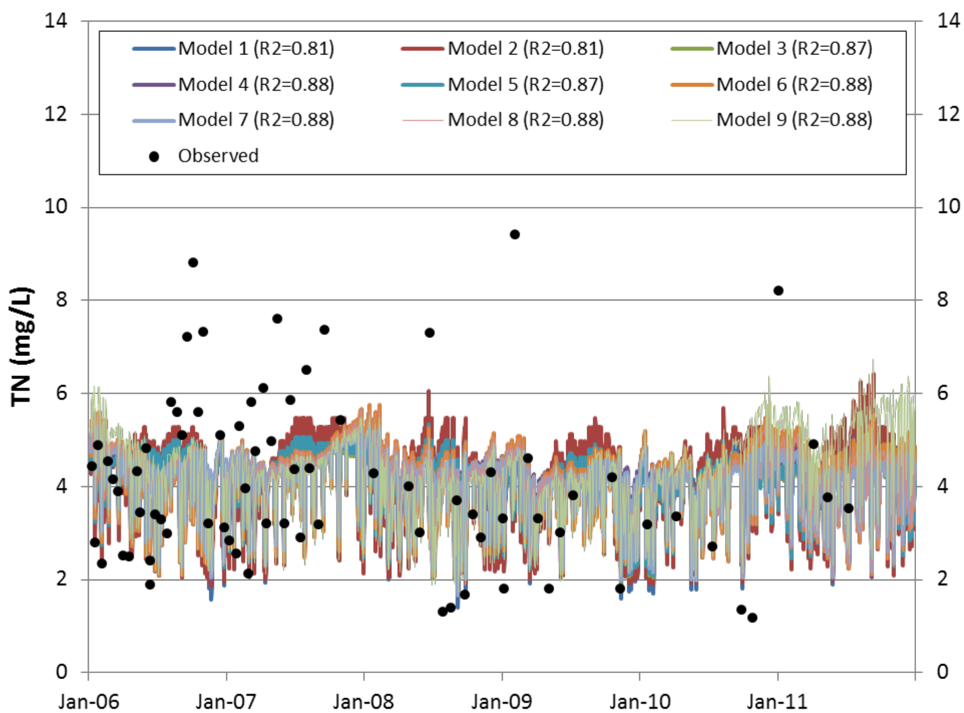

Figure A- 12 USGS LOADEST Predictions for TN (2006 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using 15 Minute Flows

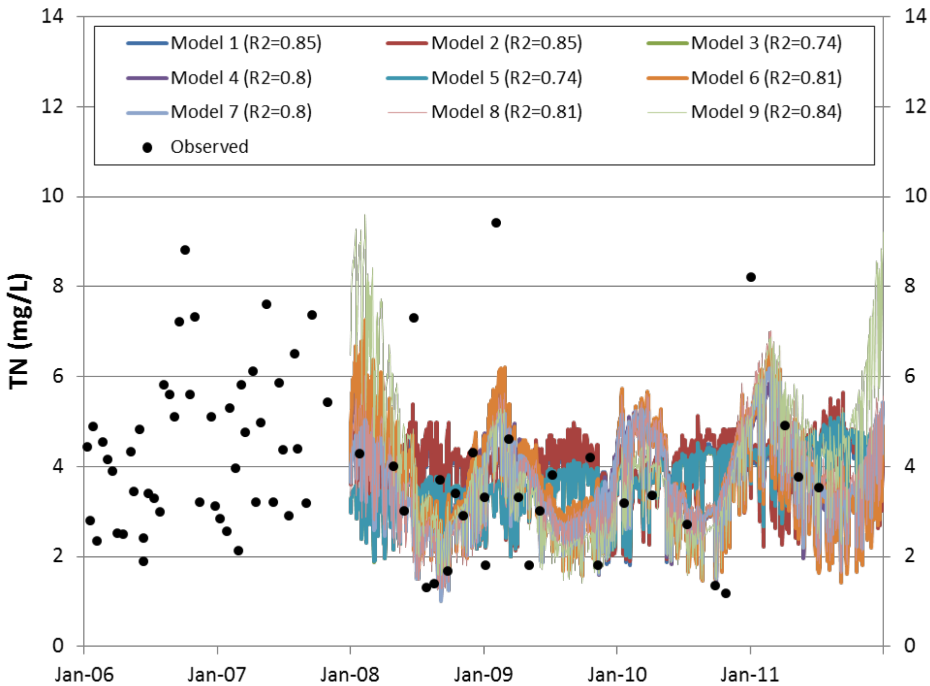

Figure A- 13 USGS LOADEST Predictions for TN (2008 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using Daily Flows

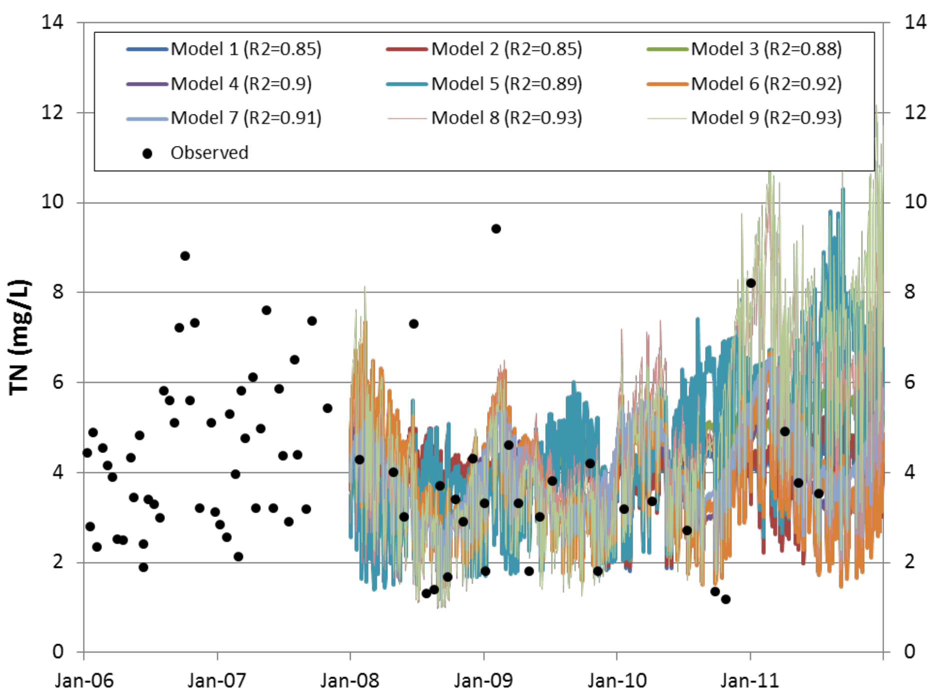

Figure A- 14 USGS LOADEST Predictions for TN (2008 to 2011) at Ellerbe Creek Downstream of the North Durham WWTP Using 15 Minute Flows

A.2 LOADEST Results for Eno River near Durham (Roxboro Road)

A.2.3 Eno River Total Phosphorus Results

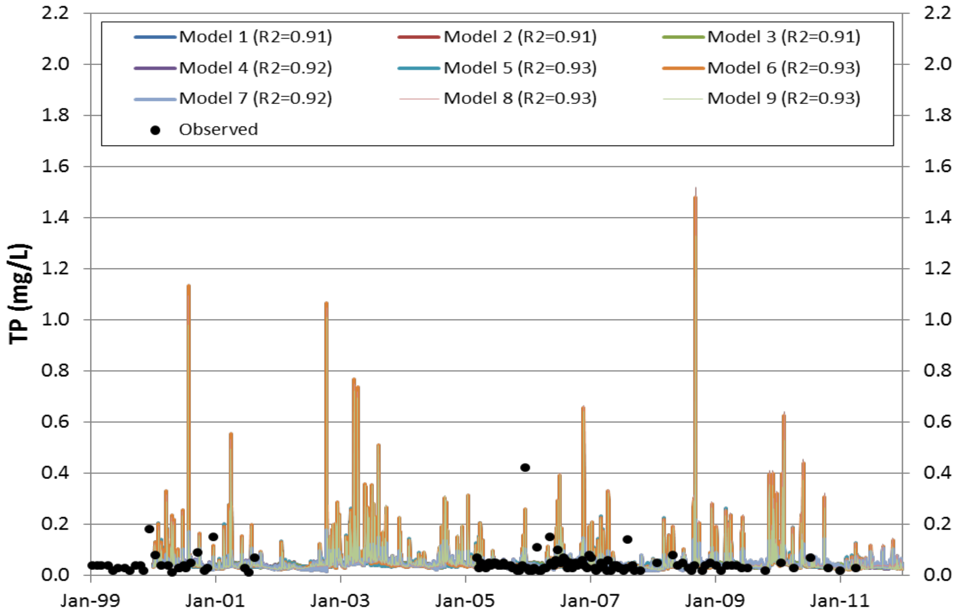

Figure A- 15 USGS LOADEST Predictions for TP (2000 to 2011) at Eno River near Durham Using Daily Average Flows

