Water Quality Data Review for High Rock Lake, North Carolina

[Waterbody IDs 12-(108.5)b, 12-(114), 12-(124.5)a, and 12-118.5]

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NC DWQ Contract Number EW03018, Project Number 2-2

Yadkin – Pee Dee River Basin

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1 Introduction

High Rock Lake in Rowan and Davidson counties in the Yadkin-Pee Dee River Basin, North Carolina has been placed on the draft 2004 North Carolina list of impaired waters (the 303(d) list) and will require estimation of Total Maximum Daily Loads (TMDLs). The upper portion of the lake is listed as impaired due to standards violations for chlorophyll *a*, low dissolved oxygen (DO), and turbidity, the Abbotts Creek Arm is listed as impaired due to standards violations for low dissolved oxygen and turbidity, while the lower portion of the lake is listed as impaired for turbidity (Table 1). DWQ has indicated, however, the low DO listing will be removed for all segments of the lake based on reanalysis of the monitoring data (email correspondence, J. Todd Kennedy, NCDWQ, to Jonathan Butcher, Tetra Tech, June 7, 2004, Re: High Rock data).

Table 1. High Rock Lake Listings on 2004 North Carolina 303(d) Impaired Waters List (Public Review Draft, 4/26/04)

Waterbody Name - (ID)	Water Quality Classification	Impaired Use and Reason for Listing	Area (acres)
Yadkin River (including upper portion of High Rock Lake below normal operating level), from mouth of Grants Creek to a line across High Rock Lake from the downstream side of the mouth of Crane Creek to the downstream side of the mouth of Swearing Creek (12-(108.5)b)	Class WS-V (water supply)	Aquatic Life (turbidity, low dissolved oxygen, chlorophyll *a*)	5,568.8
Yadkin River (including lower portion of High Rock Lake), from a line across High Rock Lake from the downstream side of mouth of Crane Creek to the downstream side of mouth of Swearing Creek to a point 0.6 mile upstream of dam of High Rock Lake, except for Abbotts Creek Arm of High Rock Lake upstream of Davidson County SR 2294 and that portion of Second Creek Arm of High Rock Lake from source to a point 1.7 miles upstream of Rowan County SR 1004 which are classified WS-V&B (12-(114))	Class WS-IV&B (water supply and primary contact recreation)	Aquatic Life (turbidity)	4,870.1
Yadkin River (including lower portion of High Rock Lake), from a point 0.6 mile upstream of dam of High Rock Lake to High Rock Dam (12-(124.5)a)	Class WS-IV&B CA (water supply, primary contact recreation)	Aquatic Life (turbidity)	855.7
Abbotts Creek Arm of High Rock Lake, from source at I-85 to Davidson County SR 2294 (12-118.5)	Class WS-V&B (aquatic life, primary contact recreation)	Aquatic Life (turbidity, low dissolved oxygen)	30.1

High Rock Lake, an impoundment of the Yadkin River, was constructed in 1929 to provide hydroelectric power and is owned and operated by the Yadkin Division of Alcoa Power Generating, Incorporated (APGI). Average daily flow in the Yadkin above the lake exceeds 3,000 cfs, resulting in short retention times, typically ranging from 15 to 30 days. Due to hydropower operation, outflow from the lake is relatively constant, but lake levels vary dramatically according to inflows. The maximum reported depth is 52 feet.

The lake is morphometrically complex (Figure 1). Although most of the flow occurs along the main (Yadkin River) axis of the lake, there are significant tributary cove areas, such as Abbotts Creek and Second Creek.

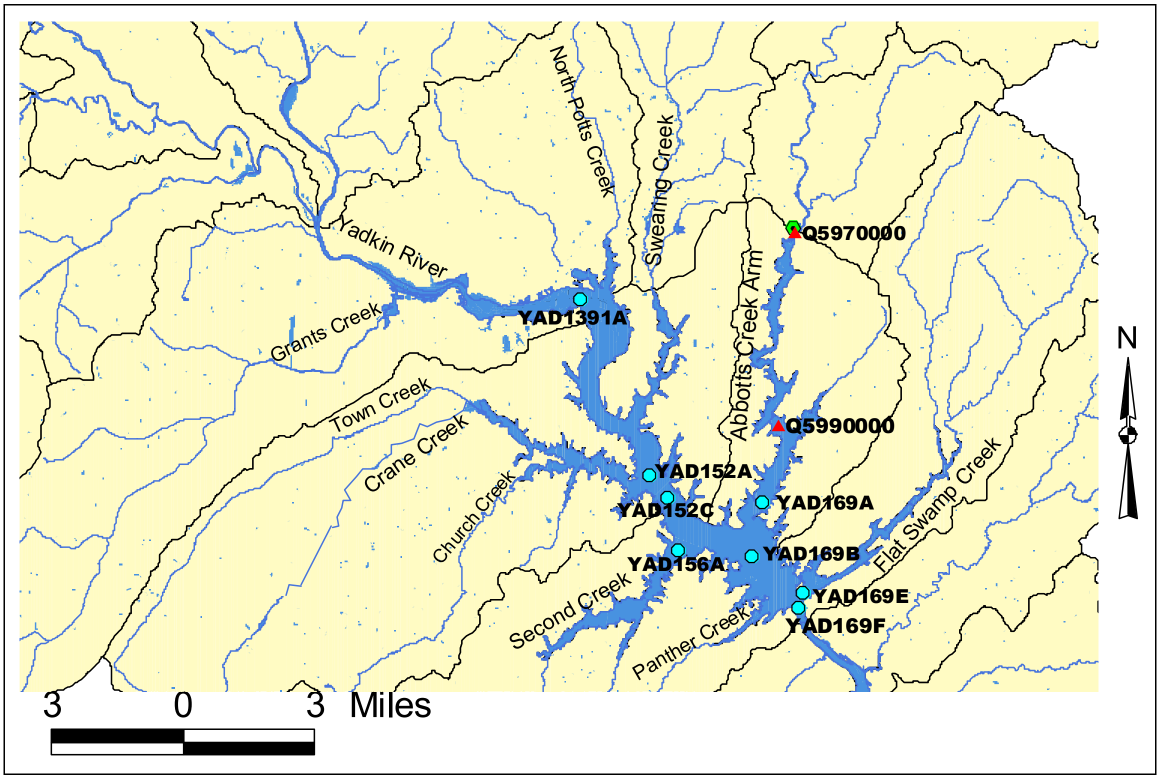


Figure 1. High Rock Lake, Showing DWQ Sampling Stations

High Rock Lake has a large watershed, including portions of 11 counties and 34 municipalities, among which are Winston-Salem, Thomasville, Lexington, Salisbury, and Statesville (Figure 2). There are over 23 major NPDES dischargers with flows greater than 1 MGD in the lake, including discharges direct to the lake or close to the lake. Total permitted discharges to the watershed amount to 126 MGD. The watershed also contains a significant proportion of North Carolina's total capacity for dairy production, including 76 registered animal operations.

High Rock Lake has been monitored since the early 1970s, and has consistently shown a high level of eutrophication, with elevated chlorophyll *a*, nutrient concentrations, and dissolved gas levels. The lake also receives large inputs of sediment, which have reduced depth noticeably in some portions of the lake. The sediment load, combined with algal production and hydropower operation, result in turbidity problems throughout the lake. A series of studies conducted by DWQ and others have confirmed the existence of impairment, but have not provided a full understanding of the linkage between stressor sources and impairment of the waterbody.

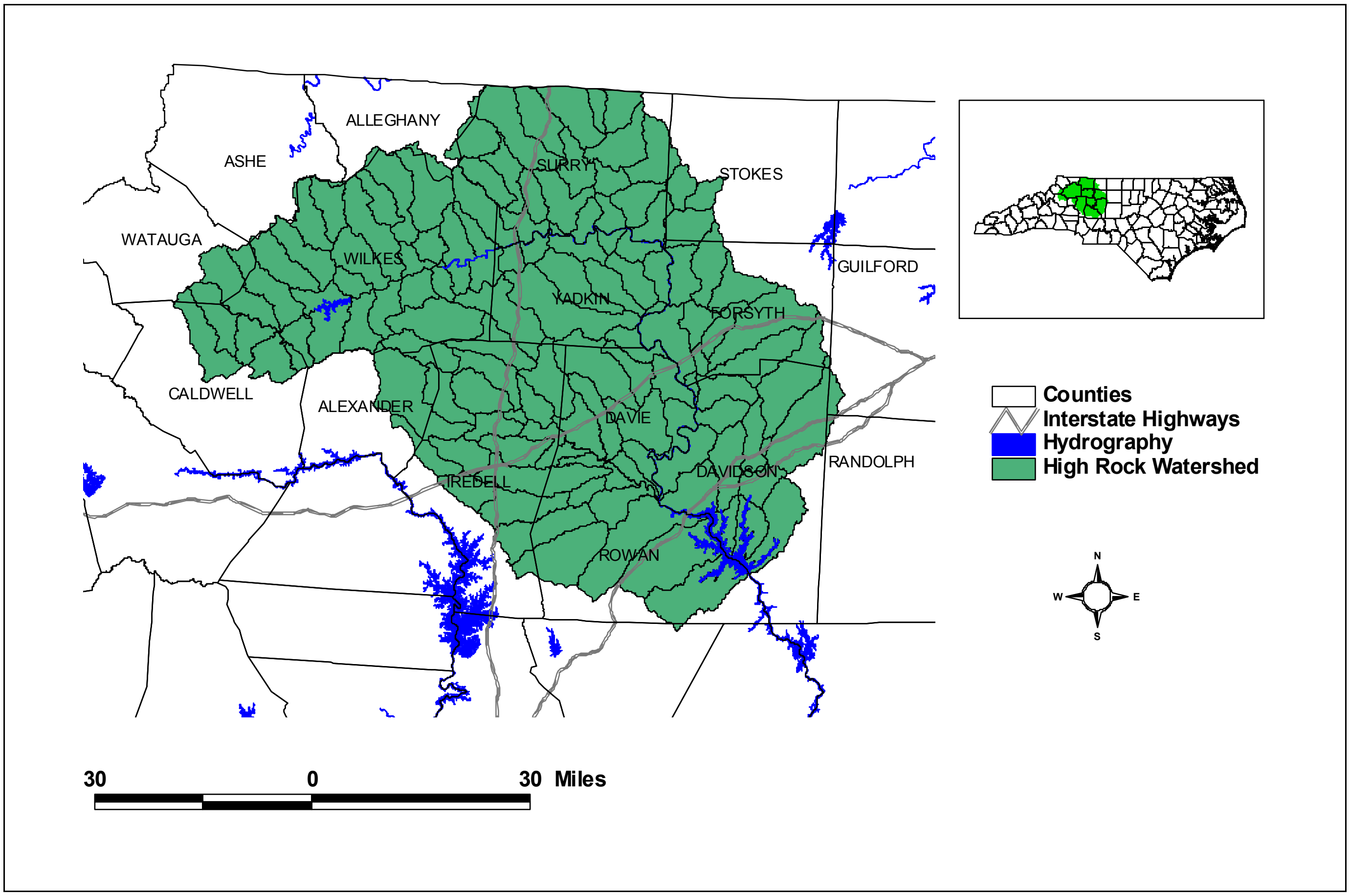


Figure 2. High Rock Lake Watershed

DWQ issued a Work Order for completion of this effort under Contract Number EW030318 on May 4, 2004. In accordance with our contract, Tetra Tech provided a detailed work plan for completion of the project on May 10, 2004.

Submittal of TMDLs for High Rock Lake is not anticipated until around 2011/2012. As a first step in the TMDL process, a review of the existing data was needed to guide additional data collection and model development. This information will help DWQ and others identify the technical goals and objectives of the project in addition to its data requirements.

Based on this review, it appears that algal response in High Rock Lake is controlled primarily by light availability and flushing, with diminished response to nutrients. Quality problems with historic chlorophyll *a* data result in a need to continue intensive sampling to build a better understanding of the system. Turbidity in the lake has a large component due to inorganic solids, but sufficient data need to be collected to resolve the contributions of algae and organic solids. Oxygen in the lake is affected by reaeration/mixing, organic carbon concentrations (CBOD), algal production/respiration, and sediment oxygen demand (SOD). At this time, data are notably lacking on CBOD and SOD in the lake.

The short residence time of High Rock Lake and temporal variability of conditions indicate that steady-state simulation models will be of limited use for management. Instead, a dynamic (time-varying) model that can simultaneously represent flow/mixing patterns, sediment transport, nutrient dynamics, algal response, and the dissolved oxygen cycle in (at least) two dimensions (longitudinal and vertical) is recommended. CE-QUAL-W2 is one candidate model appropriate for the site. However, any model is likely to confront a high degree of natural variability in the dynamic, river-like environment of the High Rock mainstem.

The monitoring and modeling strategies for High Rock Lake need to be developed concurrently, in conjunction with stakeholders, as part of a Quality Objectives process. The acceptable level of uncertainty relative to management decisions is an important consideration for both assessment information and development of modeling tools for High Rock Lake. Future monitoring should be designed to support Quality Objectives for modeling that are driven by potential decision needs. If a dynamic modeling framework is selected, an intensive monitoring program that provides multiple samples on a short time interval should be considered to provide a robust basis for model calibration and to help distinguish between natural variability and model uncertainty.

2 Physical Characteristics

High Rock Reservoir functions as a storage reservoir and serves as the principal storage and water regulation facility for the lower Yadkin-Pee Dee River. Land acquisition for the High Rock Development began in 1916, and construction was completed in 1927. The shoreline of the middle and lower portions of High Rock Lake is extensively developed, with little remaining natural shoreline (Alcoa, 2002). Many of the vacation houses surrounding the lake have yards protected by walls or riprap. The drainage area for High Rock Lake is 3,973 miles.

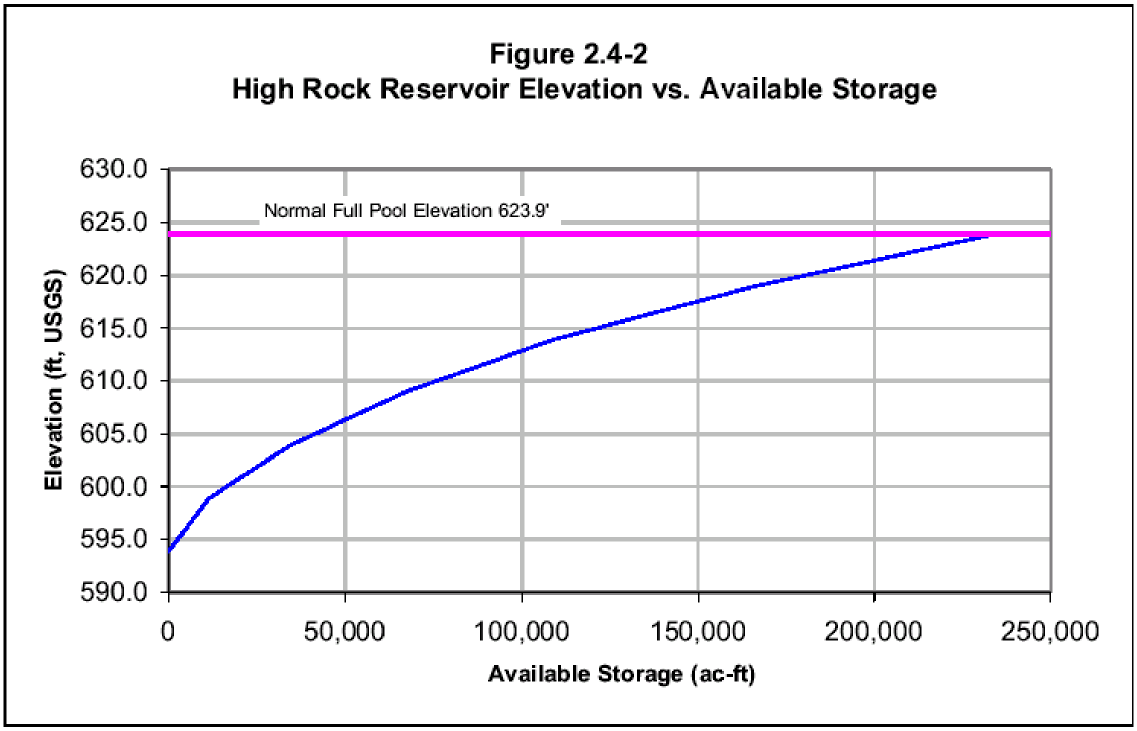
2.1.1 Lake Morphometry

The available storage capacity of High Rock Lake is 234,100 acre feet at a full pool elevation of 623.9 feet and a surface area of 15,180 acres. The reservoir has an average depth of 17 feet and a maximum depth of 62 feet. Elevation-storage-discharge curves for High Rock Lake are provided in Alcoa (2002) and reproduced in Figure 3. These represent *available* storage above the minimum turbine input invert elevation; additional dead storage exists below this level. Complete stage-storage curves for the reservoir including this dead storage have not been obtained at this time.

2.1.2 Lake Operation

Alcoa (2002) describes High Rock Dam as 936 feet long, with a maximum height of 101 feet. The dam has a gate-controlled spillway with an integral powerhouse intake. The primary purpose of the dam is hydropower generation, but operations have been modified to help preserve recreational water levels. The minimum elevation for hydropower discharge is apparently 594 feet MSL. To date, we have not been able to obtain records of actual discharge elevations from APGI's consultants, due to their involvement in ongoing FERC relicensing. This information will, however, be essential for the construction of hydrodynamic models of the lake.

The dam is currently operated in a store and release mode according to an operational rule curve established in 1968. The rule curve is written in terms of power generation, rather than elevation, but generally maintains higher lake levels from mid-May to mid-September. The pool is drawn down in the fall, then refilled during winter rains. The annual maximum drawdown averages 12 feet in winter and 5 feet in summer. The normal daily fluctuation in water level is 1 foot, with a maximum daily fluctuation of 2 to 4 feet. The influence of hydropower operation on recreational lake levels remains a major topic of controversy in High Rock Lake.



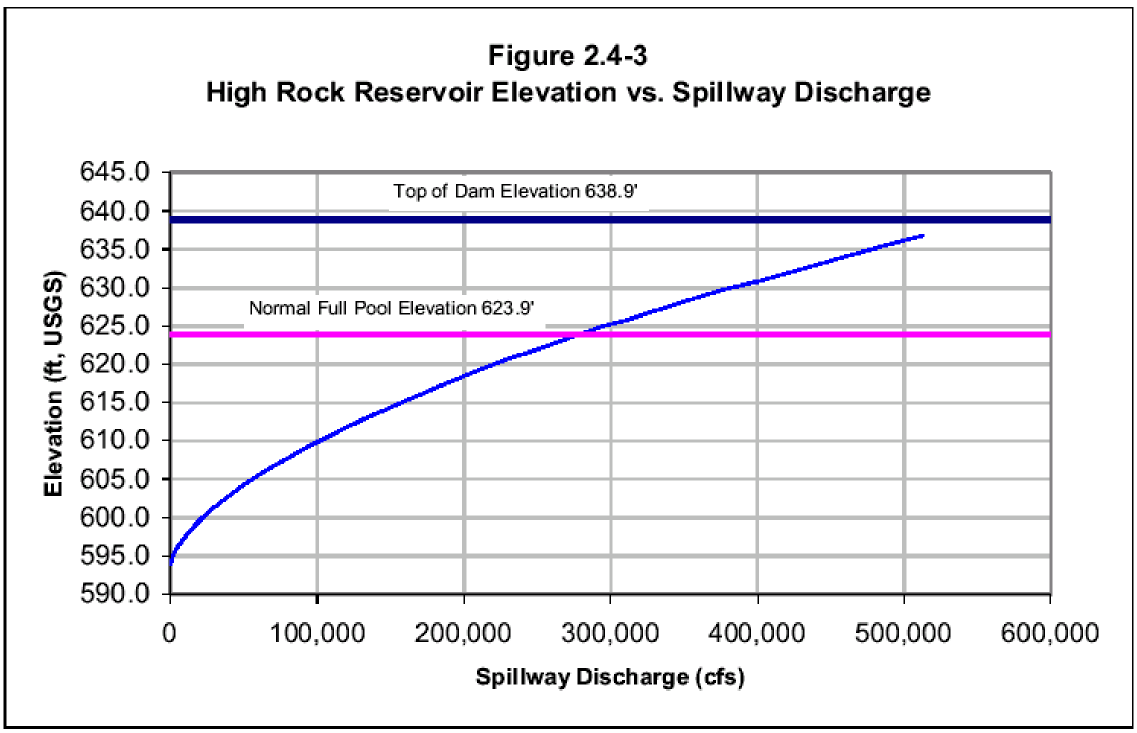


Figure 3. Stage-Storage and Stage-Discharge Curves for High Rock Lake (Alcoa, 2002)

2.1.3 High Rock Lake Watershed and Land Use

The watershed of High Rock Lake covers a drainage area of about 3,973 square miles (Alcoa, 2002), of which 97 percent (3,855 square miles) is within North Carolina, with the remainder in Virginia (refer to Figure 2). The watershed includes some or all of 16 North Carolina counties. The majority of the watershed (about 61 percent) is drained by the Yadkin River, which flows along the foot of the mountains in a northeasterly direction through Caldwell, Wilkes, and Yadkin counties, before turning south toward High Rock Lake. About 23 percent of the watershed area is drained by the South Yadkin River in the rolling Piedmont terrain of Davie, Iredell, and Alexander counties. The South Yadkin and Yadkin rivers join just above High Rock Lake. A number of smaller tributaries drain directly to the lake, and account for the remaining 16 percent of the drainage area.

High Rock Lake is the most upstream of a series of six reservoirs operated for hydropower generation on the mainstem of the Yadkin River. One major reservoir lies upstream – Kerr Scott Reservoir in Wilkes County, which impounds 348 square miles of the upper Yadkin watershed – as well as several smaller impoundments. These upstream lakes control only a small portion of the total land area draining to High Rock Lake.

Old, but comprehensive, land cover information for the High Rock watershed is contained in the National Land Cover Database (NLCD) from the Multi-Resolution Land Characterization (MRLC) Consortium (USGS, 2000), as shown in Figure 4. The NLCD is based on interpretation of Landsat satellite thematic mapper imagery recorded between 1992 and 1994 for North Carolina. A separate set of interpreted satellite data was developed by the North Carolina Center for Geographic Information Analysis, using 1993-1995 satellite imagery. The classifications in this dataset are generally less reliable than those in the NLCD, but yield similar results.

The MRLC Consortium is currently in the process of releasing interpreted year 2000 satellite imagery. This imagery should be available for the High Rock Lake watershed within the year, enabling an analysis of land use changes since 1992.

The NLCD coverage has a nominal 30-meter resolution. In essence, it is an identification of the predominant land cover (rather than land use) within each 30-m pixel. Data are classified into 21 types of land cover, including numerous forest and agricultural classes. In contrast, the information on developed land is somewhat limited. For residential land, the NLCD identifies two classes: Low-Intensity Residential is defined as areas with a mixture of constructed materials or other cover in which constructed materials account for 30-80 percent of the total area, while High-Intensity Residential is defined as areas in which constructed materials account for 80-100 percent of the total area. These attributions are made at the 30-m resolution, and so may not accurately reflect the characteristics of actual residential parcels. In addition, suburban residential development with significant tree cover may be missed entirely by the Landsat interpretation and be classified as forest.

A tabulation of the land cover from the 1992 NLCD is shown in Table 2; Figure 5 provides a summary by use categories.

