High Rock Lake Watershed Model

Prepared for

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1 Introduction

The State of North Carolina Division of Water Quality (DWQ) periodically assesses the support of designated uses in waterbodies of the state in accordance with the Federal Clean Water Act. High Rock Lake has designated uses of recreation and support of aquatic life, and is also protected for water supply. The lake has been identified as failing to support its designated uses and is thus listed as being impaired (Clean Water Act Section 303(d) listings) due to elevated levels of turbidity, chlorophyll *a*, and pH. The chlorophyll *a* and pH impairments are primarily associated with excess algal growth, which in turn is caused by elevated loads of nutrients (nitrogen and phosphorus) delivered to the lake. The turbidity impairment is primarily due to fine sediment loads, although algal growth also contributes to turbidity.

This report documents the development of a watershed simulation model to evaluate sediment and nutrient loads from the watershed of High Rock Lake. The watershed model is part of a larger study to develop both watershed and lake nutrient response models. The overall objective of the study is to develop a complete set of watershed and lake models that can simulate the sources of nutrient and sediment loads, transport to the lake, and nutrient responses within the lake to support the DWQ in the development of Total Maximum Daily Loads (TMDLs) and/or nutrient management strategies.

High Rock Lake is located in the western portion of North Carolina (Figure 1-1). The lake is a man-made impoundment, and High Rock Dam was constructed in 1927 as part of the Yadkin Project. The Yadkin Project is currently owned and operated by Alcoa Power Generating, Inc. (APGI). High Rock Lake was filled by April 1928 (APGI, 2006). The lake and dam originally supplied power to support aluminum manufacturing power generation, however now the primary use is for generation and sale of hydroelectric power. The normal pool elevation is 623.9 feet which corresponds to a surface area of 15,180 acres and a volume of 239,672 acre-feet. As the dam is used for peaking power generation, the water level in the lake fluctuates on an intraday basis.

The watershed that drains to High Rock Lake is the headwater to the Yadkin/Pee Dee river basin. This headwater area consists of the following 8-digit hydrologic cataloguing units (HUC8s):

1. 03040101, Upper Yadkin River
2. 03040102, South Yadkin River
3. 03040103, Lower Yadkin River

The total drainage area at High Rock Dam is 3,974 square miles. However, a major impoundment upstream at W. Kerr Scott Dam cuts off the uppermost 367 square miles of the watershed. Because much of the mass of sediment and nutrients originating upstream of that dam is trapped or temporarily retained in the Kerr Scott reservoir, the outflow from W. Kerr Scott Dam is treated as a boundary condition for the High Rock Lake watershed model and not explicitly simulated.

The High Rock watershed is in the Piedmont physiographic region, just south and east of the Blue Ridge Mountains. Historically the area had extensive agriculture, but over recent decades there has been a decline in agricultural land use and an increase in urban development. The present day land cover of the watershed is primarily forest and agriculture. Multiple urban centers are located within the study area and include Winston-Salem, Salisbury, High Point, Lexington, and Thomasville (Figure 1-1). The watershed includes part or all of 11 North Carolina counties – Rowan, Iredell, Surry, Yadkin, Davie, Forsyth, Stokes, Alleghany, Watauga, Alexander, and Ashe – plus a small area in Carroll and Patrick Counties, Virginia.

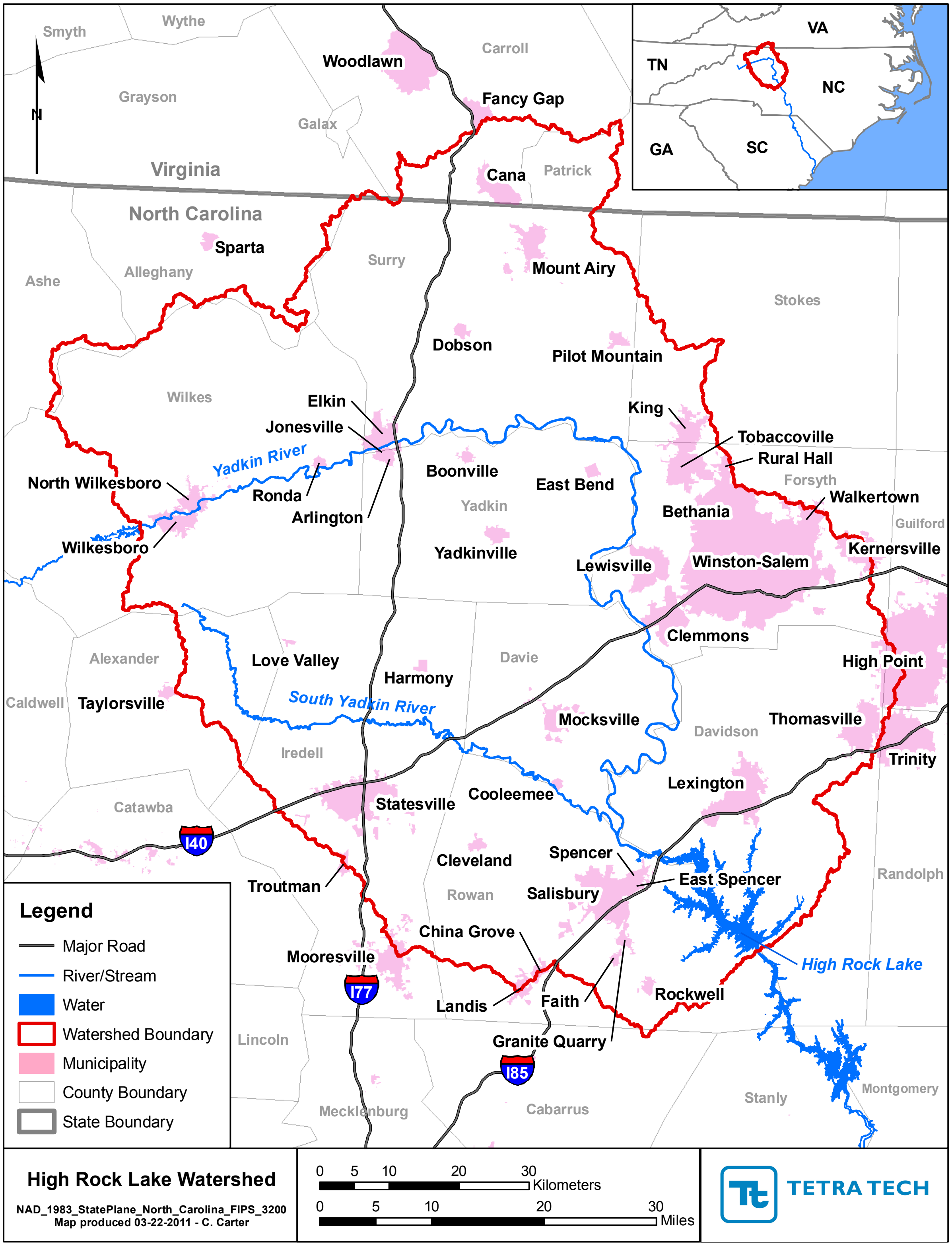

Figure 1-1. High Rock Lake Watershed Location Map

Note: The Yadkin River drainage upstream of W. Kerr Scott Dam is not included in the modeling domain.

DWQ convened a Technical Advisory Committee (TAC) in August of 2005 to assist with development of monitoring and mathematical tools for the management of nutrients, algae (chlorophyll *a*) and turbidity in High Rock Lake. The TAC is a subgroup of the High Rock Lake stakeholders and is primarily comprised of members of state agencies and local governments in addition to the Yadkin-Pee Dee Riverkeeper and Alcoa Power Generating, Inc.

The TAC met 18 times from August 2005 through March 2011 and provided recommendations for monitoring, model development, and performance criteria. The TAC helped shape many aspects of the watershed modeling process and provided:

- Feedback on monitoring plans,
- Information on effluent discharge quantity and quality,
- Information on water withdrawal amounts,
- Refinements of land cover information on roads and estimates of sediment generation from unpaved roads (provided by representatives of the NC Department of Transportation [NC DOT]), and
- Collaboration on the representation of septic systems.

In December 2008, U.S. EPA issued a task order to Tetra Tech to develop the High Rock Lake watershed hydrodynamic and nutrient response models. The task order directs use of the EPA-supported Hydrologic Simulation Program – FORTRAN (HSPF; Bicknell et al., 2001) to develop the watershed model, consistent with recommendations of DWQ and the TAC.

An initial draft of this report and accompanying model files was provided to TAC members for review and comment in January 2012. Subsequently, some omissions of data and an error in the nitrogen calibration process were detected. The model and report were therefore further refined and re-released to the TAC for final review and formal comment in March 2012. Responses to comments and descriptions of resulting model revisions are described in the supplemental document titled “High Rock Lake Technical Advisory Committee Watershed Model Review Comments and Responses, August, 2012” (Tetra Tech, 2012).

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2 Regulatory Information

NC DWQ has identified High Rock Lake as failing to support its designated uses as defined under the Federal Clean Water Act. The determination of impairment is based on the assessment of monitoring data relative to the applicable water quality standards, which are in turn determined by the designated uses assigned to the lake

2.1 WATER QUALITY CRITERIA

Water quality standards consist of three parts: an antidegradation policy, designated uses, and water quality criteria. The designated uses for the assessment units of High Rock Lake are noted in Table 2-1. Water quality criteria may be narrative or numeric; however, for High Rock Lake the identified impairments are all associated with monitored excursions of numeric criteria.

The High Rock Lake study area is inland, thus the freshwater portions of the water quality standards are relevant (15A NCAC 02B .0211). Sections of the North Carolina Administrative Code, relevant to High Rock Lake are summarized below.

> *Chlorophyll a (corrected): not greater than 40 µg/L for lakes, reservoirs, and other waters subject to growths of macroscopic or microscopic vegetation not designated as trout waters, and not greater than 15 µg/L for lakes, reservoirs, and other waters subject to growths of macroscopic or microscopic vegetation designated as trout waters (not applicable to lakes or reservoirs less than 10 acres in surface area). The Commission or its designee may prohibit or limit any discharge of waste into surface waters if, in the opinion of the Director, the surface waters experience or the discharge would result in growths of microscopic or macroscopic vegetation such that the standards established pursuant to this Rule would be violated or the intended best usage of the waters would be impaired. 15A NCAC 02B .0211(3)(a)*
>
> *pH: shall be normal for the waters in the area, which generally shall range between 6.0 and 9.0 except that swamp waters may have a pH as low as 4.3 if it is the result of natural conditions. 15A NCAC 02B .0211(3)(g)*
>
> *Turbidity: The turbidity in the receiving water will not exceed 50 Nephelometric Turbidity Units (NTU) in streams not designated as trout waters…for lakes and reservoirs not designated as trout waters, the turbidity shall not exceed 25 NTU; if turbidity exceeds these levels due to natural background conditions, the existing turbidity level shall not be increased. Compliance with this turbidity standard can be met when land management activities employ Best Management Practices (BMPs) [as defined by Rule .0202 of this Section] recommended by the Designated Nonpoint Source Agency [as defined by Rule .0202 of this Section]. BMPs must be in full compliance with all specifications governing the proper design, installation, operation and maintenance of such BMPs. 15A NCAC 02B .0211(3)(k)*

2.2 DESIGNATED USES

The classification, or designated use, of a waterbody is determined by the state of North Carolina and described in the North Carolina Administrative Code. All waters of the state must, at a minimum, meet uses for the propagation of aquatic life and secondary recreation. Table 2-1 presents the use classifications relevant to High Rock Lake. Classifications of individual assessment units are shown below.

Table 2-1. North Carolina Waterbody Classifications (Designated Use) Applicable to High Rock Lake

Classification	Description
WS-IV	Waters protected as water supplies which are generally in moderately to highly developed watersheds; point source discharges of treated wastewater are permitted pursuant to Rules .0104 and .0211 of this Subchapter; local programs to control nonpoint source and stormwater discharge of pollution are required; suitable for all Class C uses.
WS-V	Waters protected as water supplies which are generally upstream and draining to Class WS-IV waters or waters previously used for drinking water supply purposes or waters used by industry to supply their employees, but not municipalities or counties, with a raw drinking water supply source, although this type of use is not restricted to a WS-V classification; no categorical restrictions on watershed development or treated wastewater discharges are required, however, the Commission or its designee may apply appropriate management requirements as deemed necessary for the protection of downstream receiving waters (15A NCAC 2B .0203); suitable for all Class C uses.
B	Primary recreation and any other usage specified by the “C” classification.
C	Aquatic life propagation and survival, fishing, wildlife, secondary recreation, and agriculture.
CA	Water supply critical area (supplemental classification).

