Key Findings from the UNRBA Falls Lake Models

The UNRBA developed three models to simulate water quality in Falls Lake. Multiple models provide a better understanding of the system. The watershed model provides inputs to the lake models. These inputs include stream flows and nutrient loading to Falls Lake.

Nitrogen and phosphorus are the major nutrients that algae need to grow. The lake models predict the growth of algae and concentrations of chlorophyll-a. This green pigment is an algal indicator used as a water quality standard in North Carolina. The chlorophyll-a standard requires less than 40 micrograms per liter (40 µg/L) in water samples from Falls Lake.

The UNRBA models evaluate potential management strategies and resulting impacts on water quality. The three lake models are listed below:

- Watershed Analysis Risk Management Framework (WARMF) Falls Lake Model
- Environmental Fluid Dynamics Code (EFDC) Falls Lake Model
- Data driven statistical/Bayesian Falls Lake Model

Key findings from the watershed modeling are available here. Key findings from the lake modeling are listed below. Additional information follows on subsequent pages. To review the full UNRBA Lake Modeling Report, click here. Additional information is also available in the UNRBA Resource Library.

- Most of the nutrient load enters Falls Lake at the upper end (green area of Figure 1). This area is shallow and wide. The physical characteristics and loading patterns lead to higher algal growth in this part of the lake. However, water quality in this area has significantly improved and stabilized since the lake was filled. This improvement is due to reductions in nutrient loading to the lake. Historic trends in nutrient loading to Falls Lake are summarized here.

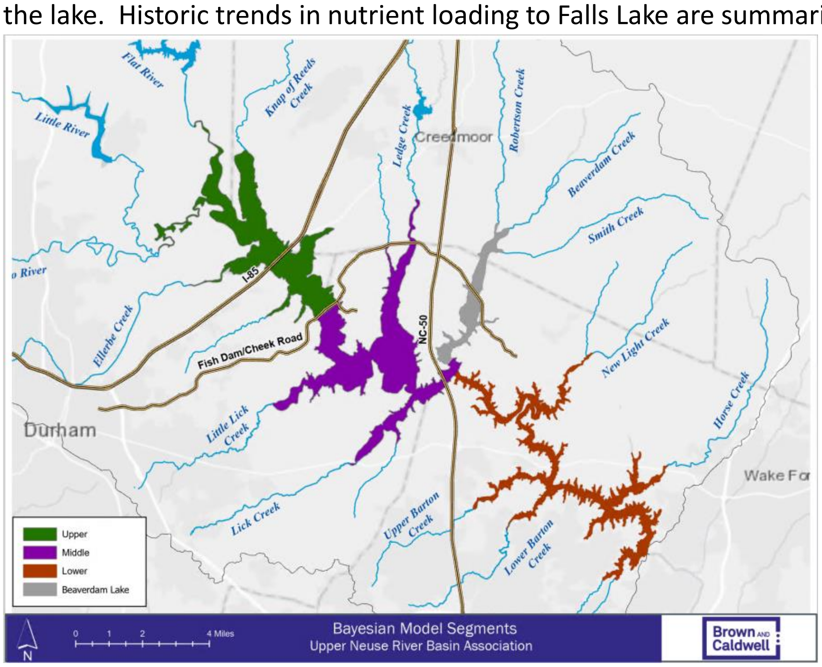


Figure 1. Data Summary Segments for Falls Lake

- Water quality in the middle part of the lake (purple area) is better than the upper part. Many of the nutrients have been used by algae by the time the water reaches the middle. The water is a little deeper here, but still spread out wide.
- Water quality in the lower part of Falls Lake (brown area) has always been relatively stable and better than the middle and upper parts. The lower lake is narrow and deep. Most of the nutrients have already been consumed by algae or have settled out of the water into the lake sediments. Most of the recreational access points are in or near the lower lake. The City of Raleigh withdraws water from the lower lake for its water supply.
- Lake monitoring data indicates that algal growth has stabilized throughout Falls Lake. A summary of lake monitoring data is available below (see page 3). A more comprehensive summary is available here. UNRBA lake modeling confirms these findings (more information is provided below; see page 10). Increasing or decreasing nutrient load by 20% is not predicted to affect compliance with the chlorophyll-a standard. To meet the standard 90% of the time in the upper lake, total nitrogen reductions of 50% would be required. These reductions would be in addition to the reductions already achieved in the watershed (summarized here). The additional reductions are not predicted to meet the chlorophyll-a standard. Most of the watershed (75%) is unmanaged or natural, like forests and wetlands. These areas contribute approximately one-half of the nutrient load to Falls Lake (summarized here). Because significant reductions in nutrient loading have already been achieved, reducing nutrient loading by another 50% is not achievable. The UNRBA has developed recommendations for a revised nutrient management strategy to address these challenges. A concise set of consensus principles was developed to facilitate approval of the recommendations by every UNRBA member.
- The UNRBA developed a hypothetical scenario to evaluate conversion of all land in the watershed to forest. Wastewater treatment plants, onsite wastewater treatment systems, and nutrient application to land surfaces were also removed. Sub-impoundments (Lake Michie, etc.) were not removed. Atmospheric deposition was not changed. Initial conditions for the lake sediments were not changed. Stream flows and nutrient loads were evaluated following a 25-year modeling period to allow conditions to stabilize in response to these changes.
  This scenario reflects a hypothetical "management" alternative that reduces most sources of human impact. While chlorophyll-a concentrations decreased, the upper lake still did not meet the standard. Modeling shows that further nutrient reductions may improve water quality, but the standard can never be achieved as currently applied.
  The UNRBA recommends continued nutrient management to protect and improve water quality. The regulatory assessment of Falls Lake will need to be revised. Meeting the water quality standard is a required goal of a watershed improvement plan. If there is no way to meet the standard, then the standard or its assessment method needs to be changed. Revisions require approval by the NC Division of Water Resources and NC Environmental Management Commission. The UNRBA is evaluating potential options to align the assessment methodology and/or the standard with the conditions present for Falls Lake and its watershed.

More information on each of these findings is provided on the following pages.