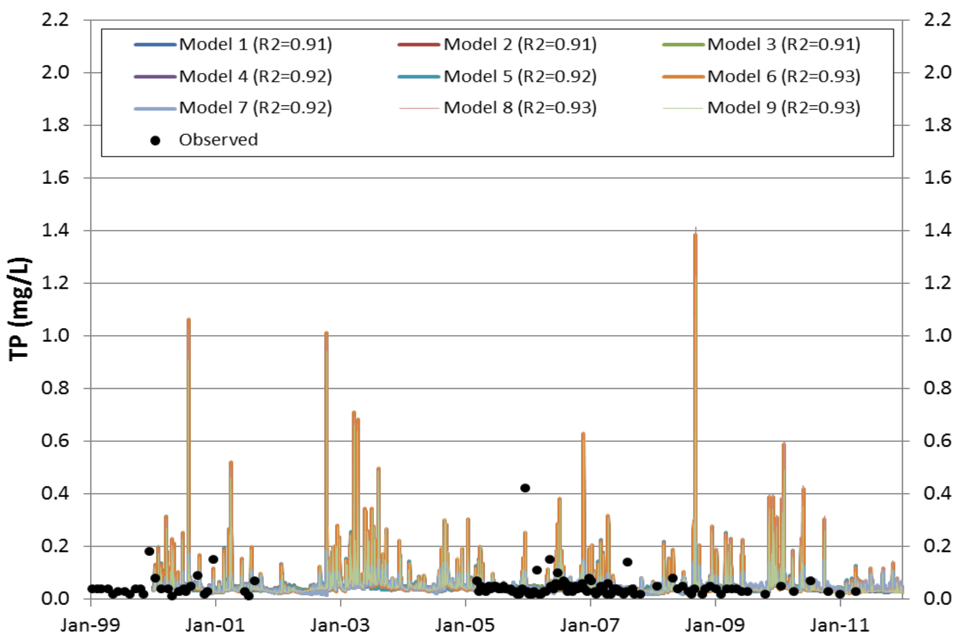

Figure A- 16 USGS LOADEST Predictions for TP (2000 to 2011) at Eno River near Durham Using 15 Minute Flows

A.2.4 Eno River Total Nitrogen Results

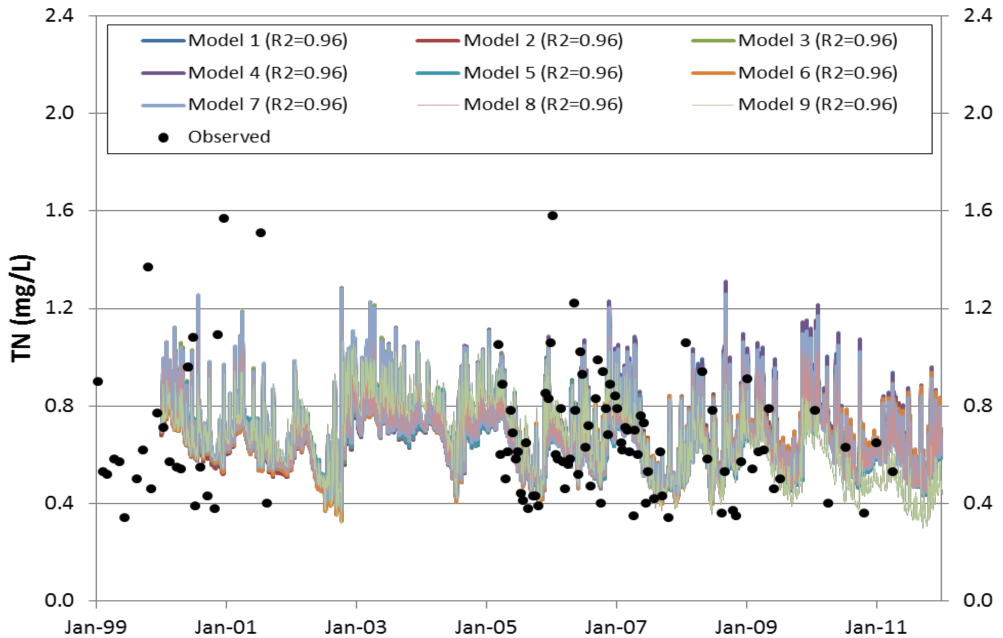

Figure A- 17 USGS LOADEST Predictions for TN (2000 to 2011) at Eno River near Durham Using Daily Average Flows

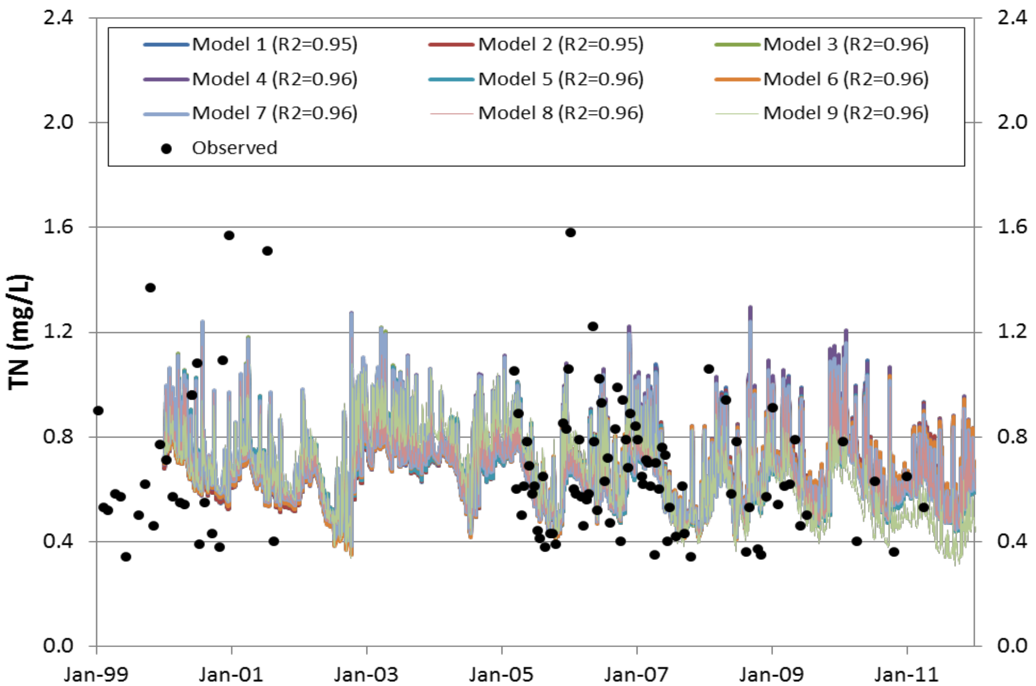

Figure A- 18 USGS LOADEST Predictions for TN (2000 to 2011) at Eno River near Durham Using 15 Minute Flows

A.3 LOADEST Results for Flat River below Lake Michie Dam

A.3.5 Flat River Total Phosphorus Results

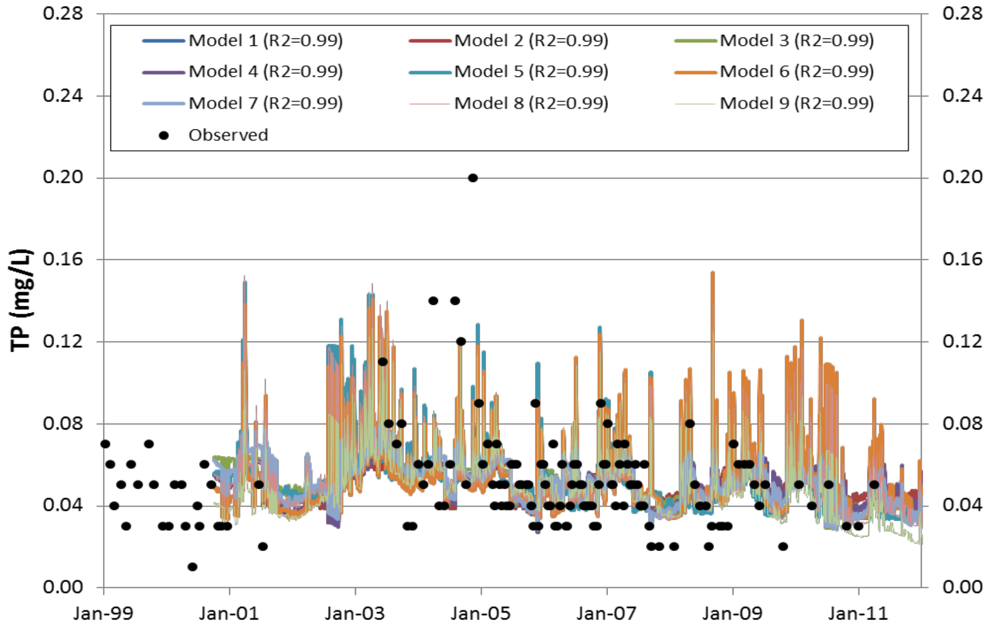

Figure A- 19 USGS LOADEST Predictions for TP (1999 to 2011) at Flat River below Lake Michie Dam Using Daily Average Flows