Reference: 15A NCAC 02B .0301(c) (NCDNR, 2007)

2.3 ASSESSMENT UNITS AND IDENTIFIED WATER QUALITY IMPAIRMENTS

NCDWQ uses ten different assessment units to characterize water quality in High Rock Lake. These assessment units and their corresponding use classifications are shown in Figure 2-1. Each of these assessment units have been identified as impaired by one or more pollutants.

The identified impairments (Clean Water Act Section 303(d) listings) in High Rock Lake were obtained from the 2010 Integrated Report (NCDENR, 2010). The relevant impaired assessment units in the study area are listed in Table 2-2. The table includes a description of the assessment unit, the classification and whether it is listed as impaired for chlorophyll *a*, turbidity, and/or pH. Three segments of the main lake are listed as impaired for all three constituents, two additional segments are impaired for chlorophyll *a* and turbidity, and one is impaired for chlorophyll *a* and pH. In addition, two segments of the Abbotts Creek arm are listed as impaired for chlorophyll *a*, and one of these segments is also impaired for turbidity. Finally, the Second Creek arm of the lake is listed as impaired for chlorophyll *a* and pH.

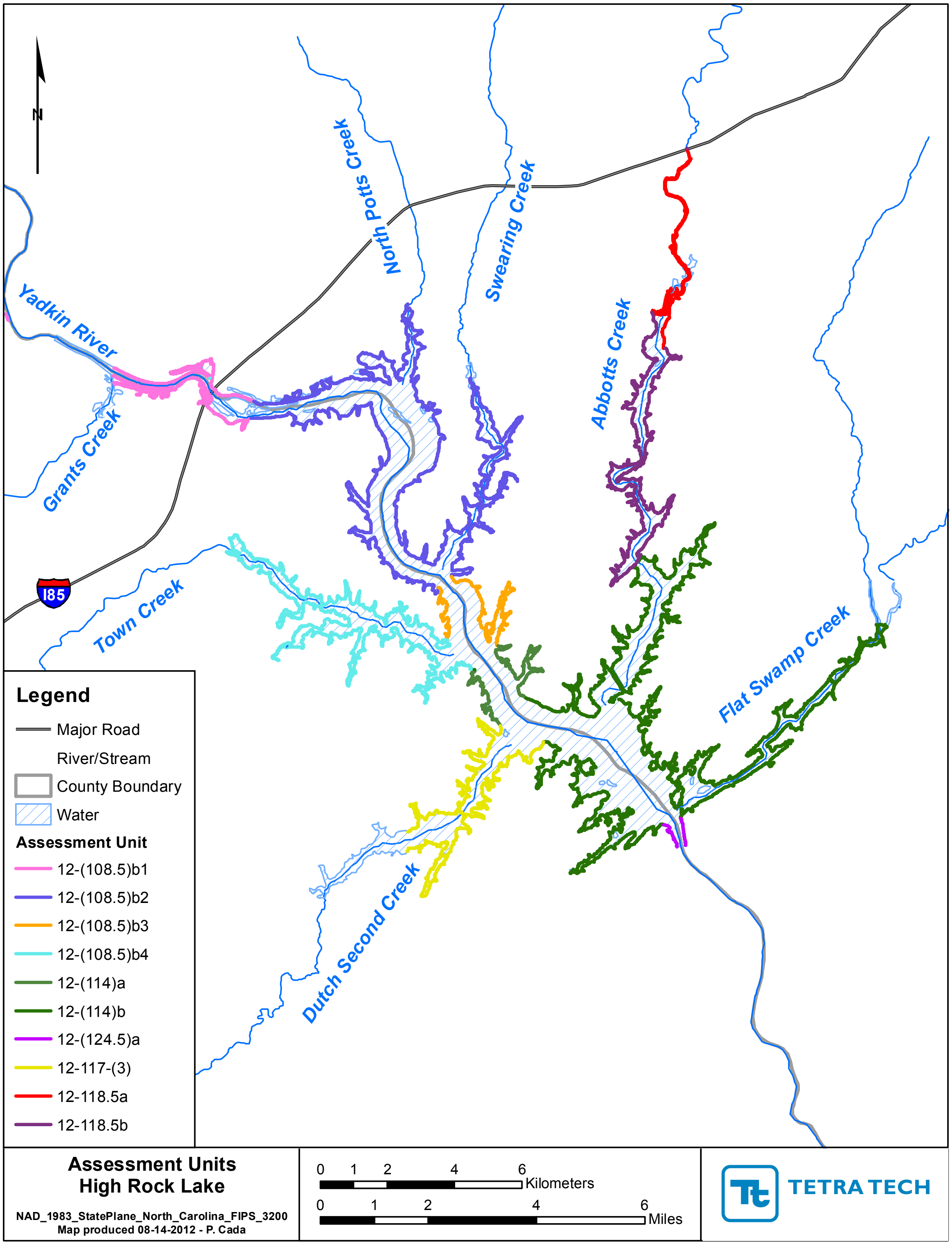

Figure 2-1. High Rock Lake Assessment Units

Table 2-2. Description of High Rock Lake Assessment Units and List of Impairments

Description	Segment ID	Classifi-cation	Listed for chlorophyll *a*	Listed for turbidity	Listed for pH
Yadkin River from mouth of Grants Creek to Buck Steam Station	12-(108.5)b1	WS-V	**X**	**X**	**X**
Yadkin River from Buck Steam Plant to a line across High Rock Lake from downstream side of mouth of Swearing Creek	12-(108.5)b2	WS-V	**X**	**X**	
Yadkin River from downstream of mouth of Swearing Creek arm of High Rock Lake to downstream side of the mouth of Crane Creek arm of High Rock Lake	12-(108.5)b3	WS-V	**X**	**X**	**X**
Crane Creek arm of High Rock Lake	12-(108.5)b4	WS-V	**X**	**X**	
Yadkin River from a line across High Rock Lake from the downstream side of the mouth of Crane Creek to Second Creek arm of High Rock Lake	12-(114)a	WS-IV, B	**X**	**X**	**X**
Yadkin River from Second Creek arm of High Rock Lake to above dam	12-(114)b	WS-IV, B	**X**		**X**
Second Creek arm of High Rock Lake from a point 1.7 miles downstream of Rowan County SR 1004 to High Rock Lake	12-117-(3)	WS-IV, B	**X**		**X**
Abbotts Creek arm of High Rock Lake from source at I-85 to NC 47.	12-118.5a	WS-V, B	**X**		
Abbotts Creek arm of High Rock Lake from NC 47 to Davidson County SR 2294	12-118.5b	WS-V, B	**X**	**X**	
Yadkin River from a point 0.6 miles upstream of dam of High Rock Lake to High Rock dam	12-(124.5)a	WS-IV, B; CA	**X**		**X**

3 Watershed Model Development

The watershed model links conditions and activities on the land surface to responses in the streams and delivery to the lake. The development of a comprehensive watershed model requires data from multiple sources. Gathering the necessary data, processing and assessing it, and finally developing it into a form for model input or use in comparison represents a significant effort. The data collection effort for this study included flow gaging and stream water quality monitoring. Geographic information system (GIS) data are used to describe land, soil, elevation, reach length and more for the watershed model. Rainfall-runoff models require detailed weather time series as input. Point source discharges (flow and water quality) and water withdrawals are also important to the water and pollutant balances.

The following sections introduce the watershed model, and then briefly discuss data sources and data processing for model development. The process for model calibration and validation is described in Section 4, while the calibration and validation results are presented in Section 5.

3.1 MODEL SELECTION

Simulation of flow, erosion, sediment transport, and the loading, transport, and transformation of nutrients in the High Rock Lake watershed was accomplished through an application of the Hydrologic Simulation Program - FORTRAN (HSPF; Bicknell et al., 2001). HSPF is a comprehensive, EPA-supported watershed modeling package that can simulate water quantity and quality for a wide range of pollutants. HSPF was selected for this study because of its capability to assess the impact of point and nonpoint sources in a large watershed with varying land cover and management conditions along with its long history of application for TMDLs and water supply protection studies.

In HSPF, a subwatershed is typically conceptualized as a group of various land uses all routed to a representative stream segment. Several small subwatersheds and representative streams may be networked together to represent a larger watershed drainage area. Various modules are available and may be readily activated to simulate various processes, both on land and in-stream.

Land processes for pervious and impervious areas are simulated through water budget, sediment generation and transport, and water quality constituents' generation and transport. Hydrology is modeled as a water balance in multiple surface and soil layer storage compartments. Interception, infiltration, evapotranspiration, interflow, groundwater loss, and overland flow processes are considered. Sediment production is based on detachment and/or scour from a soil matrix and transport by overland flow in pervious areas, whereas solids buildup and washoff is simulated for impervious areas. HSPF includes agricultural components for land-based nutrient and pesticide processes and a Special Actions block for simulating management activities. HSPF also simulates the in-stream fate and transport of a wide variety of pollutants, such as nutrients, sediments, tracers, dissolved oxygen/biochemical oxygen demand, temperature, bacteria, and user-defined constituents.

HSPF has been widely reviewed and applied throughout its long history (Hicks, 1985; Ross et al., 1997; and Tsihrintzis et al., 1996). One of the largest applications of the model was to the Chesapeake Bay watershed, as part of the EPA's Chesapeake Bay Program's management initiative (Donigian, 1990, 1992). An extensive HSPF bibliography has been compiled to document model development and application and is available online at http://hspf.com/hspfbib.html.

3.2 SIMULATION PERIOD

The watershed model simulation period was selected to be from January 1, 1999 through March 31, 2010, with 1999 being used as a spin-up year for the simulation. This covers the period during which most of the water quality data for the watershed and lake have been collected and also coincides with the 2006-2007 land cover information. A minimum of a 10-year simulation period for watershed models is appropriate to represent a range of wet and dry years. The simulation period includes four dry years

(2000 – 2002 and 2007) and one atypically wet year (2003) which included a significant flood event in South Yadkin River in March 2003.

For the High Rock Lake application, model simulation is conducted at an hourly time step. This enables evaluation of hydrograph response to individual storm events in larger streams while maintaining fast and efficient model run times

3.3 MODEL SEGMENTATION

3.3.1 Subbasin Delineation

The watershed area included in the HSPF model covers 3,607 square miles and extends from the outlet of the W. Kerr Scott Reservoir dam to High Rock Lake.

The USGS 12-digit hydrologic catalog unit (HUC12) GIS coverage (http://water.usgs.gov/GIS/huc.html) was used as a starting basis for watershed delineations and was manually revised to create model subbasins (Figure 3-1). The HUC12 polygons were manually edited to develop model subbasins based on hydrologic model connectivity and the presence of flow gaging stations, water quality observation stations, and/or point source dischargers. The National Hydrography Dataset (NHD) reach (stream) coverage (http://www.horizon-systems.com/nhdplus/) and the national Elevation Dataset (NED) 30-meter grid coverage (http://ned.usgs.gov/) were used to determine connectivity and refine watershed boundaries where the HUC12 polygons were altered.

The resulting model consists of 145 subbasins and accompanying model reaches (Figure 3-1). They range in size from 0.3 to 93 square miles with an average size of 25 square miles.