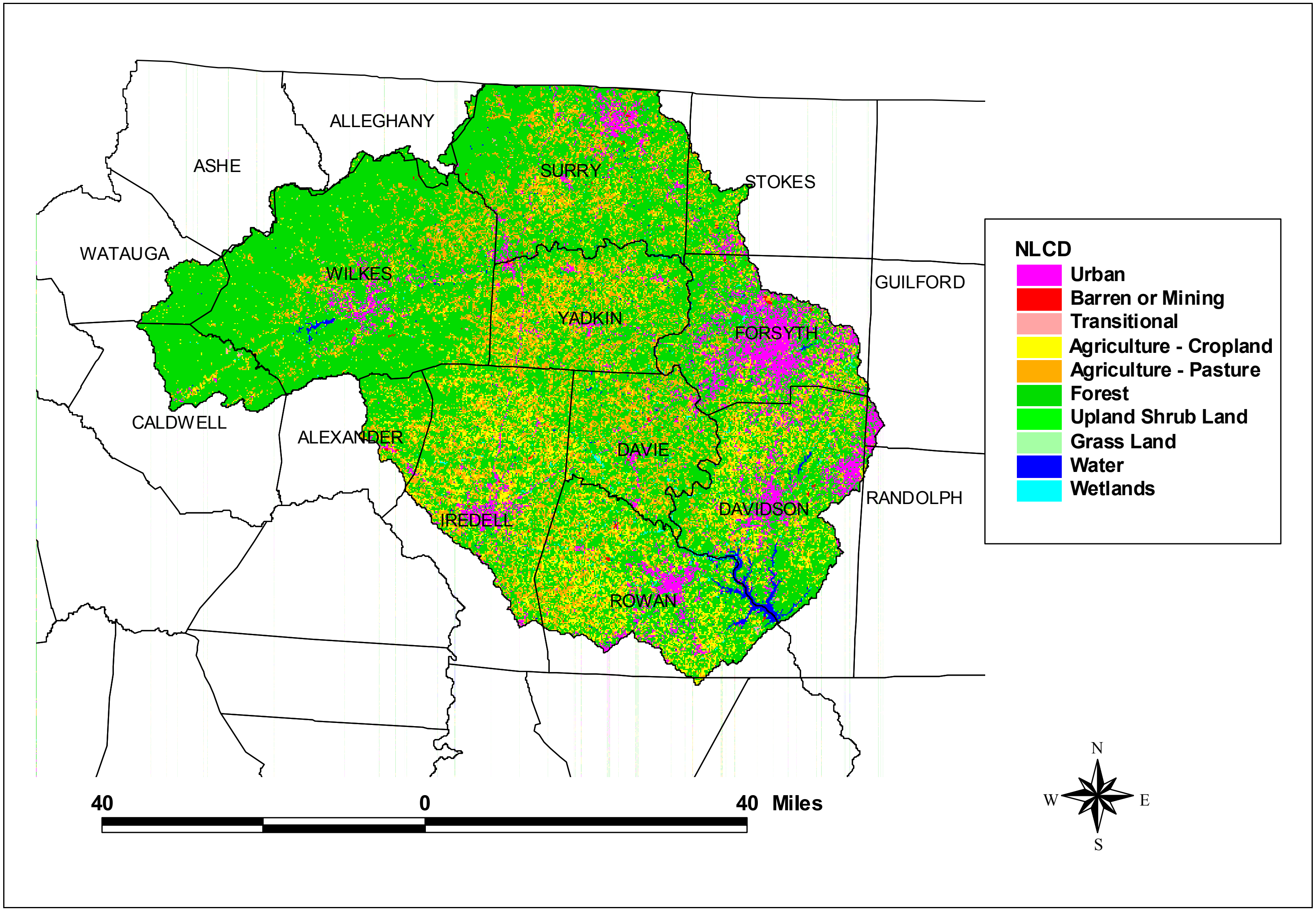


Figure 4. 1992 NLCD Land Cover for High Rock Lake Watershed

Table 2. Land Cover in the High Rock Lake Watershed, North Carolina Portion (1992 NLCD)

MRLC Code	Land Use	Area (mi^2)
11	Water	35.2
21	Low Intensity Residential	166.8
22	High Intensity Residential	29.9
23	High Intensity Commercial/Industrial/Transportation	74.6
31	Bare Rock/Sand/Clay	5.3
32	Quarries/Strip Mines/Gravel Pits	4.1
33	Transitional	2.5
41	Deciduous Forest	1382.1
42	Evergreen Forest	578.6
43	Mixed Forest	521.1
81	Pasture/Hay	634.4
82	Row Crops	378.5
85	Urban Grasses	22.6
91	Woody Wetlands	18.6
92	Emergent Herbaceous Wetlands	3.6

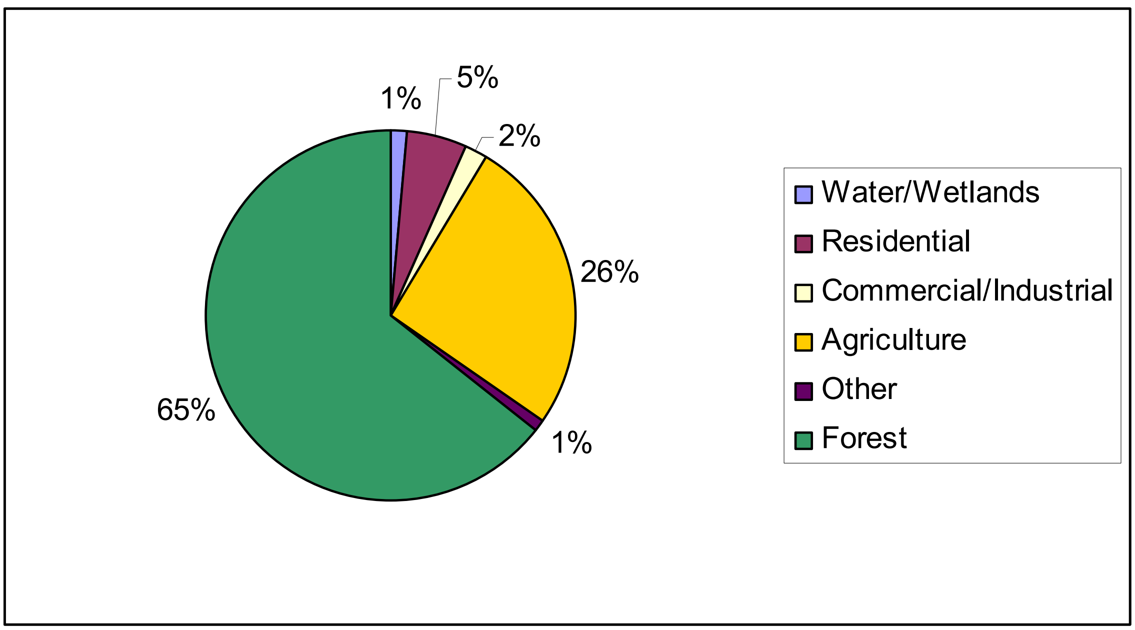


Figure 5. Land Use Distribution in the High Rock Lake Watershed (1992 NLCD)

2.1.4 Permitted Waste Discharges

The watershed of High Rock Lake covers several thousand square miles, and includes many cities, towns, and industries. NCDWQ (2003) lists a total of 155 dischargers permitted under the NPDES system upstream of High Rock Lake with a combined permitted flow of 126 MGD. Of these, 23 are classified as major dischargers (accounting for 93 percent of the flow), 15 of which are municipal wastewater treatment plants. Major dischargers (as of 2001) are listed in Table 3, taken from the 2003 Yadkin-Pee Dee River Basinwide Water Quality Plan. Of particular concern for water quality in High Rock Lake are several facilities that discharge directly to the lake, or within a few miles of the lake. The City of Salisbury Grants Creek WWTP discharges to the Yadkin River at the head of High Rock Lake. In 2001 it had a permitted flow of 7.5 MGD, which was increased to 12.5 MGD in 2002 (combining the flow from the former Town Creek WWTP discharge). Color/Tex Finishing (formerly Fieldcrest Mills) discharged 4.25 MGD near the Salisbury outfall through 2001, but has since been discontinued. On Abbotts Creek, the Lexington WWTP discharges 5.5 MGD within 2 miles of the lake.

Table 3. Major NPDES Permitted Dischargers in the High Rock Lake Watershed, 2001 (NCDWQ, 2003)

NPDES Permit No.	Company/Facility Name	County	Type of Discharge	Receiving Stream	MGD	Subbasin
NC0005266	Louisiana Pacific ABT Co. Mill	Wilkes	Industrial Process	Yadkin River	1.0	03-07-01
NC0020761	Town of North Wilkesboro WWTP	Wilkes	Municipal	Yadkin River	2.0	03-07-01
NC0021717	Town of Wilkesboro WWTP	Wilkes	Municipal	Yadkin River	4.9	03-07-01
NC0005312	West Point Stevens	Surry	Industrial Process	Yadkin River	4.0	03-07-02
NC0020338	Town of Yadkinville WWTP	Yadkin	Municipal	North Deep Creek	2.5	03-07-02
NC0020567	Town of Elkin WWTP	Surry	Municipal	Yadkin River	1.8	03-07-02
NC0021121	City of Mount Airy WWTP	Surry	Municipal	Ararat River	7.0	03-07-03
NC0026646	Town of Pilot Mountain WWTP	Surry	Municipal	Ararat River	1.5	03-07-03
NC0037834	City of Winston-Salem Archie Elledge WWTP	Forsyth	Municipal	Salem Creek[1]	30.0	03-07-04
NC0050342	City of Winston-Salem Muddy Creek WWTP	Forsyth	Municipal	Yadkin River	21.0	03-07-04
NC0005487	Color/Tex Finishing Corporation	Rowan	Industrial Process	High Rock Lake[1]	4.25	03-07-04
NC0023884	City of Salisbury Grants Creek WWTP	Rowan	Municipal	High Rock Lake[1]	7.5	03-07-04
NC0004774	Duke Energy Corp. Buck Steam Station	Rowan	Industrial Process	High Rock Lake[1]	No Limit	03-07-04
NC0004286	Fieldcrest Cannon	Rowan	Industrial Process	Grants Creek[1]		03-07-04
NC0004944	Arteva Specialties KOSA	Rowan	Industrial Process	Second Creek	2.3	03-07-06
NC0005126	Tyson Foods Inc. Harmony Plant	Iredell	Industrial Process	Hunting Creek	1.7	03-07-06
NC0024872	Davie County Cooleemee WWTP	Davie	Municipal	South Yadkin River[1]	1.5	03-07-06
NC0020591	City of Statesville Third Creek WWTP	Iredell	Municipal	Third Creek[1]	4.0	03-07-06
NC0031836	City of Statesville Fourth Creek WWTP	Iredell	Municipal	Fourth Creek[1]	4.0	03-07-06
NC0024112	City of Thomasville Hamby Creek WWTP	Davidson	Municipal	Hamby Creek[1]	4.0	03-07-07
NC0024228	City of High Point Westside WWTP	Davidson	Municipal	Rich Fork[1]	6.2	03-07-07
NC0055789	City of Lexington WWTP	Davidson	Municipal	Abbotts Creek[1]	5.5	03-07-07

[1] A portion of this waterbody is currently rated Impaired.

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3 Water Quality Investigations of High Rock Lake

A variety of studies have been undertaken in the past on High Rock Lake. These studies are reviewed below, and help to set the stage for development of future monitoring and modeling needs.

3.1 USEPA 1973

The first detailed examination of water quality conditions in High Rock Lake was undertaken by the National Eutrophication Survey in 1973 (USEPA, 1975). EPA sampled the lake three times at three stations in 1973, and sampled tributaries monthly between March 1973 and February 1974. The study concluded that the lake is highly eutrophic – but, because of the short residence time (estimated at 27 days), more closely resembles a slow-moving river than a typical lake.

The maximum chlorophyll *a* concentration reported in 1973 was 27.6 µg/L. EPA sampling found that the algal population in the spring was dominated by flagellates, while the summer population was dominated by the cyanobacteria (blue-green algae) genera *Raphidiopsis*, *Oscillatoria*, and *Microcystis*. Algal bioassays indicated that phosphorus was the limiting nutrient. Areal phosphorus loading rates per unit area of lake surface were estimated as 14.8 $g/m^2/yr$, of which 32 percent was attributed to point sources. Institution of phosphorus controls was recommended.

Analysis of the tributary and outflow data for March 1973 – February 1974 established a nutrient budget. Total phosphorus inflows were estimated as 950,075 kg/yr and outflows as 437,005 kg/yr, for a net retention of 54 percent. Total nitrogen inflows were estimated at 5,618,760 kg/yr and outflows at 5,529,775 kg/yr, for a total retention of less than 2 percent.

3.2 NC DEM 1974

The initial EPA investigation was followed up by the NC Division of Environmental Management (DEM) in 1974, with samples collected from the lake and tributaries between April and August of 1974. Numerous excursions of the fecal coliform standard were documented in the tributaries and in the tributary arms of the lake, along with high nutrient concentrations. Nutrients were noted as particularly elevated below the discharge of the NC Finishing Company (Fieldcrest Mills) below Grants Creek.

Chlorophyll *a* was not analyzed in 1974. The study also did not estimate loads; however, concentration profiles across the system (Table 4) show conditions worsening as the Yadkin River passed Grants Creek, then gradually improving across the body of the lake. The concentrations indicate significant phosphorus trapping, consistent with the EPA findings, but suggest a larger degree of nitrogen trapping.

Table 4. Selected Average Results from 1974 Sampling of High Rock Lake

	Yadkin River above Grants Creek	Yadkin River below Interstate 85	High Rock Lake at Dam
Secchi Depth (m)	0.3	0.24	0.70
Turbidity (FTU)	51	36	24
Total P (mg/L)	0.17	0.50	0.07
Total N (mg/L)	0.73	1.18	0.47

3.3 NC DEM 1975

In the following season, NC DEM (1975) conducted a followup "immediate needs" report in response to a petition from the High Rock Lake Association. This study focused on the evaluation of point source discharges, but also contains the first detailed conceptual interpretations of conditions in the lake. Significant problems were noted with a number of the point source discharges, and recommendations for improvements were made. Drainage from septic tanks associated with development around the lake was noted as a potential, but unquantified, problem and a recommendation was made to study septic tank problems in the area.

DEM noted dense algal growth in a number of tributary arms of the lake, and attributed these conditions to a combination of point and nonpoint source nutrient loading. DEM also discussed the high turbidity common in the lake. This was attributed primarily to upstream erosion and sedimentation problems in the Yadkin basin; however, shoreline erosion of the lake shore was also noted as contributing to turbidity.

A biological survey conducted from June 30 through July 3, 1975 noted dissolved oxygen was near zero at bottom stations. These hypoxic conditions encouraged the recycling of nutrients, including phosphorus and ammonia.

The study noted that the lake was affected by large organic carbon loads that contributed to hypoxia and might help explain the apparent low net retention rate of nitrogen in the system.

3.4 UNC 1977-1978

The state next supported a one-year intensive study of High Rock Lake (Weiss et al., 1978), which included detailed field work on the lake and tributaries between October 1977 and September 1978. The extensive report confirmed many of the earlier findings regarding the lake.

The UNC report concluded that High Rock was the most enriched of the major river impoundments in the region – but that this did not result in significant problems:

> *High Rock Lake is clearly a nutrient rich aquatic ecosystem that at retention periods greater than thirty days develops substantial algal populations. The growth response is greatest in the summer season, July-September, when the mean water temperatures are above 28°C. At these high ambient temperatures extensive proliferation of blue-green algae occurs. However, in the period of this study and as far as the past record can be determined the specific taxa of blue-green algae that grow in High Rock Lake have not been species that have impaired its water uses. In fact this nutrient rich lake and high algal densities has demonstrated a unique capability to assimilate the nutrient load introduced*

directly into several of the side arms as well as the nutrients introduced by the flow of the Yadkin River…

3.4.1 Nutrients

Nutrient levels remained high in 1977-78, but retention times during the study ranged from 3.5 to 56 days and apparently limited algal production. Consistent with earlier studies, Weiss et al. found that the lake was a significant trap for phosphorus, which declined during transit across the lake, but not for nitrogen. The phosphorus trapping rate was estimated at 40-50 percent during summer, while the lake appeared to be a net source of nitrogen. Kjeldahl nitrogen (organic nitrogen plus ammonium) increased during transit across the lake. This was due in part to conversion by algae, and also in part to release of ammonia from the sediments during hypoxic conditions.

3.4.2 Algae

Algal concentrations in the lake showed distinctive seasonal and successional patterns. In the mid-lake, there was a small spring peak of algal biovolume, followed by a period of low concentration and a summer maximum.

The relationship between chlorophyll *a*, algal cell density, and cell biovolume “appeared reasonably linear within seasons,” but showed significant differences between seasons and between locations. This was attributed to strong seasonal shifts in algal types. The biovolume of summer blue-green algal populations (cyanobacteria) appeared to be poorly related to chlorophyll *a* concentrations.

The early spring algal peak was dominated by *Cryptomonas erosa* (a pollution-tolerant flagellate) and *Skeletona potamos* (a diatom). The summer peak was predominantly blue-green algae (cyanobacteria). However, it was noted that the blue-green algal populations consisted mostly of “small, delicate types” and nuisance blooms were not observed.

In general, algal populations within the lake were found to be nutrient-limited by phosphorus, with surplus nitrogen. The general factors limiting algal growth are listed as residence time, light availability, and phosphorus removal by turbidity. Together, these factors appear to exert selective pressure for algae that can control their position in the water column – flagellates in the spring and buoyant cyanobacteria in the summer. Green algae in the lake appear to be limited by high grazing pressure.

3.4.3 Empirical Models

Weiss et al. explored a number of stepwise regression models for algal response. A statistical model of chlorophyll *a* in the main body of the lake as a function of total phosphorus, residence time, and depth appeared to predict well. This model, using the formulation of Rast and Lee (1978), takes the form

$$\log(Chlorophyll\ a) = 0.76\log\left[\frac{L(P)/q_s}{1+\sqrt{t_w}}\right] - 0.259,$$

where *L(P)* is the areal loading rate of total phosphorus (mg-P/m^2/yr), q_x is the overflow rate or mean depth divided by residence time (m/yr), and t_w is the residence time (yr^{-1}). This model successfully predicted measured chlorophyll *a* concentrations during low and base flow conditions, but over-predicted response at higher flows.

3.5 NC DEM 1989-1990

In 1989 and 1990, NCDEM (NCDWQ, 1997) conducted intensive monitoring in High Rock Lake and its tributaries in order to support the development of a calibrated water quality model for the reservoir. Flow, temperature, dissolved oxygen, pH, conductivity, solids, turbidity, nutrients, phytoplankton, and chlorophyll *a* were monitored monthly from April through September during 1989 and May through September during 1990. Data from this study further documents the hypereutrophic condition of High Rock Lake and were used to support development of a BATHTUB lake response model (see Section 4).

Precipitation in 1989 was greater than the monthly average from 1951-1980 for every month except August, while precipitation in 1990 exceeded the monthly average only in May. Similarly peak flows in 1989 were consistently higher than the average, while in 1990 only two peak flows in May exceeded the average. Despite these differences in flow during the sampling period the same areas of concern were evident each year.

Surface water temperatures ranged from 25-30˚C with a maximum in June. Elevated pH values were seen throughout the lake with the exception of the most upstream lake station (YAD1391A) during May through August. Turbidity values reflect differences in precipitation and flow between the two years, however YAD1391A exhibited excessive turbidity with a mean value that was significantly different than the turbidity at any other station during both years. Total solids concentration was highest for station T-3 on Town Creek and was also elevated at G-2 on Grants Creek, SC-3 on Second Creek, and T-4 on Town Creek.

Nutrient levels were elevated throughout High Rock Lake and its tributaries during both years of the study. Town Creek (T-3) was the most enriched station with the highest mean concentrations of both nitrogen and phosphorus in 1989 and 1990. Grants Creek was also identified as an area of concern with the second highest mean nitrogen and phosphorus concentrations in 1990.

Chlorophyll *a* concentrations throughout the study area violated the state standard of 40 µg/L numerous times throughout the sampling period. In 1989, the standard was exceeded at all stations except Flat Swamp Creek (FS-2) and YAD1391A. In 1990, regular exceedances occurred at North Potts Creek (P-1), and Towns Creek (T-1 and T-2), and occasional exceedances occurred at Flat Swamp Creek (FS-1), Second Creek (SC-1,SC-2), Swearing Creek (SW-1), and High Rock Lake below Town Creek (YAD152C).

Estimates of phytoplanktonic biovolume and density followed similar patterns with peaks in July and August. During both years, the largest algal populations were observed in the embayment of Town Creek. Algal populations were dominated by small, filamentous blue-green algae (*Anabaenopsis raciborskii* and *Oscillatoria geminata*) from June through September and cryptophytes in May.

3.6 APGI 1999-2001

As part of the FERC relicensing process for the Yadkin impoundments, Alcoa Power Generating, Inc. (APGI), the operator of High Rock Lake, was required to undertake a water quality study, which was contracted to Normandeau Associates. Results are reported in Alcoa (2002) and NAI (2002).

As part of this study, monthly sampling was conducted at 10 sites in High Rock Lake from June 1999 through December 2001. The focus was on dissolved oxygen conditions in the Yadkin system, but other parameters were also measured. Turbidity, however, was measured only after April 2001. Chlorophyll *a* was monitored throughout, but samples prior to February 2001 were surface grabs, while samples after February 2001 are composites over twice the Secchi depth, consistent with NCDWQ methods.

This investigation generally noted the same water quality issues as have been documented by NCDWQ, and repeats findings of nutrient enrichment with elevated chlorophyll *a* in lake arms and elevated turbidity in upper portions of the lake. However, the report additionally notes that copper, cyanide, and mercury criteria are frequently exceeded in High Rock Lake. Thermal stratification is noted as "not common in the reservoir and most occurrences of a thermocline are weak and not persistent."

Turbidity was greatest in the upstream portions of High Rock Lake, where it exceeded the 25 NTU criterion more than 50 percent of the time. Secchi depth was usually less than 0.5 m in the upper reservoir, and less than 1 m elsewhere. The limited thickness of the euphotic zone is cited as a cause of DO depletion at depth. This in turn leads to ammonia regeneration from the sediments.

The low chlorophyll *a* in the upper portion of the reservoir is discussed, but the cause is characterized as unclear, as water clarity is only somewhat worse than in the lower reservoir. Instead, it is speculated "that the hydraulic retention time in this portion of the reservoir is not great enough for algal production to reach peak levels."

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4 NCDWQ BATHTUB Model of High Rock Lake

DWQ (1997) developed an application of the steady-state BATHTUB model to High Rock Lake. BATHTUB (Walker, 1987) is a semi-empirical model developed by the U.S. Army Corps of Engineers that is designed to predict growing season average concentrations of nutrients in chlorophyll *a* in impoundments and has been successfully applied to a number of North Carolina lakes. The model is forced by estimated flow and loading rates from tributaries.

DWQ developed the model for 1989-1990 monitoring data. The lake was represented with 15 lateral segments, for all but one of which, at least some monitoring data were available (Figure 6). Due to the short hydraulic retention time in High Rock Lake, the model was implemented on a seasonal basis, as recommended in the BATHTUB manual. In general, DWQ found that the model could provide a reasonable fit to observed average total phosphorus concentrations. However, the model tended to over-predict total nitrogen, while severely underestimating observed chlorophyll *a*. The Executive Summary of the modeling report summarizes the effort as follows:

> *…While the modeling effort was successful in estimating nutrient loads to the lake and in developing a tool to predict total phosphorus levels in key portions of the reservoir, it was not possible to develop a predictive tool to evaluate the potential impacts of alternative management strategies on algal levels.*
>
> *While turbidity and detention time depress algal growth in the model, as one would expect them to in the lake, the effect of these factors on model predictions is extreme. Predicted algal levels remain low even when these factors are removed, indicating that the BATHTUB modeling framework is inappropriate for simulating algal response in High Rock Lake. The reasons for this situation are not clear, although likely factors include dynamic hydraulic conditions and differences between High Rock Lake and the reference lakes used to develop model parameters.*

A thorough review of the DWQ BATHTUB modeling effort revealed problems in a number of areas that, together, account for much of the discrepancy between model and predictions. These are: (1) errors in the construction of the input files, (2) representation of vertical mixing, and (3) specification of external loads. While some of these issues can be resolved, it still appears there are severe limits on the applicability of a BATHTUB-type approach to High Rock Lake.

4.1 Errors in Input Files

DWQ supplied the final input files for the 1989 and 1990 BATHTUB simulations in BATHTUB version 4 format. These were updated to the latest BATHTUB version (version 5.4 “bin” files) and checked for errors. The input file formulation appeared to be generally correct, with one important exception: the specification of the 11 ungaged tributaries. Flow and loading data for these tributaries are provided. However, DWQ specified them as tributary type 2. When type 2 is selected, BATHTUB attempts to estimate flows and loads from a simple nonpoint source loading model, and thus overrides the influent load specifications. For High Rock, parameters were not entered for the nonpoint source model. As a result, these tributaries were effectively being simulated as contributing zero load.

Fixing this error by changing these tributaries to type 1 has only a small effect on model predictions. This is because 90 percent or more of the influent nutrient loads enter through gaged tributaries (primarily the Yadkin River), which are correctly specified.

Figure 9
Model Segmentation and Lake Sampling Stations

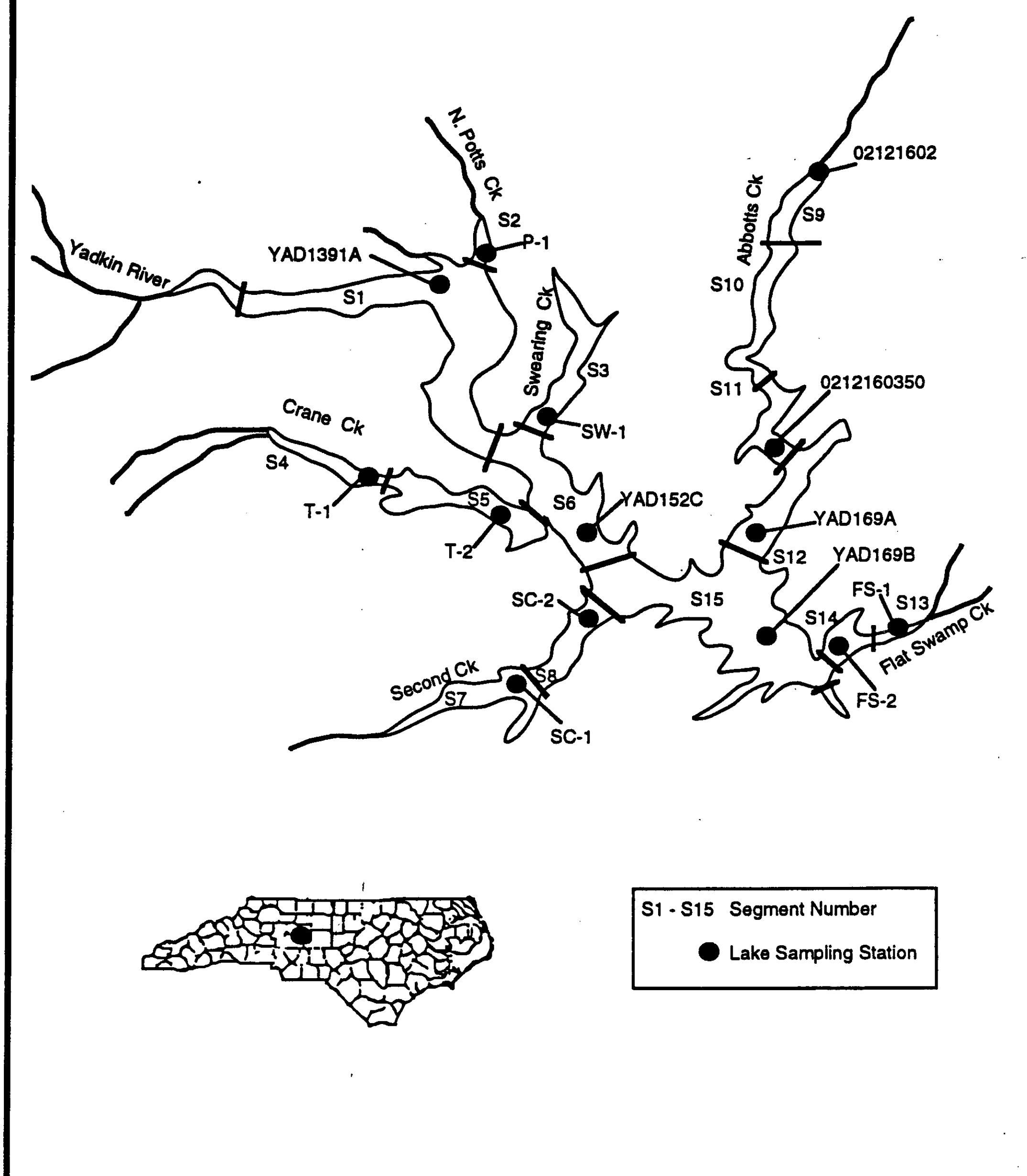


Figure 6. BATHTUB Segmentation for High Rock Lake (NCDWQ, 1997)

4.2 REPRESENTATION OF VERTICAL MIXING

High Rock Lake does not establish strong thermal stratification due to its short residence time and large throughflow. BATHTUB uses the depth of the epilimnetic mixed layer (ZMIX) to determine the averaging volume in the estimation of chlorophyll *a* concentrations. (ZMIX is not used in the nutrient balances.) The DWQ input files leave ZMIX unspecified, which causes BATHTUB to estimate ZMIX from a regression equation calibrated to the Corps of Engineers' data set. Because of the short residence time, this results in effective ZMIX values that are equal or nearly equal to the full depth of most lake segments.