Historic Trends in Water Quality in Falls Lake

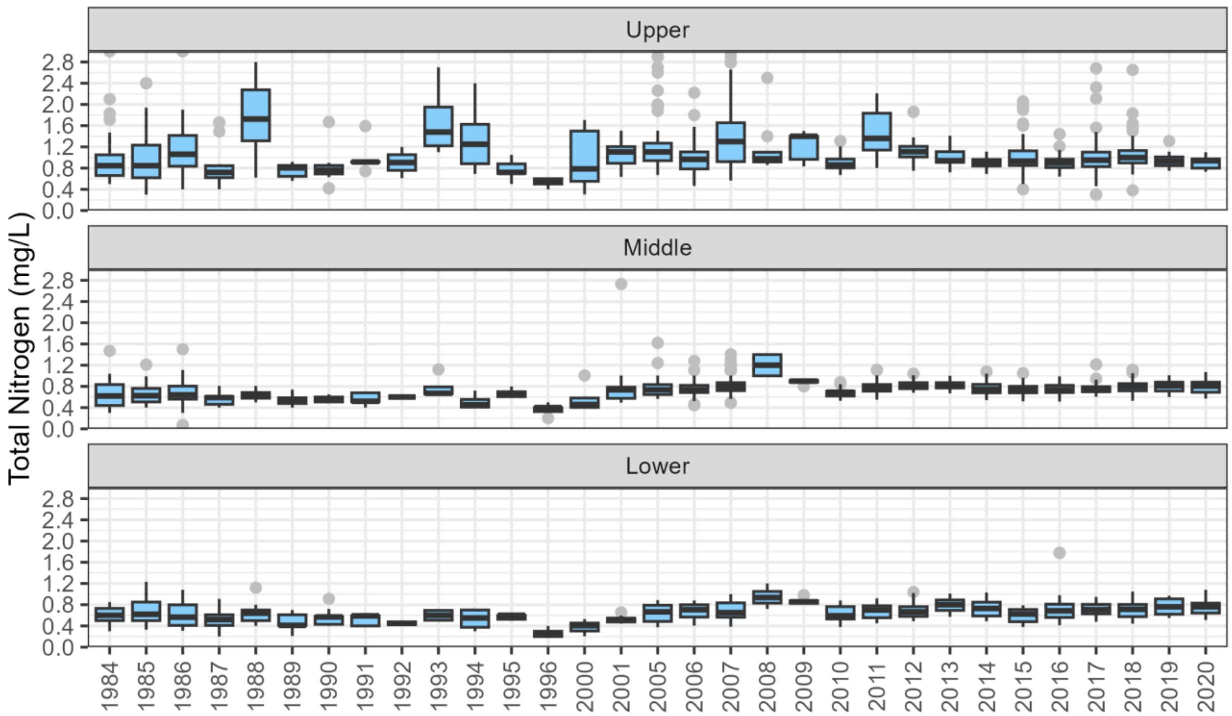
Water quality data has been collected in Falls Lake since the 1980s. Click here to review the key findings of the lake monitoring data. Part of Table 2 from that document is included on the following pages to illustrate trends in lake water quality over time. Additional lake data summaries are provided in the following documents:

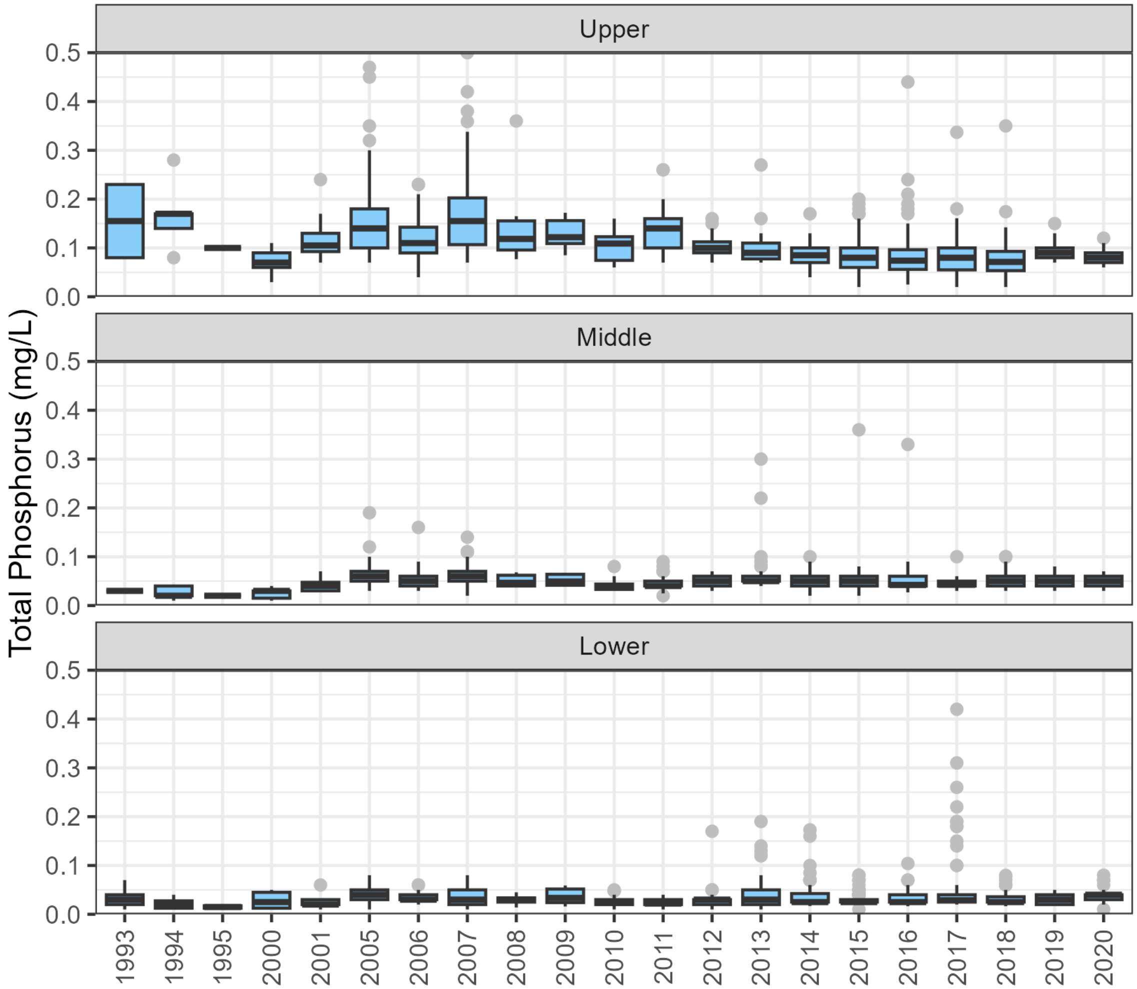
- 2019 UNRBA Annual Monitoring Report (comprehensive report)
- UNRBA Lake Modeling Report