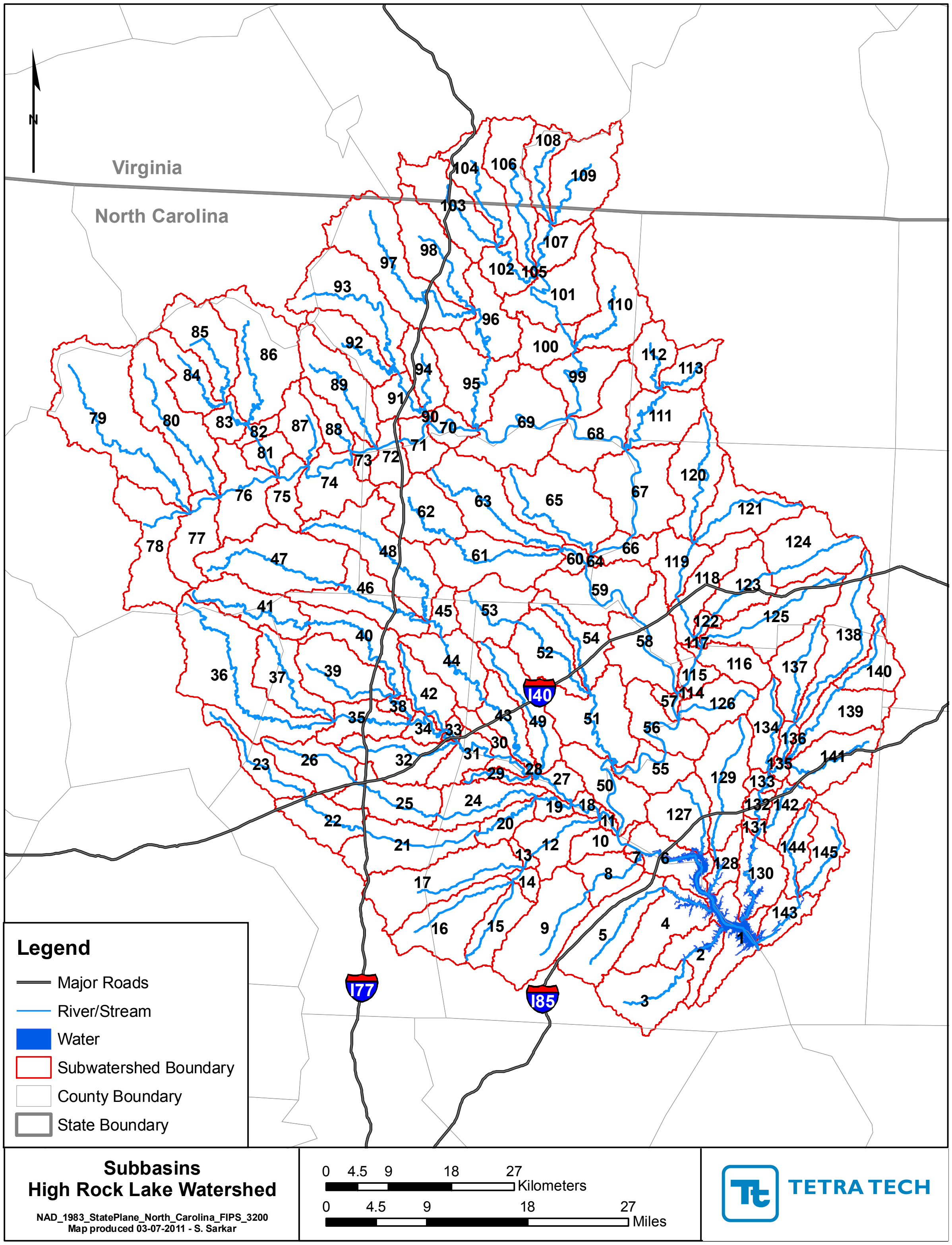

Figure 3-1. Watershed Model Subbasin Delineations for High Rock Lake Watershed

3.3.2 Reach Hydraulics

HSPF models hydrology, but does not directly simulate hydraulics. That is, the model is based on the principal of conservation of mass, but not the conservation of momentum. Hydraulic details, such as the speed of propagation of flood waves, have little impact on the water balance at time steps of a day or longer; however, hydraulics have important impacts on the energy exerted by flow, which is crucial to the examination of sediment scour and deposition. Therefore, it is important to incorporate a strong hydraulic representation in HSPF models that are designed for simulation of sediment transport.

In HSPF, the hydraulic behavior of stream reaches is specified externally through use of Functional Tables (FTables) that define stage-storage-discharge relationships. This is essentially a lookup table that enables the program to determine via interpolation, given an instantaneous value of storage in the reach, what is the corresponding depth, surface area, wetted perimeter, outflow, and flow velocity. Where available, this information can be developed directly from a hydraulic model, such as HEC-RAS. For reaches without such models, the BASINS interface develops FTables based on regional regressions to drainage area.

HEC-RAS (Brunner, 2010) is a one-dimensional hydraulic model of water flowing through natural channels that is typically used for floodplain delineation studies. Capable of modeling complex stream networks, dendritic systems or a single river reach, HEC-RAS is typically used for channel flow analysis and floodplain determination. HEC-RAS applications provide an excellent basis for creating the FTables at selected points within a stream network. The accuracy of the generated FTable is dependent upon the spacing and number of HEC-RAS cross sections throughout a stream network, as well as the accuracy of the measured flows used to correlate river stage to discharge. If several measured flows are provided with a HEC-RAS model (e.g., flows from the 10-, 50-, 100-, 500-year return periods), the HSPF modeler can interpolate additional flows using percent differences in order to complete enough points in an FTable.

For High Rock Lake watershed, Tetra Tech obtained all available HEC-RAS models from the Floodplain Mapping in the NC Division of Environmental Management. These cover portions of the Yadkin River, South Yadkin River, Flat Swamp Creek, Fourmile Branch, and Second Creek.

To use HEC-RAS to generate FTables, additional flow profiles are created for every flow change point along a modeled reach in order to account for lower flows and improve FTable accuracy. Most HEC models already contain several observed flow profiles for various flood return periods (e.g., 10-, 50-, 100-, 500-yr storms); however, more flow profiles are needed to create an FTable, and Tetra Tech developed additional flow profiles (ranging between base flow and the 500-yr event peak flow) starting with the most upstream cross section. Finally, downstream flows are calculated for each flow change point and flow profile using the mean percent flow change values.

For each flow profile, HEC-RAS models provide the following water surface profile outputs for FTable generation:

- Q Total – total flow in cross section (cfs)
- Length Wt – weighted cross section reach length based on flow distribution (ft)
- Max Chl Dpth – maximum main channel depth (ft)
- SA Total – cumulative surface area for entire cross section from the bottom of the reach (acres)
- Volume – cumulative volume of water in the direction of computation (acre-ft)

Each point (or flow profile) representing the discharge-storage-surface area relationship by computed FTable is thus a weighted average of channel stage and discharge that is based on the weighted cross section reach length within the entire modeled reach. Also included for each flow profile in the FTable are the cumulative surface area and water volume between the reaches' upstream and downstream cross section. The HEC-RAS model provides FTables for 26 out of the 145 HSPF reaches, including most of the major model segments. Headwater segment FTables were derived primarily with the BASINS default method.

The watershed contains numerous small ponds and reservoirs, most of them at a scale too small to be appropriate to include explicitly within the model. Instead, these were represented as a water land use. The one exception is Lake Thom-A-Lex, which is included in model reach 136 of the Abbotts Creek drainage. The FTable for this reach was modified to account for the storage characteristics of Lake Thom-A-Lex. In addition, parameters for this reach were modified to allow for lake (rather than stream) reaeration and algal growth.

3.4 UPLAND REPRESENTATION

3.4.1 Land Cover and Imperviousness

To support model development, a grant was awarded under Section 319 of the Clean Water act to the North Carolina Center for Geographic Information and Analysis (CGIA) to develop land cover and impervious area coverages for the state of North Carolina using 2006 and 2007 satellite imagery (http://www.cgia.state.nc.us/). The spatial data for High Rock Lake watershed are shown in Figure 3-2 and Figure 3-3.

With the exception of NC DOT (road right of way), the land cover classification scheme was adopted from the USGS National Land Cover Database (NLCD) 2001 classification descriptions (http://www.mrlc.gov/nlcd2001.php). The land cover and imperviousness were further revised by NC DOT to better represent DOT areas in the High Rock Lake watershed (NCDOT, 2009a). The percent impervious area was uniquely specified for each delineated subbasin based on the distribution of imperviousness and developed land cover class.

The land cover consists of 16 categories, which are presented in Table 3-1. Areas in each land cover class are summarized by percentage in Table 3-1. Tilled cropland ("crop") is a relatively minor portion of the watershed; however, there are extensive areas in hay and pasture. The satellite imagery does not provide a basis to distinguish hay production, fallow and recently abandoned fields, and active pasture from one another. The United States Department of Agriculture, National Agricultural Statistics Service (USDA NASS, http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats_1.0/index.asp) was used to corroborate and revise the assignment of agricultural land in the model. Based on the 2000 through 2008 agricultural statistics reported by county, the model assignment of crop area was increased by a small amount with a similar reduction to the pasture area, resulting in a net change for crop from 2.1 to 2.2 percent of the watershed area.

For roads, NCDOT determined that approximately 95 percent of NCDOT-managed road miles within the watershed are paved. As a result, unpaved roads were not simulated as a separate class. Unpaved roads may be locally important as sediment sources, but are unlikely to be a significant factor in the sediment budget of the whole watershed.

Table 3-1. Land Cover Categories

Category ID	Land Cover Description	Percent of Total Land Cover
11	Open Water	1.1%
21	Developed Open Space	9.0%
22	Low Intensity Developed	7.4%
23	Medium Intensity Developed	1.3%
24	High Intensity Developed	0.5%
29	NCDOT (road right of way)	2.4%
31	Barren	0.1%
41	Deciduous Forest	25.9%
42	Evergreen Forest	13.5%
43	Mixed Forest	4.5%
52	Scrub	0.9%
71	Grassland	0.4%
81	Pasture/Hay	30.5%
82	Crop	2.1%
90	Woody Wetland	0.4%
95	Emergent Herbaceous Wetland	0.0%