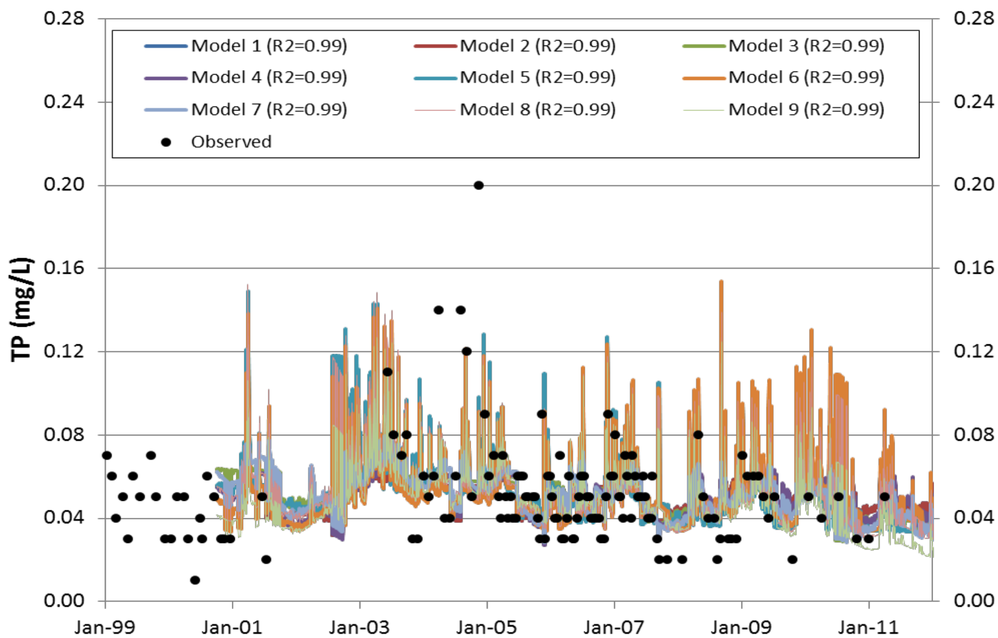

Figure A- 20 USGS LOADEST Predictions for TP (1999 to 2011) at Flat River below Lake Michie Dam Using 15 Minute Flows

A.3.6 Flat River Total Nitrogen Results

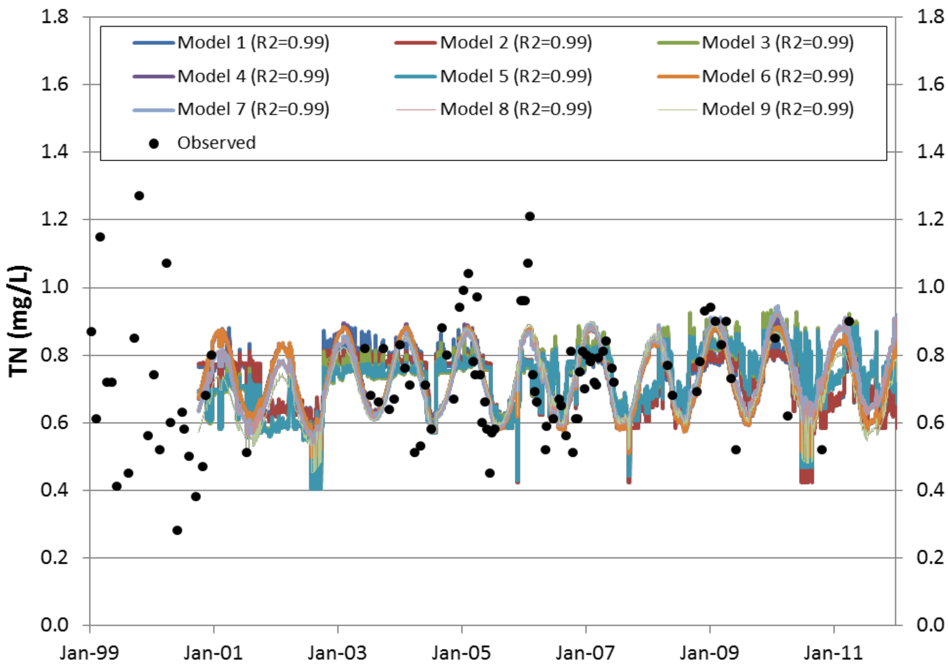

Figure A- 21 USGS LOADEST Predictions for TN (1999 to 2011) at Flat River below Lake Michie Dam Using Daily Average Flows

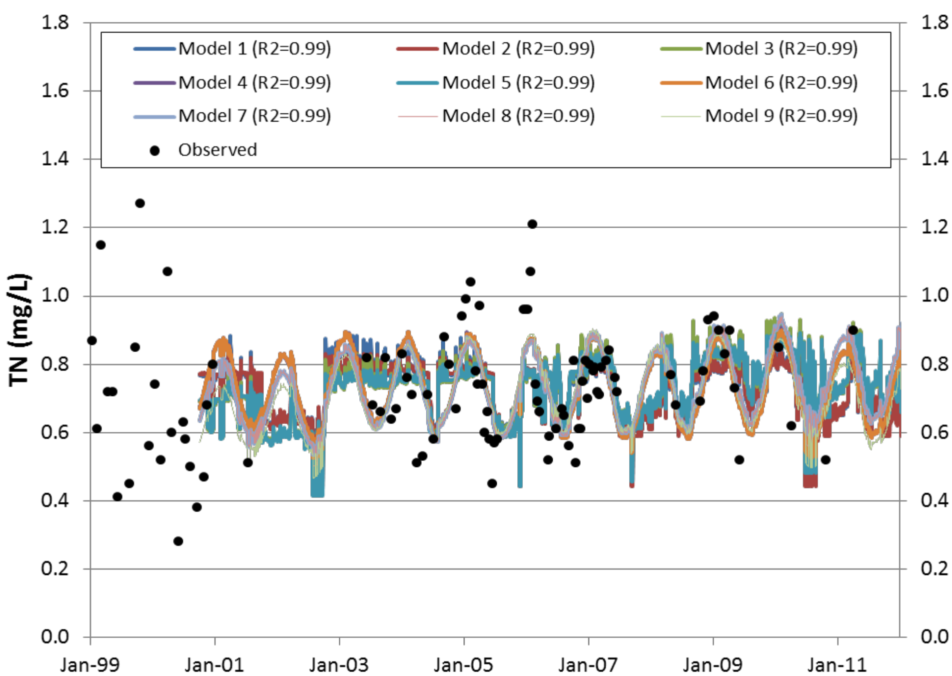

Figure A- 22 USGS LOADEST Predictions for TN (1999 to 2011) at Flat River below Lake Michie Dam Using 15 Minute Flows

A.4 LOADEST Results for Little River below Little River Reservoir

A.4.7 Little River Total Phosphorus Results

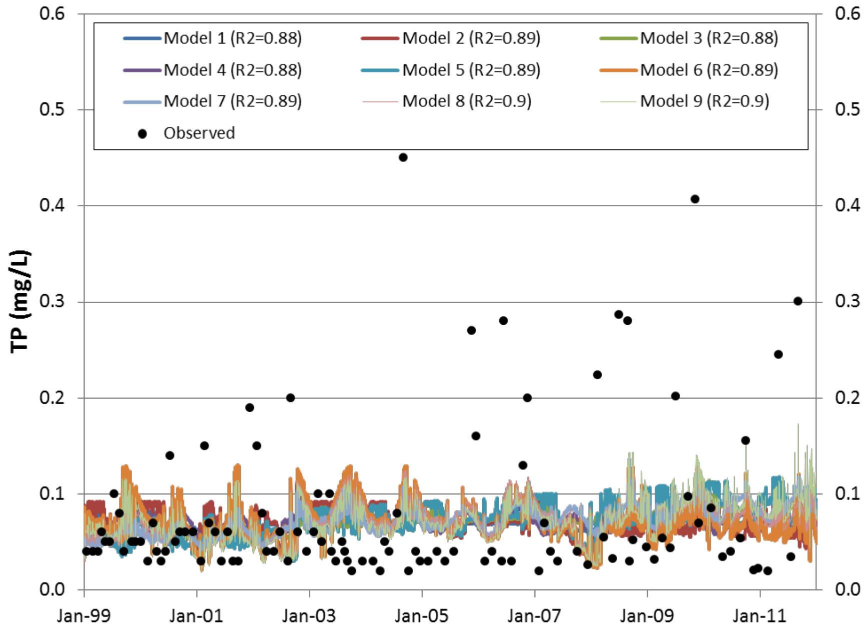

Figure A- 23 USGS LOADEST Predictions for TP (1999 to 2011) at Little River below Little River Reservoir Using Daily Average Flows

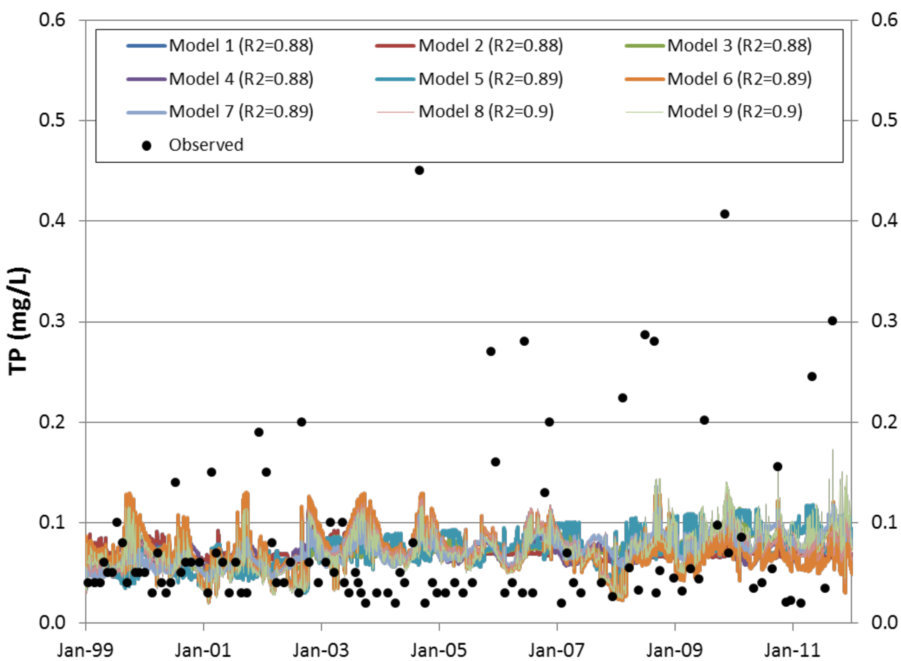

Figure A- 24 USGS LOADEST Predictions for TP (1999 to 2011) at Little River below Little River Reservoir Using 15 Minute Flows

