UPDATED FALLS LAKE DATA EVALUATION OF EXISTING CONDITIONS

CONSIDERATIONS FOR A SITE-SPECIFIC CHLOROPHYLL STANDARD

UPPER NEUSE RIVER BASIN ASSOCIATION

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1 OBJECTIVES

Investigation of environmental conditions in the reservoir referred to as Falls Lake has been extensive, particularly over the past two decades. Data from the studies completed provide a sound foundation for the evaluation of whether designated uses for the waterbody are currently being achieved and whether conditions within the reservoir indicate trends of degrading conditions. The objectives of this report are to provide a review of available data associated with algal growth in the reservoir and to utilize observations from the review as a basis for the development of a recommended approach for a site-specific chlorophyll a (Chla) standard for Falls Lake.

2 BACKGROUND

Reservoirs represent a subset of lake environments where a free-flowing river has been modified to create an impoundment with lake-like conditions. Investigations supported by the Upper Neuse River Basin Association (UNRBA) and by others provide extensive background on the history and water quality trends for Falls Lake. A synthesis of findings for studies on the physical characteristics, on water quality trends, and on the biology of Falls Lake completed through 2018 is provided in Brown and Caldwell (2019). The data and observations provided in the summary report are incorporated extensively in this review, including reproduction of key figures illustrating spatial patterns. The data evaluated in the analysis summarized in this report were provided to WSP by consultants to the UNRBA, and the data files provided include monitoring data through 2021.

The focus for the analysis summarized in this report is to understand current conditions in the impoundment in the context of the designated uses of the waterbody. For the reach of the Neuse River contained within Falls Lake, the design and construction of the impoundment was conducted by the U.S. Army Corps of Engineers (USACE) and completed in 1981. The environmental statement for the project, finalized in 1974 (USACE, 1974), anticipated the modified waterbody would experience thermal stratification during parts of the year and a corresponding depletion of dissolved oxygen (DO) in the isolated deeper waters. In terms of overall biological productivity, the environmental statement for the project indicated eutrophic conditions were likely in the reservoir. The environmental statement prepared and a separate analysis prepared by the NC Department of Natural and Economic Resources (DNER, 1973) concurred on the anticipated conditions in the reservoir and recommended advanced wastewater treatment be implemented for facilities upstream of the reservoir. Brown and Caldwell (2019) indicated advanced treatment is now in place at each major facility. For the evaluation of current data for the reservoir, the anticipated conditions in the waterbody when the modification of the Neuse River was implemented provide an important benchmark for this assessment.

Spatial patterns in water quality parameters in reservoirs have been shown in a number of investigations to follow general patterns associated with gradients in hydrologic conditions within the impounded section of the river system. Brown and Caldwell (2019) present a summary of comparative studies from the limnological literature that describe three physical zones within impounded reaches of rivers (see Thornton et al., 1990). These have been referred to as a riverine upstream zone, a transition middle zone, and a downstream lacustrine zone. The summary report highlights some similarities for Falls Lake compared with the general spatial pattern presented in the literature reviewed but also identify differences from a reservoir with a single main inflow. Falls Lake has multiple inflows that blur the application of a simple physical model, but the general physical changes associated with a transition from multiple river inputs to a lake-like environment remain a useful context with which to organize spatial patterns in the reservoir.

An important physical factor associated with the decreased water velocity within an impoundment compared with tributary inflows is the settling of a portion of the suspended sediment loads. This important transition within the upstream portion of the reservoir system affects algal production by allowing light to penetrate deeper in the water column. Monitoring of Secchi depth in Falls Lake over the past 20 years supports this spatial pattern of increased light penetration, with the median Secchi depth value increasing from 0.3 meters in zone 1 to 1.0 in zone 6 for zones defined in **Figure 1**. The transition to more lake-like conditions also tends to decrease vertical turbulence, promoting seasonal thermal layering of the water column. Both of these gradients would promote enhanced utilization of available nutrients by planktonic algae and the accumulation of algal biomass, which is typically measured as Chla. Often, there is a maximum in Chla in reservoirs associated with the transition zone and lower Chla concentration in the downstream lacustrine zone. Except in waterbodies where there are substantial direct nutrient inputs within the impoundment (excluding internal release of nutrients from sediments), the general physical changes within reservoirs provide a sound scientific basis for segmentation in the assessment of algal biomass in the waterbody utilizing data compiled from monitoring locations within a region to assess conditions in the physical zone.

The level of primary productivity (i.e. algal growth) in a reservoir system, as for lakes in general (e.g. Wetzel, 1975), is an essential determinant of the overall biological productivity supported in the waterbody. Carbon fixed by plants forms the food base for zooplankton and subsequently to higher tropic levels, including sport fish species. Assessment of Chla in a waterbody provides a general indicator of overall primary production in the system to support higher trophic level production. As a general indicator, Chla is a parameter better assessed with a central tendency metric, such as a geomean value, utilizing all data for the region being assessed, as contrasted with toxic compounds where values at a particular location may pose a risk to human uses of the system and the animals present. For reservoirs valued for production of higher trophic levels (e.g. game fish species), a sufficient level of primary production is needed to support transfer of the biomass produced to higher trophic levels in the fish community. However, excess levels of productivity (i.e. hypereutrophic conditions) can lead to degraded water quality in a waterbody and reduction in suitable habitat to support a diverse aquatic community (e.g. USEPA, 1998).

Evaluating whether the level of Chla present in a reservoir is detrimental to the system is not a simple question. A reliable evaluation requires a comprehensive assessment involving water quality parameters, data on algal biomass and the algal species present, and characterization of transfer of primary production to higher trophic levels. Excess levels of primary production in a reservoir can lead to transitions in the algal species present, production of algal toxins, increased surface water pH and DO, and increased rate of bottom water DO depletion. Understanding seasonal and spatial patterns for water quality parameters within the reservoir, in the context of reasonable expectations for a physically modified system, would be core components of the assessment. An additional complication is parameters potentially affected by high algal production may also be affected by processes in tributary watersheds upstream of a reservoir, including headwater impoundments. A reliable assessment of whether the level of productivity in a reservoir system supports a healthy biological community in the man-made system or whether there are indications of impacts from excessive algal production requires substantial monitoring data to support the assessment.

Investigations on water quality conditions in Falls Lake have been performed over several decades by agency staff and private parties. Since 2014, there have been extensive data collection efforts to characterize current nutrient loading from tributaries and conditions within the reservoir. In addition, special studies performed in recent years have investigated topics such as nutrient delivery during storm events, sediment thickness and oxygen and nutrient fluxes, the bathymetry within the reservoir, and the presence of algal toxins. When the recent data are combined with monitoring beginning in 2001, available data support assessment of both the current condition of the reservoir and potential changes in water quality conditions over time. The available data have also been utilized to develop watershed and lake modeling tools to support a re-assessment of regulations needed to protect the designated uses of the reservoir. The evaluation summarized here focuses on parameters that may be affected by high levels of algal production to characterize evidence for detrimental effects on overall habitat quality for aquatic life and suitability of the algal community to support an overall healthy ecosystem for the current level of algal production and biomass in the reservoir. An important outcome of the evaluation is to determine whether the overall conditions in the system support the need for a reduction in Chla to protect the uses of Falls Lake. The evaluation summarized in this report utilizes an examination of water quality data provided to WSP by the UNRBA combined with excerpts on the physical characteristics and biological community in the reservoir from reports prepared for UNRBA by others.

3 DATA EVALUATION

3.1 PHYSICAL SETTING

The Falls Lake impoundment was created by the USACE with the construction of Falls Dam completed in 1981. Brown and Caldwell (2019) include data and observations on the physical setting of the reservoir and the watershed areas draining into the reservoir based on regular monitoring efforts and special studies performed for the UNRBA. Key figures from the 2019 report have been excerpted and included as an Appendix to this report. In terms of watershed properties, the master plan for the reservoir indicates the approximate drainage area to Falls Lake is 760 square miles (USACE, 2013). The overall watershed and the network of monitoring locations included in investigations supported by the UNRBA to characterize nutrient loading to the reservoir are illustrated in Figure 2.1 (see Appendix). The yellow circles in the figure denote the most downstream monitoring locations within the riverine zone of the individual tributaries. In terms of overall flow into the reservoir, the upstream five tributaries entering the reservoir upstream of Interstate 85 (Flat River, Little River, Eno River, Knap of Reed Creek, and Ellerbe Creek) contribute 78% of total flow (Brown and Caldwell, 2019).

Monitoring locations within Falls Lake are predominantly within the transition and lacustrine regions of the reservoir (see Figure 2-2). In terms of physical characteristics, the reservoir upstream of Interstate 85 (I-85) is shallow, and the long-term accumulation of sediments has been minimal. Figures 5-16 and 5-17 provide results for special studies characterizing the depth of accumulated sediment and water depth, respectively, to illustrate these patterns. For monitoring studies of reservoir conditions, the upstream extent for regular sampling locations has been where the I-85 highway crosses the reservoir. From an overall reservoir perspective, the upstream monitoring locations (upstream of Highway 50; Hwy-50) would be in the transition region of the reservoir, and the locations downstream of Hwy-50 would be consistent with the lacustrine zone in the general physical conceptual model for reservoirs.

Along the main flow axis of the reservoir, there are a series of road crossings and natural constriction points that subdivide the physical system. The investigation of conditions in Falls Lake has utilized several approaches to group available data along the main axis of the reservoir. Data have been presented in summary reports prepared for UNRBA by individual station and by spatial regions defined to integrate monitoring data for different regions of the reservoir. The WARMF modeling effort for Falls Lake incorporated the road crossings and constriction points to define six zones from I-85 to Falls Dam, with Highway 50 (Hwy-50) at the downstream margin of zone 4 (see **Figure 1**). For the Baysian modeling effort currently being developed, regions of Falls Lake were reduced to three (upper, middle, and lower) segments. The three segments shown in **Figure 1** are a modified version of a 3-segment representation of the reservoir to account for physical differences in the reservoir (upstream versus downstream) and the general reservoir transition and lacustrine regions. The reservoir between I-85 and just downstream of the Hwy-50 crossing is generally wide and shallow with some spatial variation in water depth (see Figure 5-17). In contrast, the drowned river channel is deepest and narrows in the areas of the reservoir downstream of Hwy-50. The distinct differences in the physical characteristics of the reservoir zones upstream of I-85, between I-85 and Hwy-50, and downstream of Hwy-50 is illustrated in the area-depth plots developed through the UNRBA supported investigations (see Figure 5-18).

Variation in lake level across years is associated with short-term increase in water level following storm events and a progressive decrease in water level over a period of weeks during regional drought events (Brown and Caldwell, 2019). The USACE manages water level in the reservoir to typically maintain an elevation of 251.5 feet relative to mean sea level (USACE, 2013). The use of the operational guide curve would effectively limit duration of elevated water level in the reservoir following large precipitation events, as Falls Dam discharge is managed to release flood storage while not contributing to downstream flooding along the Neuse River. These temporal patterns are illustrated in Brown and Caldwell (2019) in which a review of variation in precipitation and Falls Lake water level are included for the UNRBA intensive monitoring period of 2014-2018 (See Figures 3-3 and 3-4).

3.2 CHLA DATA REVIEW

An analysis of the spatial and temporal patterns in Chla concentrations in Falls Lake was included in Brown and Caldwell (2019) for data collected through 2018. The report included summary plots with a pattern of decreasing Chla with distance downstream from the I-85 crossing of the reservoir. Data compiled for Falls Lake for the UNRBA were provided to WSP by Alix Matos at Brown and Caldwell to allow WSP staff to provide an independent evaluation of available data for Falls Lake. For this data review, Chla data from 2001 to 2021 were used. Chla concentrations were evaluated by individual station, zones in the reservoir used for the WARMF modeling, and by segments defined by the general limnology of the Falls Lake Reservoir. **Figure 1** provides the spatial designations for the two approaches to segmentation of Chla data. Zones 1 to 6 refer to the regions of the reservoir utilized for the WARMF modeling while the upper, middle, and lower segments are defined relative to the general reservoir regions (transition and lacustrine). The upper and middle segments would be in the transition region of the reservoir, and the separation to two segments reflects the spatial gradient for Chla evident in the summary prepared by Brown and Caldwell (2019).

Spatial and temporal trends in Chla over the past 20 years are illustrated in **Figure 2**. The values shown are the geomean of all data points from months during the growing season (April-October) for each of the 6 zones defined by constriction points and road crossings. For all three periods, the Chla geomean value decreases from zone 1 near the I-85 crossing to zone 6 between the Hwy-98 crossing and Falls Dam. The highest geomean values occurred for data from 2001 to 2007 when the decrease in the geomean for Chla along the main axis of the reservoir was more than 3-fold (62 to 18 µg/L). For the later monitoring periods (2010-2021), the geomean values for the lacustrine portion of the reservoir (zones 5 and 6) were similar to values for 2001-2007 but the geomean values for the zones in the transition region of the reservoir were about 30% lower. Further, the spatial patterns for 2010-2015 and

2016-2021 were generally similar with geomean values varying from 41 to 14 µg/L and 37 to 18 µg/L, respectively, indicating algal biomass and productivity in Falls Lake has been relatively stable over the past decade.

From a spatial perspective, data grouped by the three reservoir segments (upper, middle, and lower; see **Figure 1**) showed a similarity in values within each segment. This similarity in geomean values for the zones grouped to three segments (1-2, 3-4, and 5-6) was particularly evident for the data collected beginning in 2010. Thus, the Chla data grouped by monitoring period indicate algal biomass generally varies by reservoir region, with a relatively consistent algal biomass in the recent monitoring periods within a segment of the reservoir. **Figure 3** provides the cumulative distribution for each of the three segments based on monitoring performed during 2010 to 2021 when the spatial pattern for Chla along the main axis of the reservoir has been generally stable. The cumulative distributions for Chla illustrate the spatial variation in the level of algal biomass in the reservoir for the three defined segments.

The evaluation of spatial variability in Chla concentration presented in **Figure 3** indicates the average value for multi-year periods has been stable in the reservoir for 2010-2021. An additional component of this evaluation is to characterize the temporal variability of Chla in the three reservoir segments. Annual growing season geomean values for Falls Lake were calculated by reservoir segment for years in the 2010-2021 period. For the temporal evaluation, the average value for the annual growing season geomean for each of the 11 years was calculated and presented in **Table 1**, along with the standard deviation for the annual values. For the 11-year period, the standard deviation for annual geomean values was 20-26% of the overall average of the annual values for each segment. The range for annual growing season geomean Chla concentration for each segment is also listed in the table. A substantial range in the computed annual growing season geomean for Chla is evident for all reservoir segments, as illustrated in the standard deviations of the average values and the range in annual geomean values for the growing season across the 11-year period.