Use of this default at first appears appropriate for High Rock, given the lack of stratification. It is important to recognize, however, that the DWQ chlorophyll *a* samples are collected as composites over twice the Secchi depth (the euphotic zone), and this sampling depth is generally much less than the segment depth. For instance, in the downstream mainstem segment, the segment mean depth is 9.12 m, but twice the Secchi depth is only 1.2 m, or 13 percent of the total depth.

As implemented, the High Rock BATHTUB model makes the implicit assumption that the algal concentration over twice the Secchi depth (the top 0.8 to 1.2 m) is equal to the algal concentration over the full depth of the lake. This would only be true if there is strong vertical mixing. Further, the mixed representation will significantly depress predicted chlorophyll *a* concentrations, as there is sufficient light for algal growth only in the top layer.

It is likely that an assumption of strong vertical mixing is inappropriate, despite the lack of stratification. High Rock Lake has a short residence time (on the order of a week in the mainstem during 1989-90) and rapid axial flow. The lack of stratification in the mainstem is thus due in part to the movement of relatively homogenous Yadkin River water through the lake, rather than vertical mixing. This would allow higher algal concentrations to be present in the euphotic zone than in deeper waters. In the more quiescent side coves, less mixing is expected, and blue green algae are likely able to use buoyancy adjustment to further increase concentrations in the euphotic zone.

Figure 7 and Figure 8 show, for 1989 and 1990, the observed segment-average summer chlorophyll *a* predictions from the original model as implemented by DWQ, and predictions that are obtained from a revised model with ZMIX set to twice the Secchi depth. (The error in the type specification for ungaged tributaries is also corrected.) Except in the upstream mainstem segment, the original model consistently underpredicted chlorophyll *a*. With the reduced value for ZMIX in the revised model, model predictions shift above the observed line for the mainstem stations and most of the tributary stations. This suggests that the problems encountered with underprediction of observed chlorophyll *a* are largely due to the assumption of complete vertical mixing.

Both the original and revised models continue to underpredict chlorophyll *a* in the tributary segments for Second Creek and Flat Swamp. For these segments, phosphorus concentration is also significantly underpredicted – leading to the underestimate of chlorophyll. Finally, in segment 1 (upper mainstem), both the original and revised models overpredict chlorophyll *a*, likely due to an overestimate of light availability in this turbid headwater.

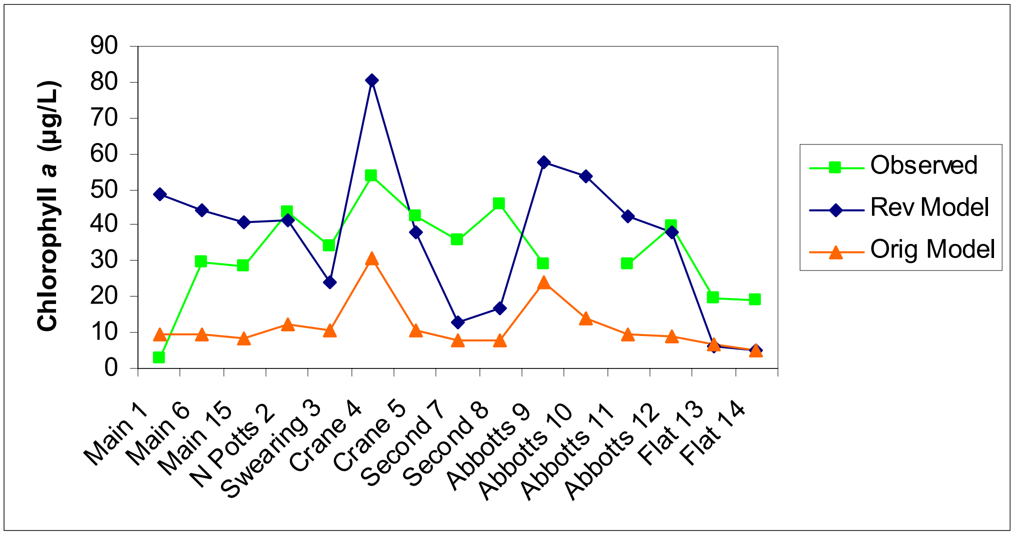


Figure 7. Comparison of Chlorophyll *a* for Original DWQ Model and Revised Model with ZMIX Set to Twice the Secchi Depth, 1989 Results

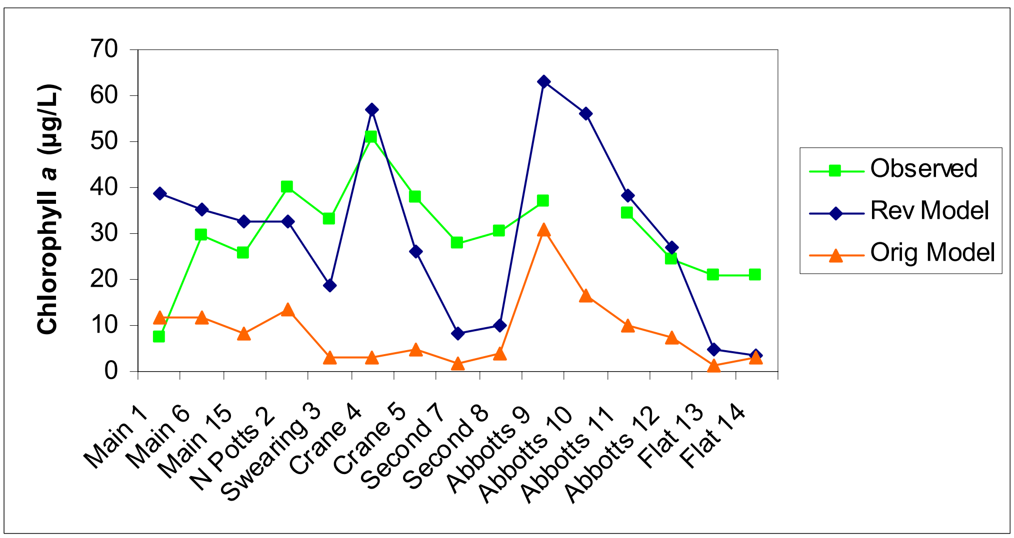


Figure 8. Comparison of Chlorophyll *a* for Original DWQ Model and Revised Model with ZMIX Set to Twice the Secchi Depth, 1990 Results

4.3 Specification of Tributary Loads

While total phosphorus predictions in most segments are generally in range of observations, the observations and predictions of total nitrogen show considerable discrepancy and were judged not to be calibratable by DWQ within the range of adjustment factors to sedimentation rates recommended by the BATHTUB documentation. Nutrient concentrations in BATHTUB do not depend on the mixing depth. Thus, these errors most likely reflect problems in the specification of tributary loads.

The problem for total nitrogen is actually worse than reported by DWQ. This is because nitrogen sedimentation model 1 is employed, which computes available nitrogen based on a weighted sum of influent total and inorganic nitrogen. With this sedimentation model, when the fraction of organic nitrogen in the inflow is large (as is the case for High Rock Lake), BATHTUB will report total nitrogen that is less than organic nitrogen concentration. In any case, the overestimation of nitrogen by BATHTUB is almost entirely due to overestimation of organic nitrogen concentrations, as shown in Figure 9 – suggesting that organic nitrogen loads are specified too high.

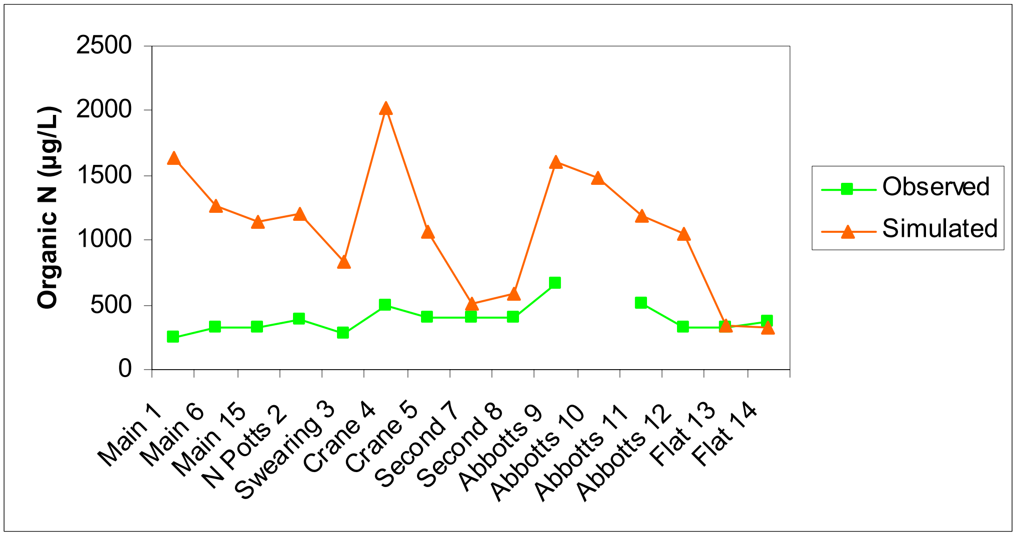


Figure 9. Observed and Simulated Organic Nitrogen, 1989

DWQ developed loads for monitored tributaries using the FLUX approach (Walker, 1987), which is recommended for BATHTUB applications. The original FLUX input files were not supplied, so it is difficult to check these calculations. It is relevant to note, however, that none of the nitrogen load estimates were stratified – which usually improves results – because of concern over small sample size and underrepresentation of high flows. Estimated coefficients of variation for total nitrogen are, however, in the range of 10 to 16 percent, which is well less than the discrepancy observed for in-lake concentrations.

The ungaged watershed area is small relative to the gaged area, and is reasonably extrapolated from the gaged results. Of greater concern is the fact that a number of point sources (including Mocksville, Statesville, Holly Farms, Lexington, and Salisbury Spencer) are located downstream of the tributary monitoring sites and thus must be added to the FLUX estimates. For these dischargers, DWQ has assumed that all the nutrients released are delivered to the lake. Further, no nutrient reductions of any kind are assumed between the monitoring station and the lake. As noted in their report on p. 12 (DWQ, 1997): "Since it is rather unlikely that all nutrients discharged by facilities in the watershed reach the lake in the summer during which they are discharged, these estimates represent an upper limit on the total point source contribution… "

For Town Creek, DWQ chose to ignore the FLUX results and instead calculated loads by scaling the nonpoint loads from Crane Creek and adding the Salisbury Town Creek WWTP effluent load. The rationale for this decision is presented as follows (p. A-6):

> *Initial FLUX runs generally yielded load estimates below the estimated 1989 seasonal load of Salisbury's Town Creek WWTP, located a short distance upstream from the sampling station. The problem is particularly acute for*

> *nitrogen – all calculation methods yielded estimated TN loads less than one half that of the estimated WWTP load. It is extremely unlikely that this difference can be accounted for by instream nitrogen decay, given the proximity of the WWTP to the sampling site… Month to month variations in effluent nutrient concentrations were substantial, however, and the high WWTP load is due in part to several periods of extremely high concentration. Under these conditions ambient sampling will not accurately reflect the point source loading, especially at small sample sizes…*

Town Creek flows into the Crane Creek arm (Segment 4) of High Rock Lake. In Segment 4, the BATHTUB application for 1989 predicts organic nitrogen of 2,020 µg/L, whereas the observed organic nitrogen concentration was only 490 µg/L. Clearly, use of the FLUX estimates would provide a better fit. Further, as acknowledged in the paragraph cited above, there is considerable uncertainty in the estimate of the Salisbury WWTP load, and the discrepancy may be due in large part to an overestimate of this load.

In sum, the poor model fit for nitrogen in the lake appears to be largely due to an overestimate of tributary loading, particularly the loading from WWTPs located downstream of the monitoring stations and the loading from Town Creek. For future modeling applications it will be important to ensure accurate characterization of both tributary loads and loads from WWTPs downstream of the monitoring sites. Further, the modeling framework should be carried upstream to the monitoring sites to allow simulation of nutrient loss between those points and the lake.

4.4 Applicability of the BATHTUB Model to High Rock Lake

By addressing the issues discussed in the preceding three sections, a much closer fit of BATHTUB model predictions to observations for 1989 to 1990 could be obtained. However, considerable uncertainty would still remain and the most significant adjustment, that for mixed depth, would need to be based on professional judgment and empirical curve fitting. This would increase uncertainty in the interpretation of model output, particularly in regard to application to evaluation of scenarios outside the calibration range.

In addition, the hydraulic characteristics of High Rock Lake limit the applicability of the BATHTUB model. BATHTUB is designed to evaluate summer average conditions, based on either annual or growing season load. During the summers of 1989 and 1990, the hydraulic residence time in the lake was on the order of one week. This means that nutrient concentrations in the lake tend to be driven primarily by short-term inflows, and a stable average condition is not established. Algae will be rapidly flushed from the lake, and the damped "memory" of the system means that the short-term flushing rate and transient changes in light availability due to turbidity input and weather become increasingly important factors controlling algal growth. On the other hand, the short residence time means that nutrient and algal sedimentation rates – which are the primary calibration factors available in BATHTUB - are of correspondingly lesser importance. These facts suggest that simulation of nutrient response in the lake would be better addressed through use of a dynamic model that represents the temporal course of external forcing rather than by the steady-state BATHTUB approach.

5 Existing Data Compilation

Water quality data have been collected by multiple agencies for High Rock Lake and tributaries. A list of files received and the data they contain is provided in Appendix A. This section describes the principle monitoring programs and summarizes key findings for water quality parameters of interest.

5.1 MONITORING EFFORTS

NCDWQ has extensively monitored water quality in High Rock Lake reservoir since 1973. Collection of data at a consistent set of sites began in 1981 as part of the Lakes Assessment Monitoring Program (Figure 10). Data include dissolved oxygen, Secchi depth, suspended solids, chlorophyll *a*, and nutrient concentrations. Data on algal biomass and species numbers are also available for two of the lake stations for 1989 and 1990.

DWQ has also collected monthly data on tributaries to High Rock Lake through the Ambient Surface Water Monitoring Program beginning in 1974 (Figure 24). Parameters monitored include flow, stage, dissolved oxygen, nutrients, and turbidity.

In 1989 and 1990, DWQ conducted water quality monitoring at 13 sites focusing on the arms of the lake and primary tributaries. Samples were collected monthly for 6 months in each year, and parameters included dissolved oxygen, nutrients, and chlorophyll *a*.

The United States Geologic Survey (USGS) has collected data at 44 sites in the High Rock Lake watershed, commencing in the 1950s. Many of these stations were monitored only briefly, and only nine of the stations have data since 1980 as monitoring by USGS was replaced by monitoring by NCDWQ (Figure 24). The only USGS water quality station of immediate relevance to the study of High Rock Lake since 1980 was located on the Yadkin River at Yadkin College (coincident with a DWQ monitoring location) and was discontinued in 2001.

The Yadkin Pee Dee River Basin Association (YPDRBA) monitors water quality throughout the Yadkin Pee Dee River Basin (Figure 24). Eighteen sites are located on tributaries to High Rock Lake, and five of these correspond with DWQ monitoring stations. Data is available from 1998-2003.

The Yadkin division of Alcoa Power Generating Inc. (Yadkin) operates the High Rock Dam and reservoir and is currently involved in the relicensing process for the Yadkin project that includes the High Rock Development. As part of this relicensing process, Yadkin has initiated a modeling effort to reconcile calculated discharge with measured inflows. The result of this effort will be a 75-year dataset based on USGS gages where inflows, headwaters, and discharges are all based on consistent data. Yadkin will submit this dataset to USGS for review in July/August 2004.

5.2 REVIEW OF HIGH ROCK LAKE MONITORING DATA

NCDWQ water quality monitoring sites in High Rock Lake are shown in Figure 10 and summarized in Table 5. Two additional monitoring sites along the Yadkin River are located within the normal pool backwater of the lake, but have a primarily riverine nature and are thus discussed with other tributary stations in Section 5.3. The two stations in the upper part of the Abbotts Creek arm of High Rock Lake and the station in Town Creek arm have conditions that may differ significantly from the mainstem of the lake, and are discussed separately in Sections 5.2.3 and 5.2.4.

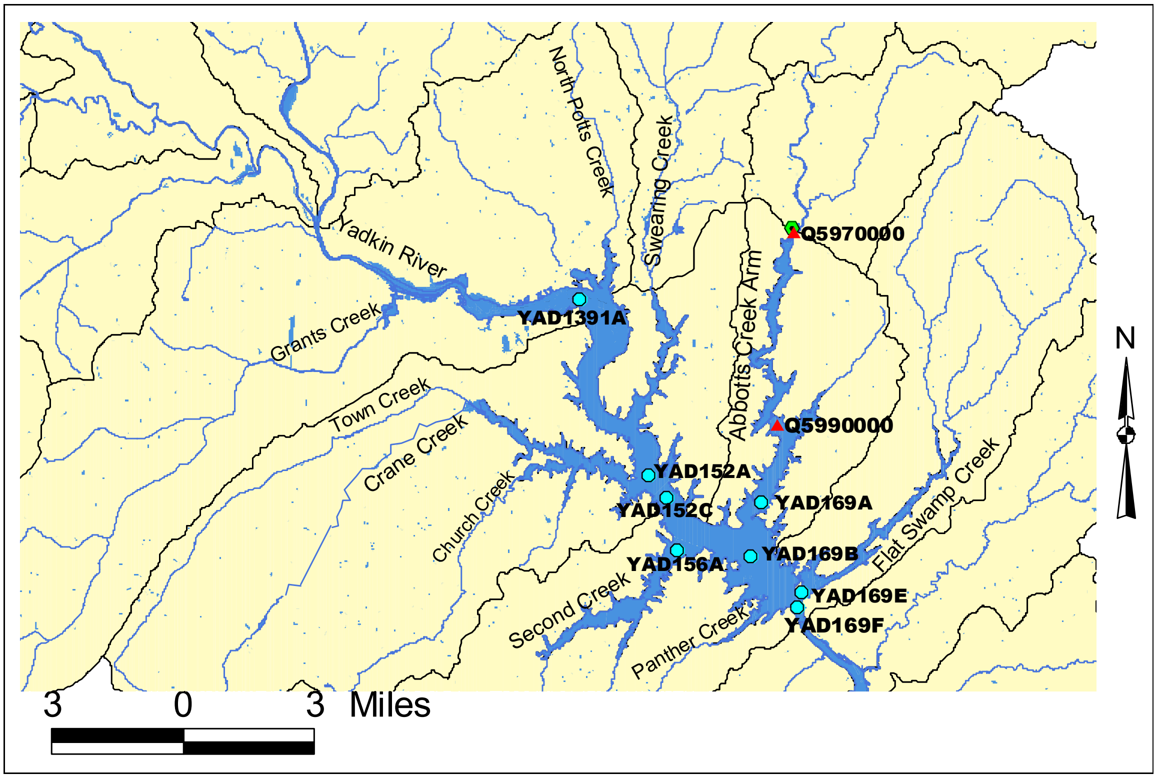


Figure 10. Location of NCDWQ Monitoring Sites in High Rock Lake

Table 5. NCDWQ Monitoring Sites in High Rock Lake

Station Number	Station Description	Dates
YAD13191A	High Rock Lake upstream of South Potts Creek	1981-2002
YAD152A	High Rock Lake at Town Creek	1981-2002
YAD152C	High Rock Lake Near Rockwell	1981-2002
YAD156A	High Rock Lake at Second Creek	1981-2002
YAD169A	Abbotts Creek at NC Hwy 8	1981-2002
YAD169B	High Rock Lake upstream of Panther Creek	1981-2002
YAD169E	High Rock Lake at Panther Creek	1981-2002
YAD169F	High Rock Lake at High Rock Dam	1982-2002
Q5990000	Abbotts Creek at SR 2294 nr Southmont Duracell	1981-2000
Q5970000	Abbotts Creek at NC 57 nr Cotton Grove (DWQ and YPDRBA)	1981-2003
Q5360000	Town Creek near Duke	1981-2003

5.2.1 Physical Parameters – Lake Mainstem

5.2.1.1 Temperature and Thermal Stratification

Summer surface water temperatures ranged from 22 to 32° Celsius. Depth integrated sampling data were limited to once a month in June, July and August for most stations. Temperature depth profiles were examined for 1997 and 2000 because data for June, July and August were available for all stations in those years.

Thermal stratification is generally found to be weak and non persistent in High Rock Lake, due to the energetic mixing conditions caused by short residence time and hydropower releases. When stratification occurs, it happens in early summer and begins to break down by July.

Thermal stratification was not observed in 1997 and 2000 in the upper portion of the lake (YAD1391A, YAD152A, and YAD152C). Weak stratification may develop in the Second Creek Arm (YAD156A) in June, but was not present in July. Stratification was present in June in Abbotts Arm (YAD169A), but began to break down by July. Summer subsurface dissolved oxygen concentrations often dropped below 5 mg/L below 4 meters depth and may approach zero below 6 meters depth in June and July. Weak stratification was present in the lower portion of High Rock Lake (YAD169B) in June, but generally broke down by July.

Despite limited thermal stratification, dissolved oxygen concentrations below 5 mg/L occurred throughout the summer below 4 meters depth. Stratification in the main lake below Panther Creek and above the dam (YAD169E) occurred in June 1997, but dissipated in July, while dissolved oxygen below 4 meters depth began to approach zero in late July. Similar results were found just above the High Rock Lake Dam (YAD169F). Temperature and DO depth profiles for 1997 at the mid-lake station YAD169B are displayed in Figure 11.

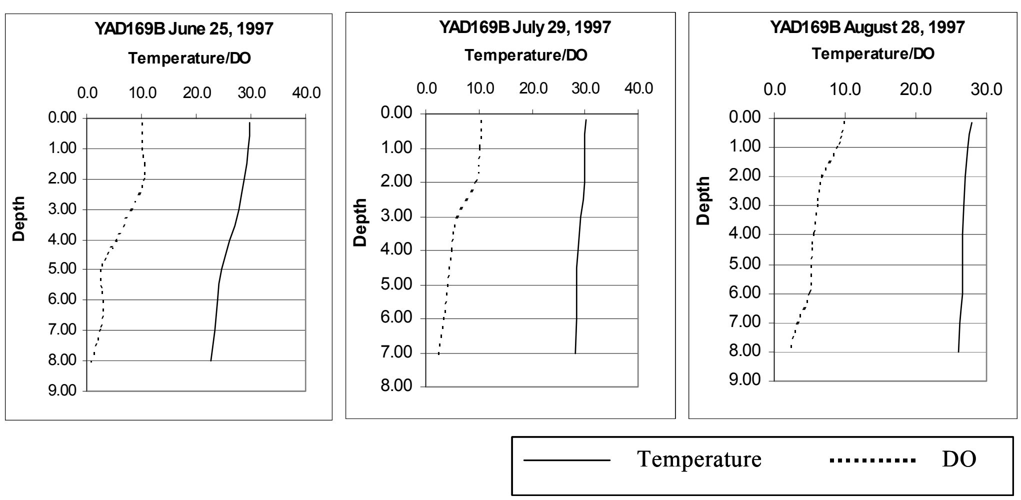


Figure 11. Vertical Profiles at Station YAD169B

5.2.1.2 Dissolved Oxygen

North Carolina's water quality criterion for dissolved oxygen of 5 mg/L is applied to surface waters of lakes, as oxygen depletion is expected to occur in deeper waters. Table 6 summarizes observations of surface dissolved oxygen (0.15 meters below the surface) from 1981 to 2002 for the main axis of High Rock Lake (excluding the upper part of Abbotts Creek arm). Dissolved oxygen concentrations (Figure 12) have remained relatively constant over time and generally remain above the state water quality standard of 5 mg/L. One exception is the station just above the dam (YAD169F) where dissolved oxygen below 5 mg/L was observed on August 26, 1999 and July 1, 2002. It should be noted, however, that the observed data are primarily later morning observations that do not reflect the minimum of the daily dissolved oxygen cycle caused by algal respiration overnight.

Due to extensive algal production in the lake, it is more common to observe excess dissolved gases in the surface water than depleted oxygen. North Carolina water quality regulations specify that total dissolved gases shall not exceed 110 percent saturation. With the exception of the most upstream station (YAD1391A) this standard is often exceeded in the summer throughout High Rock Lake. Table 6 summarizes surface DO concentration and percent saturation data during the summer months for the period of record.