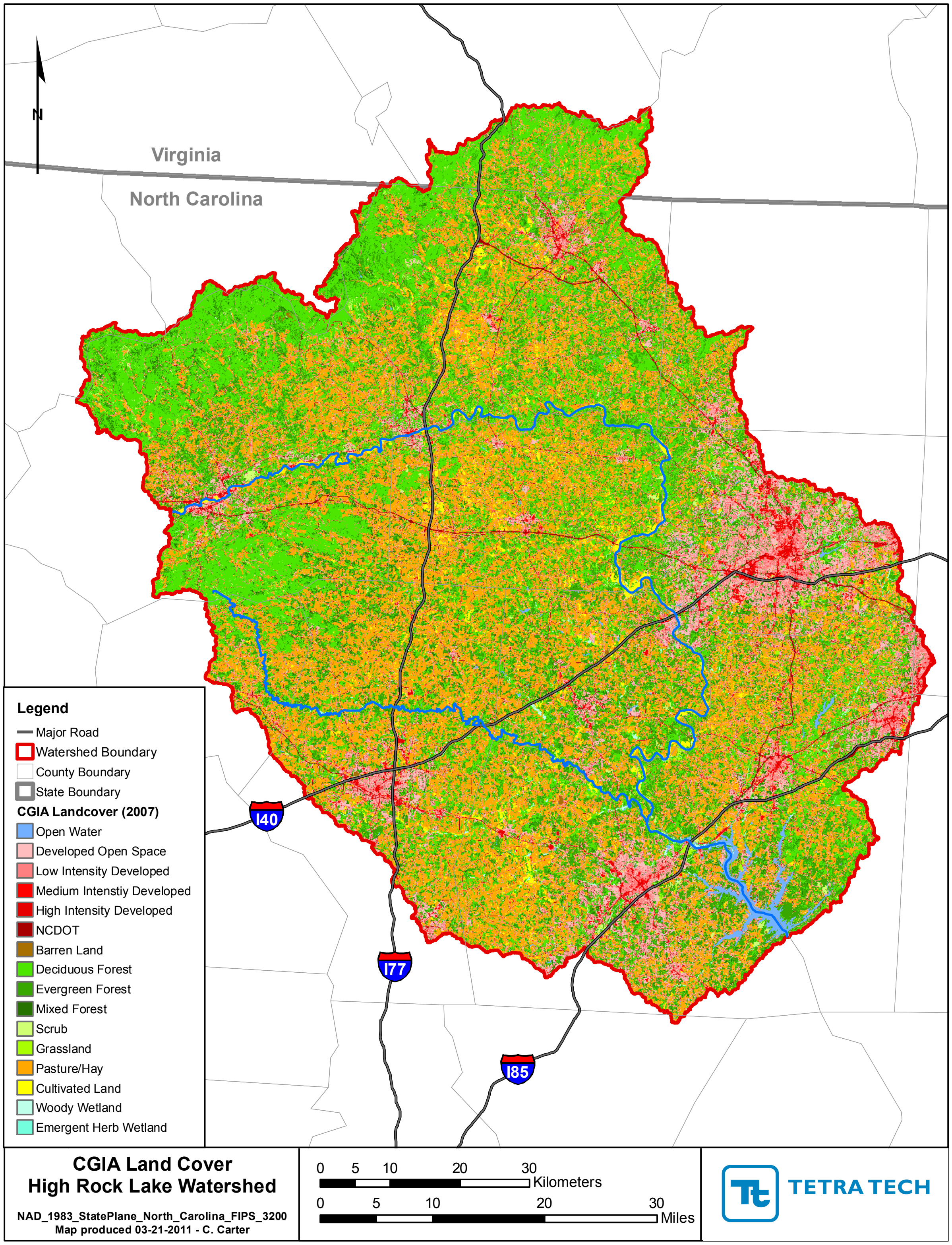

Figure 3-2. Land Cover for High Rock Lake Watershed, 2006-2007 Imagery

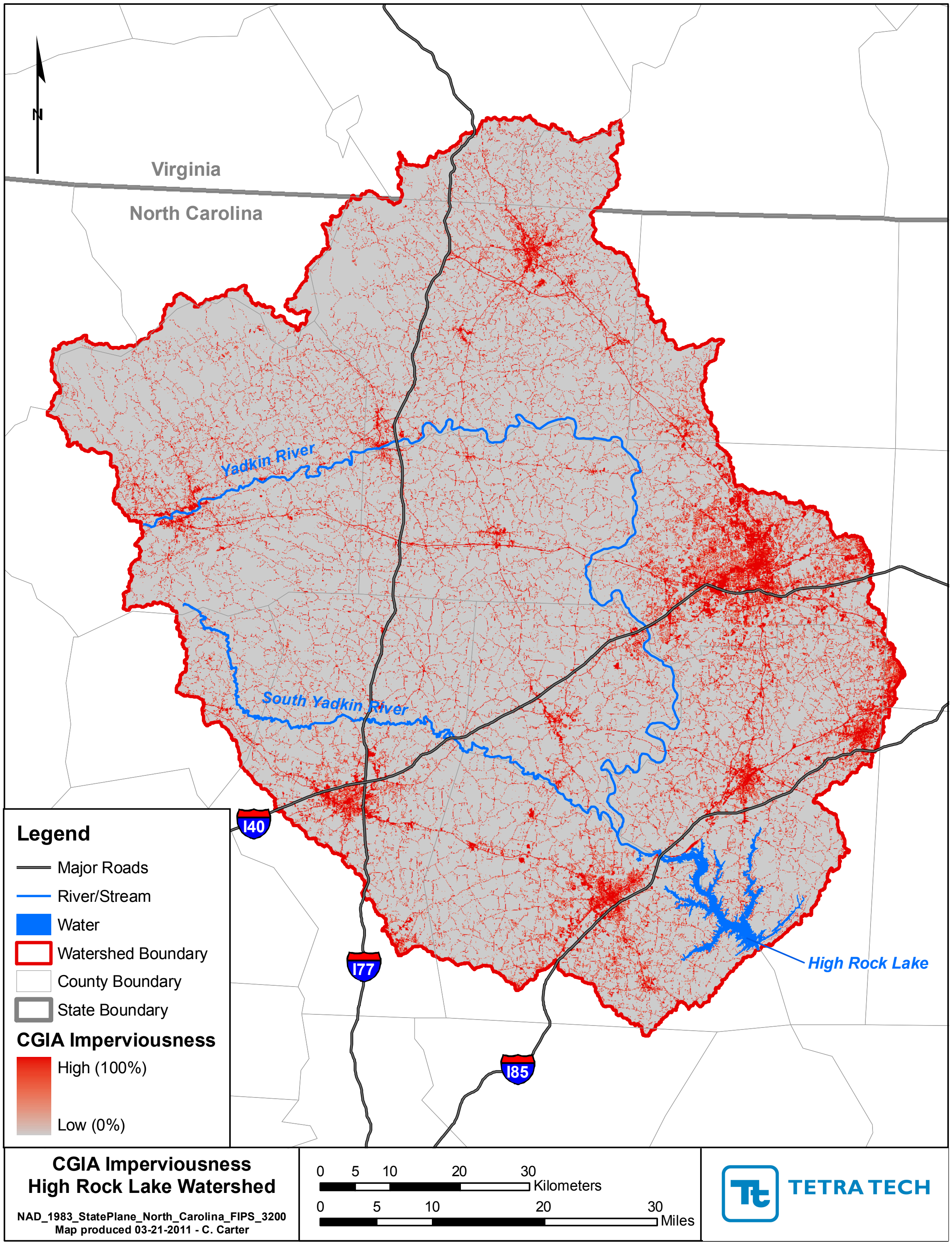

Figure 3-3. Estimated Imperviousness for High Rock Lake Watershed

3.4.2 Soils

The USDA SSURGO and STATSGO soil polygons for the study area were downloaded from the NRCS Geospatial Data Gateway (http://datagateway.nrcs.usda.gov/). The corresponding state template databases were downloaded from the NRCS Soil Data Mart (http://soildatamart.nrcs.usda.gov/). The soils coverage was geoprocessed with the model subbasins to assess the dominant hydrologic soil group (HSG) in the High Rock Lake watershed. The general descriptions of the HSG categories are shown in Table 3-2.

Table 3-2. Description of Hydrologic Soil Groups (USDA, 1986)

Hydrologic Soil Group	Description	Soil Texture
A	Low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well- to excessively-drained sand or gravel and have a high rate of water transmission (greater than 0.30 in/hr).	Sand, loamy sand, or sandy loam
B	Moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (0.15-0.30 in/hr).	Silt loam or loam
C	Low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission (0.05-0.15 in/hr).	Sandy clay loam
D	High runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0-0.05 in/hr)	Clay loam, silty clay loam, sandy clay, silty clay, or clay

HSG B was the dominant category in the study area (Table 3-3) and collectively HSG's B and C accounted for 95 percent of the watershed (Figure 3-4). Therefore those two hydrologic soil groups were adopted for the modeling work. Small areas of A soils were combined with the B soils, while any D soils were combined with the C soils.

Table 3-3. Hydrologic Soil Group Distribution in Study Area

Hydrologic Soil Group	Percent of Study Area
B	81 %
C	14 %
Remaining	5 %

The soils coverage was also used to help constrain input parameters for the sediment simulation. The Soil Data Viewer, an extension to ArcGIS maintained by NRCS, was utilized to create soil-based maps. In the absence of the SSURGO dataset, STATSGO was used. The soil properties grid was intersected with the hydrologic response unit grid (HRU) (see Section 3.4.34) to determine HRU specific soil properties. These properties include soil erodibility factor (K), available water content (AWC) to 100 cm depth, soil organic carbon (SOC) to 100 cm depth, percent sand, percent silt and percent clay.

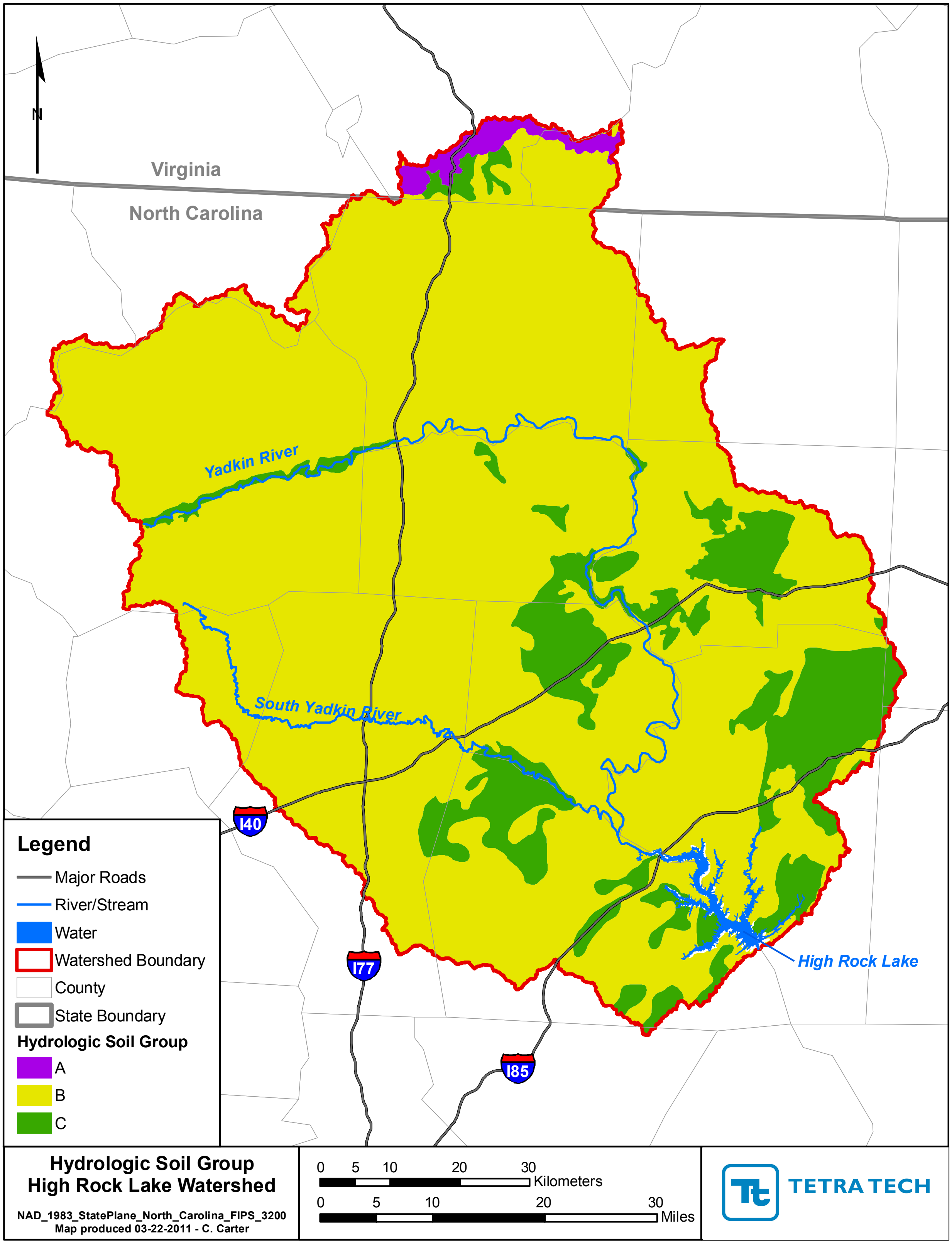

Figure 3-4. Hydrologic Soil Groups in the High Rock Lake Watershed

3.4.3 Animal Operations

The North Carolina Division of Soil and Water Conservation (DSWC) produced rapid watershed assessment documents for the three HUC8s of the study area in February 2007 (DSWC, 2007a, 2007b, 2007c). The reports generally describe the HUC8s and provide characteristic information such as land cover distribution, point sources, and agriculture operations. The reports also indicate resource concerns and existing conservation programs. Animal operations were cited in each of the three reports produced by DSWC as a cause for concern related to water quality. There was not enough information available to explicitly represent the impact of animal operations in the watershed model; instead, loading associated with animals on pasture is incorporated into the general pasture land use classification. Manure from confined animals is typically used as fertilizer and spread on cropland and is thus incorporated into the crop land use classification. For example, the South Yadkin River watershed had relatively higher animal counts and this knowledge was used to set the parameters in the model which affected pollutant loading. In support of the findings in the DSWC reports, an exercise was conducted to explore potential contributions of nutrients from animal operations. This used cattle and chicken populations as shown in the National Agricultural Census as indicators of the density of all farm animals. The results of this exercise are presented in Appendix D. Although animal operations could not be explicitly represented in the model, this exercise serves a useful first-step in understanding their potential contributions.

3.4.4 Hydrologic Response Units

The watershed land surface was represented on a hydrologic response unit (HRU) basis in the model. Each HRU represents a unique combination of land use/cover and soil properties associated with a specific set of meteorological time series data.

Hydrology and pollutant load generation characteristics depend largely on the interaction of land cover and soil characteristics. The land cover information was overlain with information on hydrologic soil group (HSG) from the soils coverage to develop HRUs, as shown in Table 3-4.

The original CGIA land cover categories were combined to simplify the development of model input while maintaining significant land cover categories. As stated above, the CGIA land cover was revised by DOT to incorporate DOT right-of-way and imperviousness. The revised land cover, hydrologic soil group, and MS4 boundaries were used to help create model land units, the intermediate step in developing HRUs.

Individual HRUs were also referenced to a specific weather station. The weather station assignments to model land units were based on a nearest neighbor approach. Table 3-4 also summarizes how raw land cover categories were combined for use in the model environment to meet the limit on the number of operations in HSPF and combine categories that are expected to have similar characteristics.