Table 1. Variability in annual growing season geomean Chla values by reservoir segment for data collected in 2010 to 2021. The Chla value listed is the average of the 11 growing season geomean values for the segment. Standard deviation of annual geomean values by segment is expressed as a concentration (µg/L) and a percent of the average for annual geomean values for the 11-year period.

Segment	Years	Chla (µg/L)	Standard Deviation µg/L (%)	Range (µg/L)
Upper	11	35.2	9.28 (26%)	19.7 to 55.2
Middle	11	29.6	6.01 (20%)	17.0 to 38.9
Lower	11	18.1	4.08 (23%)	11.6 to 26.9

3.3 WATER QUALITY REVIEW

Monitoring data on parameters potentially impacted by the level of algal biomass in a reservoir were reviewed to assess evidence for impacts on habitat quality associated with Chla concentrations. Data included in the assessment were from monitoring efforts in Falls Lake during the 2001-2021 period for locations throughout the reservoir. Water quality parameters potentially altered by high algal production are the pH and DO of surface waters. High levels of algal production can increase the pH of surface waters through the scavenging of CO_2 present in surface waters and can increase the DO concentration to a value well above the level of saturation with atmospheric O_2 as a biproduct of primary production. For evaluation of pH data, North Carolina has implemented standards for surface waters at 6.0 to 9.0 for freshwaters such as Falls Lake (15A NCAC 02B). Data for DO is not as straightforward to interpret, since the potential impact on aquatic life is generally associated with high total dissolved gases (>110% saturation; 15A NCAC 02B) of which oxygen contributes 21% of the atmospheric gas pressure. Data utilized for the assessment of potential alteration of water quality conditions during periods in which high Chla concentration was present in surface waters was from measurements of pH, temperature, and DO at different depths from the water surface and the photic zone composite sampling performed for determination of Chla concentration on the same date and location. Parameter values were plotted against Chla concentration for all data available for each of the zones defined for WARMF modeling (see **Figure 1**).

Water quality monitoring data indicate pH in surface waters varies substantially for the same measured Chla concentration. Comparison of measured pH of surface waters at a depth of approximately 0.2, 1.0, 2.0, and 3.0 meters below the water surface is shown in **Figure 4** for zones 1 (upper), 3 (middle), and 5 (lower) plotted against the reported Chla concentration on the same date for a photic zone composite sample. The comparisons were performed for each of the six zones, with representative plots shown for each of the three segments of the reservoir. In terms of the photic zone, the median Secchi depths for zones 1, 3, and 5 from monitoring data for the reservoir are 0.3, 0.6, and 0.9 meters, respectively. Thus, readings at the 0.2 and 1.0 meter depth would generally be in the photic zone (NCDWR defines as Secchi depth x 2), and the readings at 2.0 and 3.0 would be deeper than the typical photic depth in each zone. The range in Chla incorporated into the analysis includes data from 2001-2008 with higher values (see **Figure 2**). The spatial pattern evident for Chla concentration in Falls Lake is evident in the higher range for Chla values in the upper segment (zone 1) of the reservoir compared with the middle (zone 3) and lower (zone 5) segments. The x-axis used in the plots is the same for all three zones to allow comparisons across zones. The overall range in pH values was similar for the 3 zones shown, with values of pH exceeding 9.0 rare in all three zones.

A frequency analysis was done to quantify how often the pH of the near surface reading was greater than 9.0, as a potential threshold of concern for protection of aquatic life. Chla data in the frequency analysis were binned by overlapping ranges (0-40, 20-60, 40-80, and 60-100 µg/L) to increase the number of observations from which to derive a frequency of elevated pH. In the analysis, the maximum occurrence was 4% (2 samples) of observations for Chla 60-100 µg/L in zone 1 (**Table 2**).

Table 2. Frequency of pH values outside range for freshwater standard by Chla range. Values are shown at a depth of 0.2 meters for pH > 9.0 and for a depth of 3.0 meters for pH < 6.0. Data were grouped by Chla range to examine linkage to algal biomass.

Zone	0-40 µg/L	20-60 µg/L	40-80 µg/L	60-100 µg/L
0.2 meter readings – frequency pH > 9.0				
1	0%	0%	0%	4%
2	1%	1%	1%	0%
3	0%	0%	1%	6%
4	0%	0%	0%	0%
5	0%	0%	0%	0%
6	1%	1%	1%	1%
3.0 meter readings – frequency pH < 6.0				
1	29%	30%	39%	55%
2	43%	46%	52%	53%
3	37%	33%	34%	25%
4	41%	39%	39%	19%
5	33%	31%	32%	36%
6	28%	36%	45%	67%
Notes: (1) zones are utilized as defined for WARMF modeling – see Figure 1; (2) Chla ranges for grouping pH data are overlapping to increase available data to compute frequencies.				

The maximum frequency for zones 2 through 6 was < 2% for all Chla ranges. In terms of variation in pH with depth, the pH of waters in Falls Lake generally decreased with depth for measurements taken at depths ranging from 0.2 to 3 meters below the water surface (see **Figure 4**), and thus, the occurrence of pH values greater than 9.0 below the near surface reading at 0.2 meters would be extremely rare. Overall, the frequency analysis was performed for all four depths and each of the six zones. The 0.2 meter reading had the highest frequency of pH values greater than 9.0, which represents a maximum potential impact.

Measurements of pH below the standard range of 6.0 to 9.0 were reported from the monitoring programs for all six zones. The occurrence of low pH values in rivers and impounded stretches of a river are often associated with drainage from tributaries with high organic matter, which in North Carolina would include wetland and swamp areas. In the context of an evaluation of potential contribution of high algal production to values of pH less than 6.0, enhanced decay of algal biomass settling to the bottom of the reservoir could contribute to decreases in pH within a reservoir through the release of CO_2 during the mineralization of the organic matter. However, the plots of pH of surface waters in Falls Lake in zones 1, 3, and 5 of the reservoir plotted against the photic zone Chla concentration do not show an increase in occurrence when Chla concentration is elevated. For the data included in the three zones shown in **Figure 4**, there was only one occurrence of pH < 6 when Chla was > 50 µg/L, which occurred at a depth of 3 meters in zone 1 when Chla was 87 µg/L. In fact, the occurrence of measurements of pH < 6.0 for the three zones shown were associated with Chla concentrations of 10-48 µg/L, and the occurrence of pH < 6.0 was more common in zone 1 in the region downstream of the main tributary inflows to the reservoir. Brown and Caldwell (2019) summarized data for the tributaries to Falls Lake and noted pH values < 6.0 in monitoring data for a number of the tributaries on some dates (see Figure 3-17). Thus, the occurrence of low pH values in Falls Lake appears to be associated with intermittent low pH for tributary inflows rather than associated with algal production within the reservoir.

The potential impact of high algal biomass on the DO concentration in surface waters was assessed by comparing DO concentrations as a percentage of saturation with the atmospheric O_2 levels with reported Chla concentration for the photic zone on the same date. The DO saturation percentage (DO_{sat}) was estimated from measured DO concentrations based on the reported temperature of the water on the sampling date (at 200 µS/cm and 760 mm Hg) utilizing the U.S. Geological Survey web tool DOTABLES, which is based on equations in Benson and Krause (1980, 1984). In the comparison, values of DO_{sat} greater than 100% typically indicate the production of O_2 within the water column, with the primary source from photosynthesis by planktonic algae in reservoir systems such as Falls Lake. For a comparison with the total dissolved gas criterion of >110% saturation, the equivalent DO_{sat} to contribute to a total gas saturation of 110% would be approximately 147%, accounting for the partial pressure of O_2 in the atmosphere (0.21 atm). The DO_{sat} is plotted against Chla values for zones 1, 3, and 5 in the reservoir in **Figure 5**, although plots were prepared and reviewed for all six zones. Data for zones in each of the three segments in Falls Lake are presented in the figure to illustrate spatial patterns. There are four observations >147% in zone 1, one in zone 3, and none in zone 5 for monitoring performed during 2001-2021. The individual measurements of DO_{sat} >147% occurred when the photic zone Chla ranged from 22 to 180 µg/L.

The frequency of supersaturated DO concentrations of potential concern was further evaluated by computing the percentage of DO measurement when the DO_{sat} value was greater than 120% by Chla range for each zone and water depths of 0.2, 1.0, 2.0, and 3.0 meters below the water surface. Results for the frequency analysis for data from depths of 0.2 and 1.0 meters are presented in **Table 3** to illustrate the pattern for samples in the photic zone. The overall frequency of DO_{sat} > 120% is low and decreases with depth below the water surface. In zone 1 where Chla concentrations are higher than in the downstream zones, the frequency of DO_{sat} > 120% for the reading at 0.2 meters was 28% of available dates when Chla was 60-100 µg/L but decreased to 13% for dates when Chla was 40-80 µg/L. Further, the maximum frequency for DO_{sat} > 120% in zone 1 for the DO reading at 1.0 meters decreased to 11% of

Table 3. Frequency of DO saturation > 120% and deeper water depletion by Chla range. Frequencies of DO greater than 120% of saturation are shown at depths of 0.2 and 1.0 meters while frequencies for DO concentration less than 2 mg/L are shown for a depth of 3.0 meters. Data were grouped by Chla range to examine linkage to algal biomass.

Zone	0-40 µg/L	20-60 µg/L	40-80 µg/L	60-100 µg/L
0.2 meter readings – frequency DO_{sat} > 120%				
1	3%	6%	13%	28%
2	4%	5%	8%	8%
3	3%	6%	11%	6%
4	1%	2%	2%	6%
5	2%	2%	2%	0%
6	1%	3%	9%	0%
1.0 meter readings – frequency DO_{sat} > 120%				
1	1%	2%	5%	11%
2	0%	1%	1%	0%
3	1%	2%	2%	0%
4	1%	1%	0%	0%
5	1%	1%	2%	0%
6	0%	0%	9%	0%
3.0 meter readings – frequency DO < 2.0 mg/L				
1	35%	44%	62%	70%
2	53%	55%	59%	61%
3	31%	30%	38%	19%
4	31%	32%	35%	13%
5	24%	24%	27%	18%
6	17%	22%	27%	33%
Notes: (1) zones are utilized as defined for WARMF modeling – see Figure 1; (2) Chla ranges for grouping pH data are overlapping to increase available data to compute frequencies.				

dates when Chla was 60-100 µg/L. The cumulative Chla distributions by segment presented in **Figure 3** indicate conditions when DO_{sat} may be > 120% occur at a low percentage of dates during the growing season. For example, Chla is greater than 60 µg/L in the upper segment on < 14% of dates during the growing season when the DO reading at 0.2 meters was greater than 120% on 28% of dates. Given the decrease in DO_{sat} with depth and general low frequency of occurrence of $DO_{sat} > 120\%$, algal production in Falls Lake does not appear to generate conditions of DO saturation that would impact aquatic life habitat.

Dissolved oxygen concentrations in subsurface waters may also be affected by enhanced primary production in the photic zone of a reservoir. As planktonic algae are mixed or settle from near surface waters to subsurface waters, the mineralization of the algal cells has the potential to contribute to the depletion of DO concentration. **Figure 5** includes estimated DO_{sat} for measurements of DO concentration at depths of 2 and 3 meters below the water surface, which would generally be just below the photic depth for all zones in the reservoir. In the figure, there are survey dates when low DO concentration (<20% of saturation) were reported for monitoring locations in all six monitoring zones, with data from zones 1, 3, and 5 depicted in the figure. The occurrence of low DO in zone 1 occurred across a wide range of Chla concentrations while low DO seemed to be less frequent in zones 3 and 5 in the middle and lower segments. The frequency of low DO concentration by Chla range is included in **Table 3** for measurements reported for a depth of 3.0 meters. In the comparisons, the maximum percentage was for the Chla range of 60-100 µg/L in zone 1. Overall, the percentages of dates with low DO concentration at a depth of 3.0 meters were highest in zones 1 and 2 and decreased in zones 3-6. In part, the decrease in frequency of DO < 2.0 mg/L for the downstream zones reflects the deeper water column in the segment (see Figure 5-18).

Brown and Caldwell (2019) report a regular seasonal occurrence of low DO concentration in bottom waters of the reservoir during warm months. Available data for Falls Lake include profiles of measured DO concentration and physical parameters at locations throughout the waterbody. Brown and Caldwell utilized the available data to estimate the volume of subsurface waters in different segments of the reservoir below DO concentrations of 4 mg/L and 1 mg/L, which represent thresholds of potential ecological importance to fish and benthic invertebrate populations. Estimated volumes for DO concentration < 1 and < 4 mg/L for upper + middle (middle) and lower (lower) segments of the reservoir (upstream and downstream of Hwy-50) were provided to WSP to evaluate potential associations with overall Chla levels in the reservoir for the sampling date and for the overall growing season from April to the sampling date.

The depletion of DO in subsurface waters followed a general pattern consistent with seasonal warming of waters in the reservoir and associated thermal stratification of the water column (**Figure 6**). In the middle segment, the volume of water with a DO < 4 mg/L was low during the months of April and October and showed a general increase in volume from April through July. However, there were dates for all months where the calculated volume of waters with DO < 4 mg/L was low, which indicates physical mixing processes maintain or reaerate subsurface water DO in some years in all months of the growing season. The seasonal increase in subsurface waters with DO < 4 mg/L was more pronounced in the lower segment, with depletion of 20% of volume in the months of June to September in all years shown. As with the middle segment, there was substantial variability in the volume of subsurface water with DO < 4 mg/L among the different monitoring years. Variability was highest in the lower segment in the month of October, with low volume in some years and continued seasonal depletion in others.

The volume of waters with DO < 4 mg/L was compared with average Chla for the growing season for the middle and lower segments to determine if variability in the overall biomass of algae in the segment could explain differences in subsurface DO depletion among years. The right panels in Figure 6 show comparisons for the months of August and September for each segment. For the comparisons, variation in the subsurface volume with DO < 4 mg/L is evident, but variation in growing season average Chla does not appear to explain the variation in low DO volume.