Table 6. Dissolved Oxygen Data for High Rock Lake, 1981-2002

Parameter	Station	n	Mean	Median	Maximum	Minimum
Dissolved Oxygen (mg/L)	YAD13191A	18	7.5	7.4	11.3	5.7
	YAD152A	22	9.9	10.4	12.7	6.2
	YAD152C	25	9.6	9.7	12.2	6.4
	YAD156A	22	9.5	9.8	11.8	6.7
	YAD169A	24	9.0	9.0	12.3	6.2
	YAD169B	23	9.2	9.8	11.7	6.8
	YAD169E	22	8.7	8.9	11.2	5.6
	YAD169F	23	8.3	8.2	12.0	3.1
Percent Saturation	YAD13191A	18	95%	90%	154%	71.3%
	YAD152A	22	124%	126%	161%	79%
	YAD152C	25	122%	125%	157%	81%
	YAD156A	22	121%	127%	154%	85%
	YAD169A	24	112%	112%	150%	63.6%
	YAD169B	23	118%	122%	151%	84.5%
	YAD169E	22	111%	112%	147%	72%
	YAD169F	23	104%	104%	156%	39.7%

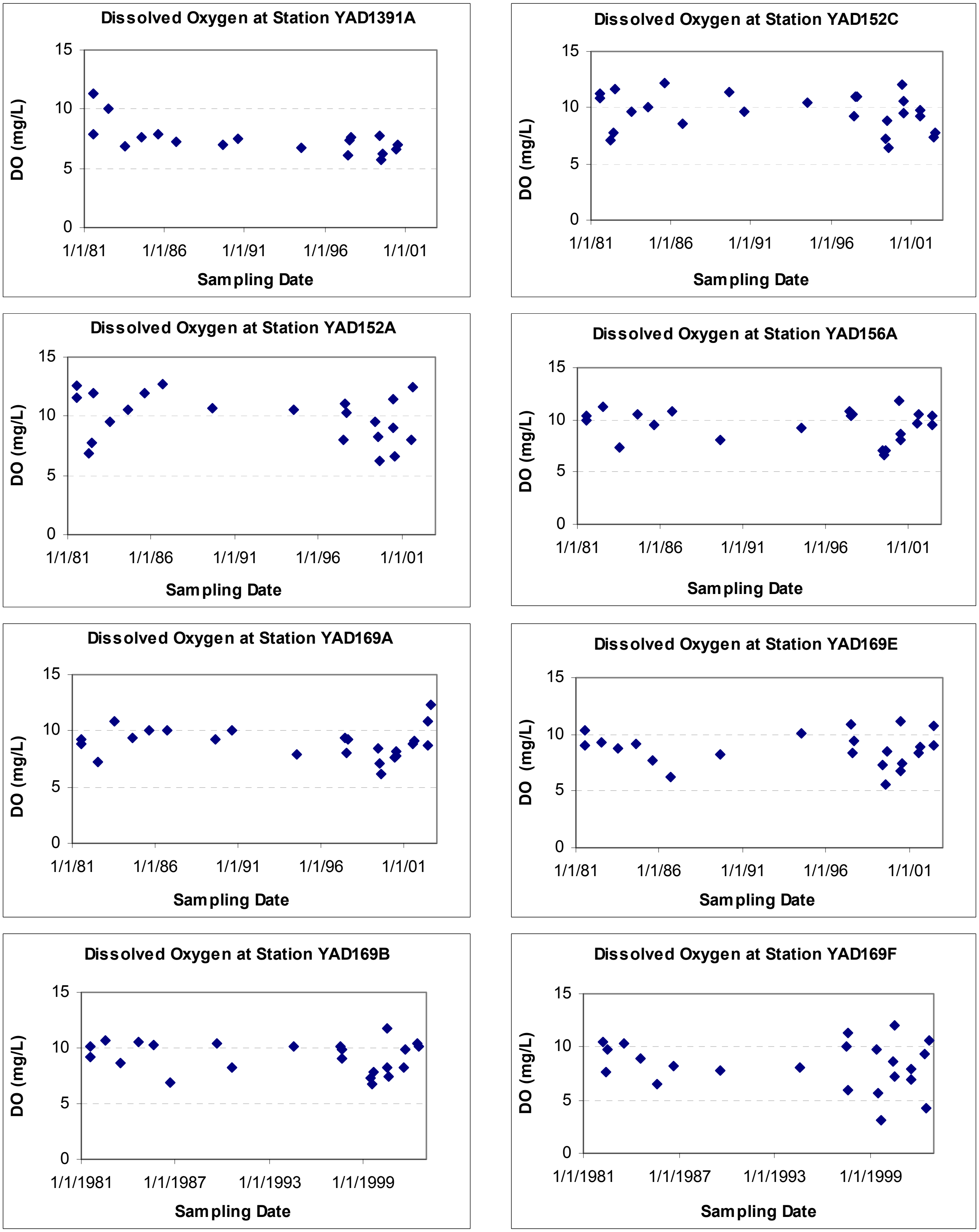


Figure 12. Dissolved Oxygen Concentrations in High Rock Lake

5.2.1.3 Solids

Solids concentrations in High Rock Lake are summarized in Table 7. Solids are moderately high and include a large component of dissolved solids (total solids – suspended solids). Total and suspended solids are highest in the uppermost portion of the lake (YAD13191A) and decrease with distance downstream. Dissolved solids are highest in Second Creek Arm (YAD156A).

Turbidity is an indicator of water clarity and is related to suspended sediment concentration. North Carolina has a water quality standard of less than 25 NTU for turbidity in High Rock Lake. Turbidity measurements exceed this standard greater than 10 percent of the time in the upstream portion of the lake. There is a 50 percent exceedance rate at Station YAD1391A and 28 percent at YAD152A.

Table 7. Solids Data for High Rock Lake, 1981-2002

Parameter	Station	n	Mean	Median	Maximum	Minimum
Total Suspended Solids (mg/L)	YAD13191A	17	36.4	28.0	140.0	10.0
	YAD152A	20	23.7	13.0	180.0	6.0
	YAD152C	23	14.9	12.0	78.0	5.0
	YAD156A	21	15.7	12.0	79.0	4.0
	YAD169A	22	10.5	9.5	24.0	2.0
	YAD169B	22	9.7	9.0	26.0	1.0
	YAD169E	20	9.5	9.5	19.0	3.0
	YAD169F	21	11.0	9.0	47.0	1.0
Total Solids (mg/L)	YAD13191A	17	129.4	120.0	260.0	98.0
	YAD152A	20	120.3	105.0	279.0	75.0
	YAD152C	23	102.5	99.0	161.0	68.0
	YAD156A	21	125.1	100.0	380.0	75.0
	YAD169A	22	105.4	97.5	180.0	71.0
	YAD169B	22	99.1	97.0	150.0	72.0
	YAD169E	20	96.4	92.0	140.0	69.0
	YAD169F	21	98.9	98.0	140.0	72.0
Turbidity	YAD13191A	16	50.2	28.0	300.0	4.6
	YAD152A	18	21.5	11.5	80.0	4.9
	YAD152C	21	11.8	9.2	45.0	5.0
	YAD156A	20	20.9	8.3	200.0	5.9
	YAD169A	21	8.6	6.1	30.0	4.3
	YAD169B	21	8.0	6.4	21.0	3.1
	YAD169E	19	7.2	5.5	16.0	2.6
	YAD169F	18	7.8	6.2	18.0	3.0

5.2.2 Eutrophication Parameters – Lake Mainstem

In the typical paradigm for impaired lakes, excess nutrient loads result in an overgrowth of algae, leading to disruptions of the oxygen cycle and decreased water clarity – a process called eutrophication. Summer average (June through September) water quality conditions for nutrients and algae over the period of study are summarized in Table 8, and discussed in more detail below. Stations are arranged from upstream to downstream. In general, nutrient concentrations decrease with distance downstream. Chlorophyll *a* concentrations are highest in the middle portion of the main body of High Rock Lake.

Table 8. Average Summer Water Quality, High Rock Lake, 1981-2002

Station	n	pH	Conductivity (µS/cm)	Secchi Depth (m)	Total P (mg/L)	Total N (mg/L)	N:P Ratio	Uncorrected Chlorophyll *a* (µg/L)
YAD1319	19	7.4	108.7	0.35	0.18	1.08	6.9	16.5
YAD152A	22	8.3	107.8	0.52	0.12	0.89	8.5	35.3
YAD152	25	8.4	112.9	0.56	0.089	0.86	10.1	38.5
YAD156A	23	8.6	116.5	0.62	0.089	0.83	10.4	36.5
YAD169A	24	8.6	120.5	0.66	0.060	0.67	12.8	28.8
YAD169B	24	8.6	116.1	0.73	0.060	0.67	11.8	34.0
YAD169E	23	8.4	113.7	0.78	0.050	0.65	14.2	27.2
YAD169F	22	8.2	114.0	0.76	0.055	0.67	14.8	26.0

5.2.2.1 Phosphorus and Nitrogen

A major portion of nutrient load to High Rock Lake enters through the Yadkin River. As a result, nutrient concentrations are highest in the most upstream portion of High Rock Lake. Concentrations of phosphorus, which is more readily lost to sedimentation than nitrogen, decline from upstream to downstream in the lake. Both total nitrogen and total phosphorus concentrations appear to have remained relatively constant at most stations throughout the sampling period.

Figure 13 and Figure 14 provide the time series for total phosphorus and total nitrogen for the eight monitoring stations. Sampling frequency was once per summer beginning in 1981 and increased to three times per summer in 1997. Concentrations observed over the last five years are similar to and in some cases higher than concentrations in the limited data from the previous decade.

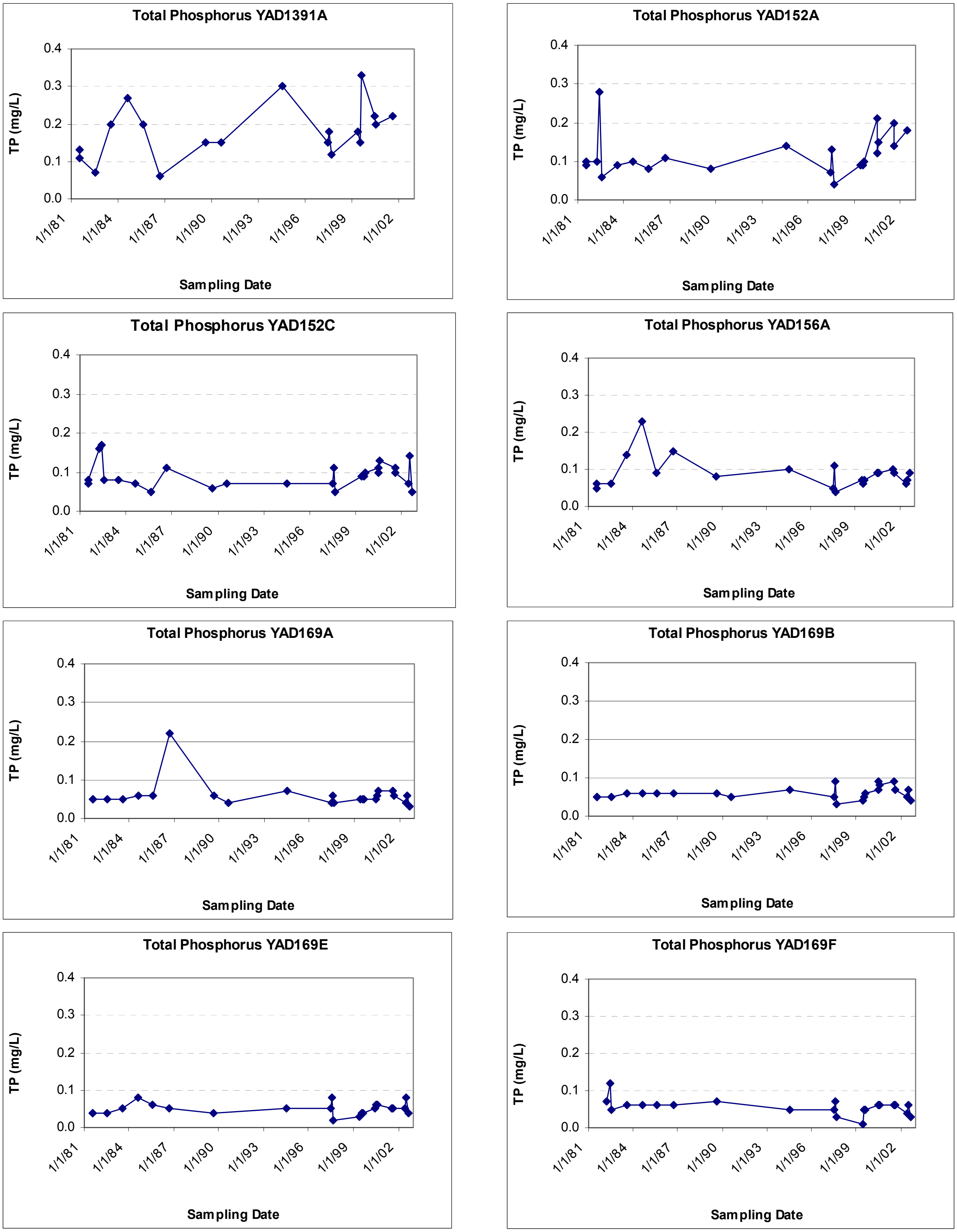


Figure 13. Total Phosphorus Concentrations, High Rock Lake

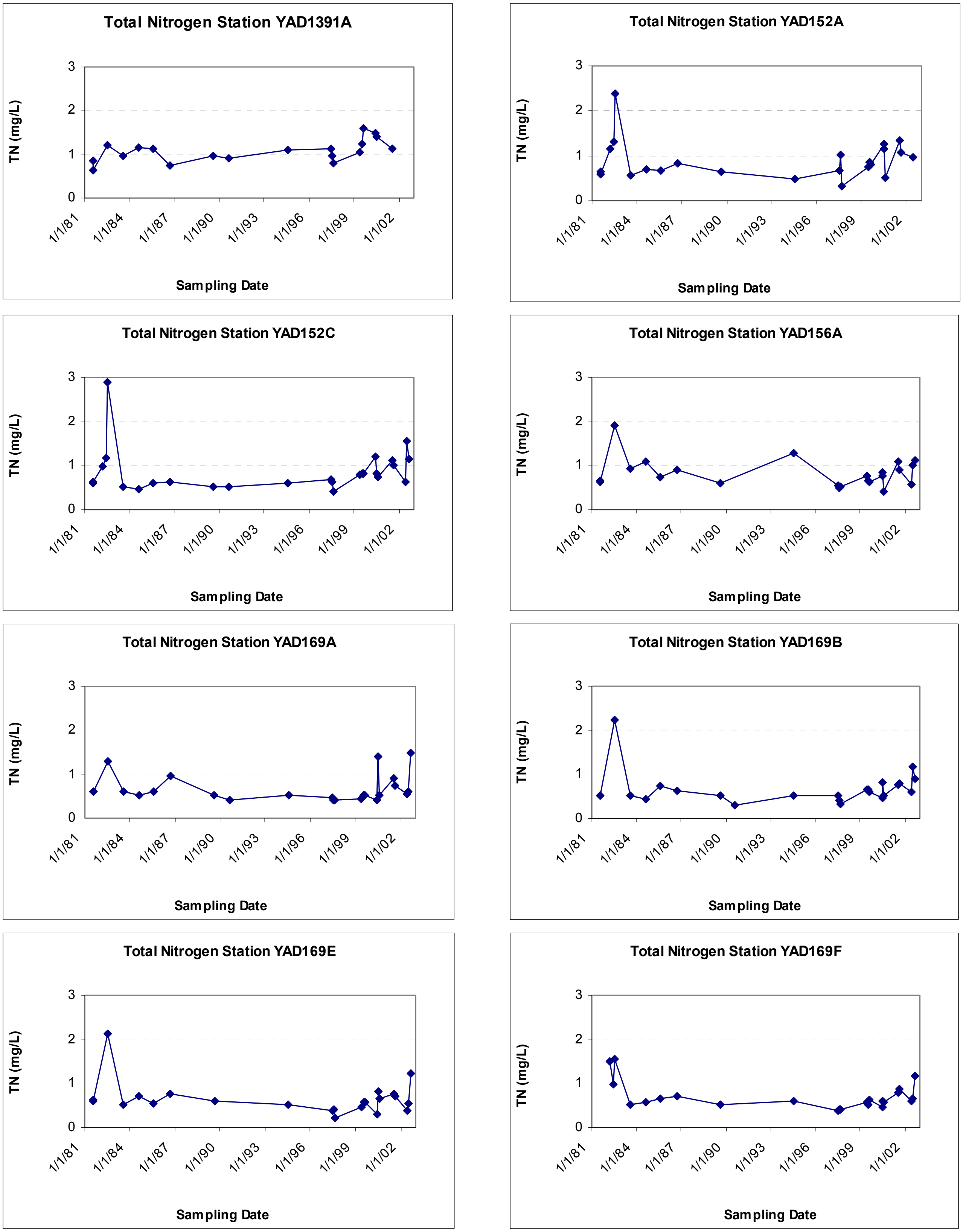


Figure 14. Total Nitrogen Concentrations, High Rock Lake

It is also of interest to examine nitrogen to phosphorus (N:P) ratios. On average, algae require nutrients in a nitrogen-to-phosphorus (N:P) ratio of approximately 7-to-1 by weight, known as Redfield (1958) ratio (16.1 molar, 7:2.1 by weight). Deviations from this ratio in ambient water samples may indicate a potential nutrient limitation; thus the N:P ratio is often used as an indicator of the nutrient that is most limiting on algal growth. A ratio less than 7:1 shows a tendency toward nitrogen limitation, and a ratio greater than 7:1 shows a tendency toward phosphorus limitation – although, in systems with an abundance of both nutrients, algal growth may be most limited by other factors such as light availability. Due to variability in cell composition among different algal groups, the ratio should not be considered as an exact threshold. Accordingly, Thomann and Mueller (1987) suggest that ratios greater than 20:1 likely reflect phosphorus limited systems, while ratios of 5:1 or less likely indicate nitrogen limited systems.

The average summer N:P ratio in High Rock Lake increases with distance downstream. In the upper segment of the lake (YAD1391A and YAD152A), the N:P ratio suggests nitrogen is most likely to be the limiting nutrient. Downstream of YAD152A, the N:P ratio suggests both nitrogen and phosphorus can be limiting. Variability among sampling dates visible in Figure 15 suggests that nitrogen and phosphorus may be limiting at different times at the same location.

The N:P ratio may also have an effect on algal species composition, and is often discussed as a factor leading to predominance of certain blue-green algae (cyanobacteria) that are considered nuisance species because of their unsightly and malodorous blooms. Some, but not all, cyanobacteria contain heterocysts that enable fixation of nitrogen from the atmosphere for growth. The ability to fix atmospheric nitrogen has been thought to play a role in enabling certain blue-green algae to out-compete other species which nitrogen is limiting. This hypothesis was initiated by Schindler (1977) and Smith (1983), and Smith (2001) cautions against implementing nitrogen reductions alone, or reducing the N:P loading ratios to levels that may promote blue-green algae.

More recent research suggests that N:P ratios may be of limited importance in predicting blue-green algal dominance in temperate lakes. Hyenstrand et al. (1998) note a total of nine factors that can encourage blue-green algal dominance: nutrient ratio competition, differential light requirements, carbon dioxide competition, buoyancy, high temperature tolerance, herbivory avoidance, cellular nutrient storage, ammonium-nitrogen exploitation, and trace element competition. Downing et al. (2001) suggest that nutrient ratios play a less important role than previously believed. They analyzed data from 99 well-studied lakes, and showed that the ambient N:P ratio was the poorest predictor of blue-green dominance; instead, physical and biological constraints appeared to be of the greatest importance. Ferber et al. (2004), studying a hypereutrophic lake in Vermont, found that there was minimal reliance on atmospheric fixation as a source of nitrogen among the dominant blue-green algae. The authors hypothesize that the blue green algae may have dominated the assemblage by monopolizing benthic sources of ammonium, or by forming surface scums that shaded other algae in the nitrogen limited system.

In High Rock lake, nutrients are generally in abundant supply. Rather than N:P ratios, it is likely that limited light due to turbidity and the ability of many blue-green algae to adjust their position in the water column (buoyancy), coupled with high temperatures, encourage summer blue-green algal dominance.

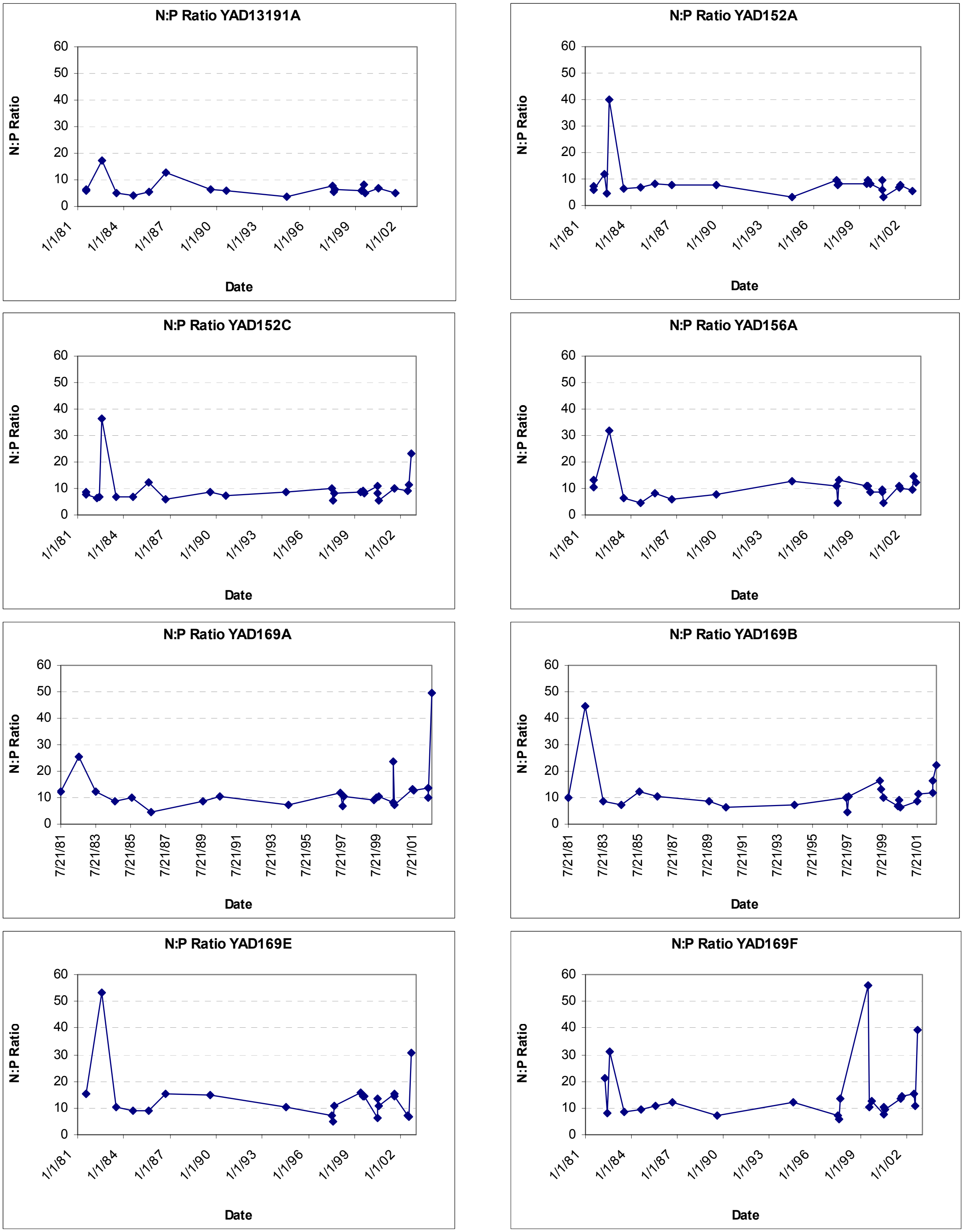


Figure 15. Nitrogen to Phosphorus Ratios, High Rock Lake

5.2.2.2 Chlorophyll *a*

Chlorophyll *a* is the primary photosynthetic pigment in most algae and is often used as an indicator of algal density. The chlorophyll *a* values may be "uncorrected" or "corrected" for the presence of pheophytin *a*, a degradation product of chlorophyll *a*. Corrected values are preferred as indicators of live algal concentration, and North Carolina's chlorophyll *a* standard is defined in terms of corrected concentration. Data collected prior to 1996 are reported as corrected chlorophyll *a* concentrations, however, there are analytical and quality control problems with much of the NCDWQ historical database for chlorophyll *a* that cause the corrected values to be unavailable from September of 1996 through 2001. DWQ was able to re-estimate uncorrected chlorophyll *a* concentrations from the raw data for this time period. Depending on the amount of pheophytin α in each sample, the corrected values should always be less than or equal to the uncorrected values. Corrected and uncorrected chlorophyll *a* values prior to September of 1996 should be compared to determine if there is generally a large difference between these values in High Rock Lake.

As previously noted, chlorophyll *a* values are highest in the middle portion of the main body of High Rock Lake (YAD152A, YAD1552C, YAD169B) and Second Creek Arm (YAD156A). Highest concentrations of chlorophyll *a* commonly occur in the warm summer periods (June-September). In-lake monitoring only occurred during the summer months, and summer averaged values from 1982-2002 are presented in Figure 16. There is an overall decrease in chlorophyll *a* concentration over the sampling period for the most upstream station (YAD1391A). Chlorophyll *a* concentrations have increased since 1994 just below Crane Creek (YAD152C), in Abbotts Arm (YAD169A), and in Second Creek Arm (YAD156A). Chlorophyll *a* values began to increase in 1997 in the lower portion of High Rock Lake (YAD169B, YAD169E, YAD169F). North Carolina's water quality standard for chlorophyll *a* is 40µg/L. Over the period of record, the most exceedances occurred in the middle portion of the main body of High Rock Lake with 48 percent of samples exceeding this standard just below Crane Creek (YAD152C).

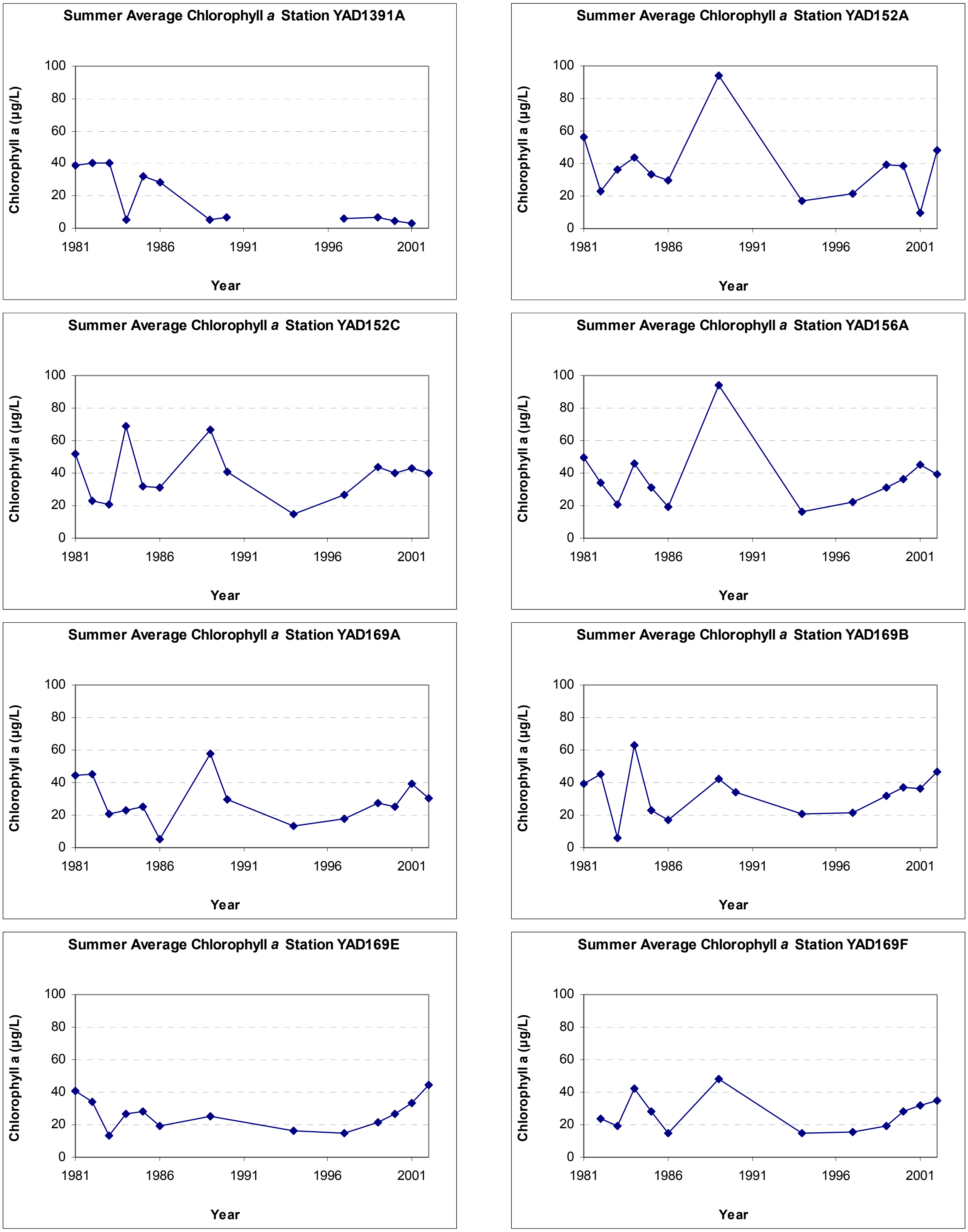


Figure 16. Summer Average Chlorophyll *a* Concentration, High Rock Lake (corrected values reported prior to September 1996 and uncorrected values thereafter)

5.2.3 Monitoring Data for Abbotts Creek Arm of High Rock Lake

Two additional monitoring stations are maintained in the middle and upper portion of the Abbotts Creek Arm of High Rock Lake. The Abbotts Creek Arm has a longer residence time than the main body of the lake, receives drainage from Lexington, High Point, and Thomasville, and represents conditions that differ from those in the mainstem of the lake. The Abbotts Creek stations are listed in Table 5.