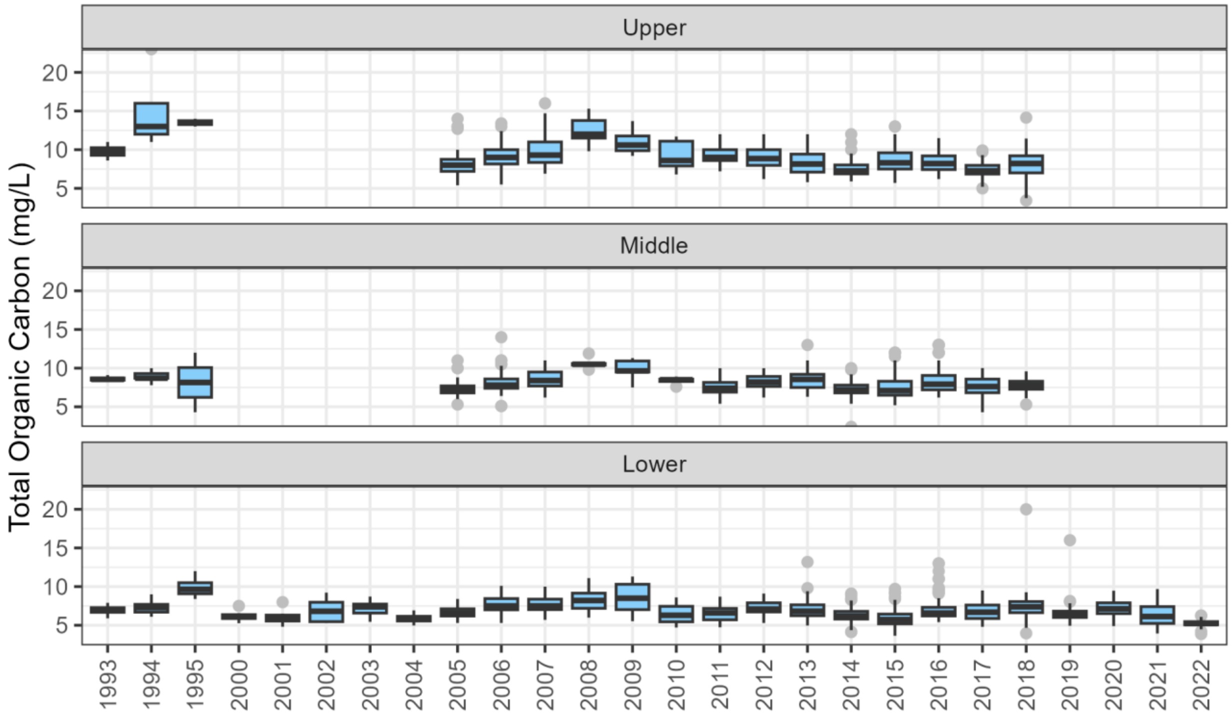
Several key findings of the lake monitoring data were critical to the development of the UNRBA recommendations for a revised nutrient management strategy and Falls Lake Rules:

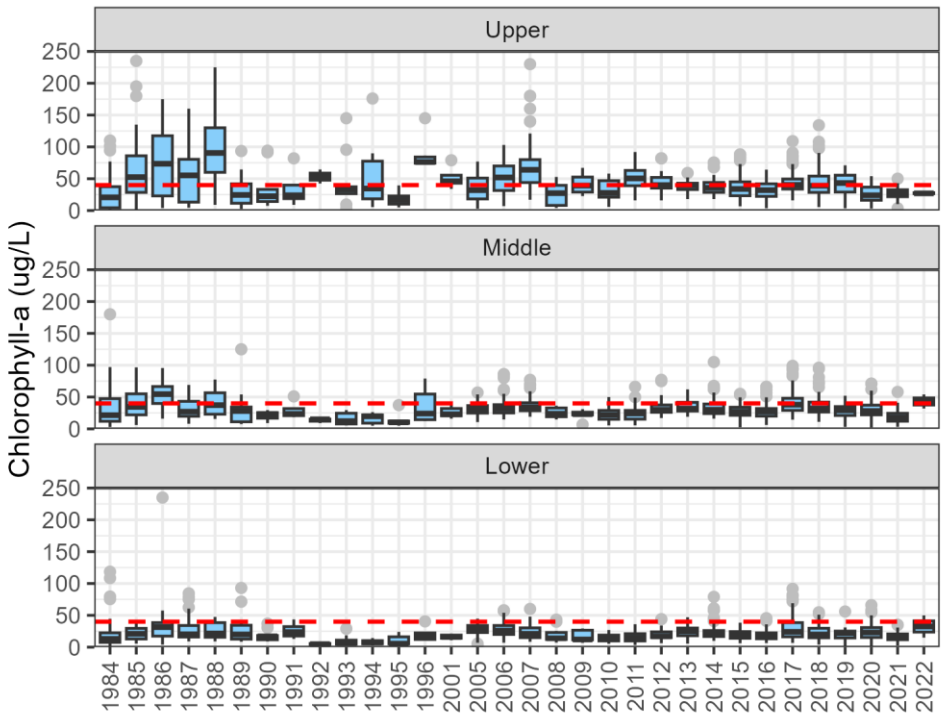
- Falls Lake is meetings its designated uses (fishing, swimming, aquatic life). Table 1 (here) provides examples of input from the Technical Advisors Work Group and users of Falls Lake. Additional information and data are provided in the UNRBA Lake Modeling Report.
- Water quality in Falls Lake has improved since the 1980s and stabilized in the past two decades. The UNRBA has summarized the Falls Lake data for three lake segments (Figure 1). The upper lake receives most of the nutrient loading from the watershed. This area of the lake is also wide and shallow. These two characteristics result in higher and more variable concentrations of nutrients and algal indicators compared to the middle and lower lake segments.
- Water quality in the upper lake has improved significantly due to reductions in nutrient loading from the watershed. Click here for a summary of the historic trends in nutrient loading to Falls Lake.
- Water quality in the lower lake has always been stable, even when nutrient loading to the lake was high (1980s). The table below shows the water quality trends since the 1980s for three parts of the lake. Data are summarized for total nitrogen, total phosphorus, chlorophyll-a, and total organic carbon. Chlorophyll-a is a green pigment used as an indicator of algal growth. Chlorophyll-a is used as a water quality standard in North Carolina. The chlorophyll-a standard requires less than 40 micrograms per liter (40 µg/L) in water samples from Falls Lake. Data summaries for other parameters are provided in the UNRBA Lake Modeling Report.
- Falls Lake sediments accumulate and release nutrients slowly over time. This process delays how quickly the lake will respond to changes in nutrient loading. Nutrient releases from the lake sediments contribute to the stability of nutrients and chlorophyll-a in Falls Lake.
- Several organizations have collected data in, or studied, Falls Lake (see Table 3 here). Each of these studies were integrated into the UNRBA Falls Lake models.