The original environmental assessment for the Falls Lake project anticipated thermal stratification would occur in the reservoir and be a factor affecting the DO concentration of subsurface waters (see USACE, 1974). In evaluating the linkage between algal biomass and potential depletion of DO in subsurface waters in a reservoir, thermal stratification of the water column can confound simple comparisons between Chla and DO concentrations. Thermal stratification promotes the depletion of DO in subsurface waters by isolating deeper waters from sources of O_2 (atmospheric and photic zone algal production) that could replenish O_2 utilized to support heterotrophic processes within the water column or in sediments. Also, stratification has the potential to promote retention of planktonic algae in the photic zone and contribute to higher Chla concentrations in the photic zone. The importance of thermal stratification as a confounding factor was evaluated by computing the thermal gradient for surface waters to a depth of 3.0 meters for dates on which the DO concentration was < 50% and > 70% of the saturation value. The average temperature difference between the values at 0.2 and 3.0 meters by zone are listed in **Table 4**. For zones 1-4, there is a clear association of decreased DO concentration at 3.0 meters with a thermal gradient in the 0-3 meter portion of the water column. The lack of a difference for zones 5 and 6 may reflect a deeper mixed surface layer associated with the deeper water column in the lower segment of the reservoir (e.g. Figure 5-18).

Table 4. Average temperature gradient (°C) for 0.2 meter depth compared to the value at 3.0 meters. Values are the mean (standard deviation) for data from the growing season.

Zone	Dates DO_{sat} < 50%	Dates DO_{sat} > 70%
1	2.55 (1.70)	0.63 (0.70)
2	2.75 (4.00)	0.71 (0.70)
3	2.60 (4.12)	0.69 (0.76)
4	1.93 (1.07)	0.61 (0.79)
5	1.25 (0.94)	0.93 (1.14)
6	0.86 (1.11)	0.91 (1.57)

The potential for enhanced accumulation of algal biomass as Chla in the upper segment of the reservoir was examined by comparing Chla concentration for the photic zone with the temperature gradient for depths of 0-3 meters. Data for the growing season were used in the analysis. In the evaluation, dates were grouped by the temperature difference for readings at 0.2 and 3.0 meter into three bins: < 1°C, 1-2°C, and > 2°C. The average photic zone Chla was computed for each bin. For zone 1 data, average

Chla increased from 38.5 µg/L for dates when ΔT was < 1°C to 48.9 µg/L for dates with a ΔT > 2°C. An average value of 46.0 µg/L was computed for dates with a ΔT of 1-2°C. However, the potential increase in Chla for dates with higher ΔT for the upper portion of the water column was not evident in data from zone 2 for which average Chla was higher (41.4 µg/L) for dates with a ΔT < 1°C compared with 38.0 µg/L for dates with a ΔT > 2°C. Thus, the potential for the concentration of algal cells in a surface layer relative to subsurface waters may be intermittent and affected by other physical factors influencing the rate of accumulation of algal cells in the upper segment of the reservoir (e.g. meteorological mixing events and residence time).

3.4 BIOLOGICAL REVIEW

The algal assemblage present in a waterbody can affect the transfer of primary production to higher trophic levels such as zooplankton and the fish community. Two primary topics related to the biological assemblage will be considered in this evaluation: (1) general algal groups present; and (2) production of toxins by the species present. Data to consider each topic were included in the summary report prepared by the UNRBA (Brown and Caldwell, 2019), as well as data for Falls Lake available from other studies. For spatial and temporal characterization of the algal assemblage present, the report included data for three locations in the reservoir (NEU013B, NEU018E, and NEU019P) monitored as part of the NC Division of Water Resources (DWR) monitoring program. The report also presented data on the presence of toxic compounds released by algae that were collected by the City of Raleigh at several locations in the reservoir.

Variation in estimated biovolume at the three monitoring locations sampled by DWR for algal community enumeration for eight algal taxonomic groups for 2014-2018 is presented graphically in UNRBA Figures 3-32, 3-33, and 3-34. The figures illustrate substantial variation in the abundance of the phytoplankton groups over time at individual locations and among the locations for an individual sampling date. The report concluded that algal abundance and composition was not uniform in the reservoir over time and space. In terms of this evaluation, the proliferation of blue-green as the predominant algae present could potentially diminish the trophic transfer efficiency of primary production to zooplankton and fish, since there are blue-green algal species that represent a poor food source for zooplankton. Brown and Caldwell (2019) indicated the three groups with the largest estimated biomass were blue-green algae, Diatoms, and Prymnesiophytes. Thus, the algal taxonomic data show that blue-green algae are an important component of the algal community at all three locations, with high biovolume for the blue-green algae component on some dates. The algae community data, however, indicate there were also peaks in Diatoms, Prymnesiophytes, Euglenoids, Chrysomonads, and Cryptomonads on different dates.

The contribution of blue-green algae to total algal cells present and the overall biovolume was compared with the reported Chla concentration for the same date to evaluate whether dominance of blue-green algae changes with the overall density of algae (**Figure 7**). Data for the three DWR monitoring locations are included in the figure utilizing different symbol color. For all three locations, there were dates where blue-green algae were dominant in terms of number of cells present, but the occurrence of a blue-green contribution to biovolume > 50% was less frequent. Further, the overall contribution of blue-green algae to the algal assemblage was highly variable across the range of Chla concentrations reported for the DWR monitoring program; the range in the contribution of blue-green algae to the overall algal assemblage biovolume for dates with Chla > 30 µg/L was <5% to about 90% depending on date.

Hall and Piehler (2023) examined the variation in algal and zooplankton abundance in Falls Lake for monitoring in all three segments shown in **Figure 1**. An important feature in the seasonal patterns was a spring decrease in Chla corresponding to the seasonal maximum in zooplankton abundance. Following the spring peak in zooplankton abundance, Chla increased to relative summer peaks in the upper and middle segments of the reservoir, with the seasonal peak in the lower segment in the winter months. The authors concluded seasonal variation in the biomass at the two trophic levels examined (algae and zooplankton) appeared to be affected by grazing by the next higher trophic level (zooplankton on algae and fish on zooplankton). Thus, the diversity in algal composition in the different regions of Falls Lake would indicate the species present represent a sufficient food base for zooplankton.

Data on key fisheries in Falls Lake were provided to WSP by Brown and Caldwell and examined to evaluate whether variation in fishery statistics can be explained by variation in the density of algae or the volume of subsurface DO depletion among years for which the statistics are available. Available fisheries data for Large Mouth Bass (LMB) and Crappie were collected by the Wildlife Resources Commission and are reported for the entire reservoir on an annual basis. Metrics included are catch per unit effort (CPUE), relative weight for individual fish for the measured length (health indicator), and percent of fish larger than target lengths (%Keeper). Fishery data are provided in **Table 5**, along with the mean Chla for the growing season and the maximum subsurface volume with DO < 4 mg/L for the year. Simple comparisons of the fishery metrics with mean Chla indicate variability in the average algal biomass did not explain the year-to-year variability in either LMB or Crappie metrics. Further, the variation in the maximum extent of DO depletion of subsurface waters among years also did not explain variation in the fishery metrics. It appears the fish community in the reservoir is sufficiently supported by the algal assemblage present.

In addition to the potential alteration of water quality of surface waters and the composition of the algal food base, the production of toxins by algae species present has been a topic of considerable concern in lake assessments (e.g. USEPA, 2021). The taxonomic group with which toxin compounds have been primarily associated is blue-green algae, which are present in Falls Lake at the DWR monitoring stations. However, the presence of blue-green algae in a system is not a reliable indicator for the presence of algal toxins at concentrations that may impact suitability for recreational use or impact aquatic life (e.g. Schnetzer, 2023). Conditions in a waterbody that trigger production of toxins is not well understood (e.g. Wiltsie et al., 2017). Identifying the production and release of algal toxins in a waterbody requires monitoring data to determine whether the compounds are being produced at levels of potential concern.

Table 5. Fishery Statistics for Falls Reservoir reported by WRC. Descriptions of statistics are provided in the legend.

Year	Mean Chla (µg/L)	Volume DO <4 (acre-ft)	Crappie			Large Mouth Bass		
			CPUE	%Keeper	Rel Weight	CPUE	%Keeper	Rel Weight
1986	76.5			13.9	76		31.9	100
1988	47.7			13.9	80		43.5	97
1989	32.5			50.1	84		57.7	96
1990	24.4						72.9	98
1991	30.0						53.2	96
1992	22.0						55.8	96
1993	24.0			90.7	99		63.6	100
1994	22.5						55.5	95
1995	13.7			85.1	97		58.1	89
1996	48.1			78.3	84			
1997							52.4	93
1998				69.1	81			
1999							60.3	92
2000		26,073	28.2	93.9	93			
2002			25.5	79.5	90			
2004			23.9	71.1	89			
2005	32.9	17,746				87.8	50.8	96
2006	40.2	23,648	57.7	90	97			
2007	43.8	20,602				67.1	52.2	93
2008	25.4		21	78.8	92			
2009	25.8					73.2	43.2	91
2010	23.0	27,220	13.3	77.8	82			
2011	26.9	20,942				37.8	41.8	88
2012	30.7	37,669	17.5	61.2	89			
2013	31.5	31,858	27.8	96.9	98	80.6	65.2	99
2015	28.7	21,539				62	39	93
2018	33.7	46,009	4.9	85.5	92			
2019	29.8					45.8	55.3	95
2020	28.1		19	93.6	90			
2021	20.3					102	60.5	96

Table 5. Fishery Statistics for Falls Reservoir reported by WRC. Descriptions of statistics are provided in the legend.

Legend: (Mean Chla) arithmetic average of all measurements throughout the reservoir for the growing season; (Volume DO <4) maximum volume of subsurface water with DO < 4 mg/L for the year; (CPUE) reported catch for unit effort; (%Keeper) percent of Crappie > 8 inch length or LMB > 14 inch length; (Rel Weight) average relative weight for individual fish; relative weight is actual weight / healthy weight for the measured length expressed as a percent.

Brown and Caldwell (2019) presented data for three common toxins (microcystin, cylindrospermopsin, and anatoxin-a) at six locations. Depending on location, microcysin and cylindrospermopsin were detected in about 13 to 30% of the 180 samples available at the time the report was prepared and anatoxin-a was detected in 10 to 20% of the samples. For the two compounds with guidelines issued (microcystin and cylindrospermopsin), detected concentrations were below drinking water and recreation guidelines. Additional recent measurements of algal toxins have been performed in Falls Lake by Dr. Schnetzer at NC State University, with similar results where toxins were detected at low levels on a number of sampling dates (e.g. Schnetzer, 2023). Monitoring of algal toxins by the City of Raleigh beginning with the 2007-2012 period confirm recent data on algal toxins represent conditions in Falls Lake for the past two decades. Thus, available data do not provide support for decreasing Chla concentrations in the lake to protect human health and aquatic life from the potential hazard associated with elevated concentrations of algal toxins. However, the regular low-level detections of algal toxins in Falls Lake in past assessment monitoring and the poor understanding of triggers for production support continued assessment of the issue in future monitoring efforts.

4 STANDARD CONSIDERATIONS

The overall outcome of this evaluation is to confirm Falls Lake is a productive reservoir in which algal biomass has been stable over past 13 years, and conditions associated with high algal biomass that may be of potential concern are very limited. This includes high pH and DO concentration in the photic zone. In terms of the anticipated conditions in the reservoir identified in the environmental statement prepared for the project before construction (see USACE, 1974), the reservoir experiences thermal stratification during the growing season and low bottom water DO concentrations have been reported associated with the stratified conditions. In terms of potential impacts on suitable habitat for the biological assemblage in the reservoir, Brown and Caldwell (2019) examined the presence of low DO bottom waters in the reservoir. When available data on DO concentration for monitoring locations and with depth are integrated with lake bathymetry, there is a volume of bottom waters in which DO becomes depleted during warm months, but generally the majority of the lake volume has a DO concentration greater than the instantaneous DO standard of 4 mg/L for freshwaters. Thus, review of existing conditions in the reservoir confirms the system is highly productive but water quality parameters are only infrequently at levels of concern.

The algal assemblage present in the reservoir is consistent with a productive reservoir. Monitoring of algae by DWR indicates blooms of several taxonomic groups occur in the reservoir. This includes blue-green algae, which are often dominant in highly productive systems. In some systems, species of blue-green algae that are a poor food source for zooplankton can contribute the majority of biomass present during warm season months. For Falls Lake, there is spatial variation in the overall algal community and the fraction of biomass contributed by blue-green algae. Further, the dominance of the algal assemblage by blue-green algae taxa is not persistent over time during warm season months. In terms of algal toxins, blue-green algae are present in Falls Lake, and toxins are present at relatively low levels at times but at levels well below the recreational guidelines and below the drinking water recommended threshold even before water treatment (see Figure 5-47). This review of present conditions in the reservoir supports a conclusion that all designated uses are being achieved, and selection of a site-specific Chla criterion consistent with recent monitoring data would be scientifically defensible.

The magnitude component of a site-specific Chla standard that is consistent with maintaining the current algal productivity in the reservoir is affected by how the criterion is defined in terms of spatial and temporal integration to assess compliance with the criterion. The magnitude consistent with current conditions is also affected by whether the criterion needs to be achieved in all years. Considerations for Falls Lake affecting these components of a site-specific Chla include:

- Integration of available Chla data by three segments representing the general differences in the physical setting of the reservoir upstream (upper and middle segments) and downstream (lower segment) of Hwy-50. The transition zone of the reservoir upstream of Hwy-50 would be divided into two segments according to the consistent spatial pattern for algal biomass upstream of Hwy-50. Data from locations within a segment would be evaluated as an assessment unit.

- The computed metric for evaluating Chla would be appropriate to represent the central tendency of Chla data for locations within a segment across growing season months. The geomean for Chla monitoring data would be appropriate.

- Monitoring data for the reservoir during 2010 to 2021 showed the overall algal biomass in the reservoir has been consistent across multi-year periods but variable across individual years. Incorporating a frequency component to the site-specific Chla standard would be appropriate to account for year-to-year variability associated with hydrology and climatic factors.

Defining the magnitude component of a site-specific standard requires agreement on the spatial segmentation, the metric to be computed, and the frequency components. Magnitude values for different segments of the reservoir can be developed when these key considerations have been developed.