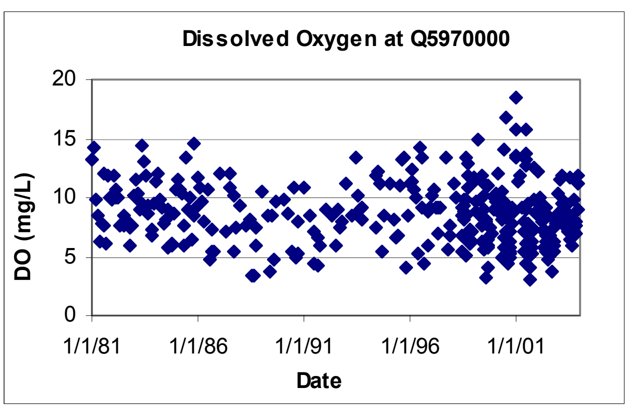
Dissolved oxygen data for Abbotts Creek are presented in Table 9 and time series plots are in Figure 17. The Abbotts Creek station directly downstream of the Lexington WWTP (Q5970000) had 19 dissolved oxygen measurements less than the NC state water quality standard of 5 mg/L during the period from 1995-2002. Station 5990000 had two violations of the water quality standard in 1997.

Solids data for the Abbotts Creek arm are presented in Table 10. Exceedances of the 50 NTU turbidity standard occurred in 9.5 percent of the samples from station Q5970000 and 9.2 percent of the samples from station Q5990000.

Eutrophication parameters for the Abbotts Creek arm are presented in Table 11. Both nitrogen and phosphorus concentrations are higher at station Q5970000 than station Q5990000. Nitrogen to phosphorus ratios suggest that Q5970000 is mostly nitrogen limited while Q5990000 can be both nitrogen and phosphorus limited (Figure 20). Corrected chlorophyll *a* data from 1981-2003, excluding the period from September 1996-2000, are presented in Figure 21. During the period from 1981-1996, 34 percent of samples collected at station Q5970000 exceeded the NC state water quality standard for chlorophyll *a* of 40 µg/L; 23 percent of the samples from Q5990000 exceeded this standard. During the period from 2001-2003, 20 percent of the samples collected from Q5970000 exceeded 40 µg/L of chlorophyll *a*. No chlorophyll *a* values were reported for station Q5990000 after 1996.

Table 9. Dissolved Oxygen Data for Abbotts Creek Arm of High Rock Lake, 1981-2003

Parameter	Station	n	Mean	Median	Maximum	Minimum
Dissolved Oxygen (mg/L)	Q5970000	363	8.5	8.3	18.4	3.0
	Q5990000	172	9.3	9.4	13.2	1.2



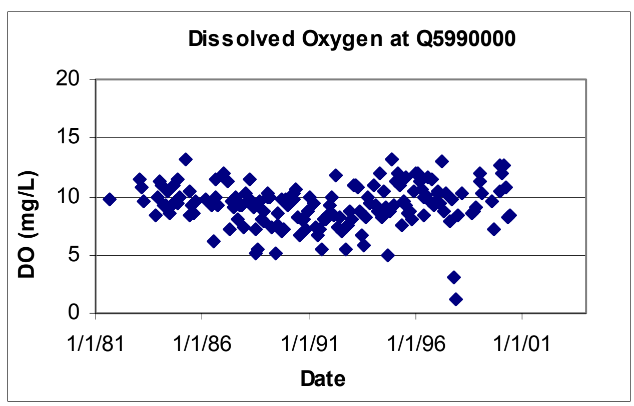


Figure 17. Dissolved Oxygen Data for Abbotts Creek Arm of High Rock Lake, 1981-2003

Table 10. Solids Data for Abbotts Creek Arm of High Rock Lake, 1981-2003

Parameter	Station	n	Mean	Median	Maximum	Minimum
Total Suspended Solids (mg/L)	Q5970000	212	31.0	23.5	370	1.0
	Q5990000	207	19.4	16	120	1.0
Total Solids (mg/L)	Q5970000	193	198.3	180	510	28
	Q5990000	189	134.7	130	257	43
Turbidity	Q5970000	253	28.1	20	270	2.2
	Q5990000	153	23.3	13	170	3.8

Table 11. Average Summer Water Quality in Abbotts Creek Arm of High Rock Lake

Station	n	pH	Conductivity (µS/cm)	Total P (mg/L)	Total N (mg/L)	N:P Ratio	Corrected Chlorophyll *a* (µg/L) (before 9/1996)	Corrected Chlorophyll *a* (µg/L) (2000-2003)
Q5970000	104	7.8	225.8	0.46	2.05	5.2	43.0	25.3
Q5990000	77	8.4	132.0	0.13	0.58	9.7	33.8	

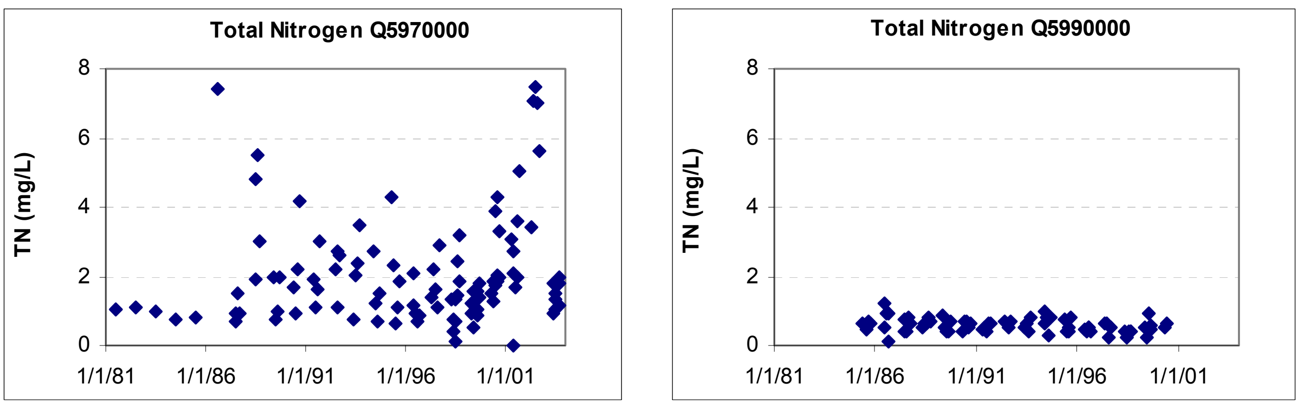


Figure 18. Total Nitrogen Data for Abbotts Creek Arm of High Rock Lake, 1981-2003

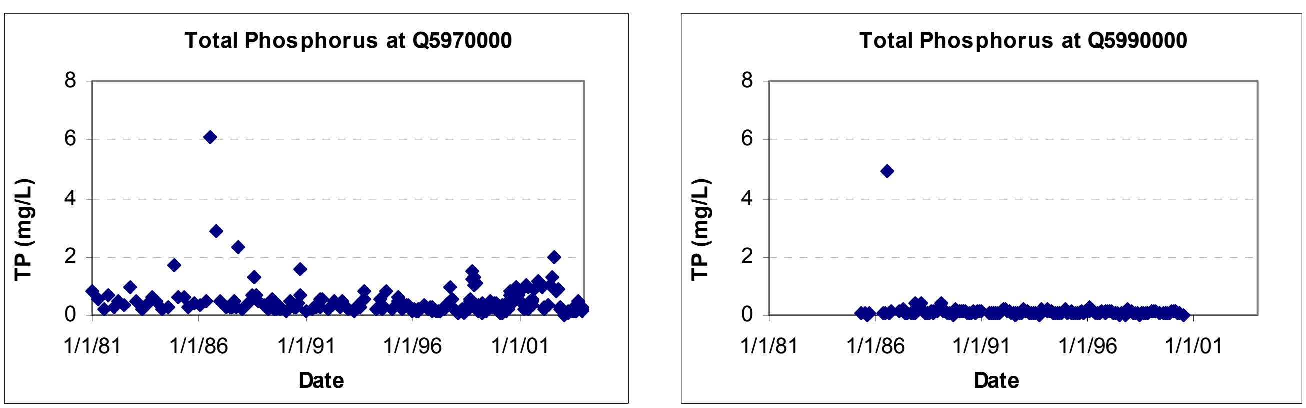


Figure 19. Total Phosphorus Data for Abbotts Creek Arm of High Rock Lake, 1981-2002

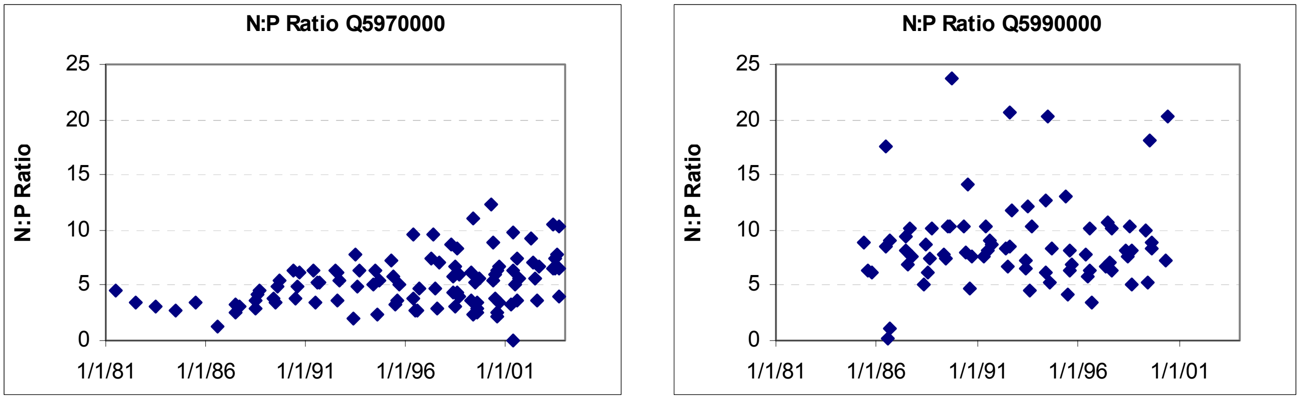


Figure 20. Nitrogen to Phosphorus Ratio Data for Abbotts Creek Arm of High Rock Lake, 1981-2002

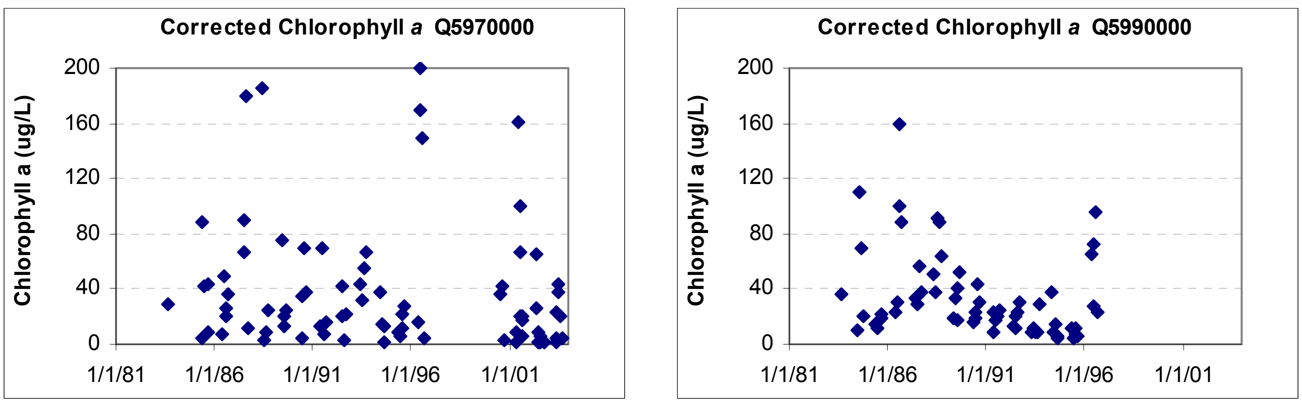


Figure 21. Chlorophyll *a* Data for Abbotts Creek Arm of High Rock Lake, 1981-2002

5.2.4 Monitoring Data for Town Creek Arm of High Rock Lake

DWQ has also conducted monitoring in the Town Creek Arm of High Rock Lake, which receives drainage from Salisbury and Spenser. Data at the station Town Creek near Duke (Q5360000) were analyzed for 1981-2003.

Dissolved oxygen concentrations (Table 12 and Figure 22) include 11 measurements (5.5 percent) below the water quality criterion of 5 mg/L. Solids data are summarized in Table 13.

Table 12. Dissolved Oxygen Data for Town Creek Arm of High Rock Lake, 1981-2003

Parameter	Station	n	Mean	Median	Maximum	Minimum
Dissolved Oxygen (mg/L)	Q5360000	200	9.4	9.4	16.0	3.0

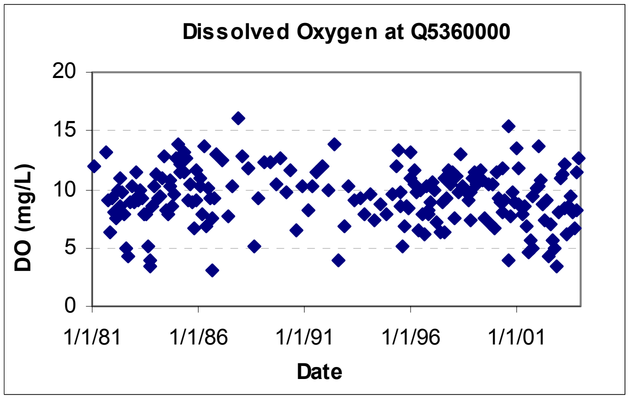


Figure 22. Dissolved Oxygen Concentrations, Town Creek Arm of High Rock Lake

Table 13. Solids Data for Town Creek Arm of High Rock Lake, 1981-2003

Parameter	Station	n	Mean	Median	Maximum	Minimum
Total Suspended Solids (mg/L)	Q5360000	165	61.9	22.0	5,300	1.0
Total Solids (mg/L)	Q5360000	100	294.5	200.0	5,500	57.0
Turbidity (NTU)	Q5360000	154	30.9	18	310	2.5

Eutrophication related parameters for the Town Creek arm of High Rock Lake are summarized in Table 14. Both the nutrient concentrations and chlorophyll *a* concentrations in this arm of the lake are somewhat higher than in the mainstem, with the average chlorophyll *a* concentration greater than the water quality criterion of 40 µg/L (Figure 23).

Table 14. Average Summer Water Quality in Town Creek Arm of High Rock Lake

Station	n	pH	Conductivity (µS/cm)	Total P (mg/L)	Total N (mg/L)	N:P Ratio	Corrected Chlorophyll *a* (µg/L) (before 9/1996)	Corrected Chlorophyll *a* (µg/L) (2000-2003)
Q5360000	55	8.7	169.5	0.11	0.72	5.6	50.4	43.1

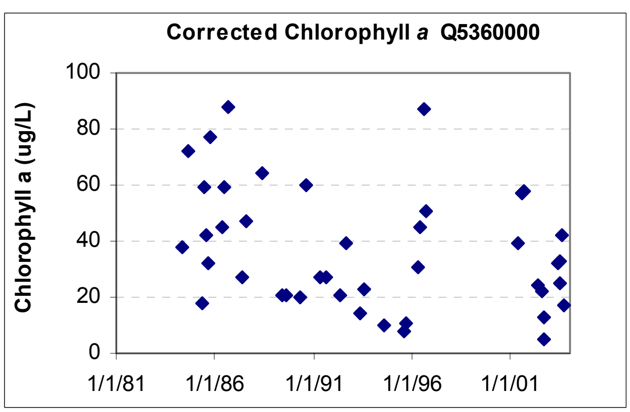


Figure 23. Summer Corrected Chlorophyll *a* Concentrations, Town Creek Arm of High Rock Lake

5.3 TRIBUTARY WATER QUALITY MONITORING DATA

Data collected from 13 monitoring stations located on primary tributaries to High Rock Lake were analyzed. Station location, collection agency and extent of data analyzed are listed in Table 15 and shown in Figure 24.

Table 15. Tributary Monitoring Stations

Station Location	Station ID	Collection Agency	Dates Analyzed
Yadkin River at Yadkin College	Q2810000 2116500	NCDWQ, YPDRBA USGS	1981-2003
South Yadkin River near Mocksville	Q3460000	NCDWQ	1981-2003
Bear Creek near Mocksville	Q3555000	YPDRBA	1998-2003
Fourth Creek near Elmwood	Q3735000	NCDWQ, YPDRBA	1995-2003
Third Creek near Woodleaf	Q3934500	NCDWQ	1985-2003
South Yadkin River near Cooleemee	Q3970000	YPDRBA	1998-2003
Second Creek near Barber	Q4120000	NCDWQ	1985-2003
Second Creek near Salisbury	Q4165000	YPDRBA	1998-2003
Grants Creek at Spencer WWTP	Q4600000	NCDWQ, YPDRBA	1981-2003
Yadkin River near Spencer	Q4660000	NCDWQ, YPDRBA	1995-2003
Swearing Creek near Linwood	Q5135000	YPDRBA	1998-2003
Town Creek near Spencer	Q5240000	YPDRBA	1998-2003
Abbotts Creek at SR 1243 at Lexington	Q5930000	NCDWQ	1981-2003
Abbotts Creek at I85 near Lexington	Q5940000	YPDRBA	1998-2003

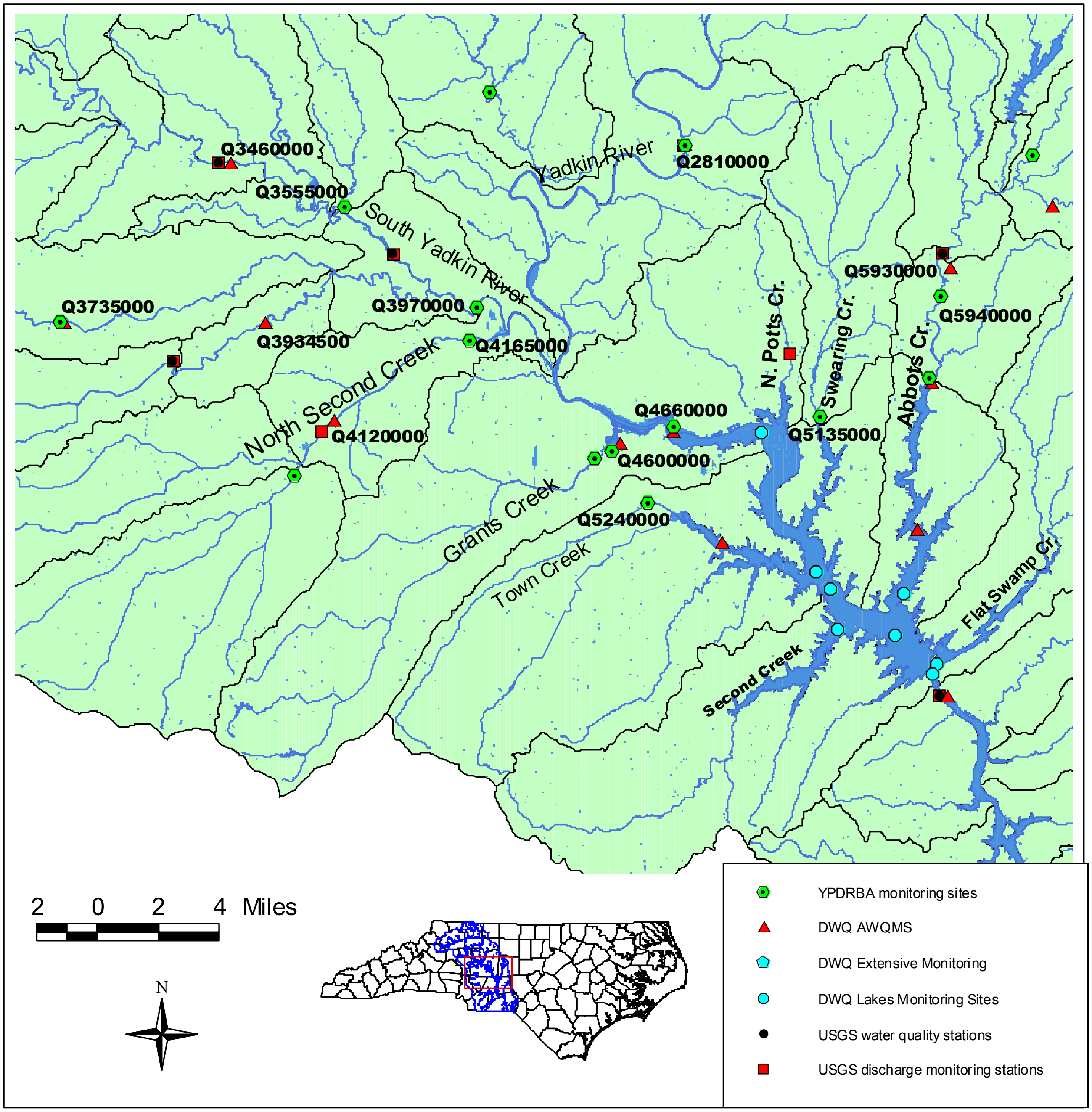


Figure 24. Monitoring Stations on High Rock Lake Tributaries

5.3.1 Physical Parameters

5.3.1.1 Dissolved Oxygen

Table 16 summarizes observations of surface dissolved oxygen data collected by NCDWQ, USGS and YPDRBA in tributaries of High Rock Lake. Dissolved oxygen concentrations have remained relatively constant throughout the period analyzed, but they do display temporal trends with high dissolved concentrations in winter months and low concentrations in summer months (Figure 25). Thirteen of the fourteen stations had at least one excursion from the water quality criterion of at least 5 mg/L dissolved oxygen. Abbotts Creek at I85 (Q5940000) had ten standards excursions from 1998 to 2003, and seven of these occurred during 1999. Abbotts Creek at SR 1243 (Q5930000) had eight standards excursions from 1981-2001, but only two after 1986. Grants Creek (Q4600000) had six standards excursions from 1982-2002, but only two after 1995. Bear Creek (Q3555000) had four standards excursions from 1998-2003, three of which occurred in 2000. It should be noted that the observed data were primarily collected during later morning and do not reflect the minimum of the daily dissolved oxygen cycle caused by overnight algal respiration.

Table 16. Dissolved Oxygen Data for High Rock Lake Tributaries

Station	n	Mean	Median	Maximum	Minimum
Q2810000	412	9.1	8.8	14.8	3.8
Q3460000	255	9.2	9.0	15.0	4.8
Q3555000	94	7.8	7.6	13.6	1.8
Q3735000	195	8.7	8.5	13.0	5.6
Q3934500	158	9.0	8.6	13.4	4.6
Q3970000	94	8.3	8.0	13.3	4.9
Q4120000	223	9.5	9.1	16.1	2.5
Q4165000	94	8.1	7.9	13.8	5.2
Q4600000	344	8.2	8.0	13.8	3.9
Q4660000	197	8.3	8.0	14.2	4.3
Q5135000	93	7.9	7.7	14.6	3.5
Q5240000	83	7.9	7.8	14.0	3.5
Q5930000	217	8.2	7.8	18.2	4.0
Q5940000	153	6.9	6.3	13.9	1.8

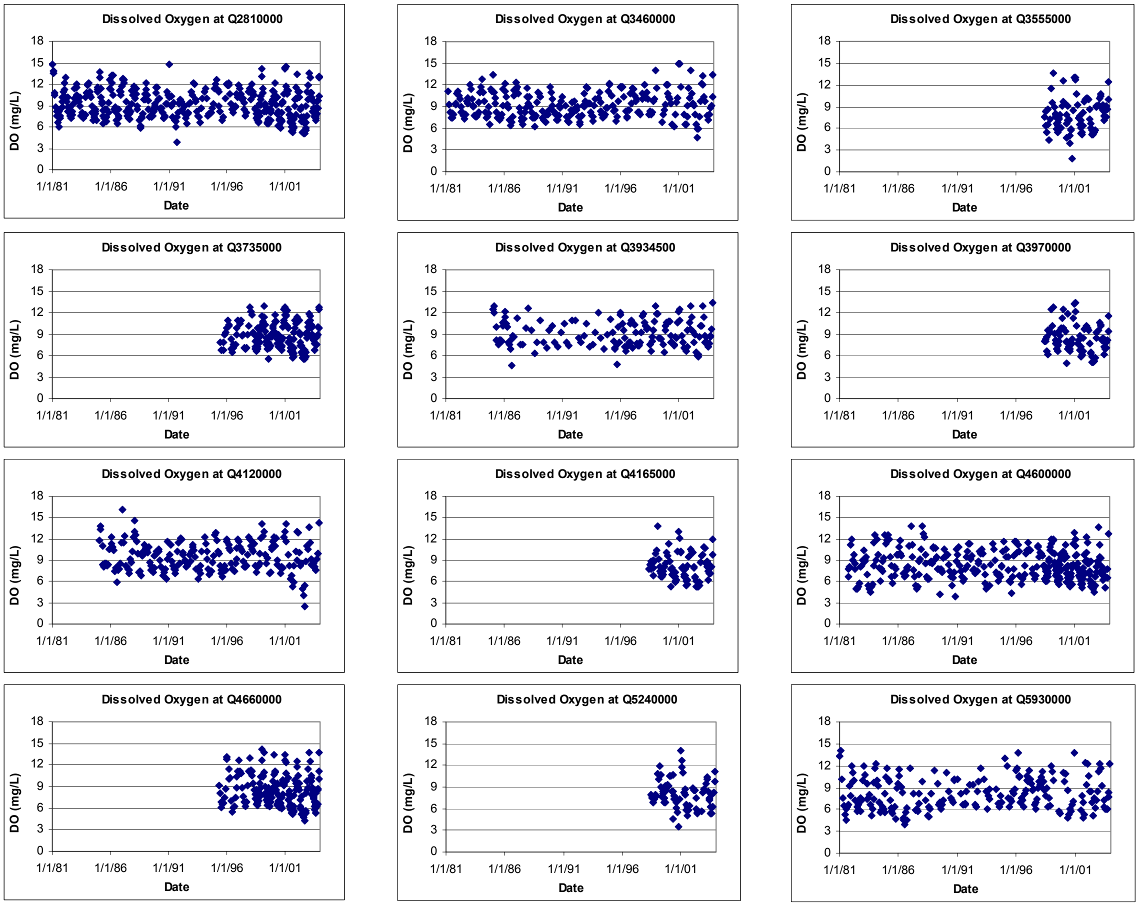


Figure 25. Dissolved Oxygen Concentrations in Tributaries to High Rock Lake

5.3.1.2 Solids

Solids concentrations in tributaries to High Rock Lake are summarized below in Table 17. Solids are moderately high at all tributary stations and most stations have a large component of dissolved solids (total solids – suspended solids). Total solids are highest in Grants Creek (Q4600000), and suspended solids are highest in the Yadkin River at Yadkin College (Q2810000). Turbidity is related to the concentration of suspended solids and is also an indicator of water clarity. The applicable water quality standard for turbidity in tributaries to High Rock Lake is less than 50 NTU. Turbidity samples exceeded this criterion greater than 10 percent of the time at nine of the twelve stations analyzed. The South Yadkin River (Q3970000) had the highest excursion rate at 20 percent, and both the Yadkin River stations (Q4660000 and Q2810000) had excursion rates of 18 percent.