A.4.8 Little River Total Nitrogen Results

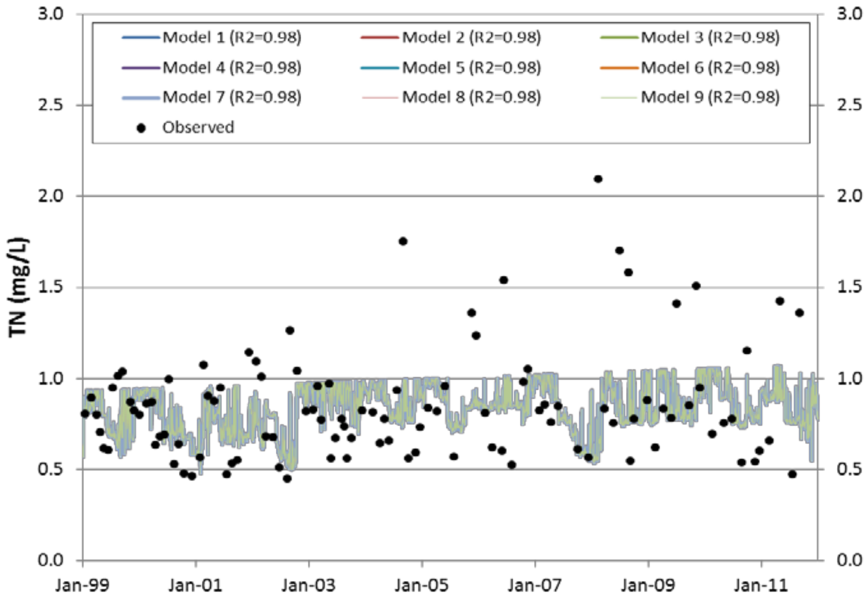

Figure A- 25 USGS LOADEST Predictions for TN (1999 to 2011) at Little River below Little River Reservoir Using Daily Average Flows

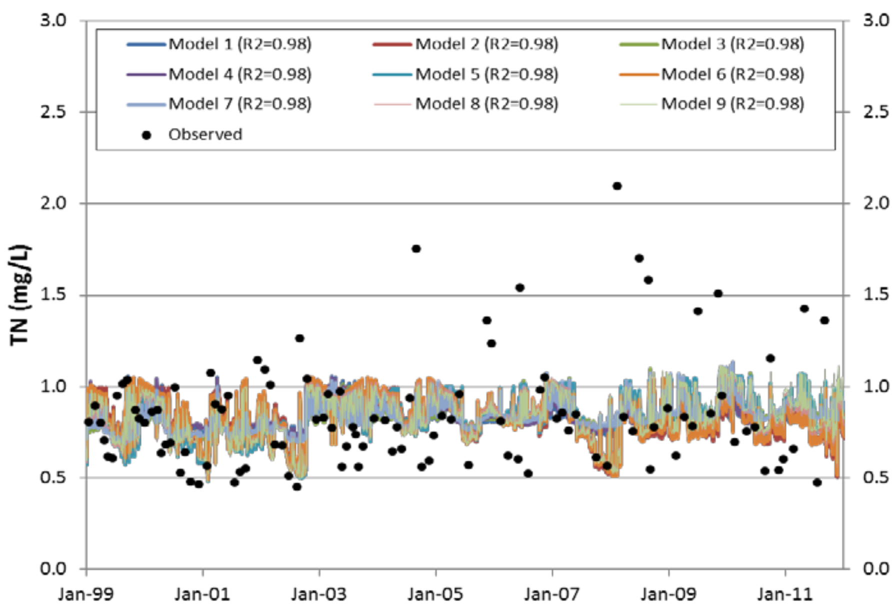

Figure A- 26 USGS LOADEST Predictions for TN (1999 to 2011) at Little River below Little River Reservoir Using 15 Minute Flows

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APPENDIX

B

FALLS LAKE NUTRIENT RESPONSE MODEL SENSITIVITY TO CHANGES IN TRIBUTARY NUTRIENT LOADING

Appendix B

B.1 Falls Lake Nutrient Response Model (EFDC Model) Sensitivity Results downstream of Interstate 85 (NCDWR Falls Lake Station Neuse013B)

B.1.1 Total Phosphorus Sensitivity at I-85

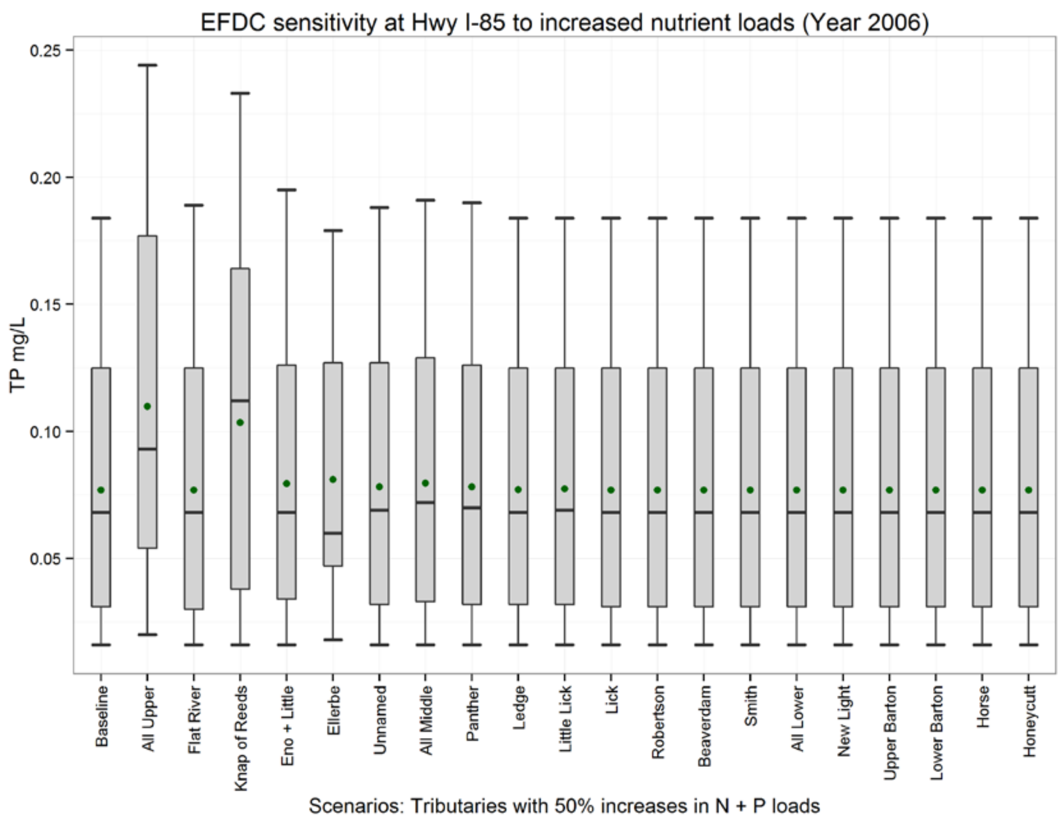

Figure B- 1 Sensitivity of Falls Lake TP concentrations downstream of I-85 to a 50% increase in N and P loading, 2006 conditions

Table B- 1 Summary Statistics for Predicted Daily Average TP in the Top Layer downstream of I-85 associated with a 50% increase in N and P loading, 2006 conditions

Scenario	Minimum	25th percentile	Median	75th percentile	90th percentile
Baseline	0.016	0.031	0.068	0.125	0.184
All Upper	0.02	0.054	0.093	0.177	0.244
Flat River	0.016	0.03	0.068	0.125	0.189
Knap of Reeds	0.016	0.038	0.112	0.164	0.233
Eno + Little	0.016	0.034	0.068	0.126	0.195
Ellerbe	0.018	0.047	0.06	0.127	0.179
Unnamed	0.016	0.032	0.069	0.127	0.188
All Middle	0.016	0.033	0.072	0.129	0.191
Panther	0.016	0.032	0.07	0.126	0.19
Ledge	0.016	0.032	0.068	0.125	0.184
Little Lick	0.016	0.032	0.069	0.125	0.184
Lick	0.016	0.031	0.068	0.125	0.184
Robertson	0.016	0.031	0.068	0.125	0.184
Beaverdam	0.016	0.031	0.068	0.125	0.184
Smith	0.016	0.031	0.068	0.125	0.184
All Lower	0.016	0.031	0.068	0.125	0.184
New Light	0.016	0.031	0.068	0.125	0.184
Upper Barton	0.016	0.031	0.068	0.125	0.184
Lower Barton	0.016	0.031	0.068	0.125	0.184
Horse	0.016	0.031	0.068	0.125	0.184
Honeycutt	0.016	0.031	0.068	0.125	0.184