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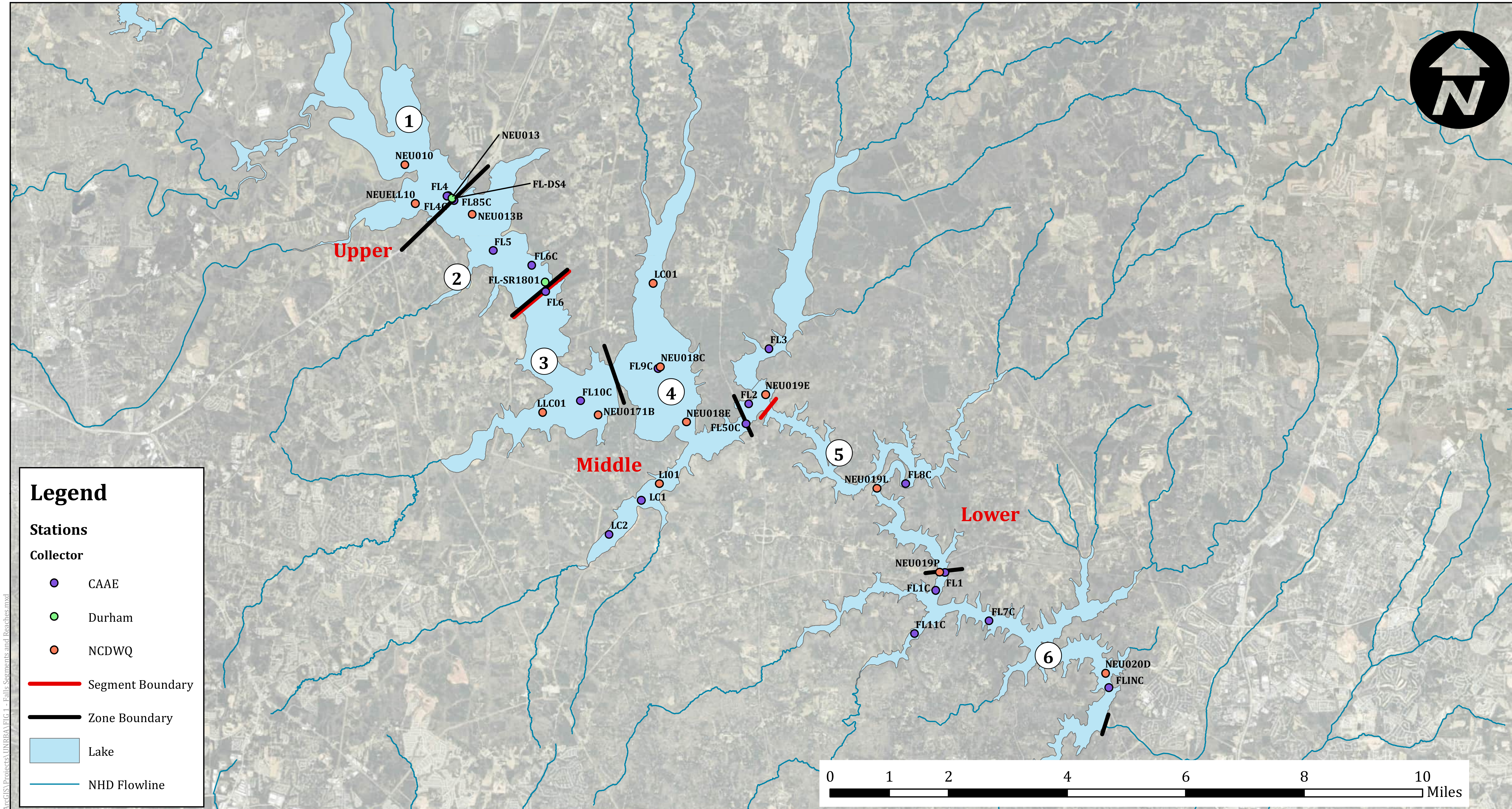
FIGURES



Notes:
(1) Zones defined by WARMF Model Segmentation.
(2) Station Locations provided to WSP by Brown and Caldwell.
(3) Lake and tributary boundaries from USGS NHD dataset, retrieved 9/29/23.

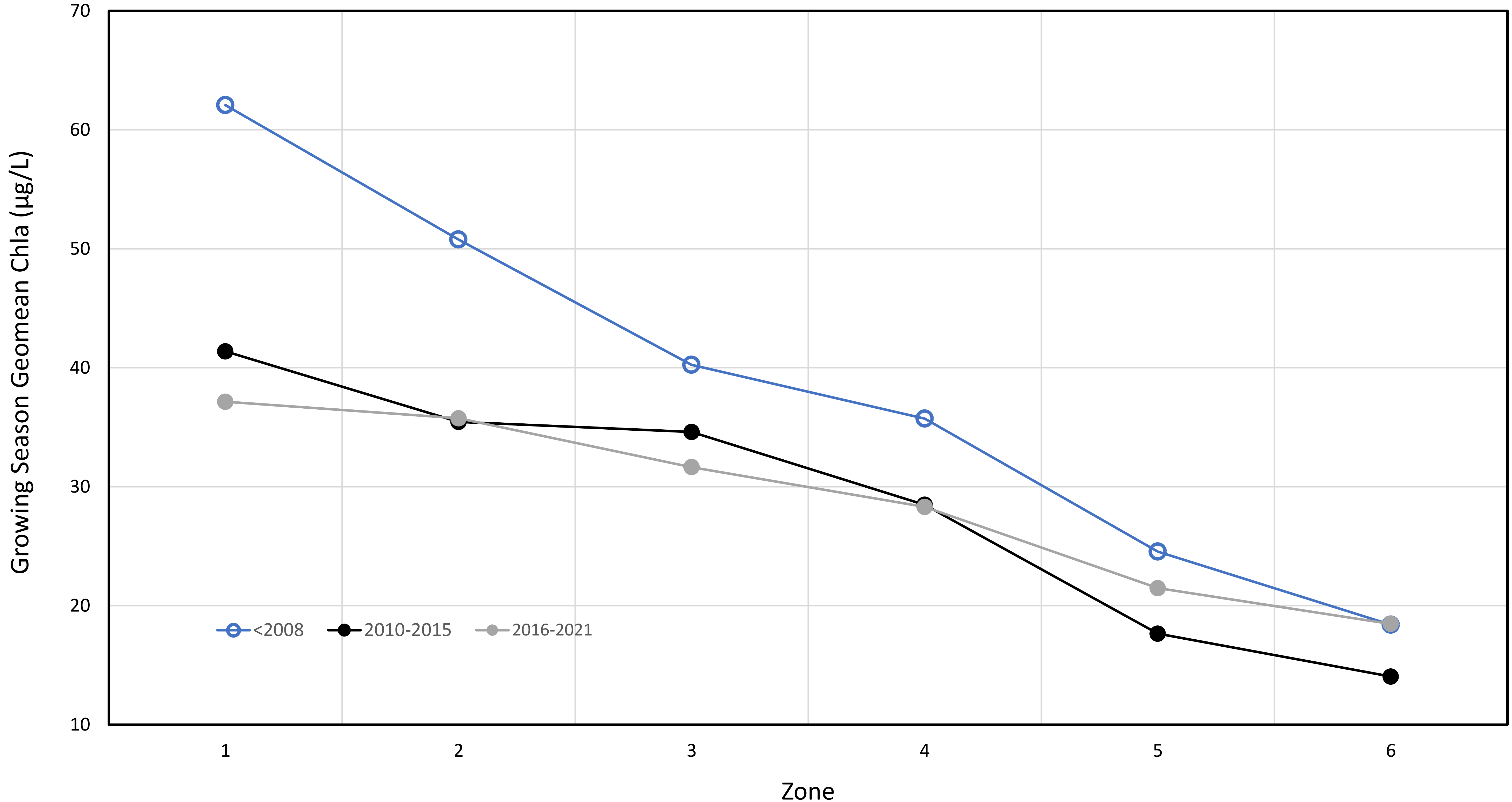
Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

WSP USA

Map of Monitoring Locations and Segmentation

DRAWN	CHECKED	DATE	FIGURE
JML	MEL	Oct 2023	1

Coordinate System: NAD 1983 2011 StatePlane North Carolina FIPS 3200 Ft US



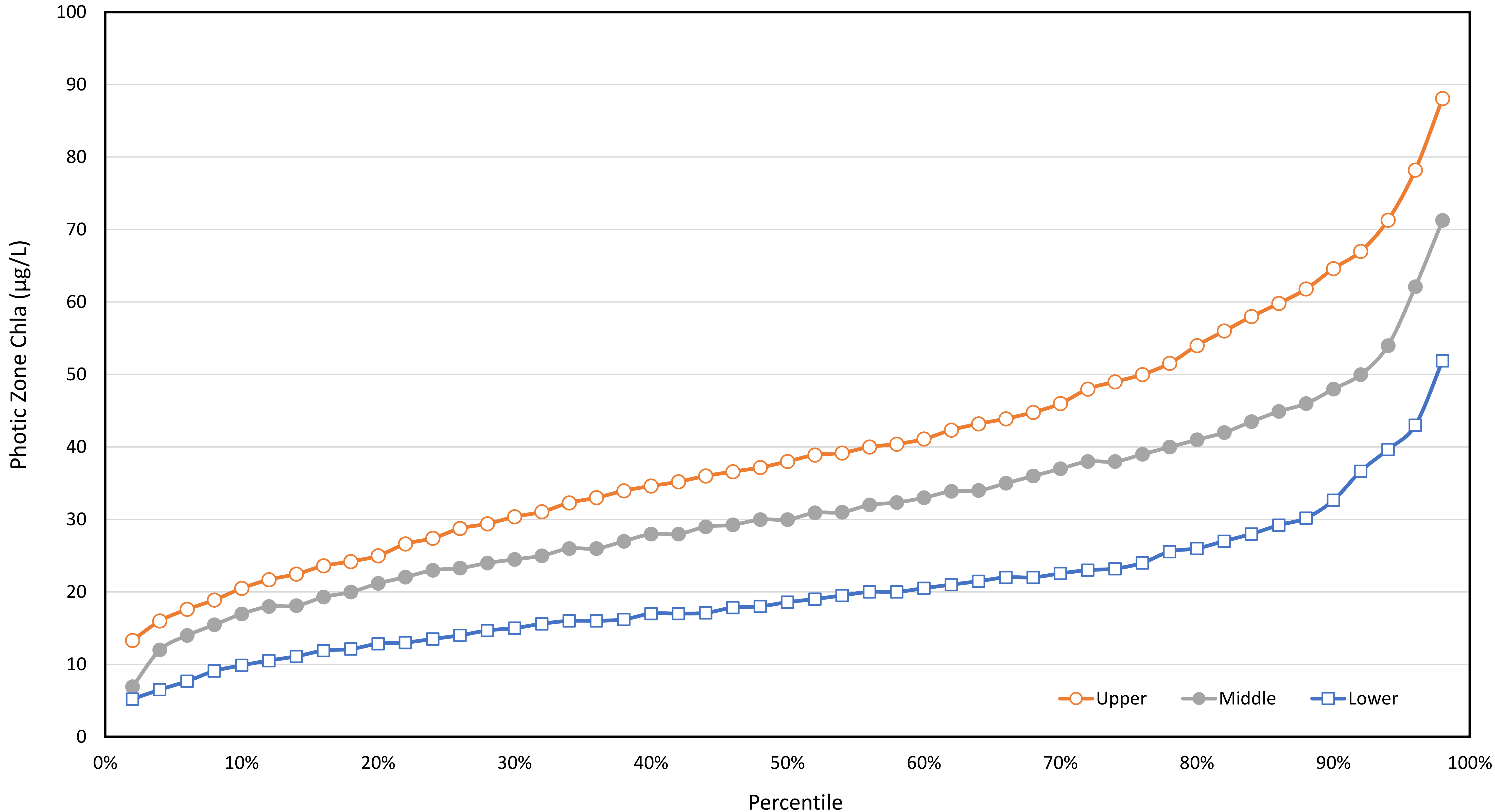
Notes:
(1) Zones defined by WARMF Model Segmentation.
(2) Growing season is defined as the months of April through October.
(3) Geomean calculated using all data for the growing season in the zone and time period.

WSP USA

Growing Season Chla
Geomean by Zone and Period

DRAWN	CHECKED	DATE	FIGURE
JML	MEL	Oct 2023	2

Coordinate System: NAD 1983 2011 StatePlane North Carolina FIPS 3200 Ft US



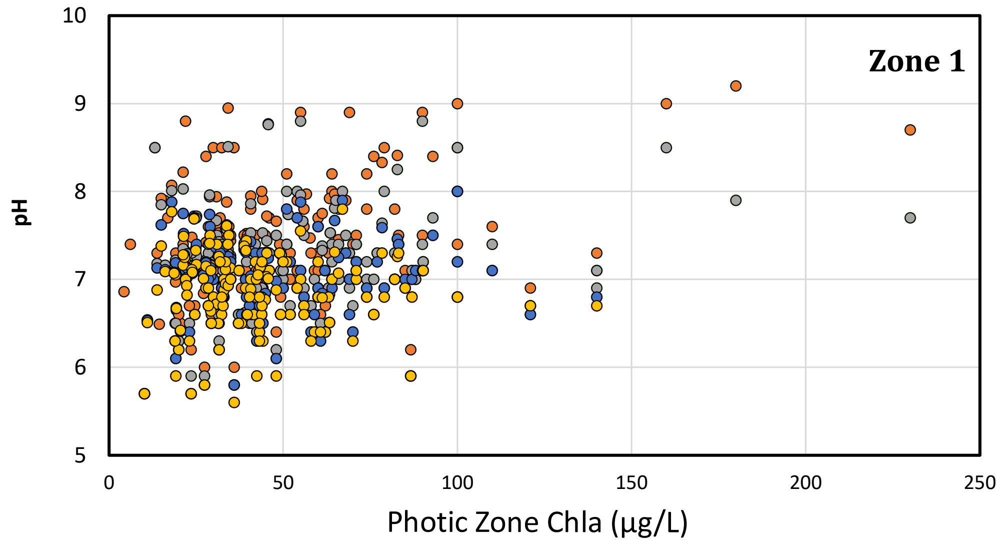
Notes:
(1) Zones defined by WARMF Model Segmentation.
(2) Upper reach defined as Zones 1 and 2, Middle reach defined as Zones 3 and 4. Lower reach defined as Zones 5 and 6 with the exception of stations FL2 and NEU019E which are included in the Middle reach.
(2) Growing season is defined as the months of April through October.
(3) Distribution calculated using 2010-2021 data for all stations in each segment for growing season months.