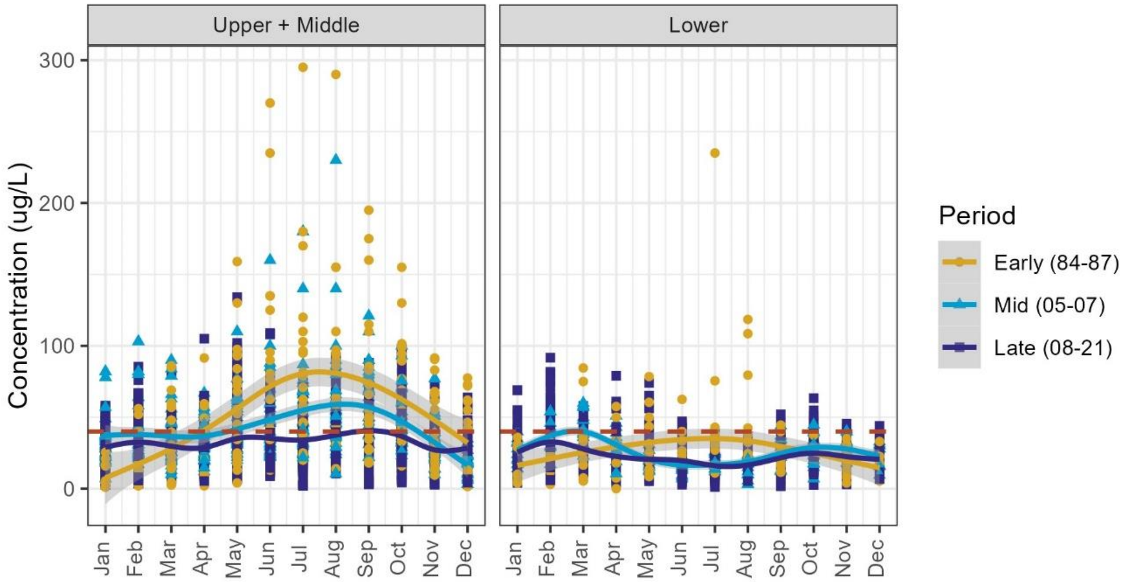
Historic Water Quality Trends for Total Nitrogen, Total Phosphorus, Chlorophyll-a, and Total Organic Carbon in the Three Segments of Falls Lake (Table 2 of the Key Findings of Lake Monitoring Data Summary)

Data Visualization	Notes
Total Nitrogen Photic Zone Composite Samples	
	Total Nitrogen by Year and Segment (y-axis cropped at 3 mg-N/L): • Higher values and higher variability in upper lake with conditions stabilizing in the last decade • Lower lake generally stable distribution through time • Middle lake is less variable than upper lake and more variable than lower • 13 samples were above 3 mg-N/L; these are not displayed on this figure • Values above 3 mg/L (clipped from figure) occurred post filling, mid-1990s, and 2007 (historic drought) • No clear time pattern regarding median or mean, but variance is lower in more recent years • Gray circles are outliers that represent 5 percent of the data

Data Visualization	Notes
Total Phosphorus Photic Zone Composite Samples	
	Total Phosphorus by Year and Segment (y-axis cropped at 0.5 mg-P/L): • Observations begin in the 1990s • Concentrations improve and stabilize in upper lake • Middle and lower lake have been relatively stable through time • 9 samples were above 0.5 mg-P/L; these are not displayed on this figure • Gray circles are outliers that represent 5 percent of the data

Data Visualization	Notes
Total Organic Carbon Photic Zone Composite Samples	
	Total Organic Carbon by Year and Segment: • Observations begin in the 1990s • Data gaps in upper and middle lake (x-axis is not continuous) • No strong trends apparent • Gray circles are outliers that represent 5 percent of the data