Table 3-4. Conversion of CGIA Land Cover Classes and Soil Hydrologic Groups to Model Hydrologic Response Units

Land Cover Class	Land Cover Area (Percent)	Model Land Unit (MLU)	Comment
11 Open Water	1.1	01 Water	Most of the water surface area is accounted for as stream reaches; the remainder is classified as an upland land use.
21 Developed Open Space	9.0	02 Urban 03 MS4 Urban	Urban land was not designated as HSG B or C because they are considered disturbed lands 02 urban is for land outside of MS4 boundaries 03 MS4 urban is for land inside of MS4 boundaries
22 Low Intensity Developed	7.3		
23 Medium Intensity Developed	1.3		
24 High Intensity Developed	0.4		
29 NCDOT	2.4	04 NCDOT	NCDOT right of way
31 Barren	0.1	02 Urban 03 MS4 Urban	Merged into developed classes due to small area
41 Deciduous Forest	25.9	05 Forest B 06 Forest C	The model land unit of forest was split into HSG B and C
42 Evergreen Forest	13.5		
43 Mixed Forest	4.5		
52 Scrub/Brush	0.9		
71 Grassland	0.4	07 Pasture B 08 Pasture C	The model land unit of pasture was split into HSG B and C
81 Pasture /Hay	30.6		
82 Crop	2.2	09 Crop B 10 Crop C	The model land unit of crop was split into HSG B and C
90 Woody Wetland	0.4	01 Water	The wetland categories were lumped into water because of the small percentage of the study area
95 Emergent Herbaceous Wetland	~0.0		

3.5 WEATHER DATA

Weather data are the primary forcings that drive simulations in water resources model applications. The gathering of observed data and processing represents a significant component of input file development. Weather data needed for the models were gathered from multiple agencies. Generally, the data from the various sources must be brought to a common format, processed for error checking, used to calculate other weather parameters, and then developed into a model specific format.

Model setup used 18 weather zones based on an initial analysis of available precipitation stations. These 18 zones complete the HRU specification – that is, each soil/landuse combination is assigned to one of the 18 weather zones using a Thiessen polygon (nearest neighbor) approach (Figure 3-5). Subsequent analysis revealed that three of the 18 candidate precipitation stations (those associated with zones 1, 2, and 3) did not have a sufficient period of quality data to support model runs over the full validation and calibration periods. These areas were assigned to adjacent precipitation stations, so a total of 15 precipitation records are actually used in the model (see Section 3.5.3 for weather data assignments.)

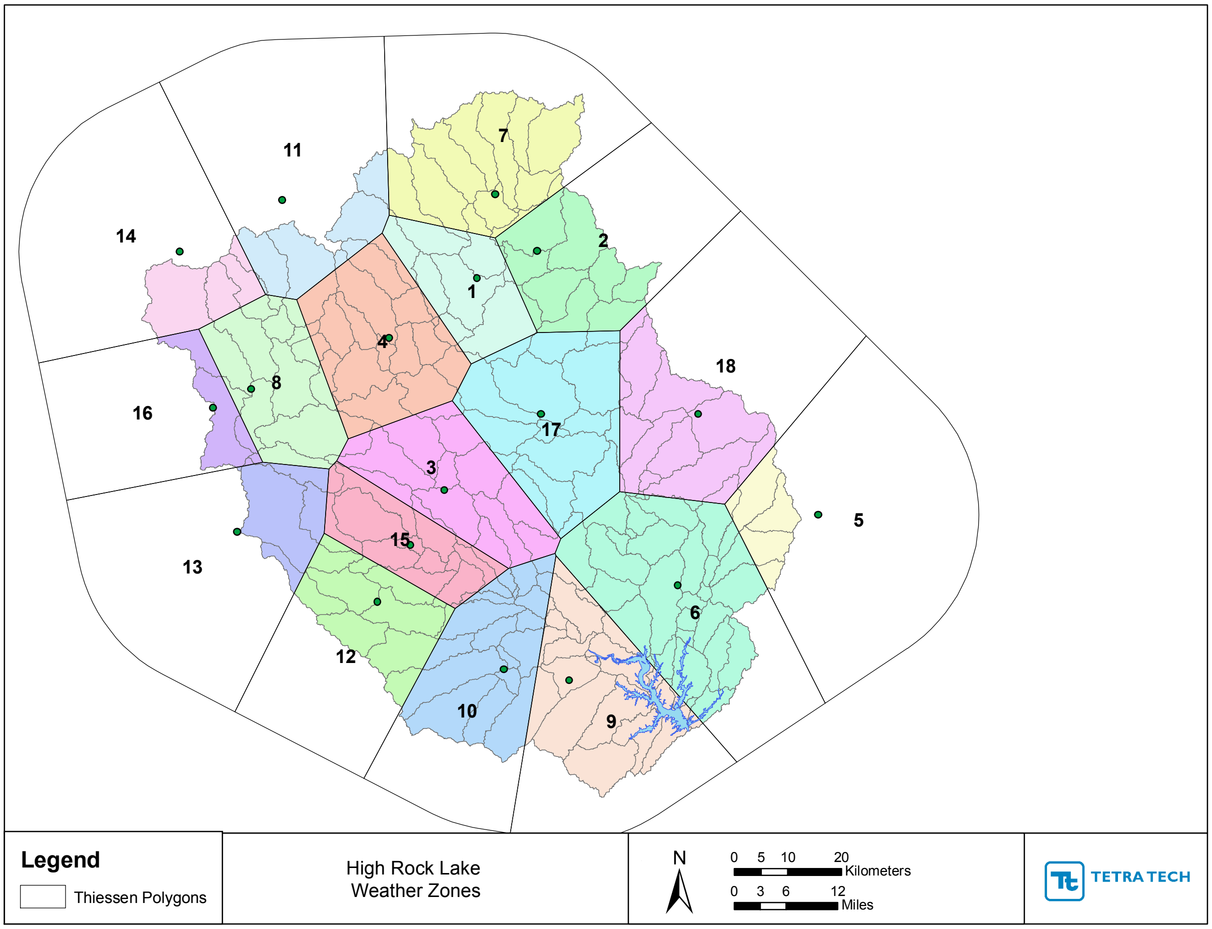

Figure 3-5. Assignment of Weather Zones in the High Rock Lake Model

3.5.1 Weather Data Sources

Weather data needs for this study include rainfall, potential evapotranspiration, air temperature, dewpoint temperature, solar radiation, cloud cover, and wind. Most of the needed constituents are observed but a few need to be calculated. Data were obtained from North Carolina State Climate Office (NCSCO, http://www.nc-climate.ncsu.edu/), National Climatic Data Center (NCDC, http://www.ncdc.noaa.gov/oa/ncdc.html), and EarthInfo CD dataset (EarthInfo, 2009, http://www.earthinfo.com/index.htm). These data were reviewed and processed to fill missing periods and distribute accumulated records.

Data were gathered from a variety of sources which resulted in sufficient observed weather data but also required more processing due to the varied formats. The primary dataset for the weather stations developed into watershed model input were the Summary of the Day (SOD) weather data maintained by the National Climate Data Center (NCDC). The NCDC SOD data were obtained from the EarthInfo CD set (EarthInfo, 2009) and the NCSCO. The NCDC Hourly Precipitation Data (HPD) and Surface Airways (SA) data were used for each hourly precipitation pattern along with other hourly meteorological constituents. The HPD data were obtained from the EarthInfo CD set and the SA data were obtained from an NCDC web subscription.

The Summary of the Day (SOD) stations report daily precipitation totals, maximum daily air temperature, and minimum daily air temperature. The SOD stations have the greatest spatial coverage for the study area. The HPD stations record rainfall amounts on an hourly basis; however their spatial coverage is much less than SOD stations. Furthermore, SOD precipitation totals had fewer issues of data integrity than HPD precipitation totals and so the HPD records were used only in the disaggregation step of the patching process. The SA data provided the least spatial coverage and generally SA stations are located at airports. Table 3-5 and Table 3-6 summarize the data elements needed in this study and indicate which data source reports those elements. Information pertaining to processing the weather data in preparation for model input can be found in Appendix A.

Table 3-5. Summary of Observed Data Elements by Source

Element	Summary of the Day (SOD)	Hourly Precipitation Data (HPD)	Surface Airways (SA)
Precipitation	Daily	Hourly	Hourly
Air Temperature	Daily maximum and minimum	NA	Hourly
Dewpoint Temperature	NA	NA	Hourly
Relative Humidity	NA	NA	Hourly
Wind Speed and Direction	NA	NA	Hourly
Pressure	NA	NA	Hourly

Table 3-6. Summary of Calculated Elements by Source

Element	Summary of the Day (SOD)	Hourly Precipitation Data (HPD)	Surface Airways (SA)
Cloud condition	NA	NA	Hourly, estimated from sky condition
Potential Evapotranspiration	NA	NA	Hourly, calculated from air temperature, dewpoint, wind, solar radiation, and coefficients
Solar Radiation	NA	NA	Hourly, calculated from latitude, date-time, and cloud cover

3.5.2 Weather Data Summary

3.5.2.1 Precipitation

The precipitation forcing in the weather input file is a primary forcing for the watershed model application. Particular attention was given to the source precipitation records to assess their integrity and repair records. Rainfall records were repaired, or patched, if the data flags present with the source data indicated data was missing or deleted. Time series precipitation records at 15 stations were patched for use in watershed model application for this study. Appendix A contains annual plots of precipitation totals both before and after patching, along with an indication of the percent of a record that was in need of repair.

The annual totals for four of the 15 patched precipitation records (with partial year totals for 2010), are shown in Table 3-7. Generally there was a 3-year period of low rainfall (2000-2002) followed by significant rainfall in 2003. 2007- 2008 also appear to be a period of low rainfall.

Table 3-7. Annual Precipitation (in/yr)

Station Name	Mt Airy 2 W	Statesville 2 NNE	W Kerr Scott Res	Yadkinville 6 E
Station ID	**315890**	**318292**	**319555**	**319675**
2000	36.0	34.3	38.3	37.5
2001	39.9	31.2	43.7	27.6
2002	41.9	44.9	44.2	47.1
2003	70.0	61.2	61.9	62.3
2004	47.5	44.8	45.6	43.8
2005	43.2	42.0	41.3	47.2
2006	48.2	40.2	43.8	41.8
2007	44.9	33.4	36.4	40.4
2008	37.7	41.8	45.6	40.9
2009	56.1	53.0	65.0	51.5
2010 (Jan–Mar)	14.0	12.7	15.2	13.1

Note: Partial year totals for 2010

Precipitation records driving the model are primarily derived from Summary of the Day records as hourly data are available at only a limited number of stations. These records are subject to repair of missing or deleted periods and disaggregation from daily totals to hourly values based on a limited number of hourly stations. The true sequence of rainfall intensities at these daily stations is unknown. In addition, the point measurements at rainfall stations are not fully representative of the average rainfall across the surrounding area, especially during summer convective storms. These issues introduce uncertainty into the hydrologic simulation.

3.5.2.2 Potential Evapotranspiration

The potential evapotranspiration time series forcing, along with precipitation, is important to the hydrologic simulation. It represents the energy available for evaporation and plant transpiration. Potential evapotranspiration was calculated using the Penman Pan method, based on air temperature, dewpoint, wind, and solar radiation, and is not directly observed. Four time series were used for the High Rock Lake HSPF application in an effort to reasonably represent the likely spatial variation of the parameter over the study area. These are summarized in Table 3-8. Generally 2000-2002 and 2007 were the higher magnitude periods, which is consistent with the coincident low rainfall periods.

Table 3-8. Potential Evapotranspiration (in/yr)

Station Name	Mt Airy 2 W	Statesville 2 NNE	W Kerr Scott Res	Yadkinville 6 E
Station ID	**315890**	**318292**	**319555**	**319675**
2000	36.8	43.7	40.1	37.0
2001	39.5	47.6	43.6	40.3
2002	40.1	46.0	43.8	40.8
2003	35.7	38.3	39.1	36.3
2004	37.3	39.5	40.7	37.5
2005	39.8	42.1	43.5	40.3
2006	42.7	44.7	46.4	42.8
2007	48.3	50.4	51.7	49.3
2008	45.2	47.3	48.6	47.8
2009	40.2	42.1	43.5	42.2
2010 (Jan–Mar)	6.0	6.0	6.2	6.3

3.5.2.3 Air Temperature

The air temperature forcing affects snow melt and water temperature in addition to being used to calculate PET. Snowmelt in this study area is small compared to rainfall across a 10 year period. However, water temperature is important as it impacts dissolved oxygen levels, algae, and many of the instream chemical transformations and processes. Compared to precipitation spatial distributions, air temperature varies less over the study area. The four stations summarized in Table 3-9 are approximately near an elevation of 1,000 feet. The monthly average values are generally within 2°F of each other. The model automatically adjusts temperature for the elevation difference between an HRU and the temperature station using a lapse rate approach.