B.1.2 Total Nitrogen Sensitivity at I-85

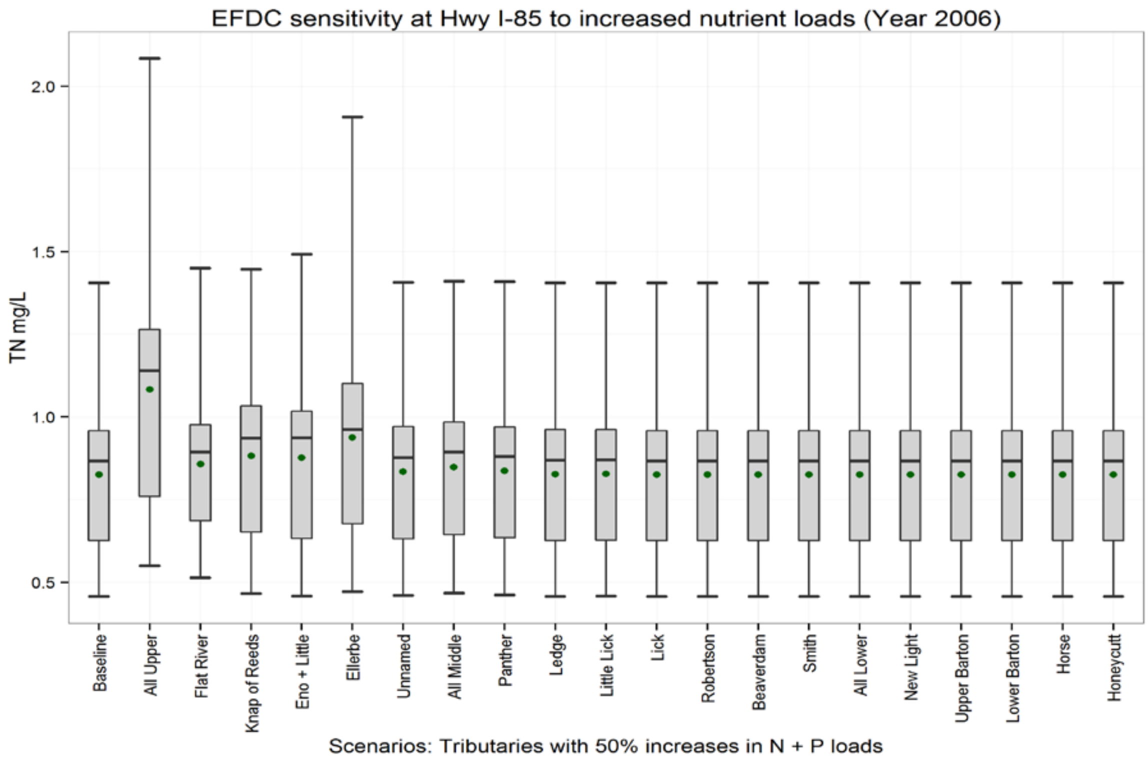

Figure B-2 Sensitivity of Falls Lake TN concentrations downstream of I-85 to a 50% increase in N and P loading, 2006 conditions

Table B-2 Summary Statistics for Predicted Daily Average TN in the Top Layer downstream of I-85 associated with a 50% increase in N and P loading, 2006 conditions

Scenario	Minimum	25th percentile	Median	75th percentile	90th percentile
Baseline	0.456	0.626	0.866	0.958	1.405
All Upper	0.549	0.75975	1.14	1.265	2.084
Flat River	0.513	0.686	0.893	0.976	1.45
Knap of Reeds	0.465	0.65175	0.935	1.033	1.446
Eno + Little	0.458	0.632	0.936	1.017	1.492
Ellerbe	0.471	0.677	0.962	1.101	1.907
Unnamed	0.46	0.631	0.876	0.97	1.406
All Middle	0.467	0.644	0.893	0.984	1.41
Panther	0.461	0.634	0.88	0.969	1.409
Ledge	0.456	0.626	0.868	0.961	1.405
Little Lick	0.457	0.627	0.87	0.961	1.405
Lick	0.456	0.626	0.866	0.958	1.405
Robertson	0.456	0.626	0.866	0.958	1.405
Beaverdam	0.456	0.626	0.866	0.958	1.405
Smith	0.456	0.626	0.866	0.958	1.405
All Lower	0.456	0.626	0.866	0.958	1.405
New Light	0.456	0.626	0.866	0.958	1.405
Upper Barton	0.456	0.626	0.866	0.958	1.405
Lower Barton	0.456	0.626	0.866	0.958	1.405
Horse	0.456	0.626	0.866	0.958	1.405
Honeycutt	0.456	0.626	0.866	0.958	1.405

B.1.3 Total Organic Carbon Sensitivity at I-85

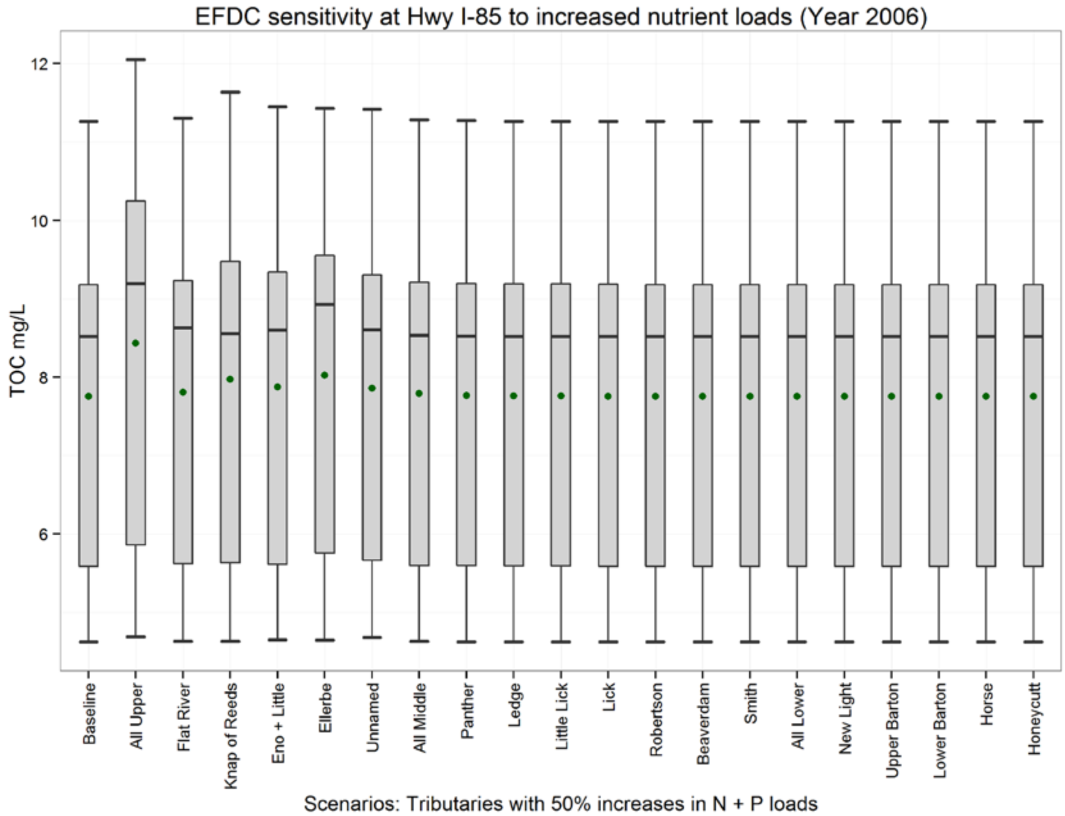

Figure B-3 Sensitivity of Falls Lake TOC concentrations downstream of I-85 to a 50% increase in N and P loading, 2006 conditions

Table B-3 Summary Statistics for Predicted Daily Average TOC in the Top Layer downstream of I-85 associated with a 50% increase in N and P loading, 2006 conditions

Scenario	Minimum	25th percentile	Median	75th percentile	90th percentile
Baseline	4.619	5.586	8.517	9.18125	11.263
All Upper	4.68	5.856	9.1885	10.247	12.048
Flat River	4.627	5.619	8.6255	9.231	11.305
Knap of Reeds	4.624	5.632	8.5545	9.47525	11.633
Eno + Little	4.646	5.611	8.5965	9.34	11.448
Ellerbe	4.642	5.75475	8.927	9.551	11.427
Unnamed	4.676	5.66075	8.6025	9.301	11.415
All Middle	4.624	5.596	8.53	9.2105	11.28
Panther	4.622	5.59175	8.523	9.194	11.273
Ledge	4.619	5.587	8.517	9.188	11.263
Little Lick	4.619	5.588	8.517	9.189	11.263
Lick	4.619	5.586	8.517	9.182	11.263
Robertson	4.619	5.586	8.517	9.18125	11.263
Beaverdam	4.619	5.586	8.517	9.18125	11.263
Smith	4.619	5.586	8.517	9.18125	11.263
All Lower	4.619	5.586	8.517	9.18125	11.263
New Light	4.619	5.586	8.517	9.18125	11.263
Upper Barton	4.619	5.586	8.517	9.18125	11.263
Lower Barton	4.619	5.586	8.517	9.18125	11.263
Horse	4.619	5.586	8.517	9.18125	11.263
Honeycutt	4.619	5.586	8.517	9.18125	11.263