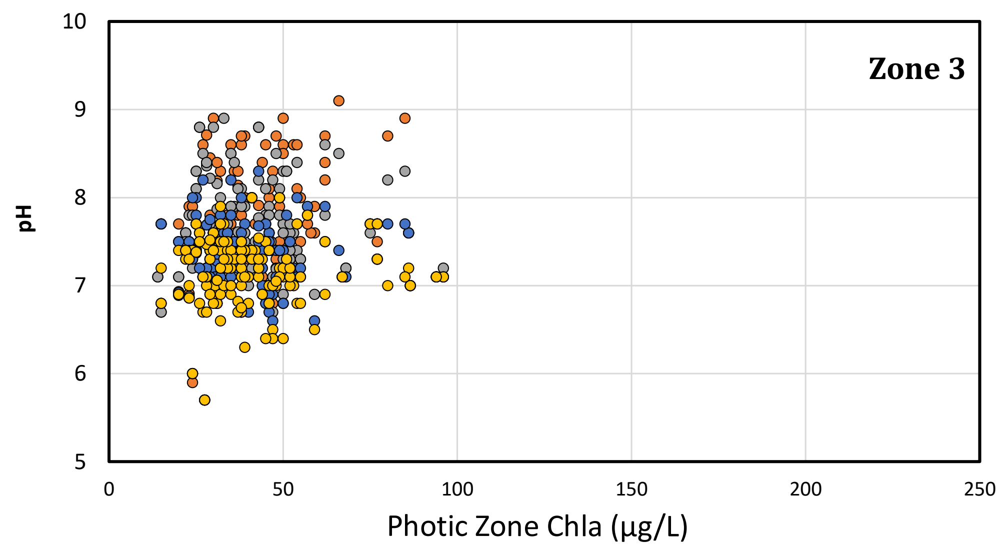
WSP USA

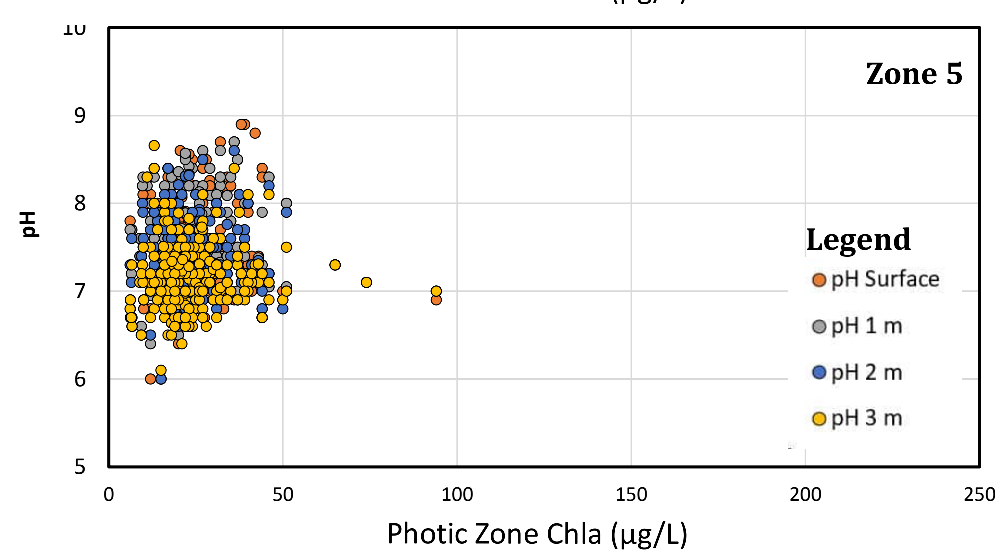
Cumulative Chla Distribution By Segment

DRAWN	CHECKED	DATE	FIGURE
JML	MEL	Oct 2023	3

Coordinate System: NAD 1983 2011 StatePlane North Carolina FIPS 3200 Ft US





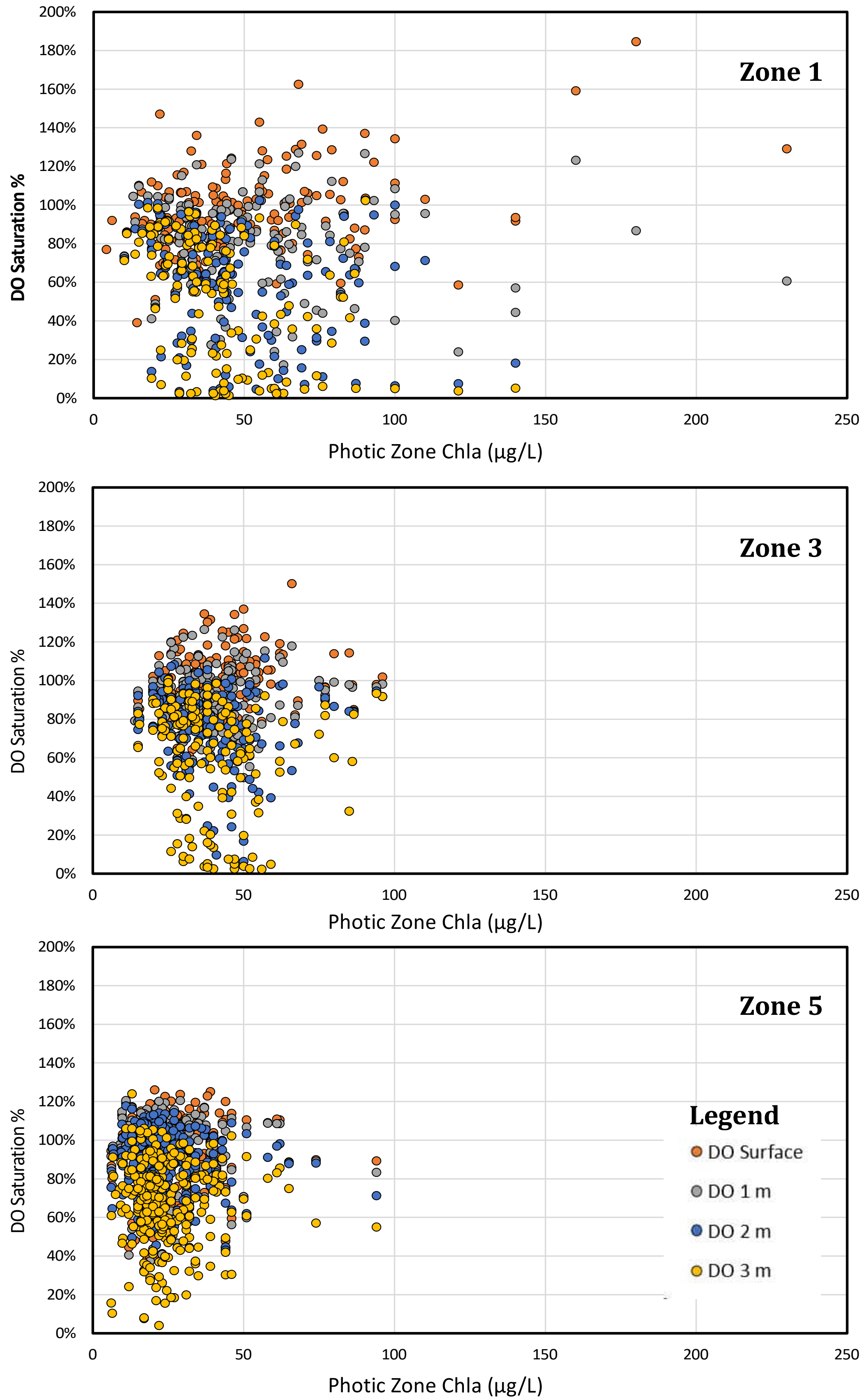


Notes:
(1) Zones defined by WARMF Model Segmentation.

WSP USA

Measured pH Versus
Chla by Zone and Depth

DRAWN	CHECKED	DATE	FIGURE
JML	MEL	Oct 2023	4



Notes:
(1) Zones defined by WARMF Model Segmentation.

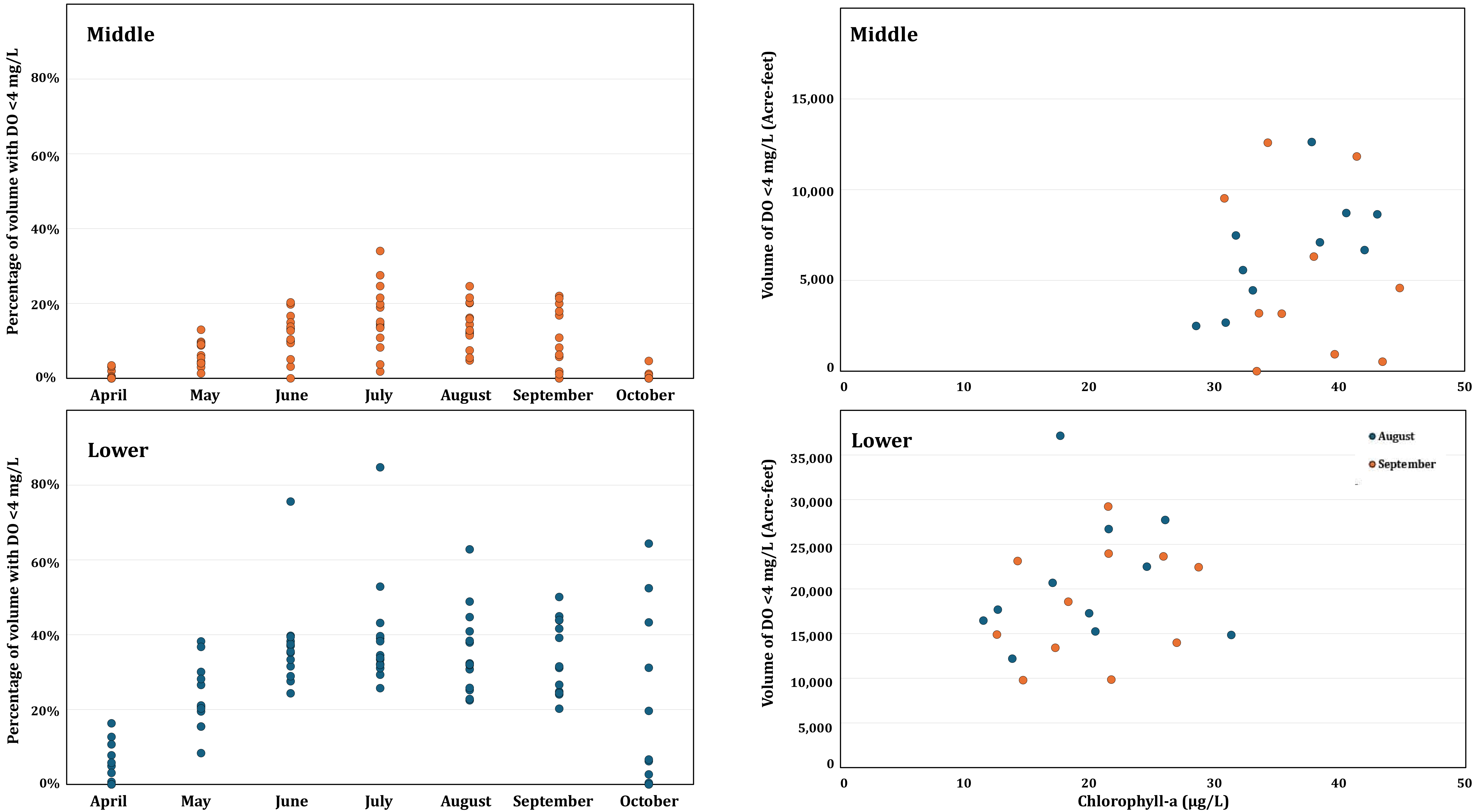
WSP USA

Measured DO Saturation (%) Versus Chla by Zone and Depth

DRAWN	CHECKED	DATE	FIGURE
JML	MEL	Oct 2023	5

Date Saved: 10/9/2023 4:46:00 PM
Document Path: C:\Users\USJL703741\Documents\ArcGIS\Projects\UNRBA\FIG 5 - DO versus Chla.mxd

Coordinate System: NAD 1983 2011 StatePlane North Carolina FIPS 3200 Ft US



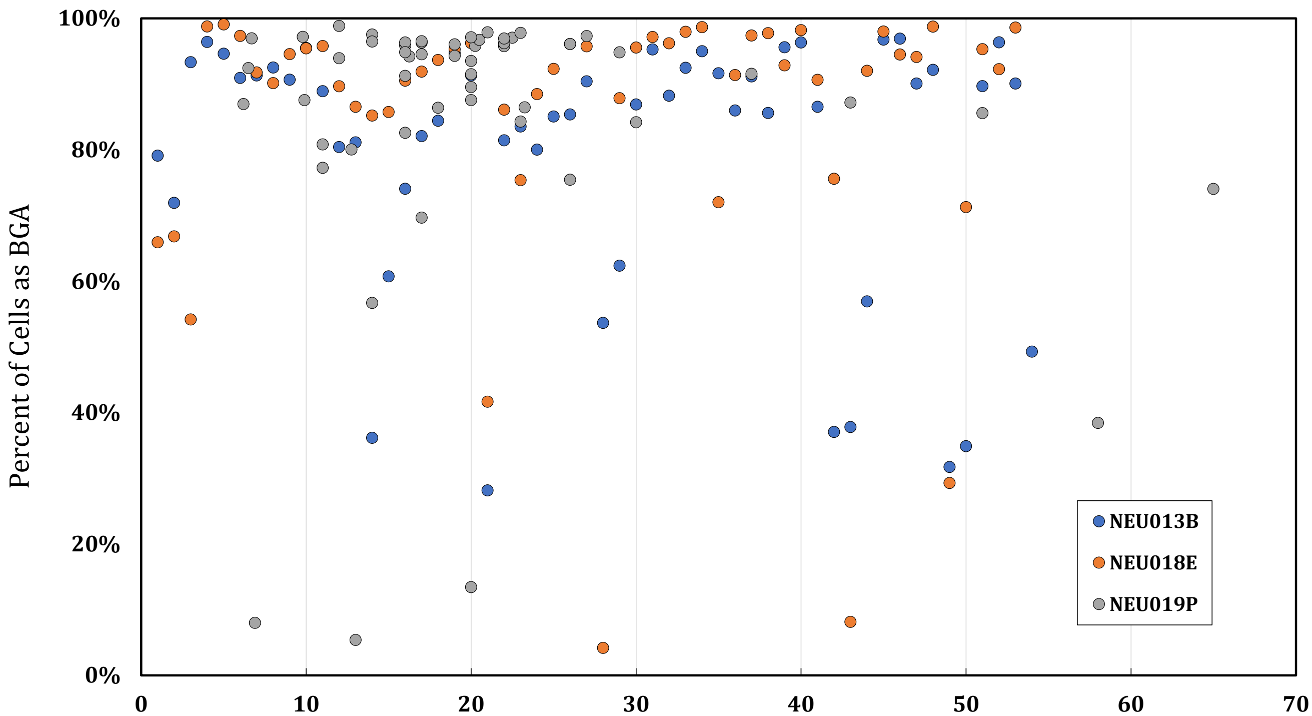
Notes:
1. Estimated reservoir volume below dissolved oxygen (DO) thresholds of 1 and 4 mg/L calculated by Brown and Caldwell and provided to WSP.
2. Middle Segment is Zones 3 and 4.
3. Lower Segment is Zones 5 and 6.
4. Chlorophyll-a values are for the growing season beginning in April through either August or September for the segment.