Table 3-9. Monthly Average (Jan. 2000-Mar. 2010) Air Temperature (°F)

Station Name	**Mt Airy 2 W (Elev 1,041 ft)**	**Statesville 2 NNE (Elev 950 ft)**	**W Kerr Scott Res (Elev 1,070 ft)**	**Yadkinville 6 E (Elev 875 ft)**
Station ID	**315890**	**318292**	**319555**	**319675**
January	35.0	37.0	36.6	35.1
February	37.3	39.5	39.0	37.6
March	45.3	48.0	47.3	46.3
April	55.3	58.1	57.3	56.4
May	62.5	65.1	64.8	63.2
June	71.1	73.3	72.9	71.8
July	73.7	75.8	75.4	74.5
August	74.0	76.0	75.8	74.5
September	66.1	68.1	67.9	66.4
October	54.9	56.7	57.0	54.7
November	46.1	47.4	48.5	46.1
December	36.3	37.7	38.2	36.2

3.5.3 Weather Data Assignments

There are differing numbers of time series for the different meteorological inputs. The series assigned in each weather zone are shown in Table 3-10.

Table 3-10. Assignment of Meteorological Time Series to Weather Zones

Weather Zone	Precipitation	Air Temperature	PET	Wind Speed	Dewpoint	Solar Radiation	Cloud Cover
1	7	7	7	17	17	17	17
2	7	7	7	17	17	17	17
3	15	12	12	17	17	17	17
4	4	16	16	17	17	17	17
5	5	17	17	17	17	17	17
6	6	17	17	17	17	17	17
7	7	7	7	17	17	17	17
8	8	16	16	17	17	17	17
9	9	12	12	17	17	17	17
10	10	12	12	17	17	17	17
11	11	16	16	17	17	17	17
12	12	12	12	17	17	17	17
13	13	12	12	17	17	17	17
14	14	16	16	17	17	17	17
15	15	12	12	17	17	17	17
16	16	16	16	17	17	17	17
17	17	17	17	17	17	17	17
18	18	17	17	17	17	17	17

Index to Stations

Weather Zone	Station ID	Station Name
4	312740	Elkin
5	314063	High Point
6	314970	Lexington
7	315890	Mount Airy 2 W
8	316256	North Wilkesboro
9	317615	Salisbury
10	317618	Salisbury 9 WNW
11	318518	Sparta 2 SE
12	318292	Statesville 2 NNE
13	318519	Taylorsville
14	318694	Transou
15	318778	Turnersburg
16	319555	W. Kerr Scott Reservoir
17	319675	Yadkinville 6 E
18	93807 (KINT)	Winston-Salem Reynolds Airport

3.6 POINT SOURCE DISCHARGES

A review of all NPDES permits for wastewater discharges in the High Rock Lake watershed at any time between 2000 and 2010 resulted in a total of 177 permitted dischargers to be considered for model input. A total of 39 dischargers were selected for inclusion in the model applications (Figure 3-6), representing 98 percent of the total permitted discharge (the percentage tabulation does not include those facilities without assigned flow limits). Generally, a point source had to have a permitted discharge of at least 0.1 million gallons per day (MGD) in order to be included in the model applications. Table 3-11 and Table 3-12 show the dischargers included in the model by major (greater than or equal to 1 MGD) and minor (less than 1 MGD) grouping, respectively.

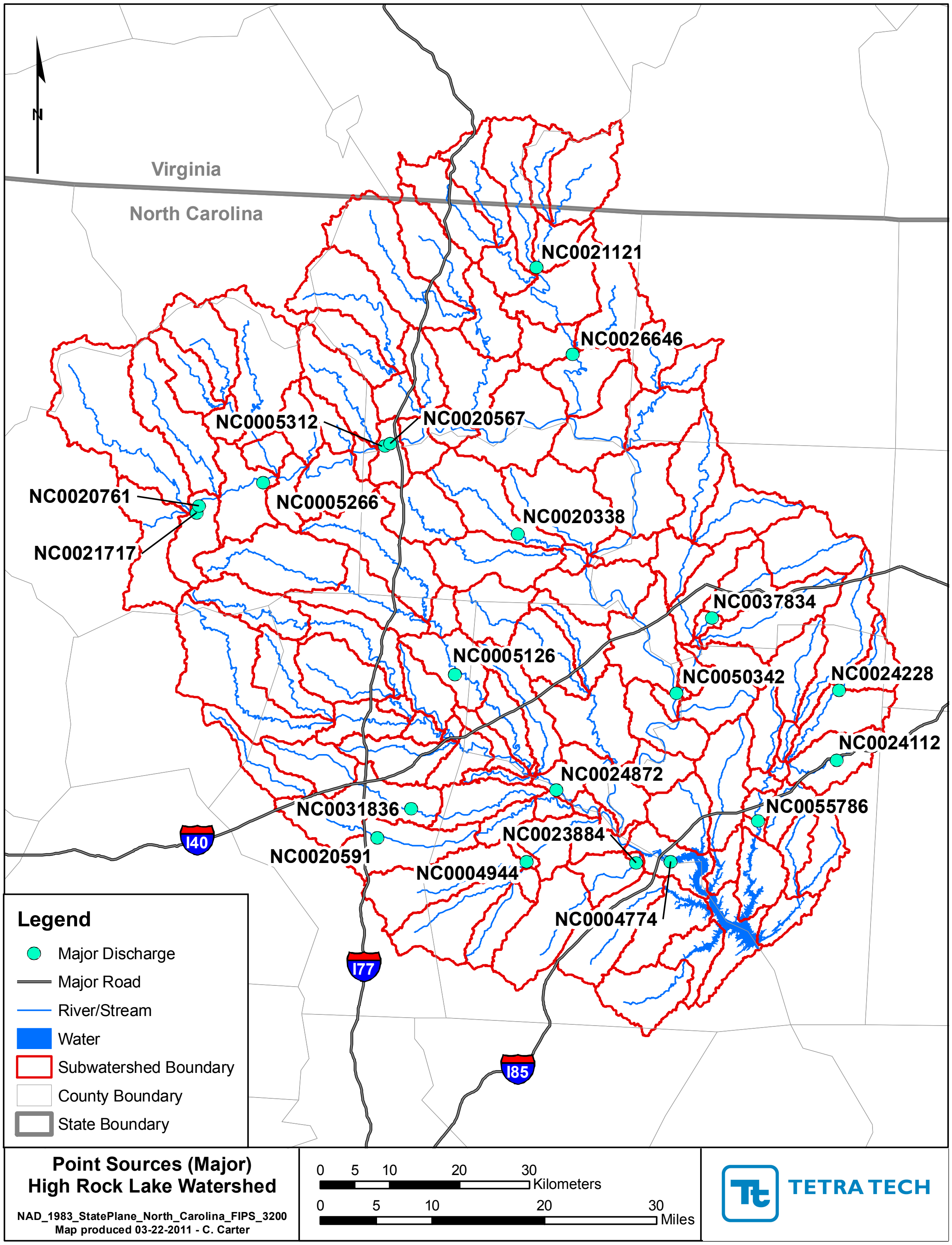

Figure 3-6. Major Point Source Dischargers in the High Rock Lake Watershed Model

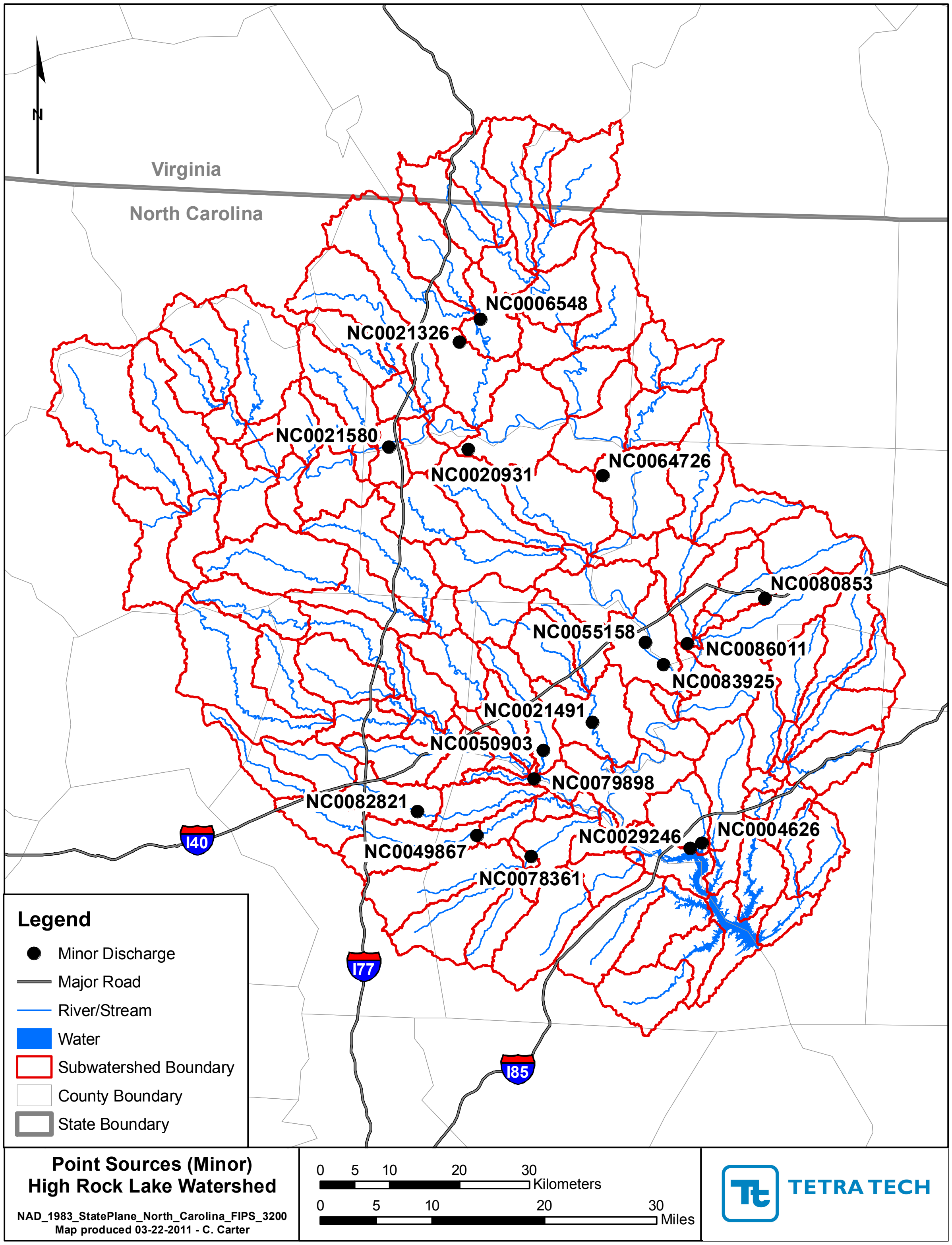

Figure 3-7. Minor Point Source Dischargers in the High Rock Lake Watershed Model

Table 3-11. Major Point Source Dischargers Represented in the High Rock Lake Watershed Model

NPDES ID	Name	Receiving Water	Permitted Flow (MGD)	Comment
NC0004774	Duke Energy Corp. Buck Steam Station	High Rock Lake	No limit (cooling water)	Industrial process
NC0004944	Invista, S.A.R.L. Salisbury Plant	Second Creek (North Second Creek)	2.3	Industrial process
NC0005266	Louisiana Pacific ABT Co. Mill	Yadkin River	1.0	Industrial process
NC0005312	Interface Fabric Elkin, Inc. WWTP	Yadkin River	4.0	Municipal wastewater
NC0005487	Color/Tex Finishing Corporation (inactive)	High Rock Lake	4.25	Industrial process
NC0020338	Town of Yadkinville WWTP	North Deep Creek	2.5	Municipal wastewater
NC0020567	Town of Elkin WWTP	Yadkin River	1.8	Municipal wastewater
NC0020591	City of Statesville Third Creek WWTP	Third Creek	4.0	Municipal wastewater
NC0020761	Town of North Wilkesboro Thurman St WWTP	Yadkin River	2.0	Municipal wastewater
NC0021121	City of Mount Airy WWTP	Ararat River	7.0	Municipal wastewater
NC0021717	Town of Wilkesboro Cub Creek WWTP	Yadkin River	4.9	Municipal wastewater
NC0023884	Salisbury-Rowan WWTP[1]	High Rock Lake	20.0	Municipal wastewater
NC0023884	City of Salisbury Grants Creek WWTP (inactive)[1]	Grants Creek	7.5	Municipal wastewater
NC0023892	Town Creek WWTP (inactive)[1]	Town Creek	5.0	Municipal wastewater
NC0024112	City of Thomasville Hamby Creek WWTP	Hamby Creek	4.0	Municipal wastewater
NC0024228	City of High Point Westside WWTP	Rich Fork	6.2	Municipal wastewater
NC0024872	Davie County Cooleemee WWTP	South Yadkin River	1.5	Municipal wastewater
NC0026646	Town of Pilot Mountain WWTP	Ararat River	1.5	Municipal wastewater
NC0031836	City of Statesville Fourth Creek WWTP	Fourth Creek	4.0	Municipal wastewater
NC0037834	City of Winston-Salem Archie Elledge WWTP	Yadkin River	30.0	Municipal wastewater
NC0050342	City of Winston-Salem Muddy Creek WWTP	Muddy Creek	21.0	Municipal wastewater
NC0055786	City of Lexington WWTP	Abbotts Creek	5.5	Municipal wastewater

[1] Salisbury-Rowan WWTP merged the City of Salisbury Grants Creek WWTP (7.5 MGD) and Town Creek WWTP (5.0 MGD). The City of Salisbury Grants Creek WWTP outfall was last used in October 1998 and the Town Creek WWTP outfall was last used in August 2000.