B.2 Model Sensitivity at Highway 50 (Creedmoor Road)

B.2.1 Total Phosphorus Sensitivity at Highway 50

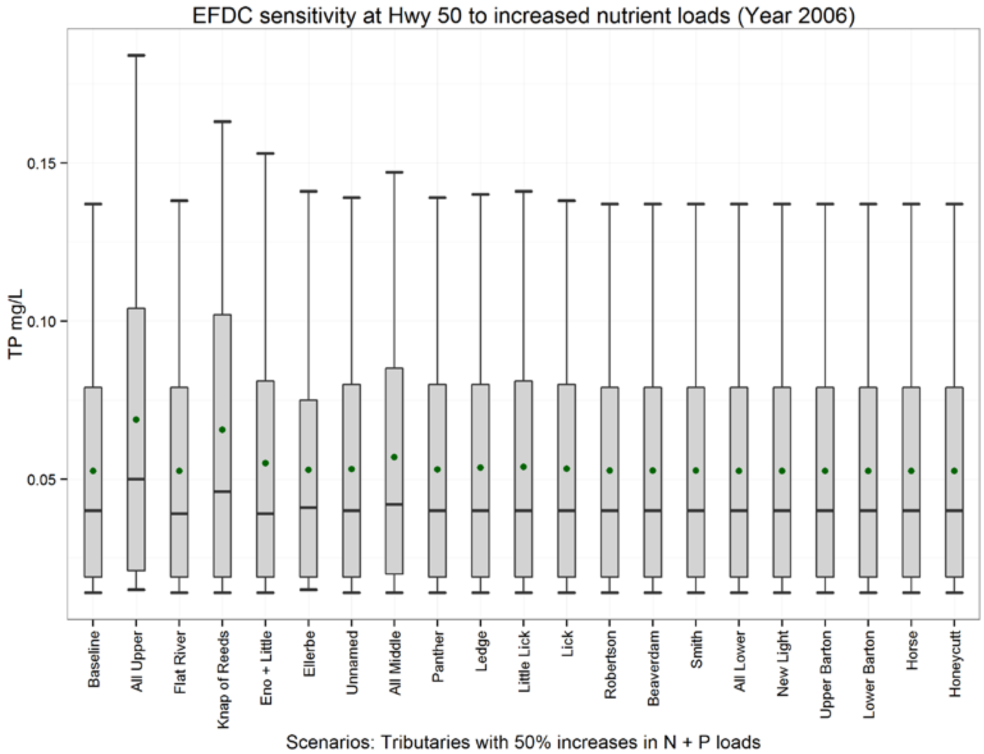

Figure B-4 Sensitivity of Falls Lake TP concentrations at Highway 50 to a 50% increase in N and P loading, 2006 conditions

Table B-4 Summary Statistics for Predicted Daily Average TP in the Top Layer at Highway 50 associated with a 50% increase in N and P loading, 2006 conditions

Scenario	Minimum	25th percentile	Median	75th percentile	90th percentile
Baseline	0.014	0.019	0.04	0.079	0.137
All Upper	0.015	0.021	0.05	0.104	0.184
Flat River	0.014	0.019	0.039	0.079	0.138
Knap of Reeds	0.014	0.019	0.046	0.102	0.163
Eno + Little	0.014	0.019	0.039	0.081	0.153
Ellerbe	0.015	0.019	0.041	0.075	0.141
Unnamed	0.014	0.019	0.040	0.080	0.139
All Middle	0.014	0.020	0.042	0.085	0.147
Panther	0.014	0.019	0.040	0.080	0.139
Ledge	0.014	0.019	0.040	0.080	0.140
Little Lick	0.014	0.019	0.040	0.081	0.141
Lick	0.014	0.019	0.040	0.080	0.138
Robertson	0.014	0.019	0.040	0.079	0.137
Beaverdam	0.014	0.019	0.040	0.079	0.137
Smith	0.014	0.019	0.040	0.079	0.137
All Lower	0.014	0.019	0.040	0.079	0.137
New Light	0.014	0.019	0.040	0.079	0.137
Upper Barton	0.014	0.019	0.040	0.079	0.137
Lower Barton	0.014	0.019	0.040	0.079	0.137
Horse	0.014	0.019	0.040	0.079	0.137
Honeycutt	0.014	0.019	0.040	0.079	0.137

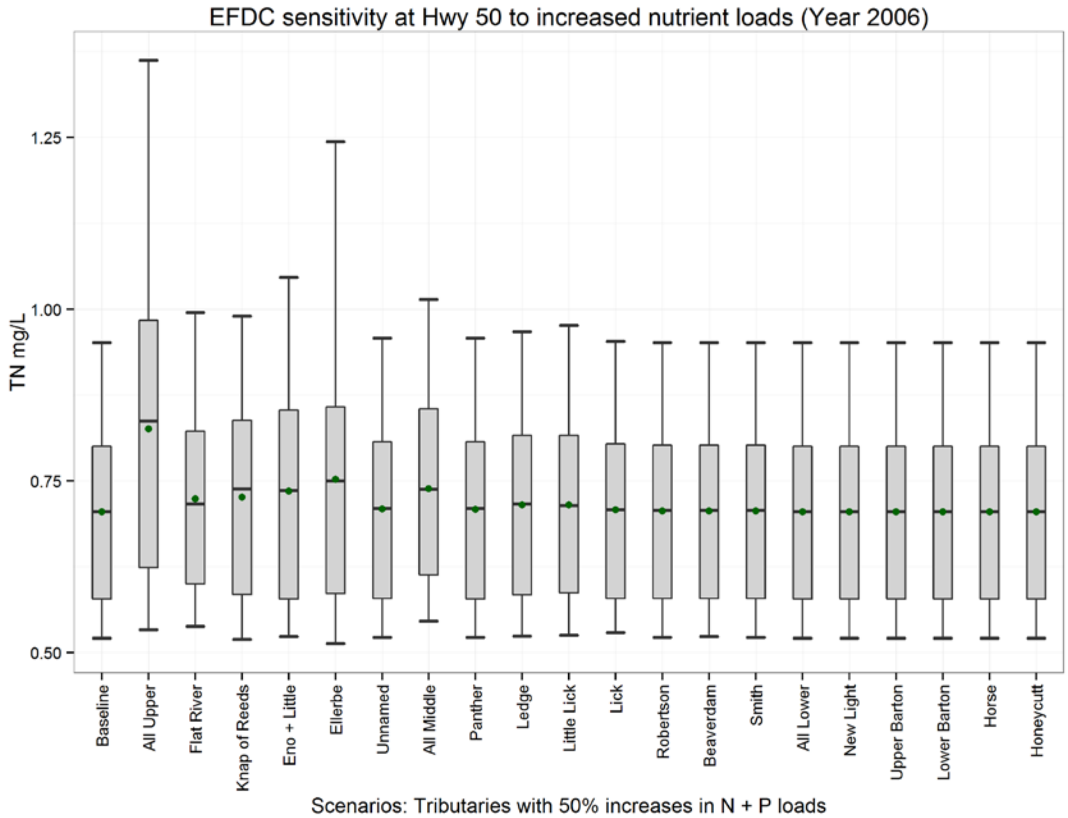

Figure B-5 Sensitivity of Falls Lake TN concentrations at Highway 50 to a 50% increase in N and P loading, 2006 conditions

Table B-5 Summary Statistics for Predicted Daily Average TN in the Top Layer at Highway 50 associated with a 50% increase in N and P loading, 2006 conditions

Scenario	Minimum	25th percentile	Median	75th percentile	90th percentile
Baseline	0.521	0.578	0.705	0.8	0.951
All Upper	0.533	0.624	0.837	0.984	1.362
Flat River	0.538	0.6	0.716	0.822	0.995
Knap of Reeds	0.519	0.585	0.738	0.838	0.99
Eno + Little	0.523	0.578	0.736	0.853	1.046
Ellerbe	0.513	0.586	0.75	0.858	1.244
Unnamed	0.522	0.579	0.71	0.807	0.958
All Middle	0.546	0.613	0.7375	0.855	1.014
Panther	0.522	0.578	0.71	0.807	0.958
Ledge	0.524	0.584	0.716	0.816	0.967
Little Lick	0.525	0.587	0.714	0.816	0.976
Lick	0.529	0.579	0.708	0.804	0.953
Robertson	0.522	0.579	0.707	0.802	0.951
Beaverdam	0.523	0.579	0.707	0.802	0.951
Smith	0.522	0.579	0.707	0.802	0.951
All Lower	0.521	0.578	0.705	0.8	0.951
New Light	0.521	0.578	0.705	0.8	0.951
Upper Barton	0.521	0.578	0.705	0.8	0.951
Lower Barton	0.521	0.578	0.705	0.8	0.951
Horse	0.521	0.578	0.705	0.8	0.951
Honeycutt	0.521	0.578	0.705	0.8	0.951