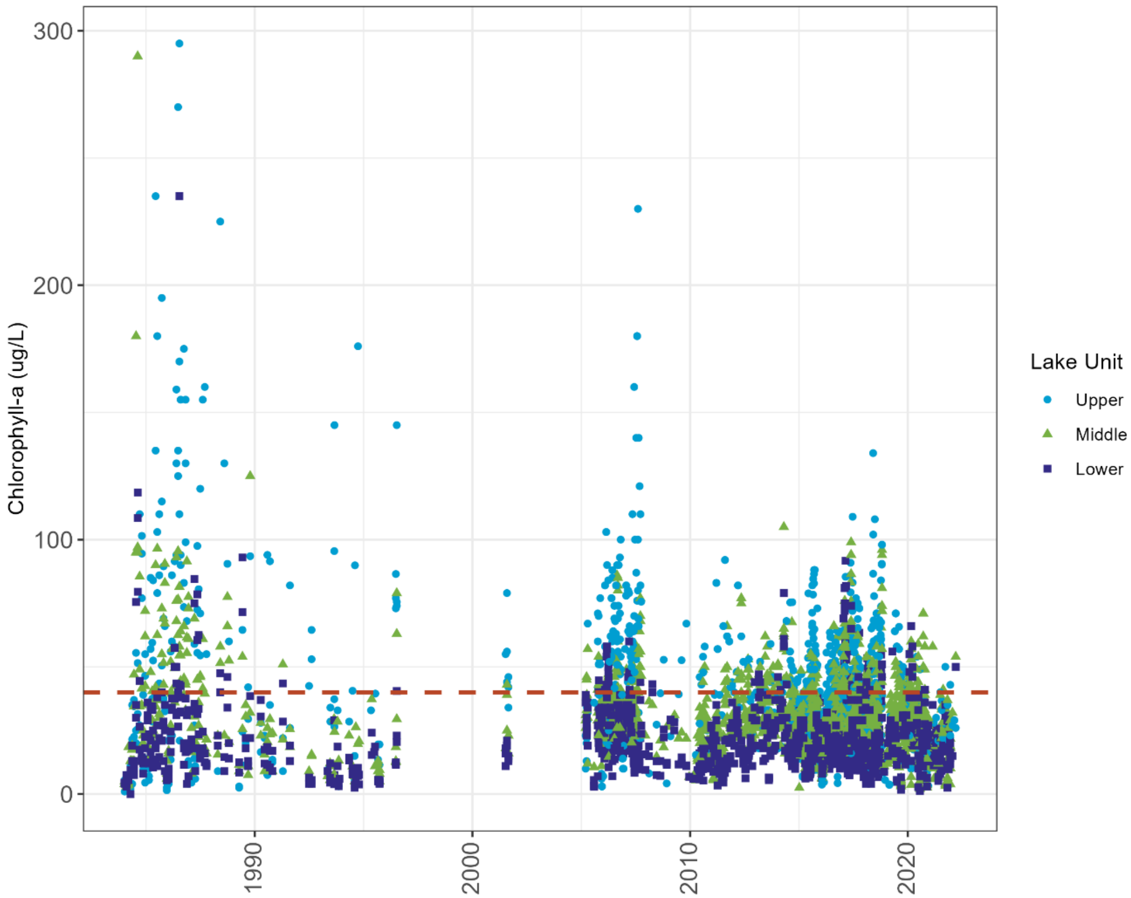
Data Visualization	Notes
<u>Chlorophyll-a Photic Zone Composite Samples</u>	
	Distribution of Chlorophyll-a by Year and Segment: • Red dashed line is the 40 µg/L NC chlorophyll-a standard • Higher variability in upper segment before 2012; much lower variability in upper segment after 2012; higher values in upper segment from 1988-2001 may be an artifact of sample bias (absence of winter data); high values in 2007 are due to the historic drought when the upper lake dried considerably • Variability is relatively high in the middle segment in the mid-1980s after reservoir filling and in 1996 (Hurricane Fran); after 2001 variability is relatively low and majority of chlorophyll-a samples are below 40 µg/L • Outliers were more common in the lower segment after reservoir filling; variability has been relatively stable across the period of record; majority of chlorophyll-a samples are below 40 µg/L • Gray circles are outliers that represent 5 percent of the data

Data Visualization	Notes
	See below

Notes

Change in Seasonal Trends Over Time

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

Data Visualization	Notes
	Chlorophyll-a Samples by Segment: • Red dashed line is the 40 µg/L NC chlorophyll-a standard • Upper lake samples are in light blue, middle lake in green, and lower lake in dark blue • Maximum values of chlorophyll-a have decreased since the post-filling period (1980s); values over 200 µg/L were observed in all three segments • Historic drought (2005 to 2007) had elevated values especially in the upper lake • Few values above 100 µg/L have been documented since 2007 • Overall decreasing trend in highest values over time and from the upstream to downstream direction

Impacts of Simulated Nutrient Load Reductions or Increases on Lake Water Quality

The UNRBA developed the lake models to evaluate how changes in the watershed would affect lake water quality. Compliance with the NC chlorophyll-a standard was the main focus of the evaluation. The UNRBA Lake Model Report shows how these scenarios would change total nitrogen, total phosphorus, and total organic carbon concentrations as well. The appendices of the lake model report further break down the nutrient species to show results for ammonia, nitrate, etc.

Four example scenarios are summarized in this document. The bullets below describe each scenario. The table below summarizes the results. Example figures follow. For a full list of scenarios and results, see the UNRBA Lake Model Report.

- The EFDC model was used to determine how much of a decrease in nutrient loading would be needed to meet the **NC chlorophyll-a standard** 90% of the time. The evaluation was conducted for the State's water quality monitoring station in the upper part of the lake (station NEU013B). See the UNRBA Lake Model Report for the load duration curves that summarize this scenario.
- EFDC was also used to evaluate how water quality would change if nutrient loading to Falls Lake was increased by 20%.
- The WARMF model was used to assess how conditions would change if precipitation increased or decreased by 20%. No other model inputs were changed. The WARMF Lake model divides the main lake into six segments (Figure 2). Simulated water quality for the precipitation scenarios and calibrated model is provided in Figure 3. Segment 1 corresponds to the uppermost part of the lake. Segment 3 is in the middle, and segment 6 is near the dam. The calibrated model represents 2014 to 2018. These years corresponds to the UNRBA monitoring period. With less simulated precipitation, the model predicts concentrations in Segment 1 that are higher than any observed in the lake. Algal growth rates in the model had to be set high to capture the magnitude of chlorophyll-a observations from 2014 to 2018. Some of the observations were as high as 100 µg/L, but the lower rainfall scenario predicts concentrations up to 400 µg/L. The combination of less precipitation and slower water movement in this shallow segment likely results in these very high values. Because some of the simulated values are higher than any ever observed in Falls Lake, they are likely an artifact of the modeling and not a realistic representation of potential outcomes. Simulation of values in Segments 3 and 6 are within observed ranges and appear reasonable.
- WARMF was also used to evaluate how nutrient loading and water quality could change if all of the watershed was converted to mature forest. Wastewater treatment plants, onsite wastewater treatment systems, and nutrient application were removed from the simulation. Atmospheric deposition was included. Results are provided in Figure 4. The high chlorophyll-a concentrations observed in 2017 were not well predicted by the calibrated model. An algae called Prymnesiophytae were dominant during this time. Sufficient data about the growth of these algae were not available to simulate them as a single algal group. Instead, they were grouped with other algae like Euglenoids. For more information regarding simulation of different algal groups, see the UNRBA Lake Model Report.