Table 17. Solids Data for Tributaries to High Rock Lake

Parameter	Station	n	Mean	Median	Maximum	Minimum
Total Suspended Solids (mg/L)	Q2810000	609	112.7	32	5138	1.0
	Q3460000	224	51.5	31	640	1.0
	Q3735000	74	44.2	19.5	400	1.0
	Q3934500	128	71.5	24.5	2100	1.0
	Q3970000	67	30.6	18	62	1.0
	Q4120000	125	46.5	21	1500	1.0
	Q4600000	166	42.3	18	820	1.0
	Q4660000	75	35.3	18	470	2.0
	Q5135000	0	-	-	-	-
	Q5240000	1	2.2	-	-	-
	Q5930000	210	30.3	19.5	440	1.0
	Q5940000	1	5.8	-	-	-
Total Solids(mg/L)	Q2810000	265	116.8	100	660	30
	Q3460000	195	128.9	98	750	53
	Q3934500	111	190.3	150	2400	4
	Q4120000	110	157.6	140	780	29
	Q4600000	96	268.6	230	1000	110
	Q4660000	63	126.0	100	690	74
	Q5135000	0	-	-	-	-
	Q5240000	0	-	-	-	-
	Q5930000	131	224.4	200	460	14
	Q5940000	0	-	-	-	-
Turbidity (NTU)	Q2810000	323	43.8	18.0	2700	.10
	Q3460000	158	35.6	23.5	300	3.5
	Q3555000	67	21.6	11	320	2.9
	Q3735000	167	34.7	15	500	3.7
	Q3934500	141	44.9	17	850	2.6
	Q3970000	67	36.7	24	200	4.5
	Q4120000	163	41.15	16	1800	2.7
	Q4165000	67	25.4	11	400	2.6
	Q4600000	215	36.4	16.7	650	2.1
	Q4660000	167	36.5	19.3	600	4.0
	Q5135000	67	23.8	15	300	3.5
	Q5240000	60	23.0	10.6	282	1.1
	Q5930000	183	24.3	17	180	1.0
	Q5940000	67	22.3	14	220	1.9

5.3.2 Eutrophication Parameters

Due to its very short residence time, High Rock Lake is likely to have a correspondingly short "memory" of nutrient loads, with conditions in-lake being largely determined by concentrations in tributary inflows, rather than loads from previous seasons. Algal blooms occur at various times throughout the year, but water column concentrations of nitrogen and phosphorus are of greatest concern for causing excess algal growth during the summer growing season (May-September). Table 18 summarizes summer median water quality conditions for tributaries to High Rock Lake.

Table 18. Median Summer Water Quality in Tributaries to High Rock Lake

Station	N	pH	Conductivity (µS/cm)	Total Kjeldahl Nitrogen (mg/L)	Nitrite + Nitrate Nitrogen (mg/L)	Total N (mg/L)	Total P (mg/L)	N:P Ratio
Q2810000	162	7.2	100.5	.40	.79	1.11	.22	5.6
Q3460000	45	7.1	60.0	.30	.58	.85	.09	10.6
Q3555000	55	7.5	140.3					
Q3735000	43	7.4	144.5	.40	1.6	2.00	.46	4.8
Q3934500	43	7.3	143.0	.30	.93	1.30	.28	5.1
Q3970000	29	7.4	106.0	.49	.72	1.08	.16	8.5
Q4120000	43	7.4	131.0	.30	.64	.98	.16	5.9
Q4165000	55	7.5	168.9					
Q4600000	130	7.2	220.0	.80	1.6	2.90	.63	4.9
Q4660000	62	7.3	123.3	.36	.76	1.10	.18	6.6
Q5135000	54	7.5	119.0					
Q5240000	25	7.4	274.0	.70	1.9	3.10	.67	6.6
Q5930000	75	7.2	250.0	.60	1.9	2.60	.40	6.1
Q5940000	29	7.3	198.9	.80	1.7	2.40	.32	7.9

5.3.2.1 Phosphorus and Nitrogen

Wastewater treatment plants discharge upstream of monitoring sites on the Yadkin River (Q2810000), South Yadkin River (Q3970000), Second Creek (Q4165000), Grants Creek (4600000), and Town Creek (Q5240000). Total nitrogen concentrations are highest on Grants Creek (4600000) and Town Creek (Q5240000). Note the use of a different scale for the Town Creek station, where total nitrogen concentrations as great as 27.4 mg/L have been observed.

Figure 26 and Figure 27 provide the time series for total nitrogen and total phosphorus for the 11 tributary monitoring stations that regularly report nutrient concentrations. Sampling frequency was once per month at stations monitored only by NCDWQ, twice per month at stations monitored only by YPDRBA, and three times per month at stations monitored by both NCDWQ and YPDRBA.

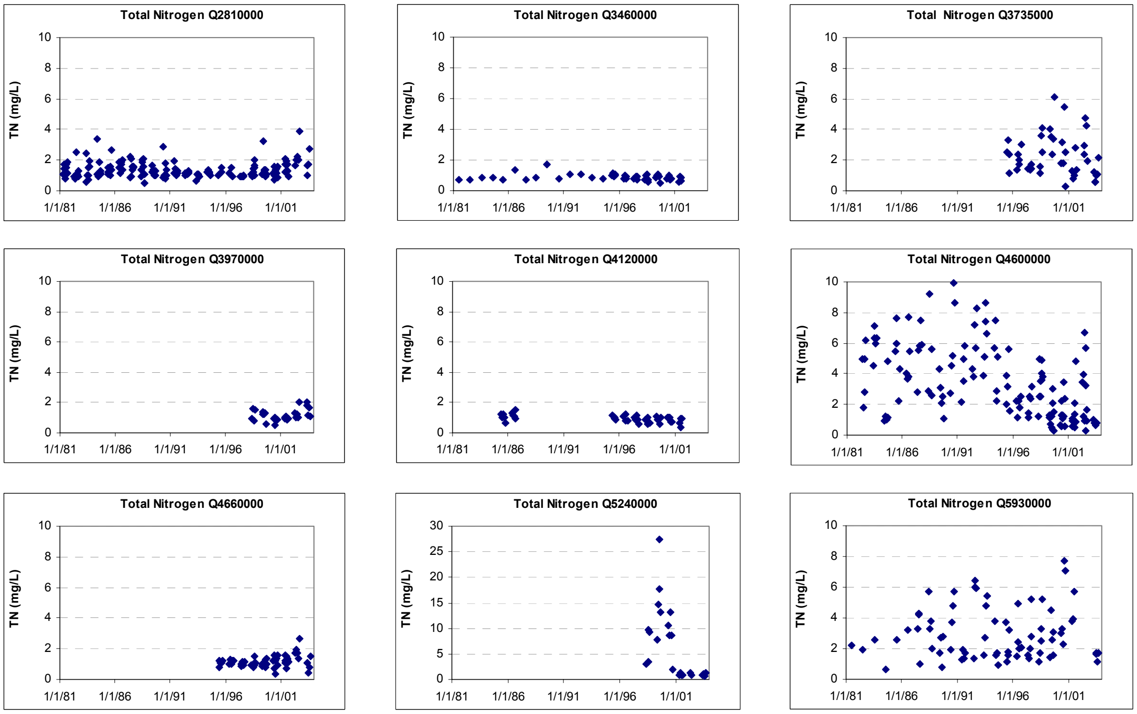


Figure 26. Total Nitrogen Concentrations for Tributaries to High Rock Lake

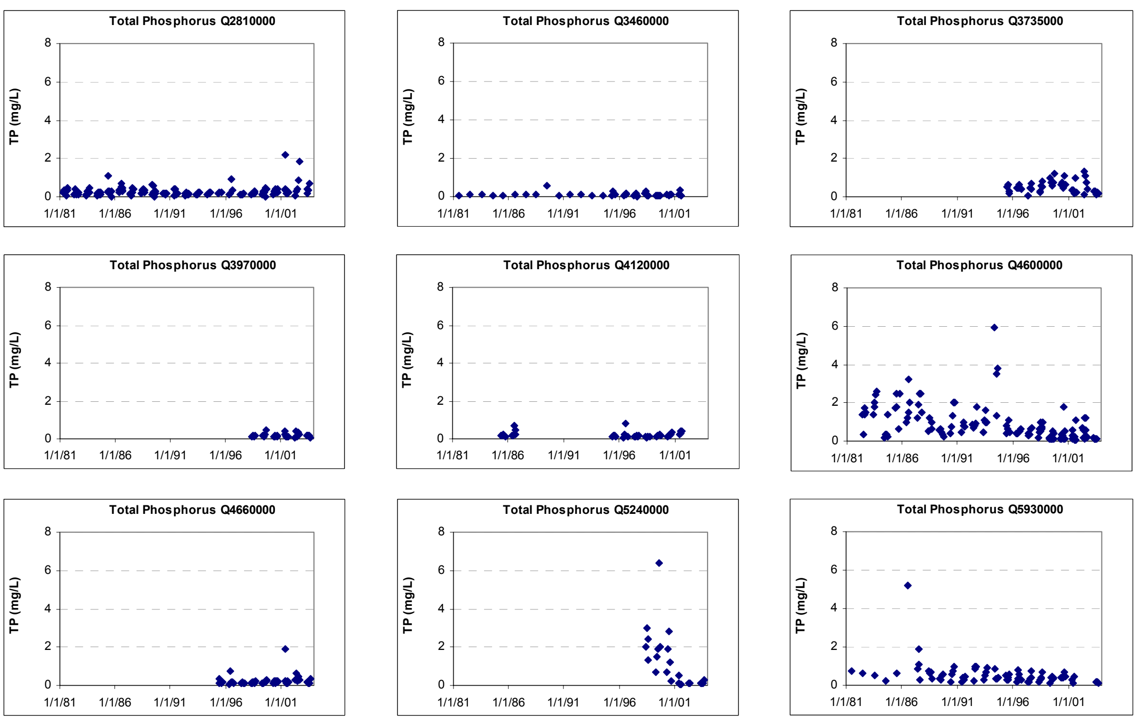
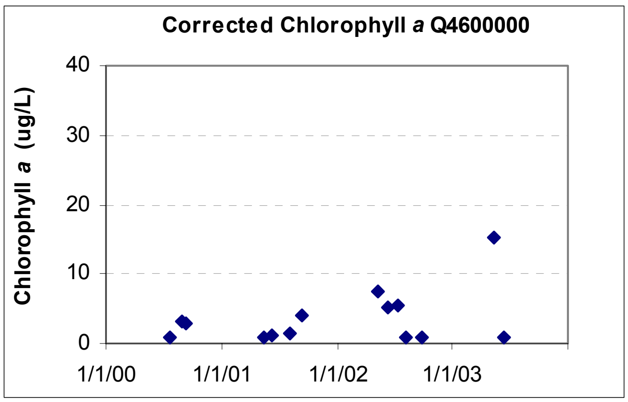


Figure 27. Total Phosphorus Concentrations for Tributaries to High Rock Lake

It is also of interest to examine nitrogen to phosphorus (N:P) ratios. Although optimal N:P ratios vary by algal taxa, a ratio of less than 10 is generally considered to indicate nitrogen limitation, while a ratio greater than 15 suggests phosphorus limitation. The summer N:P ratios at all 12 monitored stations suggest these creeks are primarily nitrogen limited, with most observations less than 10.

5.3.2.2 Chlorophyll *a*

Chlorophyll *a* is not regularly monitored by DWQ at stream sites. However, it was measured in recent years at two stations just upstream of the lake, which may help identify the influent algal load. These time series are shown in Figure 28. Average concentration in Grants Creek was 3.6 µg/L, while the average concentration in the Yadkin River at Spencer was 7.5 µg/L, with a maximum observed concentration of 33.7 µg/L. These observations suggest that the river load of algae into the lake can be significant.



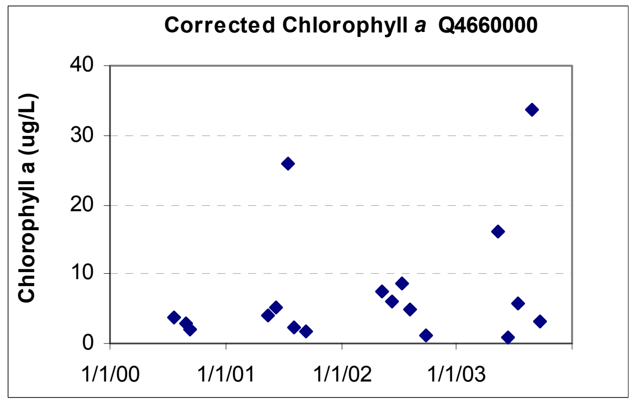


Figure 28. Summer Corrected Chlorophyll *a* Concentrations for Tributaries to High Rock Lake

5.4 Flow Monitoring

Daily streamflow has been reported by USGS for 36 stations in the High Rock Lake watershed, of which gages, 16 are active (Table 19). The last station on the list (Yadkin River at High Rock) is at the dam outflow. This station is no longer monitored by USGS, but is monitored by APGI.

Table 19. USGS Flow Gages in the High Rock Lake Watershed

Station	Site Name	County	Drainage Area (mi^2)	Dates
02111000	Yadkin River at Patterson, NC	Caldwell	28.80	1939 – Present
02111180	Elk Creek at Elkville, NC	Wilkes	48.10	1965 – Present
02111500	Reddies River at North Wilkesboro	Wilkes	89.20	1939 – Present
02112000	Yadkin River at Wilkesboro	Wilkes	504.00	1903 – Present
02112120	Roaring River near Roaring River, NC	Wilkes	128.00	1964 – Present
02112250	Yadkin River at Elkin	Yadkin	869.00	1964 – Present
02112360	Mitchell River near Station Road	Surry	78.80	1964 – Present
02112500	Fisher River near Dobson	Surry	109.00	1920 – 1932

Station	Site Name	County	Drainage Area (mi^2)	Dates
02113000	Fisher River near Copeland	Surry	128.00	1931 – Present
02113500	Yadkin River at Siloam	Surry	1,226.00	1976 – 1987
02113850	Ararat River at Ararat, NC	Surry	231.00	1964 – Present
02114450	Little Yadkin River at Dalton	Stokes	42.80	1960 – Present
02115360	Yadkin River at Enon	Yadkin	1,694.00	1964 – Present
02115500	Forbush Creek near Yadkinville	Yadkin	22.10	1940 – 1971
02115750	Muddy Creek near Lewisville	Forsyth	82.80	1964 – 1970
02115800	Silas Creek near Clemmons	Forsyth	11.80	1964 – 1970
02115842	Tar Branch Trib. at First St., Winston-Salem	Forsyth	0.04	1979 – 1982
02115850	Salem Creek at Winston-Salem	Forsyth	51.30	1964 – 1971
02115854	Salem Creek Trib. at Hawthorne Rd., Winston-Salem	Forsyth	0.50	1979 – 1982
02115856	Salem Creek nr Atwood	Forsyth	65.60	1971 – 1982
02115860	Muddy Creek nr Muddy Creek, NC	Forsyth	186.00	1964 – 1991
02115900	South Fork Muddy Creek nr Clemmons	Forsyth	42.90	1964 – 1991
02116500	Yadkin River at Yadkin College	Davie	2,280.00	1928 – Present
02117030	Humpy Creek nr Fork, NC	Davie	1.05	1968 – 1983
02117500	Rocky Creek at Turnersburg	Iredell	101.00	1940 – 1971
02118000	South Yadkin River nr Mocksville	Rowan	306.00	1938 – Present
02118500	Hunting Creek nr Harmony	Iredell	155.00	1951 – Present
02119000	South Yadkin River at Cooleemee	Davie	569.00	1928 – 1965
02119400	Third Creek nr Stony Point	Alexander	4.84	1956 – 1969
02120500	Third Creek at Cleveland, NC	Rowan	87.40	1940 – 1971
02120780	Second Creek nr Barber	Rowan	118.00	1979 – Present
02121000	Yadkin River nr Salisbury	Rowan	3,450.00	1895 – 1927
02121180	North Potts Creek at Linwood	Davidson	9.62	1979 – 1990
02121493	Leonard Creek nr Bethesda	Davidson	5.16	1978 – 1981
02121500	Abbotts Creek at Lexington	Davidson	174.00	1988 – Present
02122500	Yadkin River at High Rock, NC	Davidson	4,000.00	1919 – 1962 (USGS; continued to present by APGI)

Four active USGS gages monitor flow shortly upstream of High Rock Lake. These are summarized in Table 20 and account for about 70 percent of the total watershed area. The ungaged areas are primarily small tributaries around the lake. Continuous flow records are available for all four gages simultaneously from October 1988 to present. Assuming that they generate flow on an areal basis at about the same rate as the South Yadkin River, the total average inflow is 5,028 cfs. The Yadkin River (above Yadkin College) accounts for over 60 percent of the inflow. Maximum and minimum reported flows on the Yadkin River at Yadkin College over the period of record (1928-2003) are 66,000 and 236 cfs respectively.

Table 20. Inflow to High Rock Lake (10/1988 – 9/2003)

Gage	ID	Area (mi^2)	Average Flow, 10/88-9/03 (cfs)	cfs/mi^2
Yadkin River at Yadkin College	02116500	2,280	3,096.1	1.36
South Yadkin near Mocksville	0211800	306	351.1	1.15
Abbotts Creek at Lexington	02121500	174	185.9	1.07
North Potts Creek	02121180	10	14.4	1.50
Balance of Watershed (ungaged)	Estimated	1,203	1,380.7	1.15
Total		3,973	5,028.2	1.26

Note: Flow for Balance of Watershed estimated from areal flow generation rate (cfs/mi^2) estimated for South Yadkin River near Mocksville.

In applying the BATHTUB model for High Rock Lake, NCDWQ (1997) developed correlations to other gage records for six unmonitored tributaries (Grants Creek, Town Creek, Crane Creek, Second Creek, Flat Swamp Creek, and Fourmile Branch) using instantaneous flow data. These relationships appear to be usable, but may be superseded by the flow balance work currently being undertaken by APGI: Currently, APGI and consultants are building a Yadkin Project hydrologic simulation model as part of the FERC relicensing project (telephone conversation with Wendy Bley, APGI, 6/3/04). The model is currently under review and could not be released for this investigation. If made available, it may provide a useful basis for characterizing the hydrologic behavior of the system.

5.5 Water Quality Database

The High Rock Lake water quality database contains data collected by the North Carolina Division of Water Quality (NCDWQ), United States Geological Survey (USGS), and the Yadkin Pee-Dee River Basin Association (YPDRBA). Data collected by NCDWQ includes in-lake data from 1992-2002, tributary data from 1969-2003, and intensive survey monitoring data collected in 1989 and 1990 in conjunction with BATHTUB modeling for High Rock Lake. YPDRBA is a coalition of NPDES dischargers who voluntarily conduct water quality monitoring within the Yadkin Pee-Dee River Basin as part of an agreement with NCDWQ. YPDRBA conducts monitoring at 73 stations within the Yadkin Pee-Dee River Basin since 1998, and data from the 18 stations within the High Rock Lake watershed are included in the database. Water quality data are collected by USGS on the Yadkin River at Yadkin College and are included in the database. Discharge data from USGS are also included for Yadkin River, South Yadkin River and selected tributaries to High Rock Lake.

The High Rock Lake water quality database was compiled using Corel Paradox 10™. There are eight separate database tables that contain water quality data and are named for the collecting agency and, when applicable, the type of data collected. These separate tables may be linked by station number. Discharge data tables are indicated by the USGS station number and "discharge." Information on all water quality and discharge stations including station location and dates collected can be found in "StationLookupTable.DB." The measured parameters corresponding to the numeric field codes in the "DWQTributarydata" and "USGS02116500_Wqdata" databases can be found in the "DWQ_parametercodes" and "USGS_parametercodes" databases respectively. The definitions for the remarks contained in the water quality data collected by NCDWQ can be found in the table titled "DWQ_remarkcodes.DB." The definitions for the remarks contained in the water quality and discharge data collected by USGS can be found in the table titled "USGS_Remarkcodes.db." The original sources of data contained in the database and original file names are contained in the table "Datasource.db."

6 Exploratory Data Analysis

Statistical and empirical data analyses provide an important prelude to development of a conceptual model, and help to illuminate the relative importance of different sources of data uncertainty.

6.1 CORRELATION ANALYSIS

What controls algal density in High Rock Lake? One way to examine this question is to look at the degree to which a measure of algal density (response variable) is correlated to other environmental variables.

The available measure of algal density in High Rock Lake is chlorophyll *a* concentration. While this forms the basis for the state water quality criterion, the relationship between chlorophyll *a* concentration and algal biomass is not constant or linear. The amount of chlorophyll maintained by an algal cell varies in accordance with light availability and other factors. In addition, there are systematic differences between algal groups. Of particular concern, the cyanobacteria (blue-green algae) that often dominate in North Carolina Piedmont lakes during summer conditions tend to have lower concentrations of chlorophyll *a* per unit of dry weight biomass due to their use of a number of other pigments in the photosynthetic process.

Readily available response variables in the ambient monitoring include nutrient concentrations, Secchi depth (light penetration), and temperature. Each of these can have a significant potential effect on algal response.

For the correlation analysis, observations from the upstream station (YAD1391A) were eliminated, as it appears clear that algal response is damped at this station due to its proximity to the Yadkin inflow. The great majority of available monitoring is from the summer growing season (June – September), and samples from outside this season were also dropped. This left a total of 163 ambient samples for analysis.

Correlation coefficients among the variables are shown in Table 21. No single variable is particularly closely correlated with chlorophyll *a*. A strong correlation is present between chlorophyll and Secchi depth, with a negative sign. This is misleading, however, as algae contribute to reduced light penetration, and thus high algal concentrations can cause reduced Secchi depth. Therefore, an estimate of non-algal turbidity was calculated from Secchi depth and chlorophyll *a* concentration, using the equation provided by Walker (1987). This provides a stronger negative relationship that is consistent with expectations that algal concentrations should increase with increased water clarity (decreased NAT) if all other factors are held constant.

Table 21. Correlation Matrix for Algal Response in High Rock Lake

	Temp (C)	Secchi Depth (m)	TP (mg/L)	TN (mg/L)	NAT (1/m)	Chl a (µg/L)
Temp	1.000					
Secchi	-0.192	1.000				
TP	-0.050	-0.396	1.000			
TN	-0.088	-0.281	0.282	1.000		
NAT	-0.079	-0.592	0.567	0.195	1.000	
Chl a	0.073	-0.249	-0.059	0.138	-0.320	1.000

Correlations of chlorophyll *a* with nutrients are weak, and the correlation with total phosphorus is negative. However, total phosphorus has a relatively strong correlation with Secchi depth and NAT, and a positive correlation with total nitrogen – so it would be inappropriate to conclude that phosphorus is not related to algal growth based on this evidence.

Chlorophyll *a* concentration is plotted against total phosphorus in Figure 29. The general lack of correlation is apparent; however, there may be a positive correlation at low concentrations (total P less than about 0.075 mg/L). A plot versus total nitrogen (Figure 30) may also conceal a positive relationship at low concentration levels.