B.2.2 Total Organic Carbon Sensitivity at Highway 50

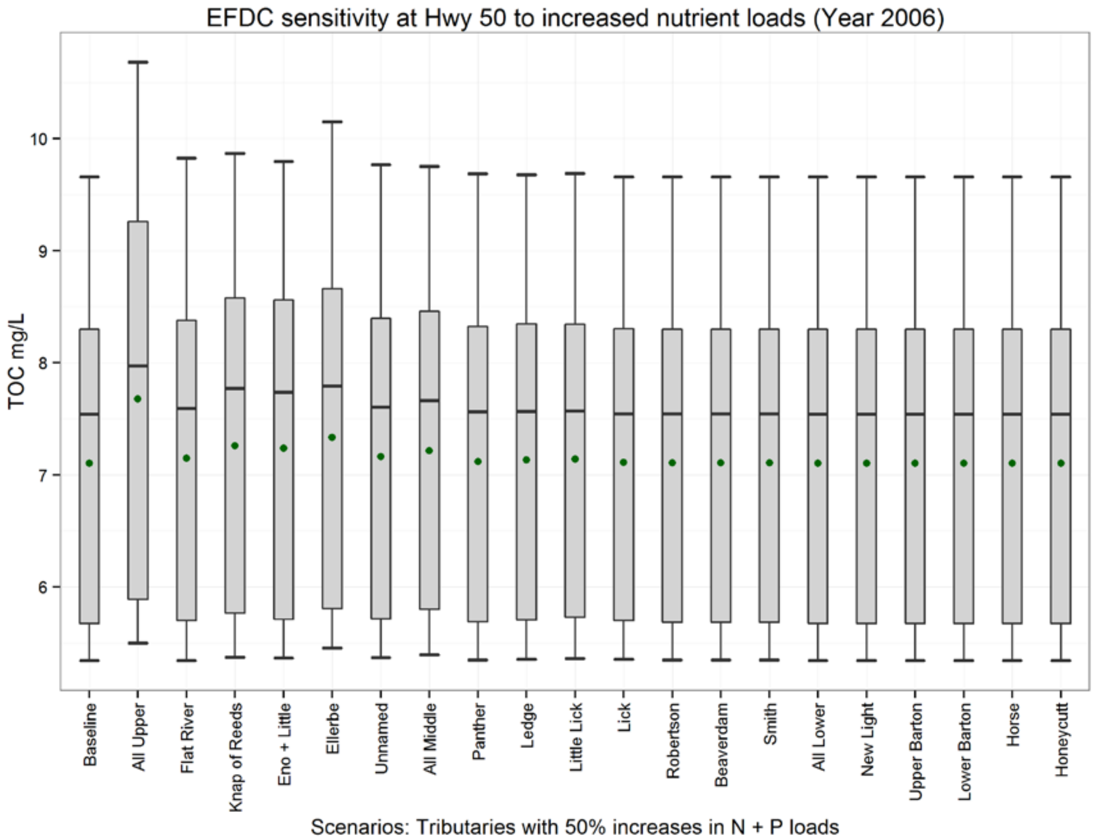

Figure B-6 Sensitivity of Falls Lake TOC concentrations at Highway 50 to a 50% increase in N and P loading, 2006 conditions

Table B-6 Summary Statistics for Predicted Daily Average TOC in the Top Layer at Highway 50 associated with a 50% increase in N and P loading, 2006 conditions

Scenario	Minimum	25th percentile	Median	75th percentile	90th percentile
Baseline	5.342	5.675	7.539	8.299	9.658
All Upper	5.498	5.890	7.972	9.260	10.682
Flat River	5.341	5.700	7.592	8.376	9.825
Knap of Reeds	5.373	5.767	7.770	8.579	9.866
Eno + Little	5.366	5.710	7.735	8.559	9.795
Ellerbe	5.453	5.806	7.794	8.66	10.149
Unnamed	5.368	5.714	7.603	8.394	9.765
All Middle	5.394	5.800	7.663	8.460	9.753
Panther	5.346	5.688	7.560	8.325	9.684
Ledge	5.353	5.706	7.567	8.345	9.677
Little Lick	5.362	5.728	7.570	8.345	9.689
Lick	5.352	5.701	7.544	8.302	9.660
Robertson	5.344	5.684	7.544	8.301	9.659
Beaverdam	5.344	5.683	7.544	8.301	9.659
Smith	5.344	5.684	7.544	8.301	9.659
All Lower	5.342	5.675	7.539	8.299	9.658
New Light	5.342	5.675	7.539	8.299	9.658
Upper Barton	5.342	5.675	7.539	8.299	9.658
Lower Barton	5.342	5.675	7.539	8.299	9.658
Horse	5.342	5.675	7.539	8.299	9.658
Honeycutt	5.342	5.675	7.539	8.299	9.658

B.3 Model Sensitivity at Falls Lake Dam

B.3.3 Total Phosphorus Sensitivity at Falls Lake Dam

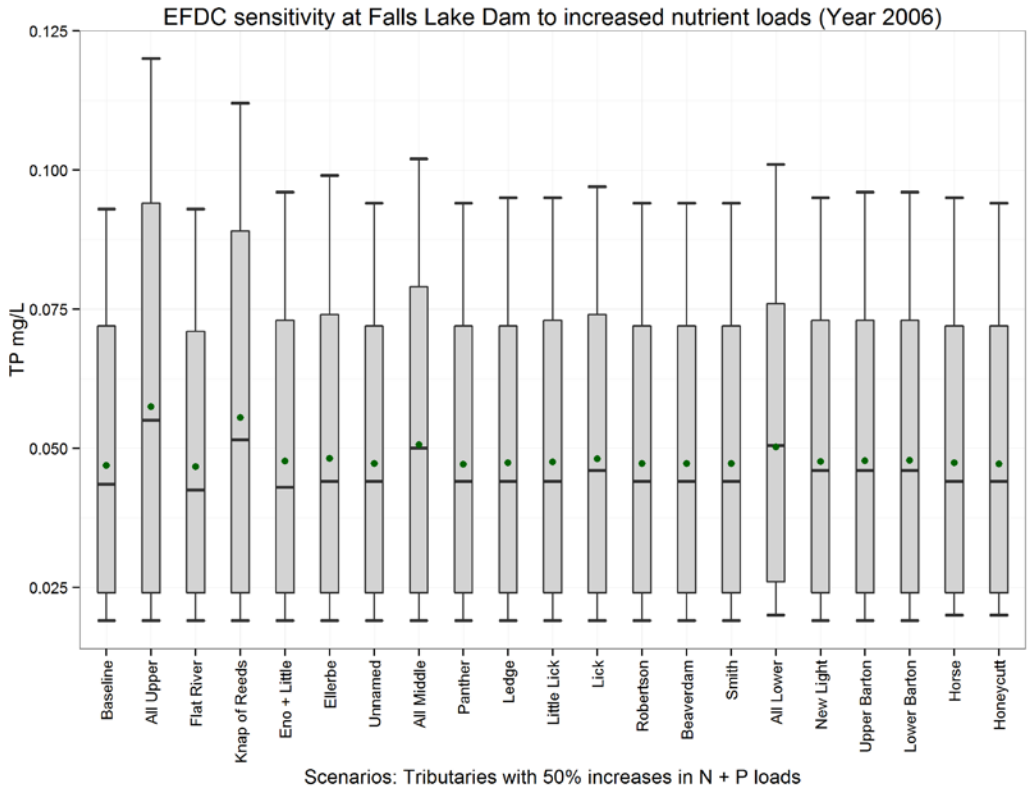

Figure B-7 Sensitivity of Falls Lake TP concentrations at Falls Lake Dam to a 50% increase in N and P loading, 2006 conditions

Table B-7 Summary Statistics for Predicted Daily Average TP in the Top Layer at the Falls Lake Dam associated with a 50% increase in N and P loading, 2006 conditions

Scenario	Minimum	25th percentile	Median	75th percentile	90th percentile
Baseline	0.019	0.024	0.0435	0.072	0.093
All Upper	0.019	0.024	0.055	0.094	0.12
Flat River	0.019	0.024	0.0425	0.071	0.093
Knap of Reeds	0.019	0.024	0.0515	0.089	0.112
Eno + Little	0.019	0.024	0.043	0.073	0.096
Ellerbe	0.019	0.024	0.044	0.074	0.099
Unnamed	0.019	0.024	0.044	0.072	0.094
All Middle	0.019	0.024	0.05	0.079	0.102
Panther	0.019	0.024	0.044	0.072	0.094
Ledge	0.019	0.024	0.044	0.072	0.095
Little Lick	0.019	0.024	0.044	0.073	0.095
Lick	0.019	0.024	0.046	0.074	0.097
Robertson	0.019	0.024	0.044	0.072	0.094
Beaverdam	0.019	0.024	0.044	0.072	0.094
Smith	0.019	0.024	0.044	0.072	0.094
All Lower	0.02	0.026	0.0505	0.076	0.101
New Light	0.019	0.024	0.046	0.073	0.095
Upper Barton	0.019	0.024	0.046	0.073	0.096
Lower Barton	0.019	0.024	0.046	0.073	0.096
Horse	0.02	0.024	0.044	0.072	0.095
Honeycutt	0.02	0.024	0.044	0.072	0.094