Table 3-12. Minor Point Source Dischargers Represented in the High Rock Lake Watershed Model

NPDES ID	Name	Receiving Water	Permitted Flow (MGD)	Comment
NC0004626	PPG Industries Fiber Glass – Lexington Facility	North Potts Creek	0.60	Industrial process
NC0005126	Tyson Foods Inc. Harmony Plant	Hunting Creek	0.50	Industrial process
NC0006548	Wayne Farms LLC	Fisher River	0.70	Industrial process
NC0006696	Carolina Mirror WWTP (inactive)	Mulberry Creek	0.50	Municipal wastewater
NC0020931	Town of Boonville WWTP	Tanyard Creek (Buck Creek)	0.20	Municipal wastewater
NC0021326	Town of Dobson WWTP	Cody Creek	0.35	Municipal wastewater
NC0021491	Town of Mocksville Dutchman Creek WWTP	Dutchman Creek	0.68	Municipal wastewater
NC0021580	Town of Jonesville WWTP	Yadkin River	0.40	Municipal wastewater
NC0025593	Sowers Ferry Road WWTP (inactive)	-	0.75	Municipal wastewater
NC0029246	Norfolk Southern Corp-Linwood Yard	South Potts Creek	0.32	Industrial process
NC0049867	Town of Cleveland WWTP	Third Creek	0.27	Municipal wastewater
NC0050903	Town of Mocksville Bear Creek WWTP	Bear Creek	0.25	Municipal wastewater
NC0055158	Bermuda Center Sanitary District WWTP	Yadkin River	0.19	Municipal wastewater
NC0078361	Salisbury-Rowan Utilities Second Creek WWTP	Second Creek (North Second Creek)	0.09	Municipal wastewater
NC0079898	Needmore Rd Landfill (HNA Holdings Inc.)	South Yadkin River	0.29	Groundwater remediation
NC0080853	Lucent Technologies Salem Business Park Remediation Site	Salem Creek	0.30	Groundwater remediation
NC0082821	Southern States Coop-Statesville	Fourth Creek	0.14	Groundwater remediation
NC0083925	Heater Utilities Inc., Salem Glen SD WWTP	Yadkin River	0.14	Municipal wastewater

Daily flow values were provided for most of the major dischargers. These records were reviewed for completeness, erroneous values, and repaired as necessary. Effluent water quality data were typically provided on a weekly to monthly basis as concentration. The data reported vary by discharger but may include some or all of the following parameters relevant to the High Rock Lake watershed model: 5-day biochemical oxygen demand (BOD5), flow, ammonia/ammonium nitrogen (NH_3), nitrite plus nitrate nitrogen (NO_2+NO_3), total Kjeldahl nitrogen (TKN, the sum of organic and ammonia nitrogen), total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS). Table 3-13 and Table 3-14 show the number of records by constituent and discharger. The flow records were typically the most complete. Missing or unreported values were estimated by averaging the reported value before and after a gap if the gap was 28 days or less. Otherwise, the last value was used to step fill the gap.

Table 3-13. Number of Daily Records for Major Point Source Dischargers (2000 – 2010)

NPDES ID	Name	BOD5	DO	FLOW	NH_3	NO_2+ NO_3	TKN	TN	TP	TSS
NC0004774-001	Duke Energy Buck Steam (001)	0	0	3,269	0	0	0	0	0	0
NC0004774-002	Duke Energy Buck Steam (002)	0	0	129	0	0	0	123	119	90
NC0004944	Invista, S.A.R.L. Salisbury Plant	0	2,875	3,743	0	0	0	0	0	0
NC0005266	Louisiana Pacific ABT Co. Mill	1,340	2,431	3,543	0	0	0	123	114	5
NC0005312	Interface Fabric Elkin, Inc. WWTP	0	0	3,723	0	0	0	541	506	0
NC0005487	Color-Tex Finishing Corp	103	228	336	0	0	0	46	46	0
NC0020338	Town of Yadkinville WWTP	1,752	2,567	3,740	792	0	0	613	611	1717
NC0020567	Town of Elkin WWTP	1,190	0	3,661	502	0	0	552	533	1577
NC0020591	City of Statesville Third Creek WWTP	2,465	2,706	3,713	888	0	0	488	490	2552
NC0020761	Town of N. Wilkesboro Thurman WWTP	1,605	0	3,743	1,606	0	0	121	123	1595
NC0021121	City of Mount Airy WWTP	2,422	2,561	3,741	1,563	0	0	123	123	2491
NC0021717	Town of Wilkesboro Cub Cr WWTP	2,565	2,572	3,742	2,115	0	0	123	123	2570
NC0023884	Salisbury Rowan WWTP	2,196	2,572	3,743	2,436	6	3	438	436	2572
NC0023892	Salisbury Town Creek WWTP	170	170	244	83	0	0	8	8	170
NC0024112	City of Thomasville Hamby Cr WWTP	2,410	2,970	3,741	2,284	0	0	127	671	2,536
NC0024228	City of High Point Westside WWTP	2,317	3,227	3,743	2,416	314	318	578	579	2,540
NC0024872	Davie County Cooleemee WWTP	1,419	0	3,674	485	0	0	130	129	1,588
NC0026646	Town of Pilot Mountain WWTP	727	1,619	3,741	1,004	1	10	387	391	1,212
NC0031836	City of Statesville Fourth Cr WWTP	2,247	2,550	3,743	1,667	0	0	487	478	2,419
NC0037834	City of W-S Archie Elledge WWTP	2,585	3,740	3,743	2,103	0	0	539	548	3,705
NC0050342-001	City of W-S Muddy Cr WWTP (001)	2,568	3,740	3,743	2,896	0	0	539	550	3,710
NC0050342-002	City of W-S Muddy Cr WWTP (002)	22	20	273	12	0	0	23	23	30
NC0055786	City of Lexington WWTP	1,955	3,123	3,712	2,144	0	0	121	580	2,453

Table 3-14. Number of Daily Records for Minor Point Source Dischargers (2000 – 2010)

NPDES ID	Name	BOD5	DO	FLOW	NH_3	NO_2+NO_3	TKN	TN	TP	TSS
NC0004626	PPG Indus Lex Facility	0	0	1,817	230	275	269	0	278	0
NC0005126	Tyson Foods Inc. Harmony Plant	0	648	1,818	0	0	0	113	80	0
NC0006548	Wayne Farms LLC	648	0	2,847	863	0	0	426	426	647
NC0006696	Carolina Mirror	0	187	988	0	0	0	15	13	73
NC0020931	Town of Boonville WWTP	363	913	3,710	406	1	1	124	124	236
NC0021326	Town of Dobson WWTP	353	1618	3,743	434	0	0	123	123	475
NC0021491	Town of Mocksville Dutchmans Cr WWTP	495	544	3,707	447	0	0	469	466	507
NC0021580	Town of Jonesville WWTP	515	31	3,743	531	15	15	64	88	534
NC0025593	Sowers Ferry Rd WWTP	734	743	1,066	503	0	0	119	121	742
NC0029246-001	NS Corp-Linwood Yard (001)	0	0	59	0	0	0	0	0	2
NC0029246-011	NS Corp-Linwood Yard (011)	44	316	1,647	0	0	0	33	34	34
NC0049867	Town of Cleveland WWTP	505	2,421	3,741	384	0	0	124	128	490
NC0050903	Town of Mocksville Bear Cr WWTP	387	451	3,108	298	0	0	104	103	402
NC0055158	Bermuda Center Sanitary District WWTP	216	0	1,802	138	0	0	76	76	272
NC0078361	Salisbury-Rowan Utilities Second Cr WWTP	428	667	3,614	432	0	0	41	41	508
NC0079898	Needmore Rd Landfill (HNA Holdings Inc.)	8	0	34	0	0	0	16	17	9
NC0080853	Lucent Tech Salem Bus Park Rem Site	0	0	1,828	0	0	0	0	0	37
NC0082821	Southern States Coop-Statesville	0	0	661	50	5	0	30	26	42
NC0083925	Heater Util Inc. Salem Glen SD WWTP	321	0	2,812	222	0	0	111	110	336

Total nitrogen and total phosphorus values were generally reported for all dischargers at concentrations above detection limits (see Appendix B for additional details). The majority of reported nondetect values were for BOD5 and ammonia. For these, the reported nondetect values were input at the detection limit value during the development of point source input. The general approach and assumptions used for developing model input to represent these point sources is summarized below based on the type of discharge.

Municipal Wastewater

- Observed data for available parameters was used first.
- Nitrogen: If only NH_3 was reported, 10 mg-N/L was assumed for NO_3 and 2 mg-N/L was assumed for organic N. If both total N and NH_3 were reported, the balance was assumed to be 83 percent NO_3-N and 17 percent organic N.
- Phosphorus: If only TP was reported, PO_4 was assumed equal to 60 percent of TP and the remaining 40 percent was assigned to organic P.
- An F-ratio of 2.5 (Thomann et al., 1987) was used to convert BOD5 concentration values to CBODu.
- A BOD5 concentration of 30 mg/L was assumed if no BOD5 concentration values were available.
- A DO concentration of 5 mg/L was assumed if no DO concentration values were available.

Industrial Process, Groundwater Remediation, and Water Treatment Conditioning

- Observed data for available parameters was used first.
- Nitrogen: If a discharger does not report nitrogen then assumed constant values were assigned similar to ambient conditions.
- Phosphorus: If a discharger does not report phosphorus then assumed constant values for PO_4 and organic P were assigned similar to ambient conditions.
- An F-ratio of 2.5 was used to convert BOD5 concentration values to CBODu.
- A BOD5 value approximating ambient conditions was assumed if no BOD5 concentration values were available.
- A DO value of 5 mg/L was assumed if no DO concentration values were available.

The frequency of observations varied by constituent and discharger. To effectively process the source data while also maintaining a reasonable representation, the reported effluent concentration data was used to calculate monthly averages. A daily concentration time series was developed by assigning the monthly average value to each day of a given month. If a given month did not contain reported effluent data, the long-term average value was assigned.

Point source monitoring of pollutants occurs much less frequently than measurement of flow and some parameters must be estimated. Loading time series from point sources are thus subject to considerable temporal uncertainty, which constrains the ability of the model to match instream observations during low flow periods in streams where a substantial portion of the flow derives from wastewater discharges.

3.7 ONSITE WASTEWATER SYSTEMS

Most households in rural areas of the watershed are served by onsite wastewater systems (septic systems). The North Carolina Department of Public Health Onsite Water Protection Branch (NCDPH OWPB) contacted all county health departments in the High Rock Lake watershed and found insufficient data available regarding location, number, flow quantity, flow quality, and failure rates to fully constrain the model representation of septic systems. A summary of available information is provided in Appendix C. In addition, NCDPH reached out to researchers who have expertise in septic tank behavior in North Carolina in an effort to obtain comments on the approach and location specific information. Researchers did not provide any additional information or comments on the approach.

An approach developed in consultation with NCDPH was selected to address the representation of septic systems in the models. Septic loads were assigned using the conceptual model shown in Figure 3-8 and were input to the models as point sources, which allowed consistency of input across the models used in this study. A combination of GIS data, literature, available data, and assumptions was used to formulate the approach. DWQ and NCDPH collaborated with Tetra Tech to develop the representation shown in Figure 3-8. The following bullets summarize the approach.