Example Scenarios Evaluated with the Falls Lake EFDC Model and Simulated Changes to Chlorophyll-a (from the UNRBA Lake Modeling Report)

Simulation of Nutrient Load Reductions Needed to Meet the NC Chlorophyll-a Standard 90% of the Time
The EFDC model was used to evaluate combinations of nitrogen and phosphorus reductions. Output compares the percent of time the chlorophyll-a standard (40 µg/L) would be exceeded. Combinations were evaluated to determine the level of load reduction needed to achieve the standard 90 percent of the time. The calibration years 2015-2016 were used for this assessment. A monitoring station in the upper lake was used for this evaluation (NEU013B). Meeting the chlorophyll-a standard at least 90 percent of the time would not necessarily result in delisting Falls Lake based on NC's current assessment methodology. Attaining the chlorophyll-a standard would require a 50 percent reduction in total nitrogen relative the UNRBA study period. This reduction is beyond what has already been achieved in the watershed. **Conclusion: Based on watershed modeling, a 50 percent reduction in total nitrogen loading to Falls Lake is not feasible. This load reduction would not result in delisting Falls Lake for chlorophyll-a based on the current 303(d) assessment methodology.**
Simulation of 20 Percent Increase in Nutrient Loads Delivered to Falls Lake
The EFDC model was also used to simulate a 20% increase in nutrient loading to Falls Lake. This scenario was used to understand potential impacts of further land use changes and increased nutrient loading to Falls Lake. In the upper lake, a 20 percent increase in nutrient loads increased the percent of time the chlorophyll-a standard was exceeded from 40 percent to 45 percent. Near the dam, the 20 percent increase in nutrient load did not affect simulated chlorophyll-a concentrations. **Conclusion: This load-increase scenario further supports the stability of chlorophyll-a concentrations in Falls Lake, particularly near the dam. Historically, water quality near the dam has been stable even under higher nutrient loading conditions.**
Simulation of Changes to Rainfall (20% Increase or Decrease)
Watershed modeling shows precipitation is the determining factor for the amount of nutrient load delivered to Falls Lake. Two precipitation scenarios were developed for the WARMF watershed model and lake model. One scenario decreased precipitation amount by 20 percent. This reduction represents rainfall amounts that occurred during the DWR baseline modeling period for the Falls Lake Rules. Lower rainfall also occurred during the forest monitoring studies conducted by the US Forest Service in the Falls Lake watershed. Another modeling scenario increased precipitation amount by 20 percent. The increase represents conditions with larger, more frequent storms. During certain times, the lower rainfall scenario results in the highest concentrations of chlorophyll-a. Less rainfall results in stagnation of the lake, allowing more time for algae to grow. The lower rainfall scenario results in 35 percent less total nitrogen load delivered to Falls Lake and 42 percent less total phosphorus load delivered to Falls Lake. On the other hand, a 20 percent increase in rainfall increases delivered total nitrogen and total phosphorus loads by 36 percent and 60 percent, respectively. These load increases do not translate to increases in simulated chlorophyll-a concentrations. While the nutrient loads increase under the higher precipitation scenario, stream flows also increase. Water moves through the lake more quickly, reducing the potential for algal growth. **Conclusion: Delivered nutrient loading is not the single determining factor for algae growth and chlorophyll-a concentrations in Falls Lake.** Rainfall patterns are also important. This scenario further confirms that algal levels are relatively stable in the lake. Sufficient nutrients are available to sustain current algal levels, despite substantial reductions or increases in loading to the lake.
Simulation of Land Conversion to Forests and Removal of Nutrient Application and Wastewater-Related Discharges ("All Forest")
This scenario establishes the lowest potential loading and resulting lake water quality. The scenario assumes conditions on the ground change instantaneously. This "all forest" scenario is further described in the UNRBA Watershed Modeling Report. The "all forest" scenario results in lower chlorophyll-a concentrations than the calibrated model. However, concentrations still exceed the 40 µg/L chlorophyll-a standard in the upper lake approximately 30% of the time. **Conclusion: Not even this hypothetical scenario can meet the chlorophyll-a standard everywhere, all the time in Falls Lake. Converting the entire watershed to forest is the lowest nutrient loading condition for the watershed. While this is a hypothetical scenario, modeling this condition illustrates that there is not a watershed-based management approach that can achieve the chlorophyll-a standard in Falls Lake as currently applied.** **Implications: These results are not presented to imply that forests are bad for water quality. On the contrary, forests are the best possible land use for watershed health. If the Falls Lake dam were not present, this scenario would attain the chlorophyll-a standard. Current watershed conditions would also likely achieve the chlorophyll-a standard if the dam were not present. However, the Falls Lake reservoir provides irreplaceable benefits to society. Expecting water quality in the reservoir, even under an "all forest" condition, to mimic the water quality of an undisturbed system without a dam, is not realistic.**