B.3.4 Total Nitrogen Sensitivity at Falls Lake Dam

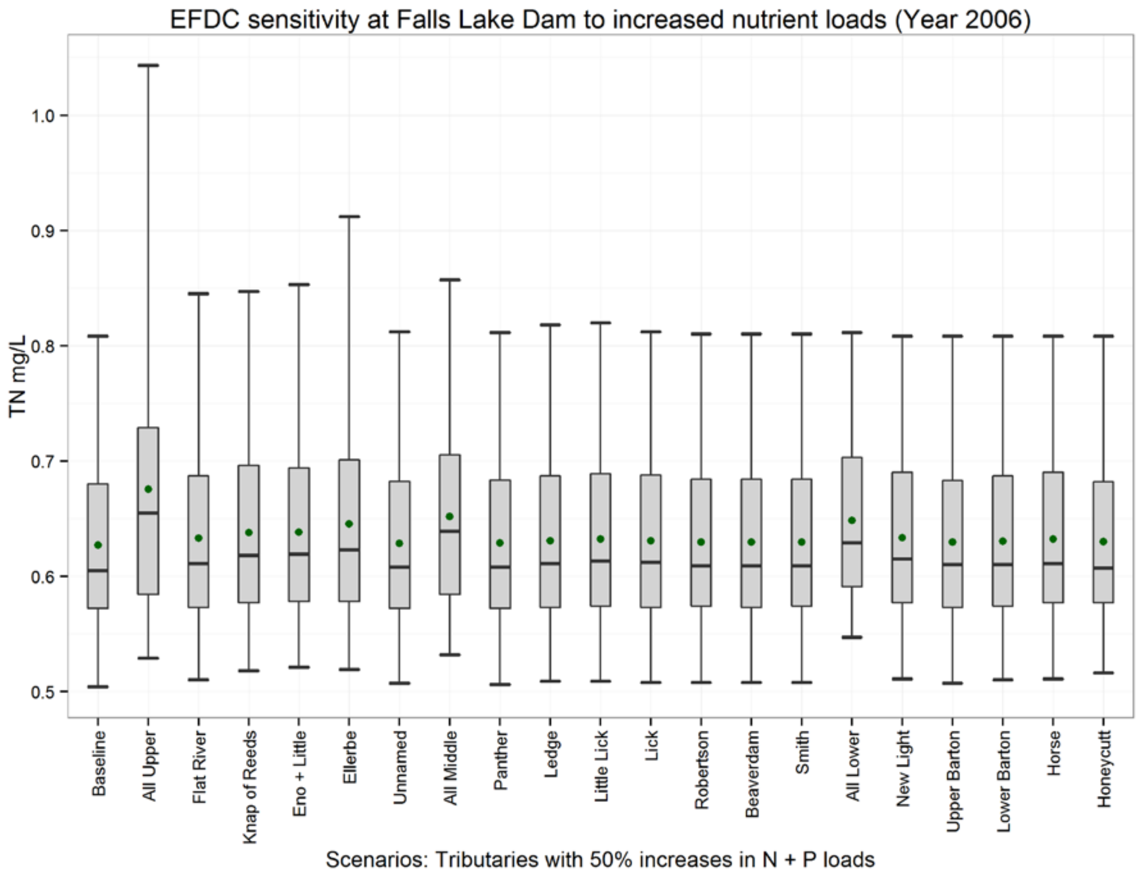

Figure B-8 Sensitivity of Falls Lake TN concentrations at Falls Lake Dam to a 50% increase in N and P loading, 2006 conditions

Table B-8 Summary Statistics for Predicted Daily Average TN in the Top Layer at the Falls Lake Dam associated with a 50% increase in N and P loading, 2006 conditions

Scenario	Minimum	25th percentile	Median	75th percentile	90th percentile
Baseline	0.504	0.572	0.605	0.68	0.808
All Upper	0.529	0.584	0.655	0.729	1.043
Flat River	0.51	0.573	0.611	0.687	0.845
Knap of Reeds	0.518	0.577	0.618	0.696	0.847
Eno + Little	0.521	0.578	0.619	0.694	0.853
Ellerbe	0.519	0.578	0.623	0.701	0.912
Unnamed	0.507	0.572	0.608	0.68225	0.812
All Middle	0.532	0.584	0.639	0.705	0.857
Panther	0.506	0.572	0.608	0.68325	0.811
Ledge	0.509	0.573	0.611	0.687	0.818
Little Lick	0.509	0.574	0.613	0.689	0.82
Lick	0.508	0.573	0.612	0.688	0.812
Robertson	0.508	0.574	0.609	0.684	0.81
Beaverdam	0.508	0.573	0.609	0.684	0.81
Smith	0.508	0.574	0.609	0.684	0.81
All Lower	0.547	0.591	0.629	0.703	0.811
New Light	0.511	0.577	0.615	0.69	0.808
Upper Barton	0.507	0.573	0.61	0.683	0.808
Lower Barton	0.51	0.574	0.61	0.687	0.808
Horse	0.511	0.577	0.611	0.69	0.808
Honeycutt	0.516	0.577	0.607	0.682	0.808

B.3.5 Total Organic Carbon Sensitivity at Falls Lake Dam

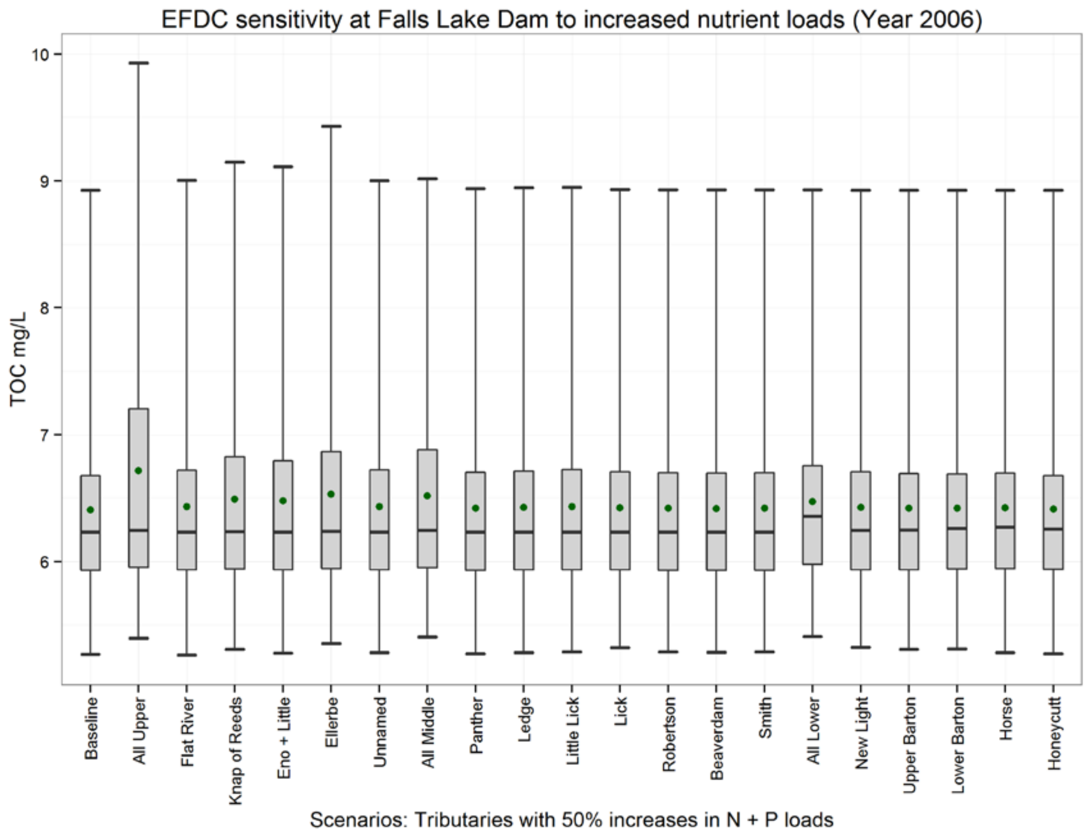

Figure B-9 Sensitivity of Falls Lake TOC concentrations at Falls Lake Dam to a 50% increase in N and P loading, 2006 conditions

Table B-9 Summary Statistics for Predicted Daily Average TOC in the Top Layer at the Falls Lake Dam associated with a 50% increase in N and P loading, 2006 conditions

Scenario	Minimum	25th percentile	Median	75th percentile	90th percentile
Baseline	5.268	5.932	6.230	6.676	5.268
All Upper	5.394	5.956	6.243	7.205	5.394
Flat River	5.261	5.934	6.231	6.721	5.261
Knap of Reeds	5.309	5.945	6.234	6.826	5.309
Eno + Little	5.278	5.935	6.231	6.794	5.278
Ellerbe	5.352	5.946	6.237	6.866	5.352
Unnamed	5.281	5.935	6.231	6.723	5.281
All Middle	5.406	5.953	6.245	6.881	5.406
Panther	5.272	5.933	6.23	6.702	5.272
Ledge	5.283	5.934	6.231	6.714	5.283
Little Lick	5.289	5.936	6.232	6.726	5.289
Lick	5.322	5.935	6.233	6.707	5.322
Robertson	5.287	5.933	6.231	6.699	5.287
Beaverdam	5.286	5.933	6.231	6.698	5.286
Smith	5.287	5.933	6.231	6.699	5.287
All Lower	5.407	5.979	6.354	6.754	5.407
New Light	5.324	5.937	6.245	6.707	5.324
Upper Barton	5.307	5.937	6.248	6.693	5.307
Lower Barton	5.311	5.942	6.260	6.691	5.311
Horse	5.280	5.944	6.270	6.696	5.280
Honeycutt	5.273	5.938	6.254	6.677	5.273