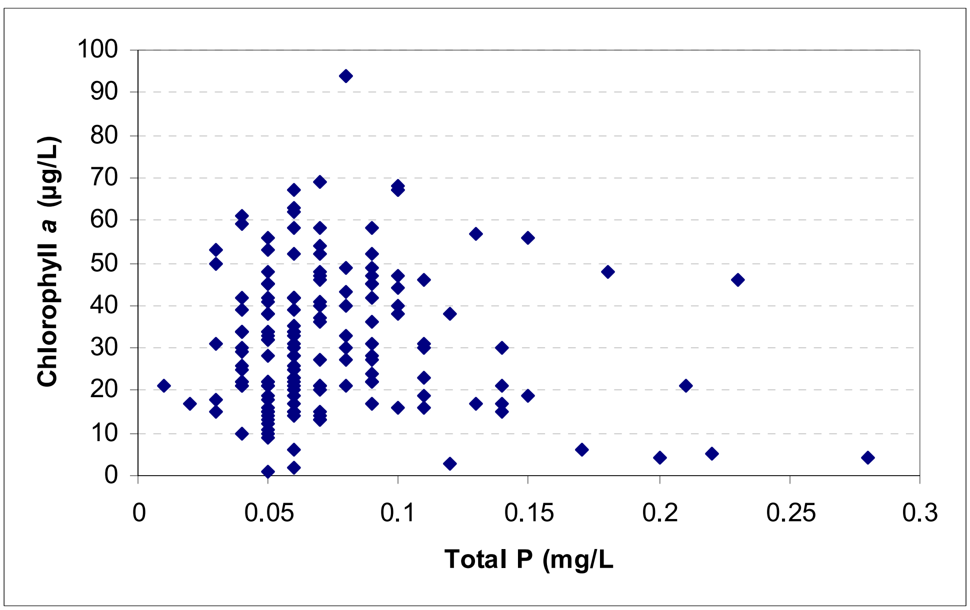


Figure 29. High Rock Lake, Relationship of Chlorophyll *a* to Total Phosphorus

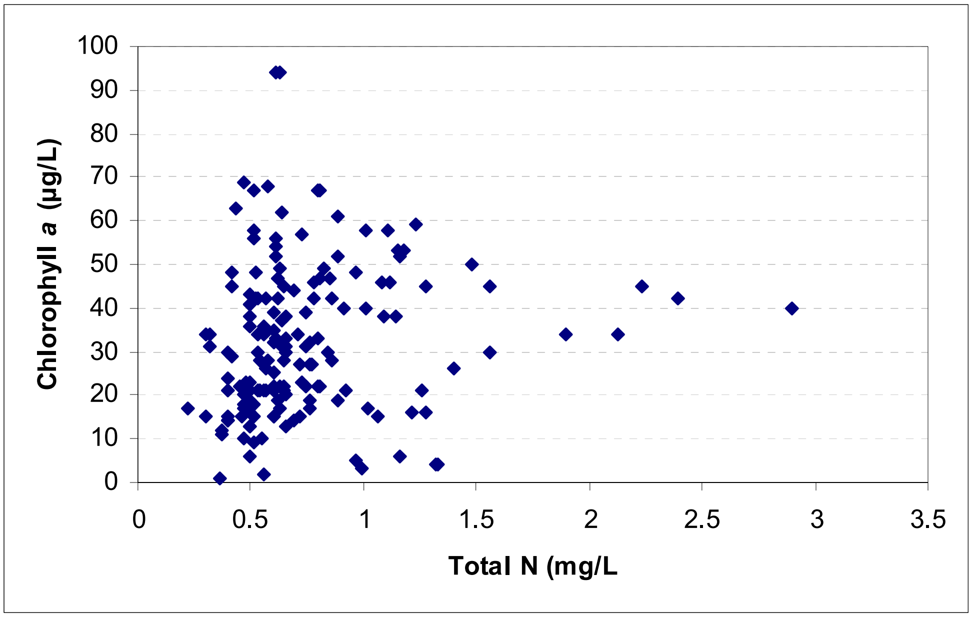


Figure 30. High Rock Lake, Relationship of Chlorophyll *a* to Total Nitrogen

Figure 31 shows the negative relationship between chlorophyll *a* and non-algal turbidity. The peculiar "striping" on the plot also reveals some of the difficulties of using the Walker estimate of NAT. NAT is estimated from Secchi depth and chlorophyll *a* concentration. Because Secchi depth was only reported at discrete tenths of meters, the data separate into discrete bands. Each of these bands represents different chlorophyll *a* concentrations associated with a given reported value for Secchi depth. NAT is thus dependent on chlorophyll *a*, and the correlation between the two measures is in part spurious.

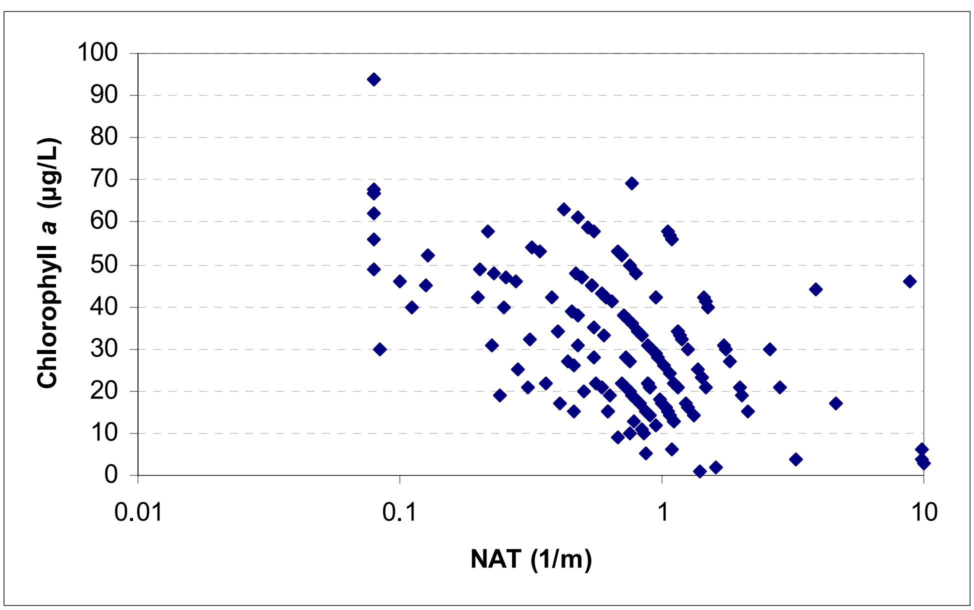


Figure 31. High Rock Lake, Relationship of Chlorophyll *a* to Estimated Non-Algal Turbidity

Unfortunately, both total suspended solids and turbidity are also affected by algal density, so an independent measure of non-algal turbidity is not available at present.

In a multiple regression of chlorophyll *a* on TP, TN, NAT, and temperature, the coefficients on TP and temperature are not significant at the 95 percent level, while the partial correlation to TN is positive and that to NAT is negative. The overall model, however, has an adjusted R^2 value of only 14 percent, and thus exhibits minimal predictive ability.

The data may also be examined by regressing chlorophyll *a* on NAT and temperature, then analyzing the relationship of residuals from the regression to nutrient concentrations. Residuals against total nitrogen and total phosphorus are shown in Figure 32 and Figure 33. There is little evident trend, and what linear trend there is has a negative sign. Thus, after accounting for the effects of NAT and turbidity, nutrient concentrations have very little power to explain observed chlorophyll *a* concentrations.

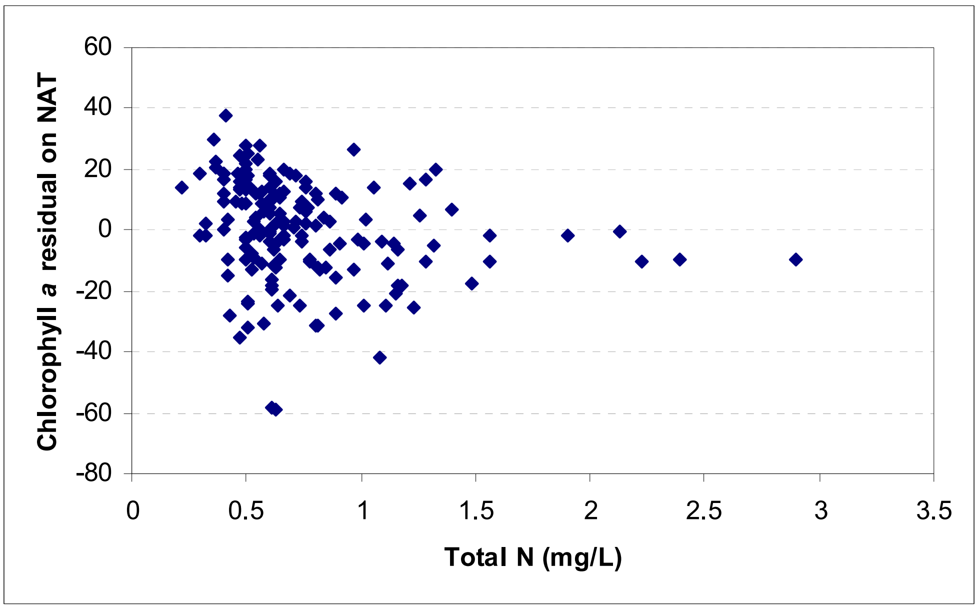


Figure 32. Residuals from Regression of Chlorophyll *a* on NAT and Temperature Plotted against Total Nitrogen Concentration

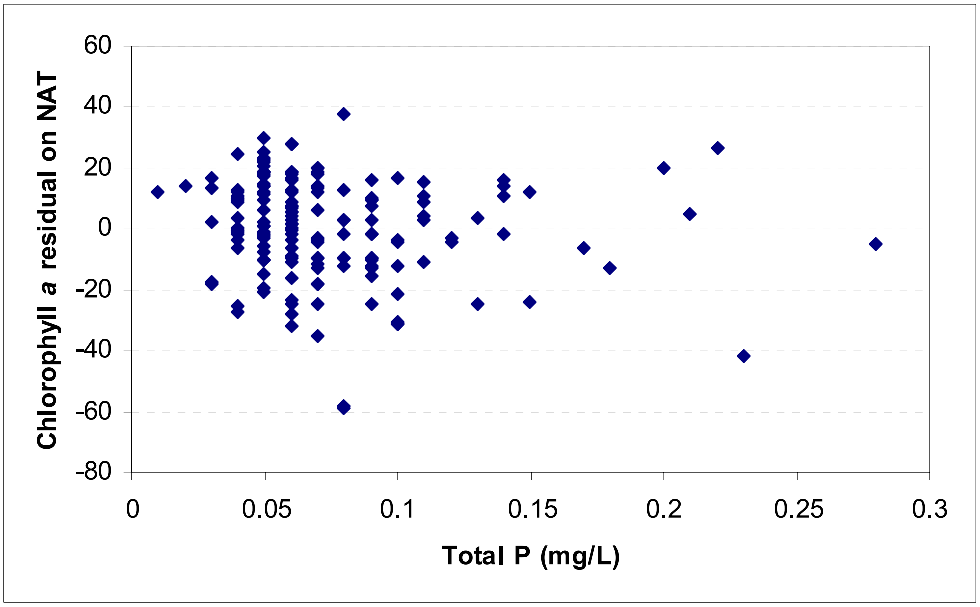


Figure 33. Residuals from Regression of Chlorophyll *a* on NAT and Temperature Plotted against Total Phosphorus Concentration

Because algal growth requires both nitrogen and phosphorus, Walker (1987) recommends use of a composite nutrient concentration, estimated as $[TP^{-2} + ((TN\text{-}150)/12)^{-2}]^{-0.5}$, with TP and TN expressed in µg/L. However, residuals against composite nutrient concentration also fail to show a clear trend (Figure 34).

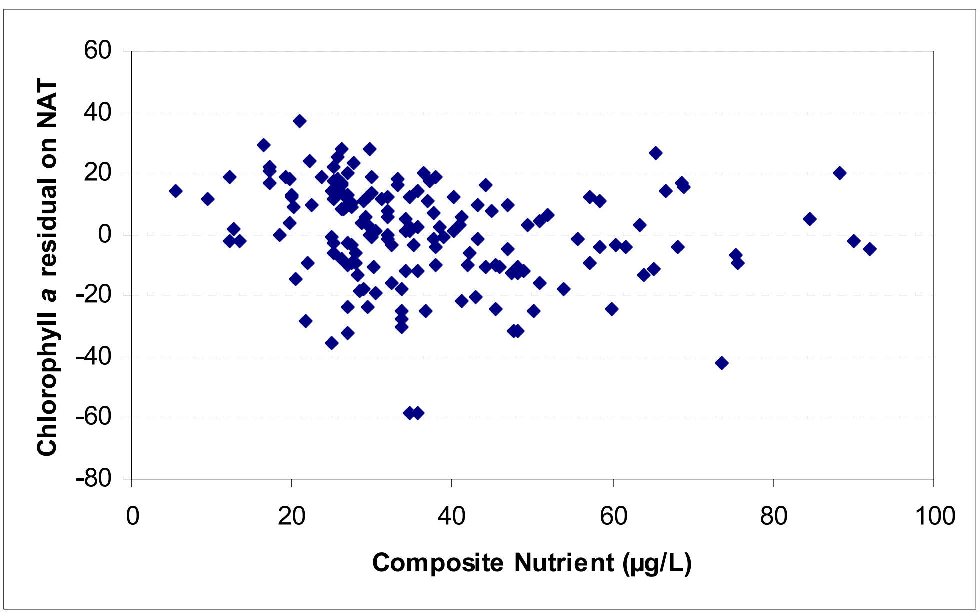


Figure 34. Residuals from Regression of Chlorophyll *a* on NAT and Temperature Plotted against Composite Nutrient Concentration

In sum, the correlation analysis shows that very little of the variability in chlorophyll *a* concentration in High Rock Lake is explained by nutrient concentrations. Light availability clearly has an effect, but explains only a relatively small portion of the variability in chlorophyll *a*. These findings suggest that the mixing dynamics of the lake – both residence time and vertical mixing – likely play an important role in the algal response.

6.2 Non-Parametric Analysis

The relationship between chlorophyll *a* and potential explanatory variables was also evaluated using the non-parametric technique of Classification and Regression Trees (CART). Using a least squares criterion this method searches the set of predictor variables to split the cluster of response variable cases (chlorophyll *a* observations) into two clusters with the maximum deduction in variance. Data from all stations was aggregated for analysis, and the resulting tree is shown in Figure 35. The first split occurs with nonalgal turbidity. High levels of chlorophyll *a* are associated with nonalgal turbidity less than .025 m. A secondary split occurs on Secchi depth.

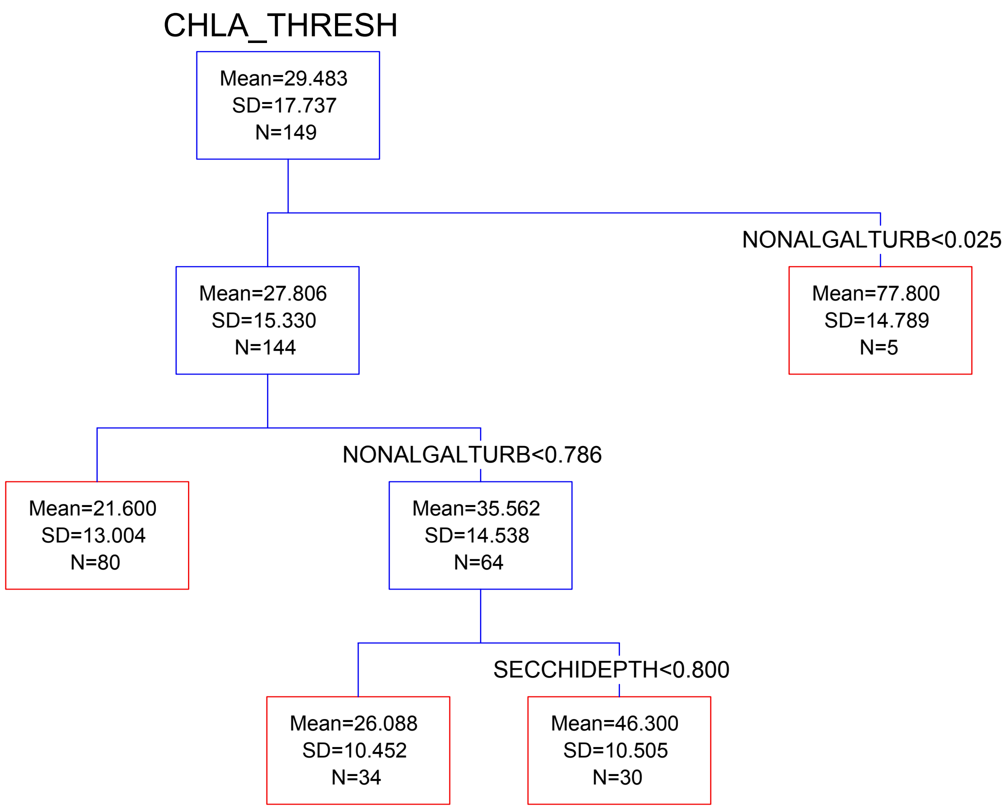


Figure 35. Classification and Regression Tree Analysis of Chlorophyll *a* Concentrations in High Rock Including Nonalgal Turbidity

Nonalgal turbidity is not independent of the response variable, which may cause statistical tests to overestimate it as an explanatory variable. A second Regression Tree was constructed excluding nonalgal turbidity as an explanatory variable (Figure 36). In this analysis, sampling location was the first split with secondary splits for N:P ratio and suspended sediment concentration.

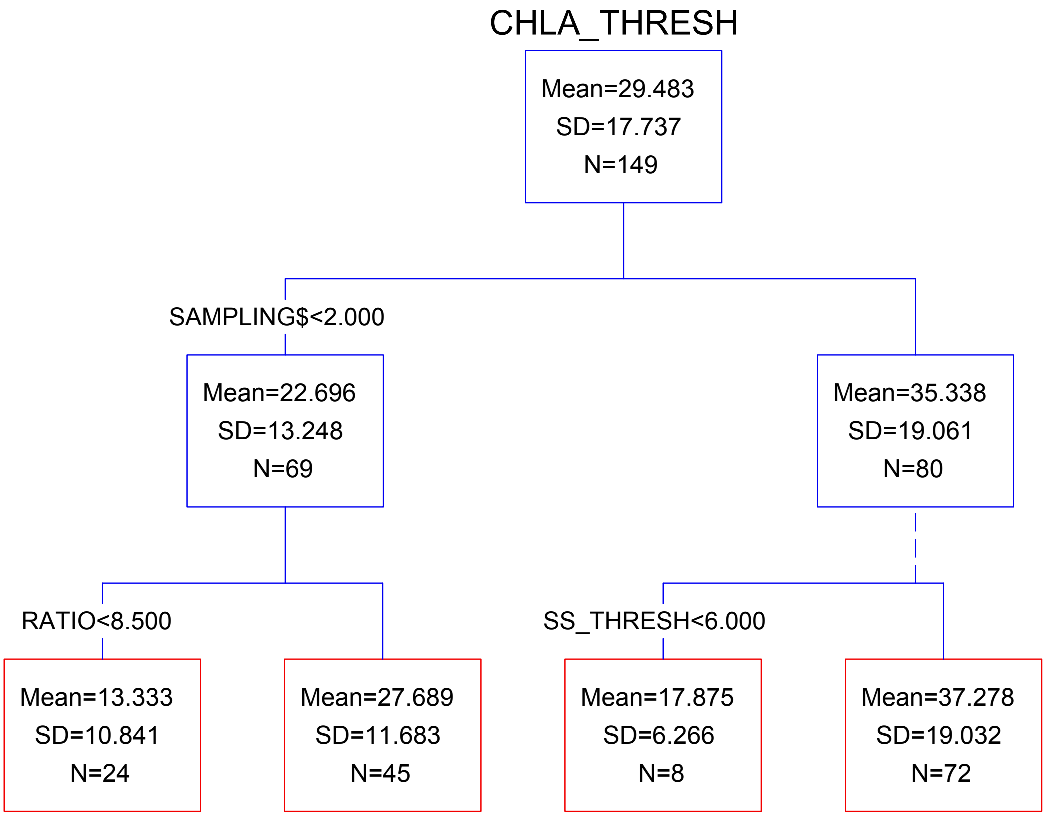


Figure 36. Classification and Regression Tree for Chlorophyll *a* Concentrations in High Rock Lake Excluding Nonalgal Turbidity

Note: "SAMPLING$" refers to sample location, with lower values upstream
Ratio is the N:P ratio
SS_THRESH is the suspended solids concentration

Stations were then analyzed individually both including and excluding nonalgal turbidity as an explanatory variable. When nonalgal turbidity was included it was the first split for 4 of the 8 stations (YAD152A, YAD152C, YAD156A, YAD169A). When nonalgal turbidity was excluded from the analysis, total nitrogen was the first split for station YAD152A, nitrogen to phosphorus ratio was the first split for station YAD152C, Secchi depth was the first split for station YAD156A, and suspended solids was the first split for station YAD169A.

Statistical analysis was continued by applying stepwise multiple linear regression to the entire dataset. Chlorophyll *a*, nonalgal turbidity, nutrient concentrations, total solids, and suspended solids were converted to a natural logarithm scale to reduce problems of heteroscedasticity. Total phosphorus (TP), nonalgal turbidity(NAT), and Secchi depth (SD) were identified as statistically significant variables in predicting chlorophyll *a* concentration according to the following equation:

$$CHL = -.38Ln(TP) - .76Ln(NAT) - 2.37Ln(SD)$$

This model has an R^2 of 52.2 percent.

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7 Data Gaps and Recommended Monitoring

Additional data collection will be needed to complete modeling and TMDL estimation for High Rock Lake. Choice of a modeling approach and monitoring needs are intimately related, as the monitoring must be adequate to support the selected modeling approach.

7.1 Potential Gaps in Existing Monitoring

DWQ's monitoring of High Rock Lake is similar to that conducted at other high-concern lakes in the state (e.g., Falls, Jordan) and subject to some of the same data gaps. A dominant characteristic of High Rock is its short residence time. Therefore, the experience in the Haw River arm of Jordan Lake, which also has a short residence time and run-of-river characteristics, may be particularly relevant.

In the period leading up to eventual TMDL development, it is assumed that regular ambient monitoring of High Rock Lake will continue, and will be supplemented by intensive studies. A general discussion of potential gaps follows; final evaluation of gaps will, however, depend on the identification of data quality objectives for modeling.

7.1.1 Chlorophyll *a* and Algae

Excursions of the North Carolina criterion for chlorophyll *a* of 40 µg/L are a basis for the identification of the upper portion of the lake as impaired. Elevated algal concentrations also contribute to elevated turbidity and sporadic low dissolved oxygen throughout the lake. Algal conditions in High Rock Lake are dynamic, and can vary quickly in time – both on a day-to-day basis and from year-to-year. Successful validation of a water quality model should include a demonstration that it performs well across a range of conditions and is capable of explaining year-to-year variations in lake response.

Problems with quality control at the NCDWQ laboratory have rendered the corrected chlorophyll *a* measurements unusable from September of 1996 through 2001. Uncorrected chlorophyll *a* estimates are recoverable for many of these observations, but are potentially subject to large, but unquantified, analytical uncertainty. Because of these concerns, chlorophyll *a* data for this time period are not optimal for modeling and are open to challenge by stakeholders. Further, the non-acidification method currently in use by DWQ differs from the method in use prior to 2001, with unknown consequences. For these reasons, DWQ and project stakeholders should plan on collecting several years of chlorophyll *a* data by current methods, with adequate quality control in place, to support development of a model.

While the North Carolina water quality criterion for algae is specified in terms of corrected chlorophyll *a* concentration, process-based nutrient response models generally simulate algal biomass as fixed organic carbon. This carbon concentration is then converted to an equivalent chlorophyll *a* prediction, using either a fixed or variable ratio. Unfortunately, direct documentation of the ratio is scant for North Carolina lakes. Experience in modeling Jordan Lake suggests that significant variability in the ratio occurs over the course of a year as a result of changes in algal species composition. Most notably, the cyanobacteria that often dominate summer algal populations typically have lower chlorophyll *a*-to-carbon ratios than the true algae that dominate at other times of the year. Further, the chlorophyll *a* content of algal cells typically varies with light conditions. If possible, direct experimental (laboratory) evidence on the ratio of organic carbon and ash-free dry weight to chlorophyll *a* for different dominant algal groups and for different seasons should be obtained for High Rock Lake to support modeling.

The mainstem of High Rock Lake behaves as a run-of-river impoundment, and typically has a short residence time. This short residence time can be expected to result in increased temporal variability in algal populations. For instance, Håkanson (1999) concluded that the natural coefficient of variation (CV; standard deviation normalized to the mean) for monthly chlorophyll *a* observations in lakes was on the order of 0.25, while Håkanson et al. (2003) proposed that the CV at the monthly scale for large rivers was on the order of 0.8. In other words, variability increases as the waterbody becomes more river-like. Scattered point-in-time chlorophyll *a* measurements are difficult to interpret in the face of such variability, as monthly samples may not provide a precise estimate of the mean. This suggests the need to perform high-frequency sampling of algae (preferably weekly or better) for at least one calibration and one validation growing season. Major tributary water quality should be sampled with at least the same frequency during such an intensive study.

7.1.2 Turbidity, Solids, and Light Penetration

Most of High Rock Lake is listed as impaired by elevated turbidity. Understanding turbidity in the lake is also very important to algal simulation, as it appears that light availability is one of the primary controls on algal density in the lake.

Turbidity is a measure of water clarity that refers to the scattering of light by suspended matter, dissolved organic compounds, and plankton in the water. In North Carolina, turbidity is typically reported as Nephelometric Turbidity Units (NTU) – which is a measure of optical scattering rather than a mass-based concentration. It is thus not easily interpreted as a mass load in the TMDL framework. Therefore, one of the keys in developing a turbidity TMDL is to establish a cause-and-effect relationship between turbidity and mass-conserving constituents such as total suspended solids and organic matter. Elevated organic matter and algae concentrations are further caused by eutrophication stimulated by excessive nutrient loading.

Water quality models typically calculate the algal concentration to turbidity (feedback mechanism), but require non-algal turbidity as an input. Measured turbidity incorporates both algal and non-algal components, so it is important to understand the relationship between algae, solids, and turbidity. Simple, generic regression approaches to estimating the non-algal component of turbidity from Secchi depth and chlorophyll *a* concentration, such as the equation provided with the BATHTUB model (Walker, 1987), do not appear to work that well for High Rock Lake, as discussed in Section 6. Similarly, Dodd et al. (1988) found that site-specific nonlinear regressions were needed to estimate nonalgal turbidity in Jordan and Falls Lake.

Relationships between suspended matter concentrations and optical properties of water are highly complex and difficult to resolve mathematically (Gallegos and Neale, 2002); however, it is clear that effects depend on both the mass concentration and type of suspended particulate matter. Particulate matter both attenuates and scatters light in the water column. Scattering also increases attenuation as the travel path length per unit depth increases. Nephelometric turbidity measures only the scattering component.

Gallegos (2001) documents an approximately linear relationship between turbidity and TSS at Chesapeake Bay sites, and a linear relationship has also often been noted in the evaluation of dredging operations. The relationship between the inorganic sediment contribution to turbidity and inorganic suspended solids can be generally described by an empirical equation

$$Turbidity = \beta \cdot TSIS^{\alpha} \qquad (1)$$

where *TSIS* is total suspended inorganic solids, α is a coefficient that is usually in the range 0.7 to 1.0 and β is an empirical fitting coefficient. The Corps of Engineers has developed method recommendations for evaluating the turbidity-TSS relationship (Thackston and Palermo, 2000).

The magnitude of the exponent *a* depends on the sediment size and organic content of suspended matter in the stream. Additional contributions to turbidity are made by algae and dissolved organic compounds, both of which have rather different light scattering properties from inorganic solids and may require separate relationships.

Algae contribute to turbidity in different ways from inorganic suspended solids. The wet density of algae is generally much less than inorganic solids. Austin (1974) found that light absorbance is inversely proportional to the total surface area of particles in the water, instead of their weight, but that algae scatter light less than inorganic particles of the same size. The effect of algae on water clarity, measured as Secchi disk depth or light transmission, is therefore generally much greater than the effect of algae on turbidity, measured as light refraction with a nephelometer.