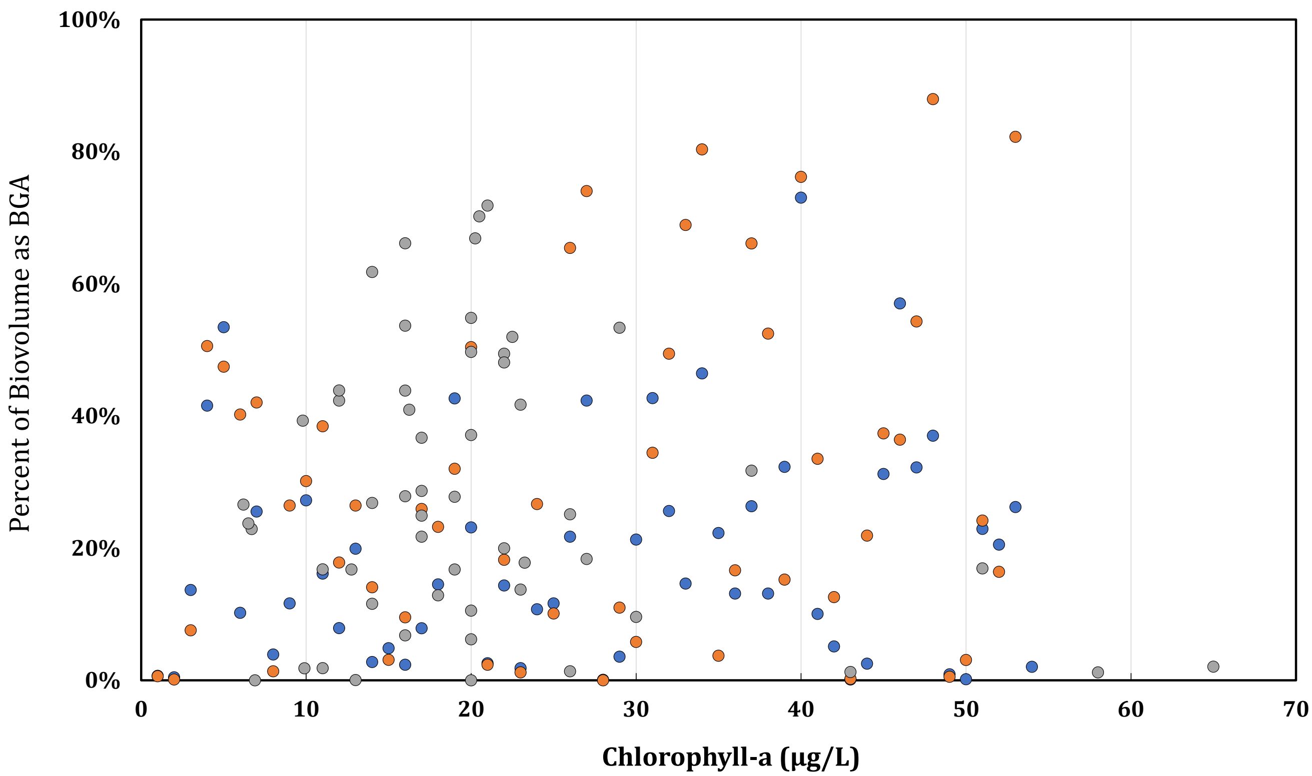
PROJECT NO. US0027311.2626

WSP USA Inc

DO Depletion By Month and Compared with Segment Chla

DRAWN	CHECKED	DATE	FIGURE
JML	MEL	Nov 2024	6





PROJECT NO. US0027311.2626 Notes: 1. Enumeration of algae and estimation of biovolumes by NCDWR 2. Data provided to WSP by Brown and Caldwell	WSP USA Inc	Blue-Green Algae versus Chla			
		DRAWN JML	CHECKED MEL	DATE Nov 2024	FIGURE 7

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Coordinate System: GCS WGS 1984

APPENDIX

A BROWN & CALDWELL (2019) FIGURES

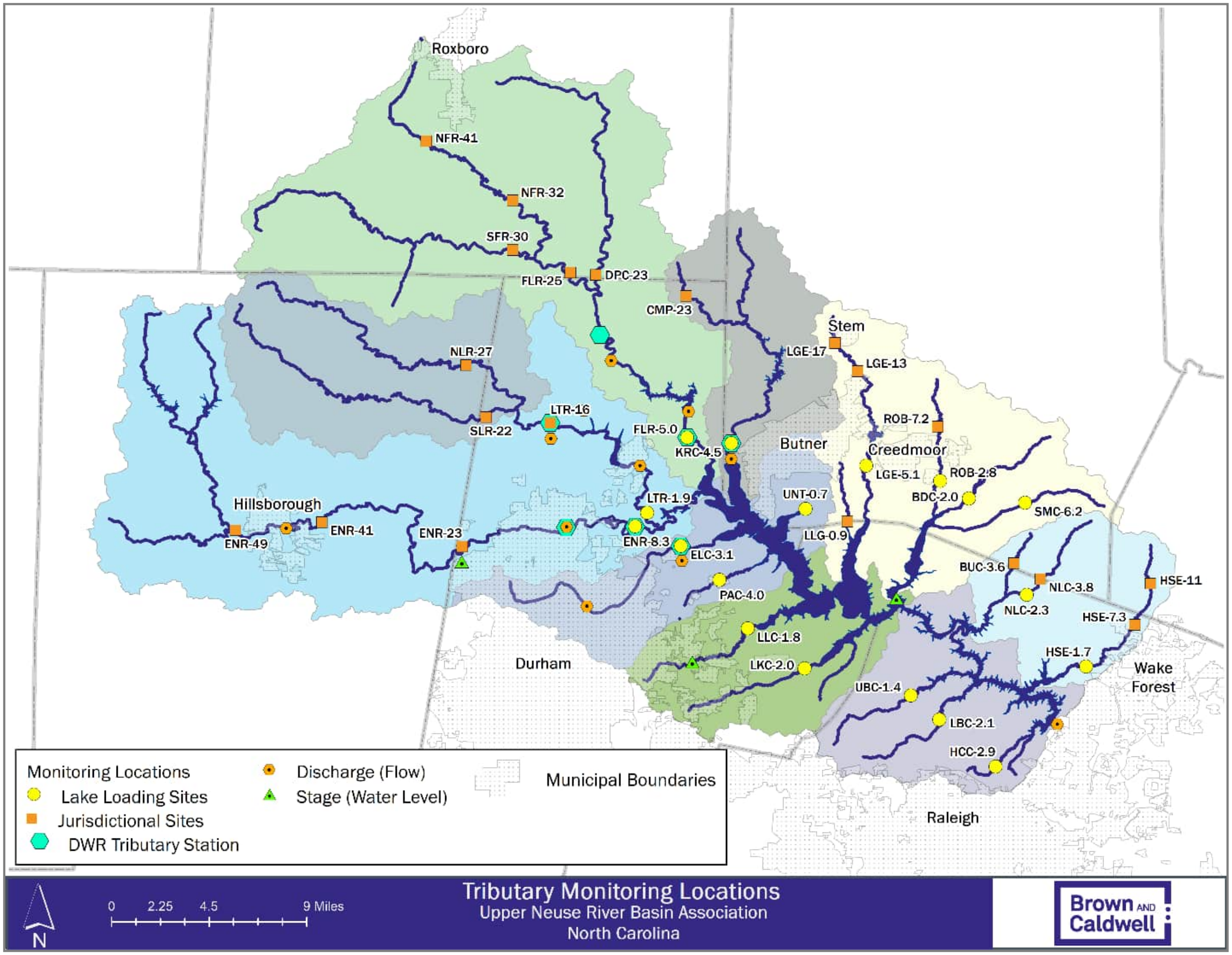

Figure 2-1. UNRBA Lake Loading and Jurisdictional Monitoring Locations (see Table 2-2 for station details) and Existing USGS Gages

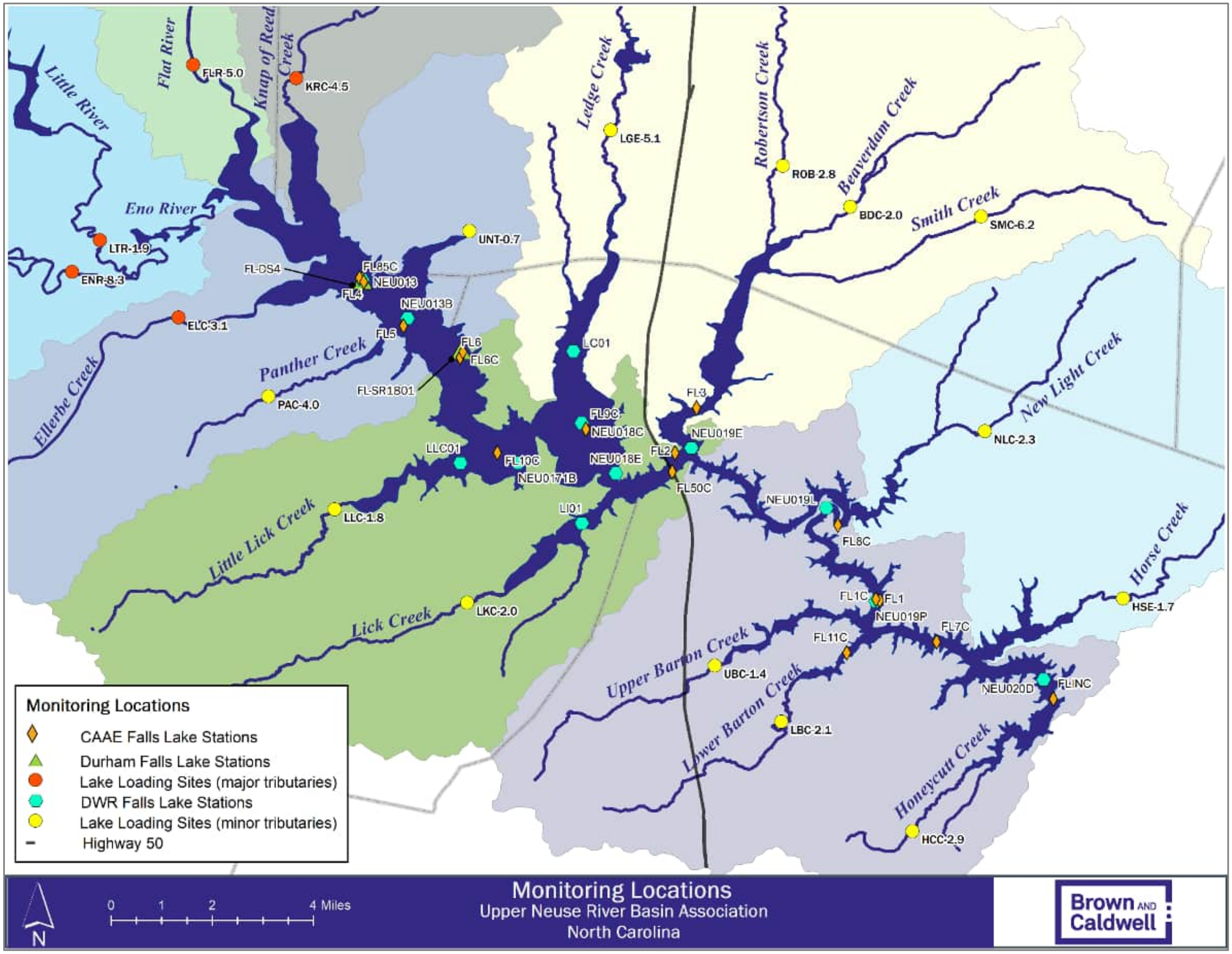

Figure 2-2. Falls Lake DWR, CAAE, and City of Durham Monitoring Locations, along with UNRBA Lake Loading Stations

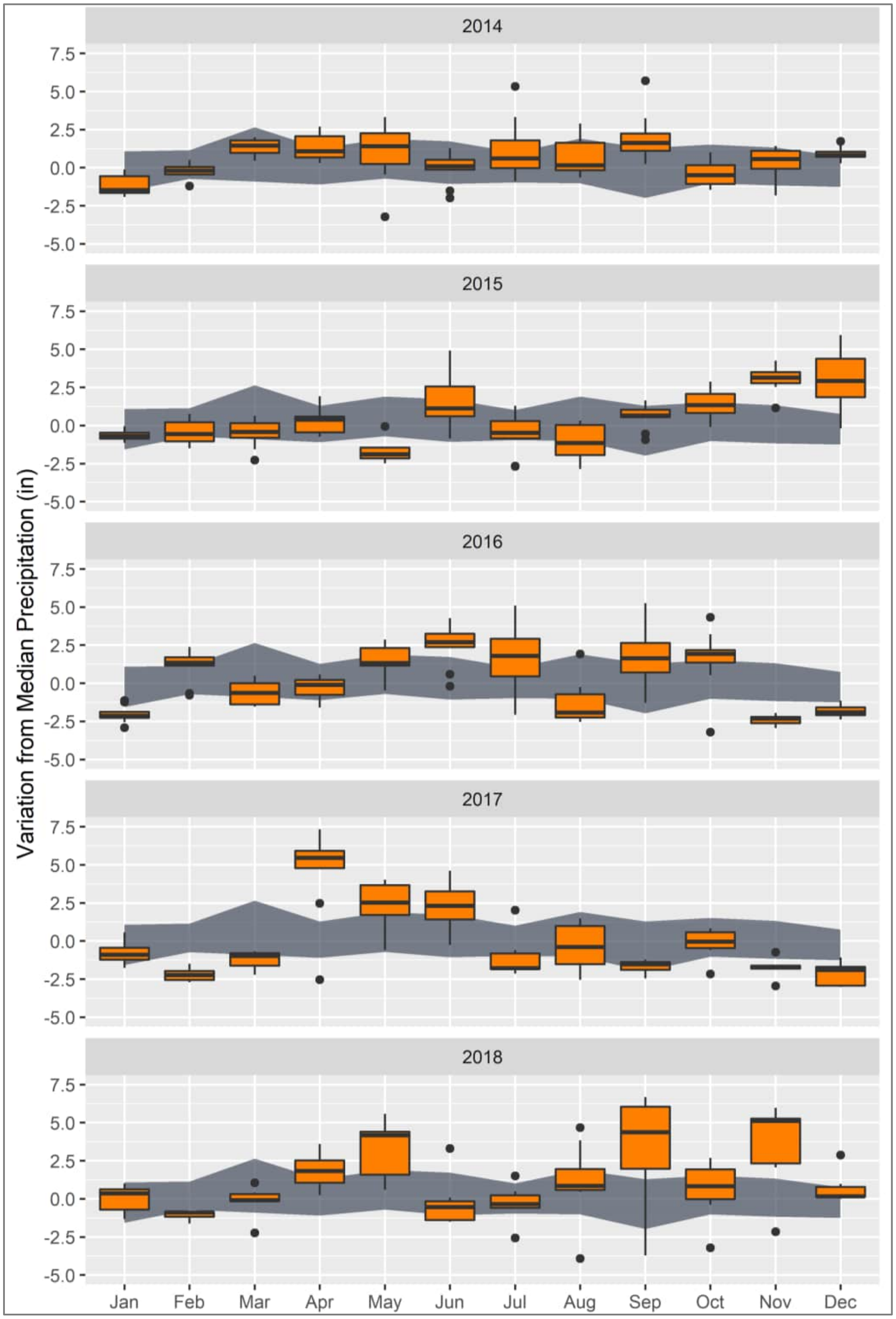

Figure 3-3. Variation from 30-Year Normal Monthly Precipitation Totals in the Falls Lake Watershed