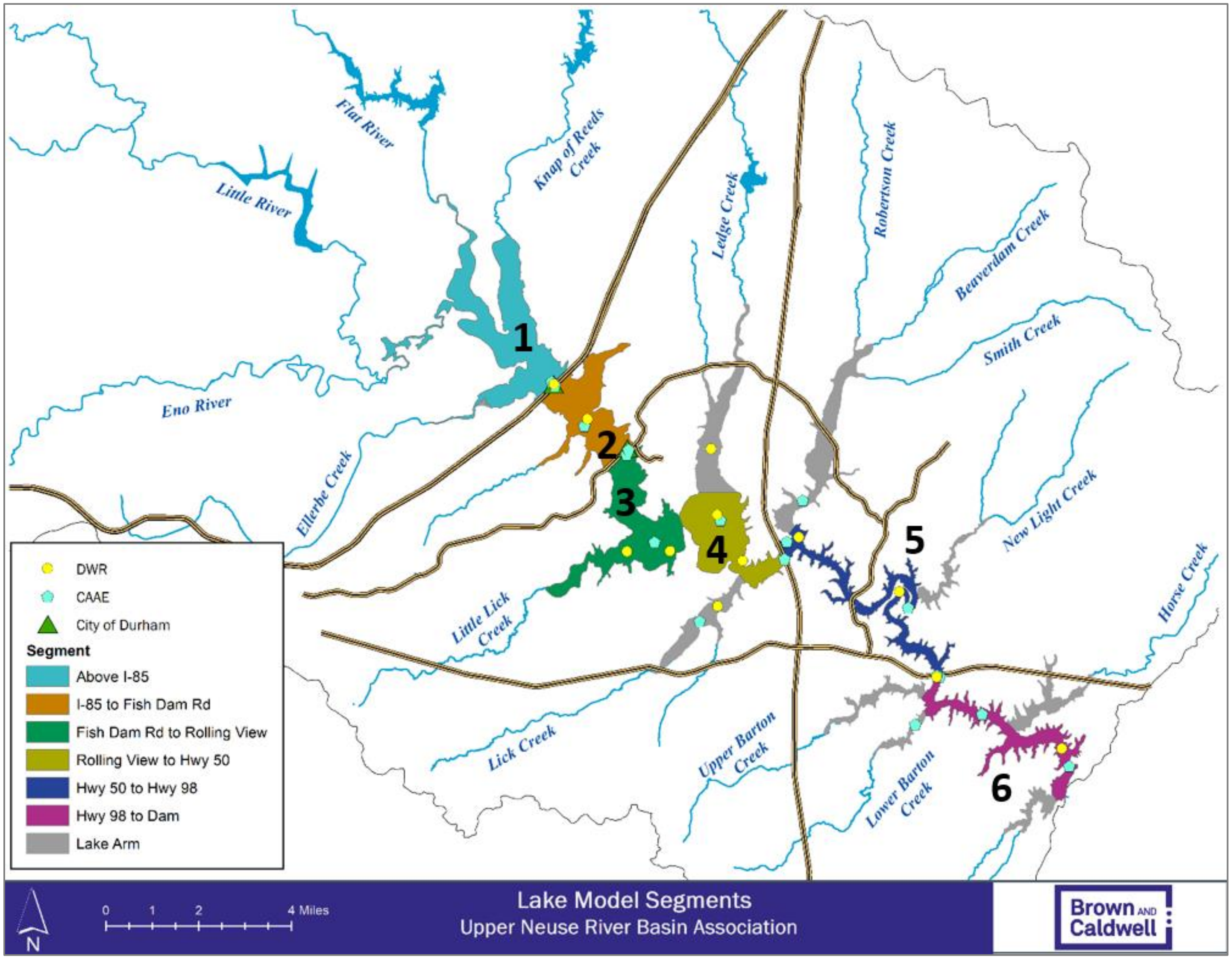


Figure 2. WARMF Lake Modeling Segments for Falls Lake

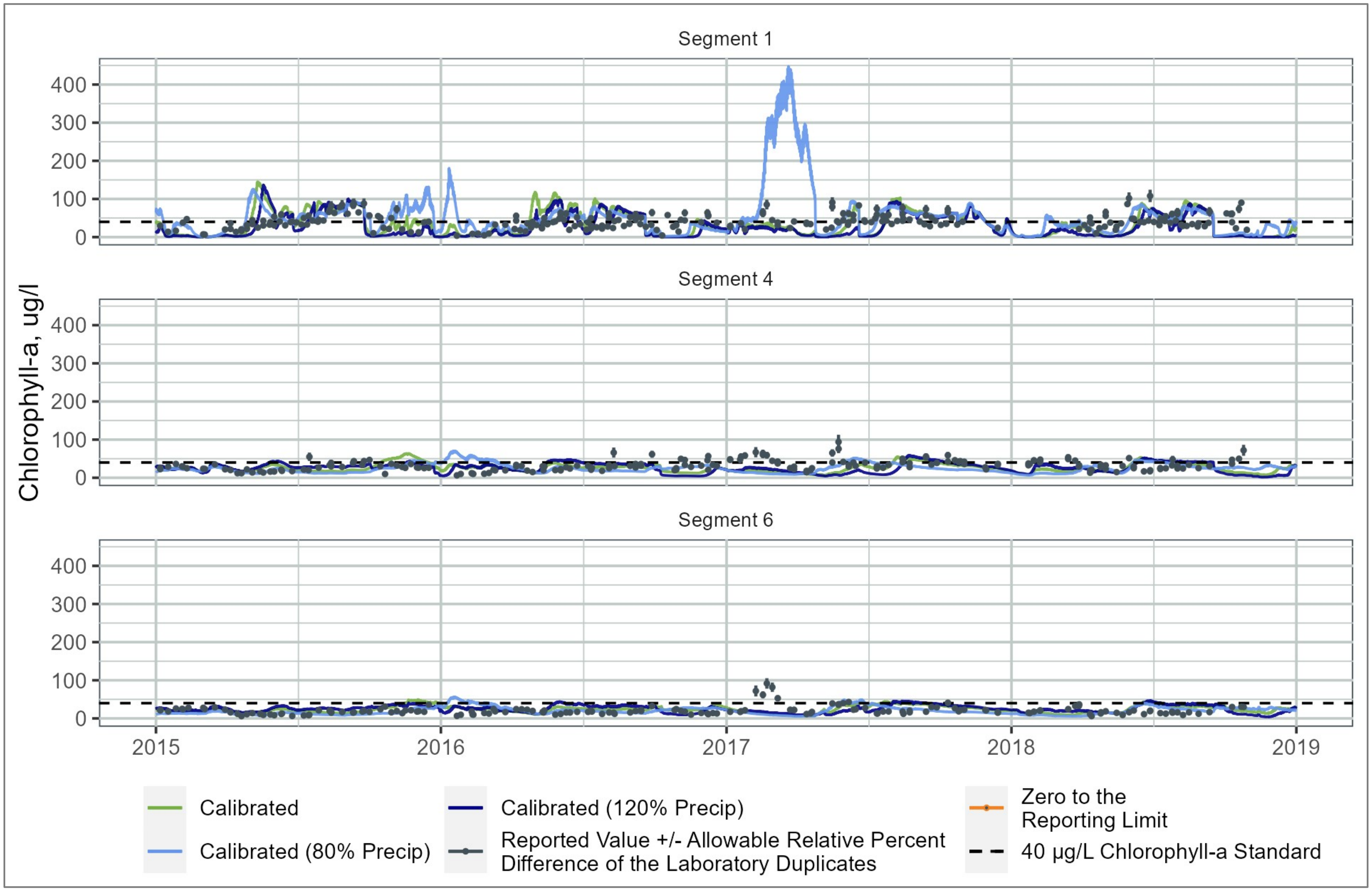


Figure 3. WARMF Lake Simulated Chlorophyll-a Concentrations for the Calibrated Model Compared to 20 Percent Increase or Decrease in Rainfall Amount in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

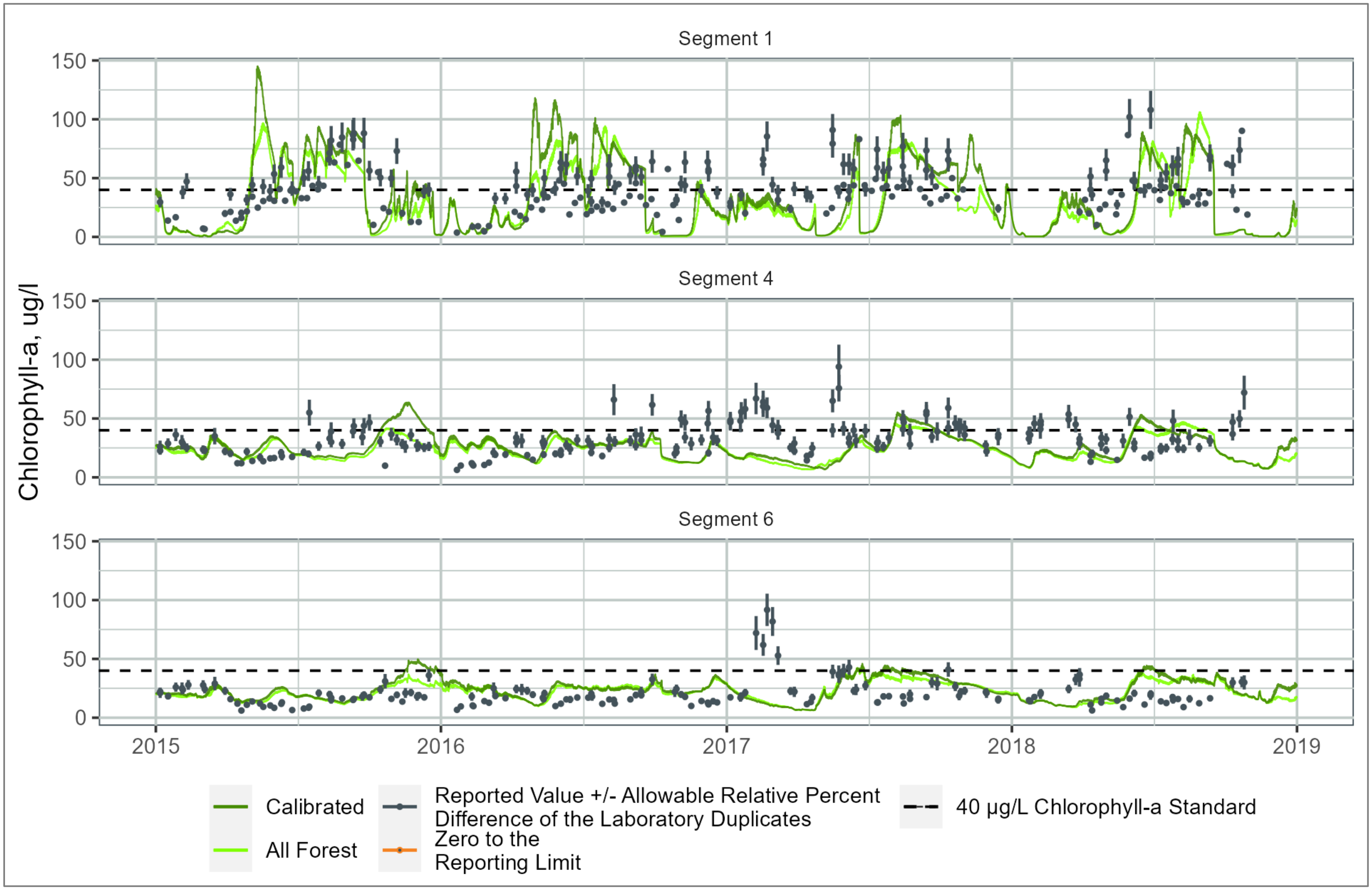


Figure 4. WARMF Lake Simulated Chlorophyll-a Concentrations for the Calibrated Model Compared to the Instantaneous Land Conversion to All Forest with Elimination of Onsite and Centralized Wastewater Treatment Discharges and Nutrient Application to Land Surfaces (Atmospheric Deposition is not Altered from the Calibrated Model) in Three Falls Lake Segments