In general, algae, measured as chlorophyll *a*, would be expected to provide an additive component to inorganic solids in the estimation of total turbidity. The relationship given in Equation (1) is, however, properly formed in terms of the suspended inorganic solids, whereas we most commonly have measurements of total suspended solids, including both inorganic and organic solids, with the latter component including the algae. A relationship of turbidity to TSS (including algae) may thus often have a negative coefficient on algae added as an independent variable, as algae scatter light less effectively than inorganic solids:

$$Turbidity = \beta_0 + \beta_1 \cdot TSS^{\alpha} - \gamma \cdot Chl\text{-}a \qquad (2)$$

The intercept term, β_0, represents a residual component of turbidity, due for instance to dissolved organic material or color. Gallegos (2001) did not find it necessary to correct TSS for chlorophyll content in analyzing turbidity in the Chesapeake, but this is likely due to the presence of near-linear correlations between TSS and chlorophyll in his data.

Given information on the percent of the dry biomass of algal cells that is made up of chlorophyll *a*, the relationship to TSS could also be corrected to remove the algal component; however, this approach would still not correct for the presence of detrital organic matter or the contribution of total dissolved solids (TDS).

A more relevant decomposition for TSS is provided by separation into total nonvolatile and total volatile suspended solids components (TNVSS and TVSS). The nonvolatile component will approximate the inorganic solids (although also containing ash residue from organic matter while losing some inorganic minerals), while the volatile component will approximate the organic matter contribution, including both algae and detritus. Assuming that the main differentiation in optical properties is between inorganic minerals and organic material, relationships based on TNVSS , TVSS, and TDS may be useful for predicting turbidity. Building on the mathematical forms presented above, these relationships could take the form:

$$Turbidity = \beta_0 + \beta_1 \cdot TNVSS^{\alpha} + \beta_2 \cdot TVS + \beta_3 \cdot TDS \qquad (4)$$

An attraction of this approach is that the contribution of algae to turbidity can be resolved given information or an assumption regarding the algal fraction of TVS (Chesapeake Bay Program, 2000). Effects on turbidity of reducing algal concentrations can then be estimated. In addition, this information could be used to develop a stronger basis for interpreting nonalgal turbidity from historic measurements of (total) turbidity, Secchi depth, and chlorophyll *a* concentration.

Data heretofore collected by DWQ for High Rock Lake include total solids and total suspended solids, from which TDS may be calculated. Information on the volatile solids content of TSS has not, however, been monitored. Such information should be added to the regular monitoring program.

7.1.3 Oxygen Dynamics

Portions of High Rock Lake are listed as impaired by low DO. While this listing is proposed for removal, it is likely that prediction of DO concentrations will continue to be an objective for a lake response model – particularly given the fact that the water quality criterion for dissolved gases is frequently exceeded in the lake.

Oxygen dynamics in a lake are affected by algal production (photosynthesis) and respiration, reaeration from the atmosphere, and the consumption of oxygen in chemical and bacterial oxidation of material in the water column (biochemical oxygen demand) and at the sediment-water interface (sediment oxygen demand).

Historical DWQ data for High Rock Lake does not include measurements of total biochemical oxygen demands (BOD) or carbonaceous biochemical oxygen demand (CBOD). Obtaining this information will be important if detailed oxygen modeling of the lake is desired. For a lake like High Rock Lake, which receives runoff from a large watershed as well as from near-lake point sources, the BOD in the lake is likely to be a wide-ranging mixture of labile and refractory components, and long-term BOD testing should be pursued to evaluate these components and their associated decay kinetics.

Information on sediment oxygen demand (SOD) is also apparently not available for High Rock Lake. If a high quality model of lake dissolved oxygen is needed, SOD measurements should be considered. Reaeration in a lake can be measured directly, but only at considerable expense. As a result, reaeration rates in High Rock Lake are likely to be estimated from wind speed.

7.1.4 Physical Measurements

Simulation of algae and dissolved oxygen requires information on a number of meteorological parameters. Some of these (air temperature, precipitation) are readily available; others, such as wind speed, humidity, and solar radiation are monitored more sparsely. Fortunately, the North Carolina Agricultural Resource Service maintains an Econet station at Salisbury, near High Rock Lake, which provides the relevant information. Project stakeholders should assure that this station remains operational for any future periods of intensive water quality monitoring.

7.1.5 Temporal Issues for Sampling

Conditions can change rapidly in High Rock Lake due to the short residence time. A measurement taken in June may have little relationship to a measurement taken in May if the water in the reservoir has been flushed out and replaced. For this reason, it would be valuable to obtain intensive monitoring data for periods of a month or more during which physical conditions are monitored continuously and water quality is measured on a subweekly basis. Only through conducting such studies will information be gained on the short term variability of response signals in the High Rock system.

7.2 Interaction with Data Quality Objectives

Data collection should be designed from a decision perspective, taking into account what degree of certainty in different components of the system is needed to reduce the risks of incorrect decisions. This evaluation begins the DQO process; however, completing the DQO process requires a series of iterations between model framework development and monitoring planning. The Council for Regulatory Environmental Modeling (2003) states that DQOs “enable the development of specifications for model quality” and “provide guidance on how to state data needs when limiting decision errors." This report provides the initial stage of DQO iterations by identifying data needs in light of a review of existing data and development of a conceptual model. DWQ will continue the DQO process, including development of uncertainty targets for the ultimate modeling framework, in an ongoing process with staff and key stakeholders.

7.3 DEVELOPING A MONITORING STRATEGY

As discussed in the previous section, development of a complete monitoring strategy for High Rock Lake will depend on the iterations between DQOs, specification of objectives and endpoints for the analysis, and model selection (see Section 8). The final monitoring strategy should be developed after completion of the DQO process and model selection, which should occur in cooperation with stakeholders. In other words, the monitoring strategy should be designed to support the selected modeling framework and provide the information necessary to address decision and management needs.

The conceptual process toward developing a final monitoring strategy is shown in Figure 37.

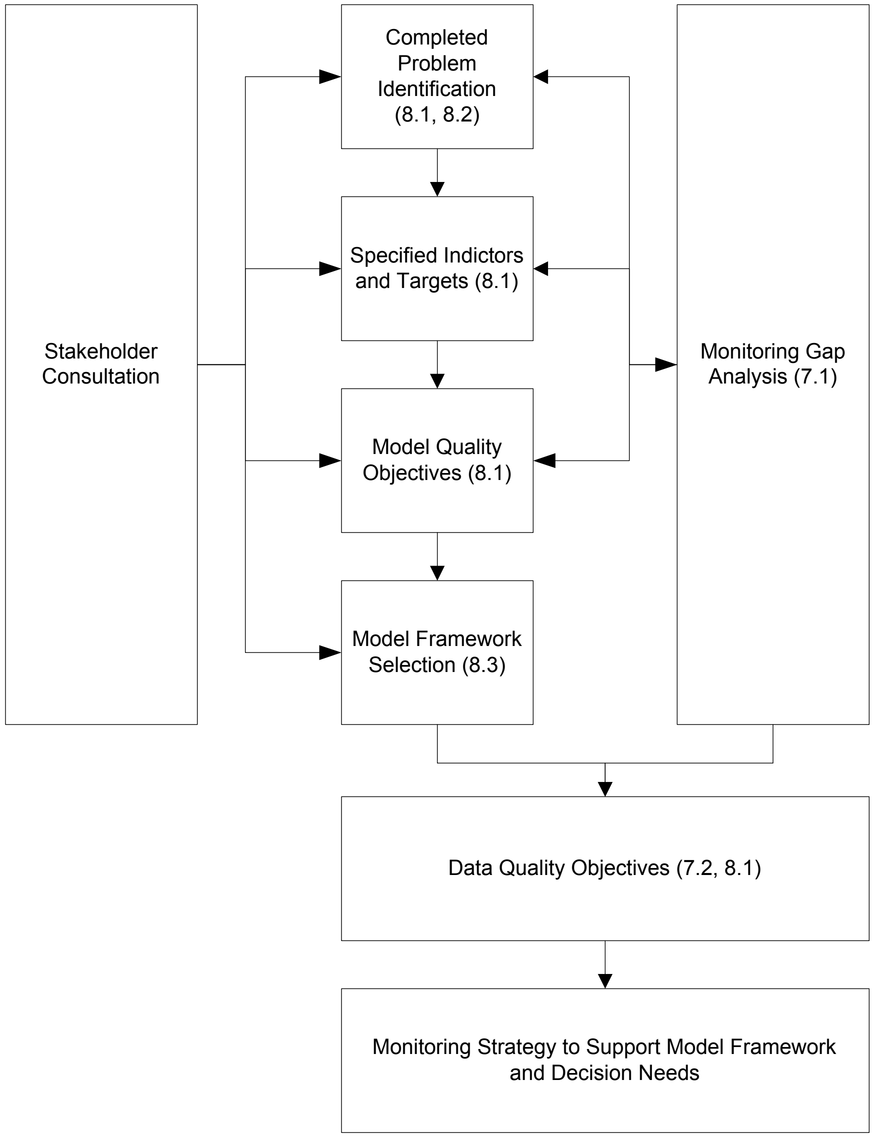

Figure 37. Process for Developing Monitoring Strategy

8 Recommendations for Modeling Framework

It is anticipated that completion of TMDLs for High Rock Lake will require the development of one or more water quality models – although the specific models are not yet defined. As noted in the basin plan (NCDWQ, 2003), "[D]evelopment of both a nutrient response model and a watershed loading model will assist in assessing water quality in High Rock Lake." The Yadkin-Pee Dee River Basin Association has expressed interest in modeling the High Rock Lake watershed, while DWQ will lead the lake response modeling effort.

According to current EPA draft guidance (Council for Regulatory Environmental Modeling [CREM], 2003), model development for regulatory purposes should follow a four-step process, consisting of (1) Problem Identification and Quality Objectives, (2) Conceptual Model Development, (3) Model Framework Construction, and (4) Development of Application Tools. This work order covers the first two steps in the model development process and provides the foundation for the third step.

8.1 Problem Identification and Quality Objectives

From a regulatory perspective, problems in High Rock Lake are defined by the water quality assessment and associated 303(d) listings for TMDL development. Specifically, the draft 2004 303(d) list enumerated portions of High Rock Lake as impaired due to elevated chlorophyll *a*, elevated turbidity, and depressed DO – although the DO listing may be removed.

The presence of excursions of the numerical criteria specified in North Carolina's water quality regulations requires that these problems be addressed. It would be a mistake, however, to restrict problem identification solely to the documented criteria excursions. DWQ intends to implement a DQO process with key stakeholders, and this process may also identify additional management goals that either relate to narrative use support (e.g., maintaining a healthy fishery) and/or present constraints on management (e.g., desire of local residents to maintain stable water elevations). The modeling framework should be developed to address significant stakeholder objectives as well as the listed parameters.

As the set of management goals is finalized, a set of associated measurable indicators and targets should be developed. For instance, a goal of maintaining a healthy warm water fishery may have a series of indicators and targets, such as maintaining summer average chlorophyll *a* concentrations between 15 and 40 µg/L, meeting the turbidity criterion, and maintaining an acceptable distribution of temperature and DO conditions in the lake. The compiled set of indicators is a list of what should be addressed by models and assessment, and forms the basis for proposing quality objectives that describe what and how accurately components of the system need to be represented to support management.

Quality Objectives for modeling describe "[h]ow accurately and precisely does the model need to predict a given quantity at the application site or in the process step of interest in order to satisfy regulatory or scientific objectives" (USEPA, 2002). Data Quality Objectives (DQOs) "provide guidance on how to state data needs when limiting decision errors (false positives or false negatives) relative to a given decision" (CREM, 2003). In essence, it is desirable to pre-specify the degree of agreement between model predictions and observed data, as well as the extent and quality of the observed data, before moving ahead with model development. These objectives should be thoroughly vetted with stakeholders early in the process.

What quality of model and data is needed to move ahead to management? It should be noted that the TMDL regulations do not allow lack of information as an excuse for inaction. That is, a

TMDL will be required whether or not the model performs well. Indeed, high levels of uncertainty in the analysis are supposed to result in more restrictive allocations under the TMDL, as a portion of the estimated assimilative capacity should be reserved to account for this uncertainty (referred to as the Margin of Safety). Clearly, however, the likelihood of achieving stakeholder buy-in to implementation increases as the proven quality of the model increases.

Defining the Model Quality Objectives and associated DQOs must take into account both spatial and temporal concerns. For instance, is it sufficient to obtain a good representation of annual average concentrations across the lake, or will a more rigorous target of predicting daily concentrations at individual points be required? Recent experience with the Jordan Lake TMDL and Nutrient Sensitive Water strategy suggests that the chlorophyll *a* criterion will be interpreted as a frequency (with a goal of 10 percent or less of observations above 40 µg/L) that is applicable to individual segments of the lake – although not necessarily to every individual monitoring point.

Given this interpretation, one of the most important objectives for model quality, and the objective most closely related to decision-making, may be the ability to predict frequency of excursions of the 40 µg/L chlorophyll *a* criterion. Note that this objective is not the same as specifying a minimum acceptable error criterion on the prediction of individual observations. Indeed, in a highly variable system (like High Rock or Jordan) the model may do a relatively imprecise job of predicting individual observations, but do a better job of reproducing excursion frequencies. This can occur if the model does a good job of explaining the algal response to external forcing of nutrients, light, and so on, but the short-term variability in these external forcings themselves is not well characterized. Model Quality Objectives should include a statement of the acceptable level of uncertainty in the prediction of the frequency of chlorophyll *a* concentrations greater than 40 µg/L that would be necessary for the model to be judged a credible tool for TMDL development.

Further clarification will be needed from DWQ on the frequency basis for interpretation of the turbidity criterion. Presumably this criterion cannot be achieved 100 percent of the time, and attainment of the standard should be judged based on an acceptable frequency of excursions, or, alternatively, as not applicable under certain extreme hydrologic regimes.

Model Quality Objectives on the error in prediction of individual observations may also be specified, and indeed may be needed to increase stakeholder confidence in model validity. In developing such targets, however, care must be taken to account for inherent uncertainty in analytical methods. EPA commissioned a multilaboratory validation and comparison study of fluorometric determination of chlorophyll *a* in 1996 (Arar and Collins, 1997), which found that the average percent relative standard deviation was approximately 23 percent, ranging from 15 to 33 percent. There is thus substantial uncertainty present in the analytical method, which will increase the magnitude of the apparent discrepancy between model and data, even in the case where the model is completely accurate.

Along with the Model Quality Objectives, criteria should be defined to determine whether model outputs achieve the needed quality. These are usually defined through statistical tests, such as root mean squared error, *t*-tests of equality of means, or various tests of predicted and observed frequency distributions, such as the chi-square test (Snedecor and Cochran, 1989). For decision-making regarding the TMDL, a minimum requirement should be a specification of the acceptable level of uncertainty associated with prediction of criterion excursions, which could be evaluated in terms of the risks (and costs) of making an incorrect decision. The tests should, of course, be applied to a data validation period that is separate from the calibration period used to develop the model.

The DQOs are a statement of data needs associated with achieving the Model Quality Objectives. Uncertainty in either the observed response data (e.g., in-lake chlorophyll *a*) or key forcing functions (e.g., tributary nutrient load) will increase uncertainty in model output.

Increasing the precision in observed frequencies of algal blooms is certainly advisable, particularly in a reservoir with a short residence time. Given high temporal variability, monthly observations of chlorophyll *a* may provide only a very imprecise estimate of the actual frequency of time in which concentrations are greater than 40 µg/L. Sampling (for at least some lake stations) on a weekly or better basis is recommended to help reduce this source of uncertainty.

For external forcing, DQOs clearly depend on the modeling approach and Model Quality Objectives. Given the short residence time typical of High Rock Lake, conditions in the water column may respond rapidly to changes in inflow quality conditions. To reproduce the frequency distribution of observations, the minimum requirement would be a representative specification of the distribution of concentrations in the inflows. However, to achieve a match between individual observations and predictions, accurate time series of observations would be needed on a sub-weekly basis.

In sum, the Model Quality Objectives and Data Quality Objectives should be developed together, in consultation with the stakeholders, and with specific statistical tests and targets in mind.

8.2 CONCEPTUAL MODEL

The conceptual model is designed to “represent the most important behaviors of the object or process relevant to the problem of interest,” consistent with the guidance from the Council for Regulatory Environmental Modeling (2003). The conceptual model provides the basis for initial recommendations regarding a modeling framework. However, initial recommendations are prone to change as additional data are collected or stakeholder management objectives are refined.

Current understanding of water quality conditions in High Rock Lake is summarized briefly below for each of the three identified water quality problems.

Chlorophyll *a* concentrations index algal growth, which in turn depends on nutrient availability, among other factors. In High Rock Lake, however, nutrients are usually not the primary factor determining chlorophyll *a* concentration. Instead, nutrients are typically present in excess of requirements of the algal standing crop, and algal growth is primarily limited by other factors, the most important of which appear to be light availability and flushing. Light availability is driven by turbidity, and its effects are likely influenced by vertical mixing patterns in the lake. For instance, when mixing (driven by wind and water velocities through the lake) is sufficiently energetic, algae will tend to be mixed out of the euphotic zone, reducing their growth potential. Reduced turbidity, however, might lead to increased algal growth unless nutrients are also reduced. Given the short residence time in the mainstem, the concentration of algae in the Yadkin as it enters High Rock Lake may also be a significant factor in observed in-lake concentrations.

Turbidity in the lake is in turn driven by algal density and non-living organic and inorganic solids. The primary influence on non-algal turbidity appears to be the suspended solids load brought in by the Yadkin River. However, turbidity conditions within the lake reflect mixing and settling patterns, and are potentially influenced by near shore resuspension.

Dissolved oxygen dynamics in the lake are driven by a variety of factors, including algal photosynthesis, algal respiration, the oxidation of organic material, and reaeration. The availability of organic material for oxidation depends largely on external loads, plus an unquantified contribution from *in situ* biomass production, while the algal component is affected by all the factors listed above for chlorophyll *a*. All these factors are influenced by mixing patterns in the lake. In addition, there is a sediment oxygen demand component that has not been measured.

8.3 MODELING FRAMEWORK

The Conceptual Model, when combined with decision needs, provides a basis for beginning the discussion of an appropriate modeling framework. A key characteristic of the reservoir is its often short retention time, while a key decision need is the ability to predict frequency of excursions of the water quality criteria. Together, these factors indicate the need for a dynamic, continuous-simulation model that can produce predictions on a short time step, rather than a model of average growing season conditions. Rapid variations in inflows and releases likely result in a condition in which model numerical stability limitations will require simulation at a sub-hourly time step.

Spatially, there are significant longitudinal gradients in observed water quality through the mainstem and in tributary arms such as Abbotts Creek. Vertical mixing in the water column may be of great importance, but lateral mixing is likely of lesser importance, particularly given the short residence time. This suggests that a 2-dimensional (vertical) model with provision for branching to represent tributary arms is appropriate. A fully 3-dimensional model could be applied, but would require a significantly greater level of effort.

To describe vertical mixing effects, the modeling framework should incorporate a full hydrodynamic simulation with a coupled water quality simulation. Vertical resolution in the water quality model should likely be at a scale of 1 m or less. Experience with the Jordan Lake model showed that creating a water quality model with a coarse vertical resolution (from a finer grid hydrodynamic model), while greatly reducing simulation time and easing the model calibration process, resulted in significant problems for interpretation of assessment data for chlorophyll *a*. These samples are collected over the euphotic zone, defined as twice the Secchi depth, and this depth varies with turbidity. Thus, a finer vertical resolution is needed in the water quality model to produce predictions that are spatially matched to observations.

For water quality processes, the modeling framework will require a full eutrophication simulation that accounts for nutrient effects, settling, and the interaction between turbidity/light availability and algal growth. Simulation of sediment transport is needed to address the non-algal turbidity component. Simulation of the DO/BOD cycle should also be included.

There are, in addition, likely certain user constraints on the model if it is to be used for regulatory purposes. Notably, it will be desirable to use a model that is open source and in the public domain. In addition, the models should be tested and verified (with application to freshwater reservoirs), well documented, and acceptable to both DWQ and EPA.

The Water Environment Research Foundation Model Selection Tool (Fitzpatrick et al., 2001) sorts through the characteristics and availability of a large number of water quality models. This tool identifies eight models fitting the general criteria outlined above; however, a number of these are proprietary (e.g., MIKE-21, GEMS-WQM) or have not been tested in freshwater reservoirs (e.g., HEM2D/HEM3D). The remaining models identified by the tool or otherwise identified by the authors of this report fit into two general categories: applications of the WASP5/EUTRO5 model (Ambrose et al., 1993) or its descendants with linkage to a hydrodynamic model (such as EFDC; Hamrick, 1996) and the CE-QUAL-W2 model (Cole and Wells, 2003).

At present there appear to be several advantages to CE-QUAL-W2 as a potential framework for modeling response in High Rock Lake:

- CE-QUAL-W2 contains an integral hydrodynamic model, whereas WASP requires linkage to an external model. For Jordan Lake, EFDC/WASP was an appropriate choice because the need was seen for three-dimensional hydrodynamic modeling. For High Rock Lake, two-dimensional (laterally averaged) hydrodynamics appear adequate.
- CE-QUAL-W2 enables the simultaneous simulation of inorganic sediment transport and eutrophication. WASP can be implemented in either the EUTRO version (eutrophication, without sediment transport) or TOXI version (sediment and toxics transport). Simultaneous simulation of sediment and eutrophication is desirable to capture the interactions between turbidity and algal growth.
- CE-QUAL-W2, unlike WASP, allows separate specification of labile and refractory organic matter components for dissolved oxygen simulation. This is advantageous for a lake that receives direct inputs of wastewater effluent together with runoff from a large watershed, likely resulting in a wide range of characteristics of biodegradable compounds.
- CE-QUAL-W2 continues to be actively supported and the new version (v 3.2) provides a useful graphical user interface.

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9 References

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Appendix A. Sources of Data

File Name	Location	Source	File Description
HR89WCO1.TXT	Source\Received from Client\BATHTUB	NCDWQ	1989 BATHTUB Model for High Rock Lake
HR90WCO1.TXT	Source\Received from Client\BATHTUB	NCDWQ	1990 BATHTUB Model for High Rock Lake
High Rock Historic Chemistry Data.xls	Source\Received from Client\DWQ Sampling	NCDWQ	Chemical data from Lakes Assessment monitoring at 8 sites within the main lake and arms from July 1981 to September 2002. Includes surface data, photic zone, and bottom data. Parameters include DO, pH, Secchi depth, temperature, %DO saturation, Nutrients, chlorophyll, solids, and turbidity. Location of sites indicated in high rock map with sites document.
High Rock Historic Physical Data.xls	Source\Received from Client\DWQ Sampling	NCDWQ	Physical data by station and depth from July 1981 to September 2002. Includes sampling depth, temperature, dissolved oxygen, pH, and conductivity.
High Rock Map with Sites.doc	Source\Received from Client\DWQ Sampling	NCDWQ	Image of topo map with Lakes Assessment monitoring sites
Butcher_20040520post1997.txt	Source\Received from Client\DWQ Sampling	NCDWQ	Tributary water quality data from Ambient Monitoring program collected from 1997 to 2003. Parameter codes and description of data is contained in AMS_data_Explanations_v2_1.pdf
Butcher_20040520pre1997.txt	Source\Received from Client\DWQ Sampling	NCDWQ	Tributary water quality data from Ambient Monitoring program collected from 1969 to 1997. Parameter codes and description of data is contained in AMS_data_Explanations_v2_1.pdf
High Rock Questionable CHLa 1997 to 2000.xls	Source\Received from Client\DWQ Sampling\suspect Chl-a	NCDWQ	Chlorophyll data from Lakes Assessment monitoring that was excluded from original data sent due to QA problems. Uncorrected chl *a* values may be used from this data set to fill in chl *a* data missing from High Rock Chemistry Data.xls.
high rock algae.xls	Source\Received from Client\DWQ Sampling	NCDWQ	Algal data collected at various sites throughout the High Rock Lake watershed. Includes data for 2 of the stations where chemical data is also available. Parameters include total biovolume, total cell density, and total taxa.
02116500_discharge.xls	Source\Created By RTP\USGSdownloads	USGS	Discharge data for Yadkin River at Yadkin College from 1928-2003.

File Name	Location	Source	File Description
02116500_WQdata.xls	Source\Created By RTP\USGSdownloads	USGS	Water quality data for Yadkin River at Yadkin College from 1955-2001. Parameter codes for WQ data can be found in the text file by the same name.
02118000_discharge.xls	Source\Created By RTP\USGSdownloads	USGS	Discharge data for South Yadkin River near Mocksville from 1938-2003.
02118000_WQdata.xls	Source\Created By RTP\USGSdownloads	USGS	Water quality data for South Yadkin River near Mocksville from 1954-1979.
02118500_discharge.xls	Source\Created By RTP\USGSdownloads	USGS	Discharge data for Hunting Creek near Harmony from 1951-2003.
02118500_Wqdata.xls	Source\Created By RTP\USGSdownloads	USGS	Water quality data for Hunting Creek near Harmony from 1955-1979.
02119000_discharge.xls	Source\Created By RTP\USGSdownloads	USGS	Discharge data for South Yadkin River at Cooleemee from 1928-1965.
02119000_Wqdata.xls	Source\Created By RTP\USGSdownloads	USGS	Water quality data for South Yadkin River at Cooleemee from 1955-1961
02120500_discharge.xls	Source\Created By RTP\USGSdownloads	USGS	Discharge data for Third Creek at Cleveland from 1940 to 1971.
02120780_discharge.xls	Source\Created By RTP\USGSdownloads	USGS	Discharge data for Second Creek near Barber for 1979 through 2003.
02121180_discharge.xls	Source\Created By RTP\USGSdownloads	USGS	Discharge data for North Potts Creek at Linwood for 1979 through 1990.
02121500_discharge.xls	Source\Created By RTP\USGSdownloads	USGS	Discharge data for Abbotts Creek at Lexington from 1988-2003.
02121500_WQdata.xls	Source\Created By RTP\USGSdownloads	USGS	Water quality data for Abbotts Creek at Lexington from 1955-1958.
02122500_discharge.xls	Source\Created By RTP\USGSdownloads	USGS	Discharge data for Yadkin River at High Rock from 1919-1962.
02122500_WQdata.xls	Source\Created By RTP\USGSdownloads	USGS	Water quality data for Yadkin River at High Rock from 1955-1973.