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

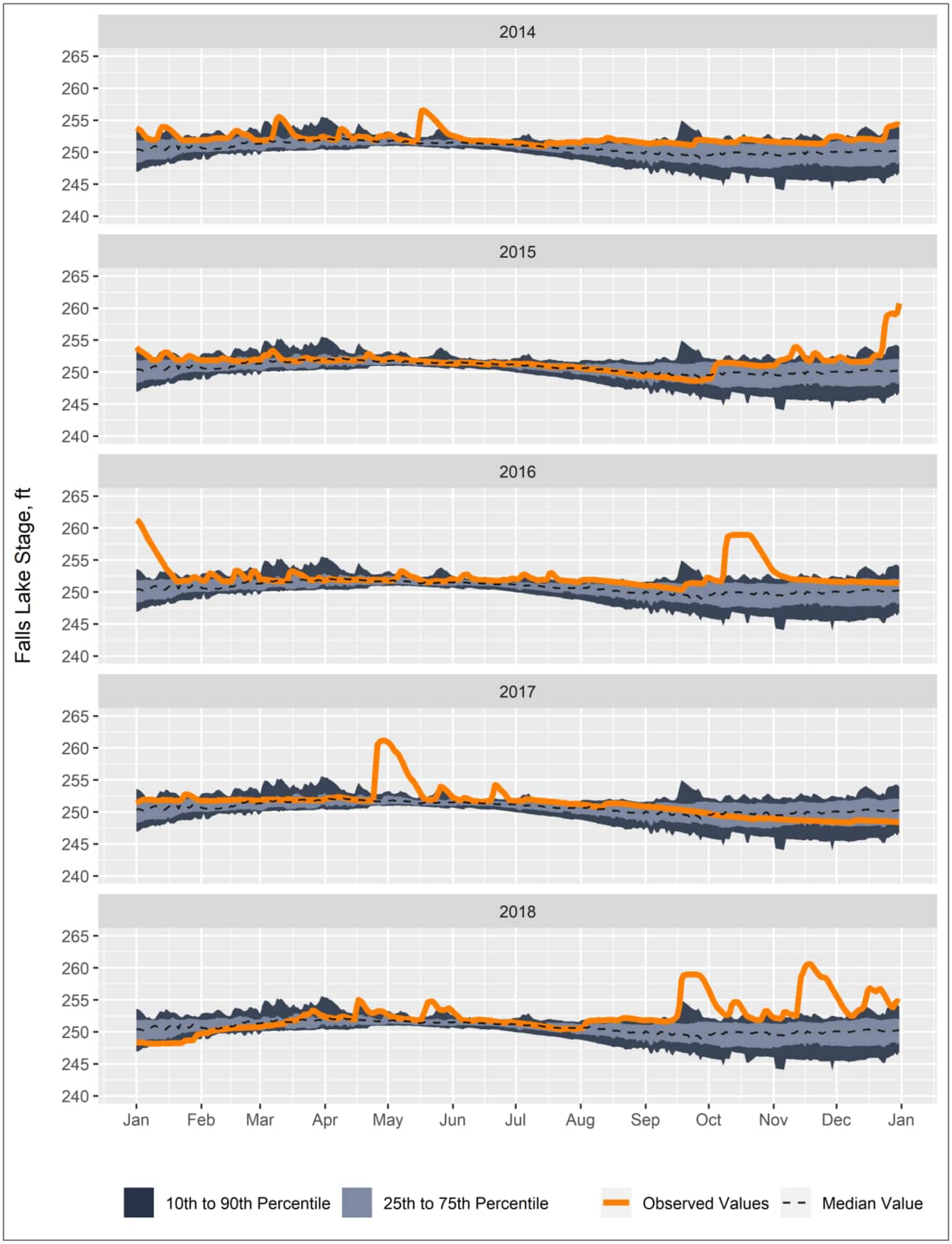

Figure 3-4. Observed Falls Lake Elevation from January 2014 through December 2018
Median values (dashed line) and percentiles are based on data 1987 to present.

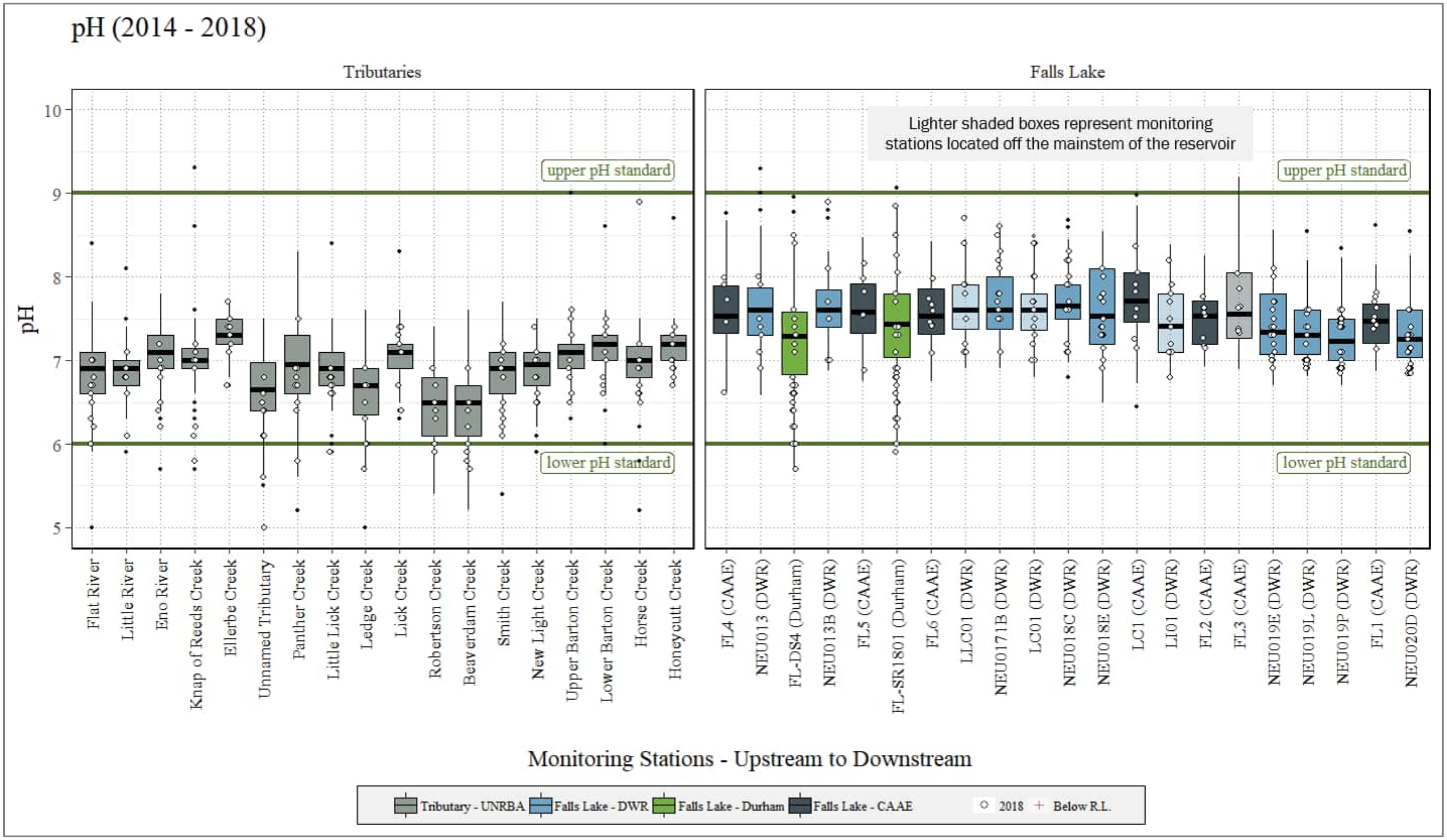

Figure 3-17. Average Photic Zone pH in Lake Loading and Lake Samples from August 2014 to October 2018

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

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

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

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

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

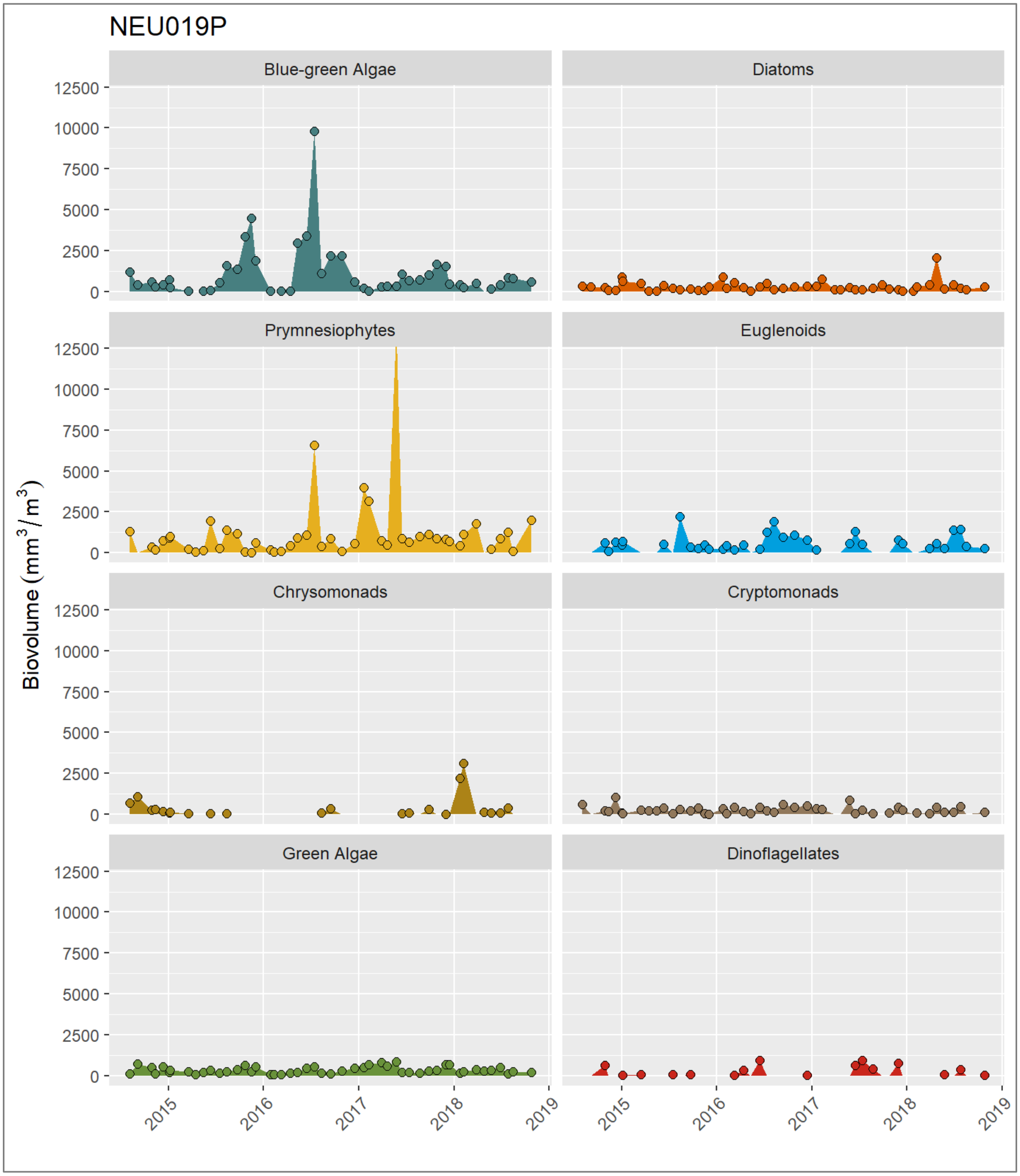

Figure 3-34. Algal Biovolumes at Station NEU019P (near Upper Barton Creek cove)

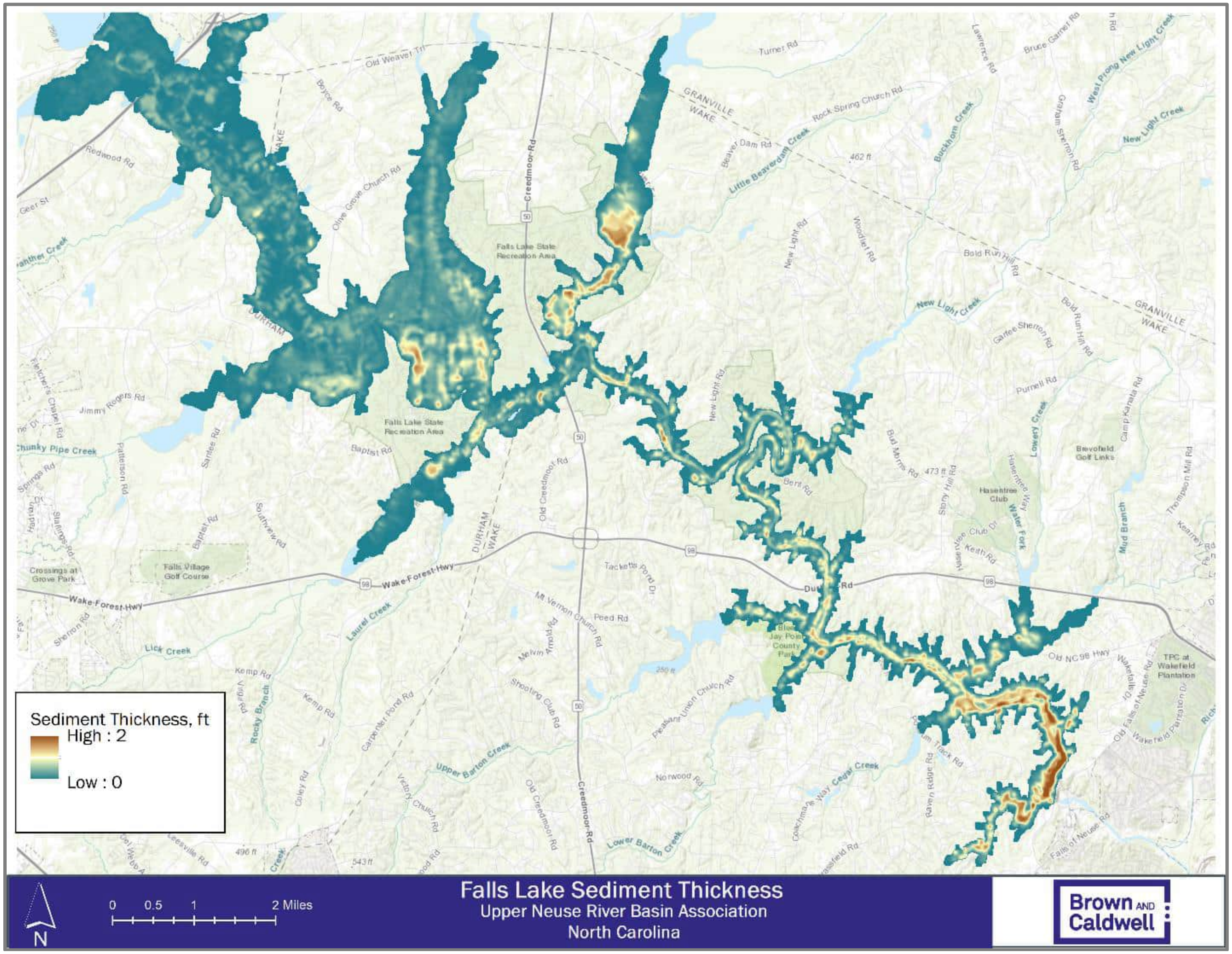

Figure 5-16. Sediment Thickness in Falls Lake

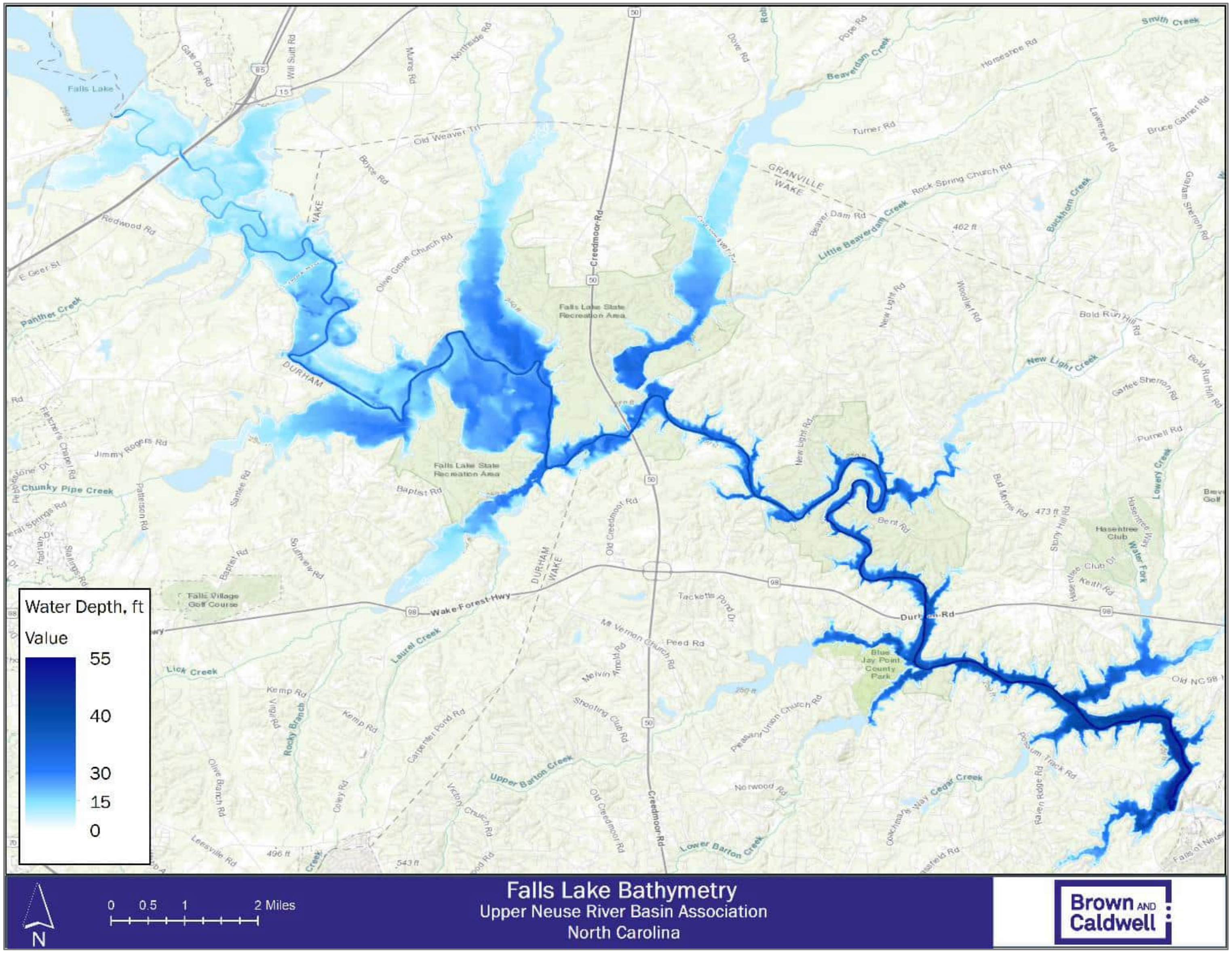

Figure 5-17. Water Depths of Falls Lake

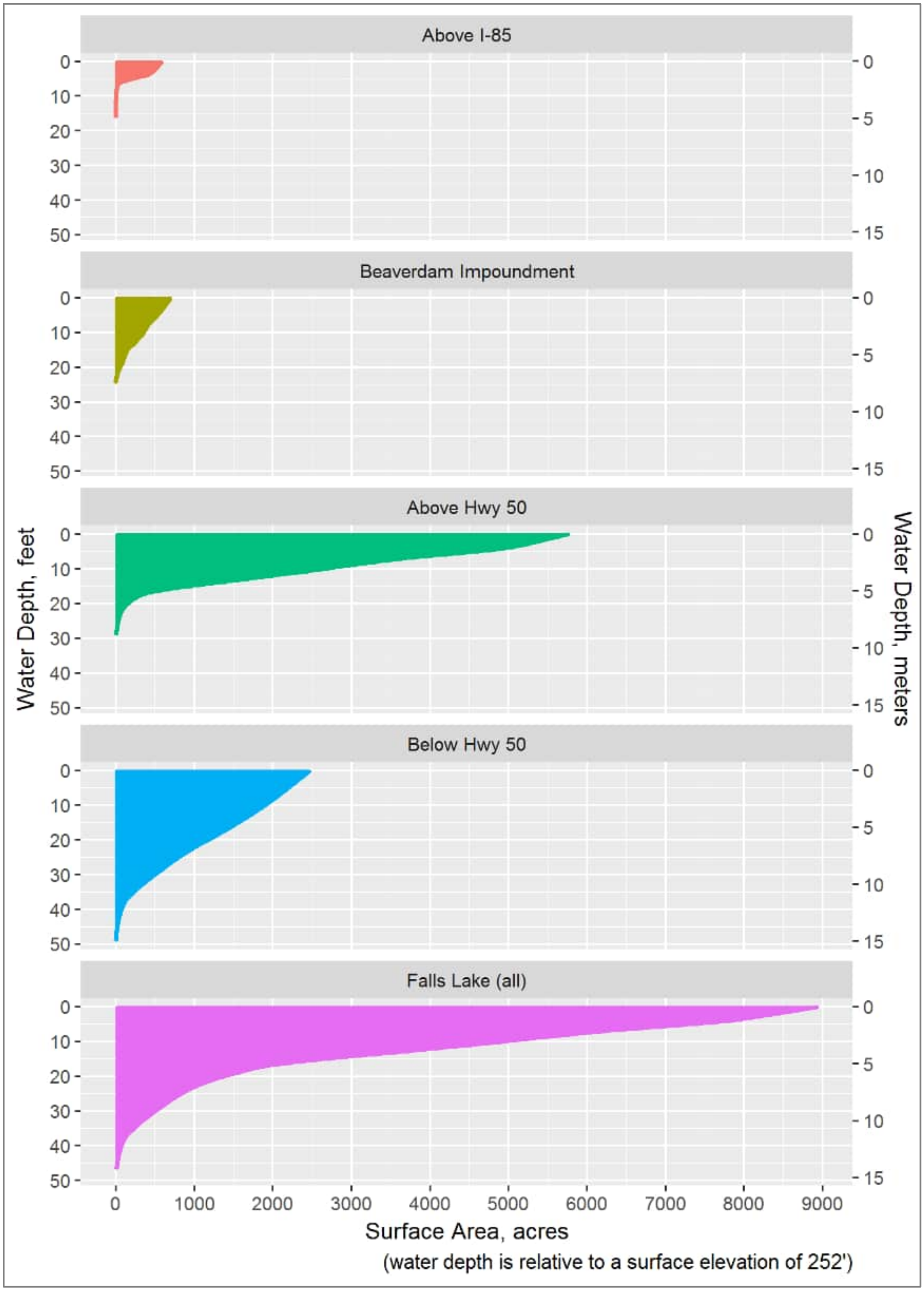

Figure 5-18. Water Depths in Segments of Falls Lake

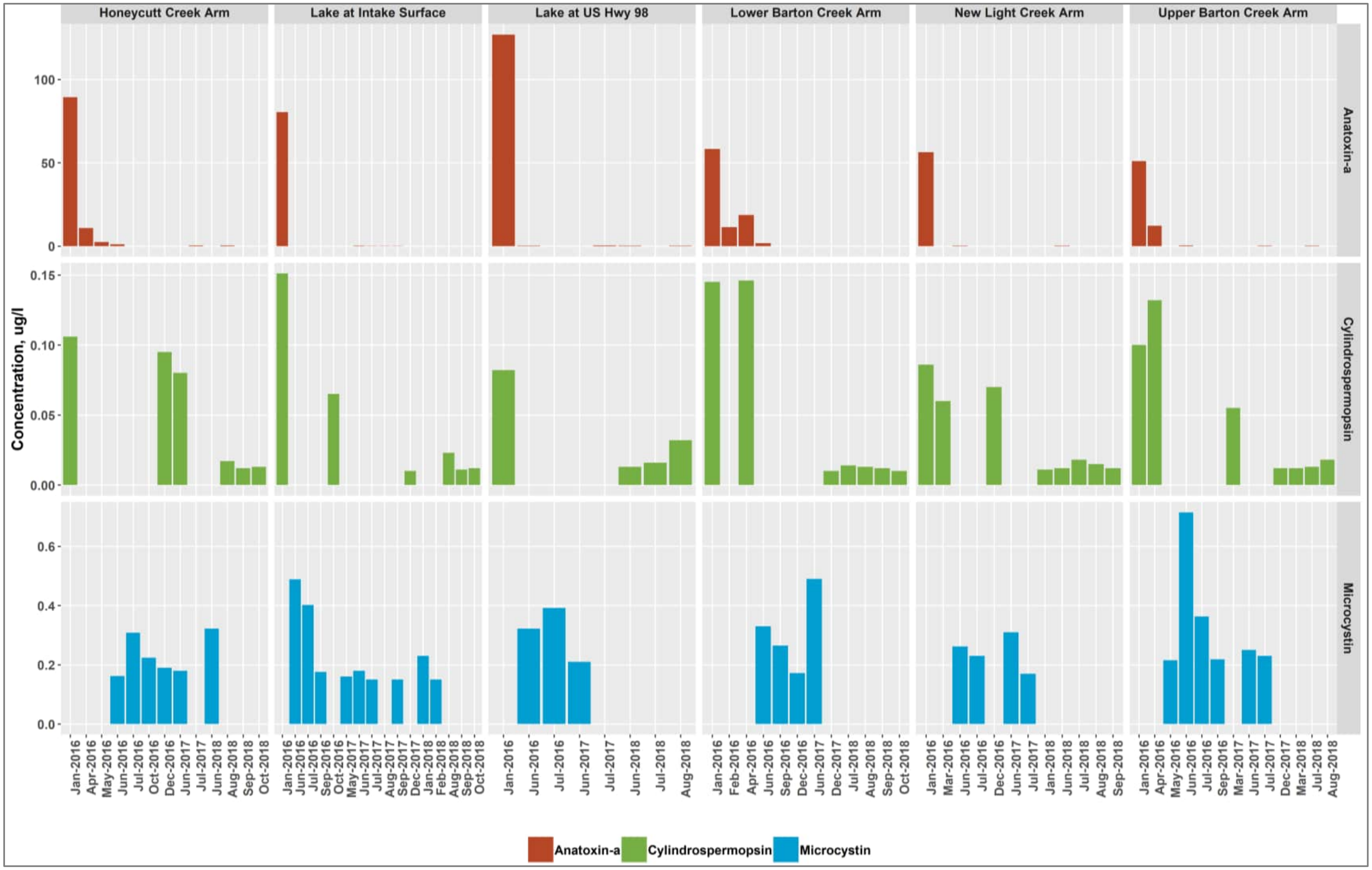

Figure 5-47. Algal Toxin Data Collected in Falls Lake

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