- Population and household estimates were based on the 2000 census block population counts.
- The public sewer service areas were represented by the public sewer GIS coverage available at NCOneMap (http://www.nconemap.com/).
- The 2000 census blocks and public sewer service area coverage were geoprocessed to estimate the population outside of the public sewer service area, but inside the study area. The decision of whether a census block is considered to be inside or outside of the public sewer service area for this analysis was based on the location of the census block centroid.
- Literature values of flow quantity (68.6 gal/person/day, USEPA, 2002) and quality (Table 3-15) provide starting values and Table 3-16 presents values for this study) were used to convert estimated population (number of persons per census block with onsite wastewater disposal) to septic system effluent loads. Septic system failure rates were assumed based upon literature and available data provided by NCDPH.
- Population density was estimated separately for a 61 meter (200 ft) strip on each side of the NHDPlus flowlines. This was done to develop the proportion of septic systems classified as near waterbodies.
- Loads were assigned using the conceptual model shown in Figure 3-8, and linked to the model as point sources at the subbasin level. Estimated population for each census block was area-weighted for census blocks that straddle subbasin boundaries.

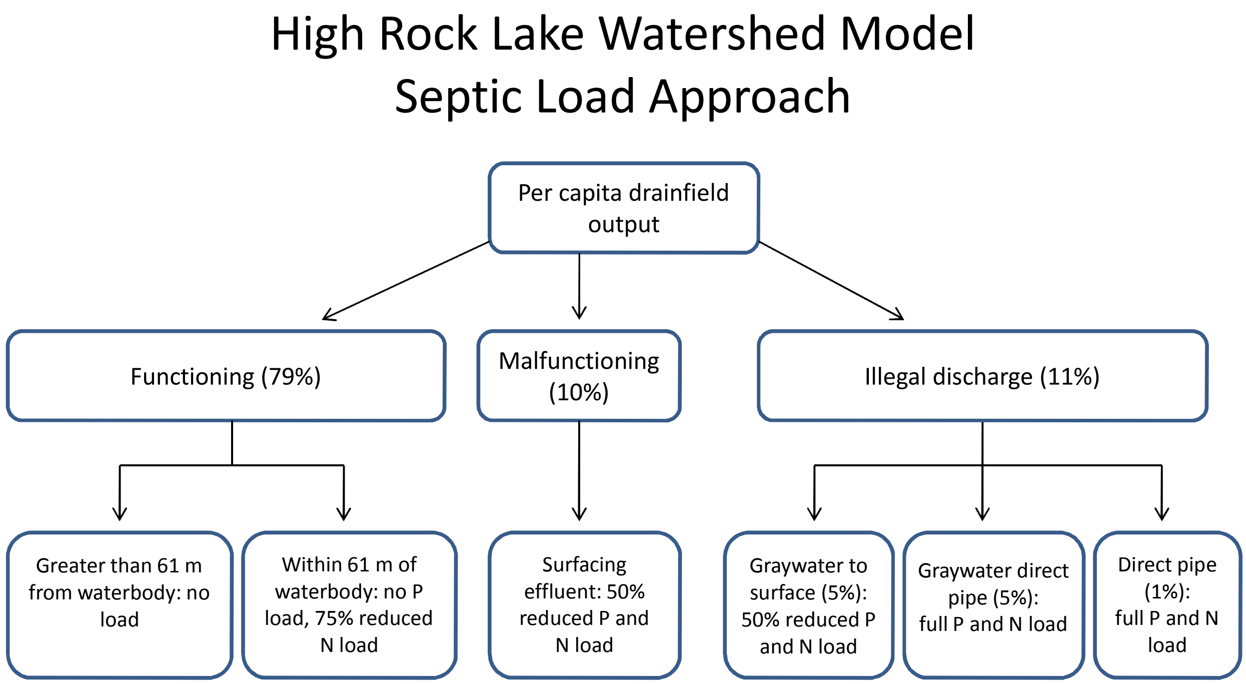

Figure 3-8. Conceptual Representation of Approach to Septic Systems

Table 3-15. Septic Tank Effluent and Water Quality at 0.6 m and 1.2 m Drainfield Soil Depth

Parameter	Septic Tank Effluent	Water Quality at 0.6 m Soil Depth	Water Quality at 1.2 m Soil Depth
BOD5 (mg/L)	154 [1]	<1	<1
TKN (mg-N/L)	58 [2]	1.01 [3]	1.01 [3]
NO_3 (mg-N/L)	0.04 [4]	28.5 [3]	17.1 [3]
TP (mg-P/L)	10 [5]	0.47 [3]	0.21 [3]

[1] Personal Communication, NCDPH

[2] McCray et al., 2005

[3] The values are scaled based on the relationship of septic tank effluent to soil water quality at depth found in USEPA (2002).

[4] USEPA (2002)

[5] WERF (2007)

A septic system failure rate was assumed based upon literature and available data provided by NCDPH. For example, one literature source indicated a failure rate of 11.4 percent in North Carolina (NCDEH, 2000). The county specific information gathered by DWQ and recommendations provided by NCDPH were also considered, resulting in a final estimated failure rate of 10 percent.

The conceptual model shown in Figure 3-8 presents four situations in which septic loads will be represented in the model. Table 3-15 was used as a starting point for assigning water quality characteristics for septic loads. The model inputs are summarized in Table 3-16 along with comments to indicate assumptions. Moreover, key assumptions are summarized below.

- The percentages for determining loading conditions presented in Figure 3-8 were first applied to any census tract in the study area.
- Assumed failure rate of 10 percent.
- Assumed one percent of systems represent straight piping of wastewater effluent.
- Gray water, water that has been used in the home such as dish washing, shower, sink, and laundry. This excludes sanitary wastewater.
- Non-failing systems within 61 meters (200 feet) of a waterbody were assumed to have no delivered phosphorus load and nitrogen concentrations that were equivalent to 25 percent of soil water quality concentrations at 1.2 meters drainfield depth. The nitrogen was assumed to be all in the form of NO_3.
- Surface failing septic systems within 61 meters (200 feet) of a waterbody were assumed to have concentrations that were equivalent to 50 percent of soil water quality concentrations at 0.6 meters drainfield depth (EPA, 2002).
- Direct straight pipe load was assumed to be equal to septic tank effluent concentrations as presented in Table 3-15.

The tabulation of population assumed to be on septic systems is provided in Appendix C.

Table 3-16. Septic Tank Loading Assignments Summary

Septic Loading Condition	BOD5 (mg/L)	TKN (mg-N/L)	NO_3 (mg-N/L)	TP (mg-P/L)	Comment
Nonfailing outside of 61 meters from waterbody	0.0	0.0	0.0	0.0	Not explicitly modeled; assumed to form part of the regional background groundwater concentration.
Nonfailing, within 61 meters of waterbody	1.0	0.0	4.3	0.0	No phosphorus, 25 percent of literature value at 1.2 meters, except BOD5. All nitrogen as NO3-N.
Surface failing, buffered load (10%)	1.0	0.51	14.2	0.23	50 percent of literature value at 0.6 meters, except BOD5.
Direct pipe, full load (1%)	154	58	0.04	10	Septic tank effluent values.
Gray water, direct pipe (5%)	154	10	0.04	5	Based on NCDPH recommendations.
Gray water, surface (5%)	77	5	0.02	2.5	50 percent of gray water direct pipe.

3.8 WATER WITHDRAWALS

The inclusion of water withdrawals in the model is important for representation of the water balance. Like point sources, these withdrawals may exhibit a notable impact in stream flow during low flow periods. Withdrawal data is not as readily available as point source discharge records. A memo was delivered to the TAC in the fall of 2009 to gather available time series information for withdrawals. A time series of municipal and industrial withdrawals was sought for each identified withdrawal with primary focus on larger withdrawals. If a time series could not be obtained, the withdrawal was entered with a constant value as provided by DWQ. Figure 3-9 shows the withdrawals considered in the model and Table 3-17 lists the withdrawal and approximate magnitude. Note that Duke Power Buck Steam (0057-0011) withdrawal is represented in the lake model, not the watershed application.

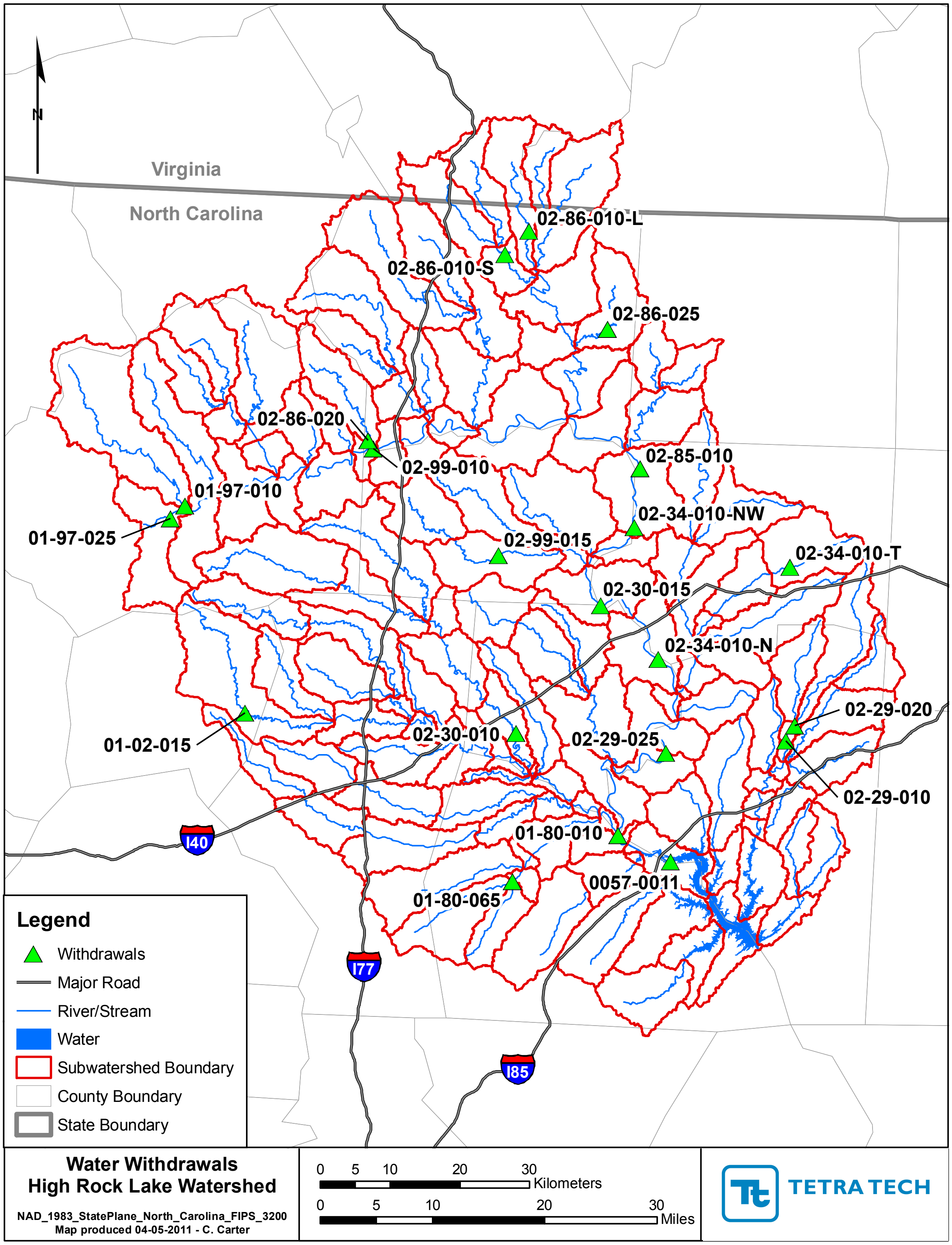

Figure 3-9. Water Withdrawals Represented in the High Rock Lake Model

Table 3-17. Withdrawals in the High Rock Lake Watershed Study

Withdrawal ID	Withdrawal Name	Source Water	Approximate Withdrawal (MGD)	Constant or Time Series
02-34-010-N	Winston-Salem Neilson	Yadkin River	37	Time Series
02-99-015	Yadkinville	South Deep Creek	0.9	Constant
02-30-015	Davie County	Yadkin River	2	Constant
02-86-010-L	Mount Airy, Lovills Cr, S.L. Spencer	Lovills Creek	2	Time Series
02-34-010-T	Winston-Salem Thomas	Kerners Mill Creek	8.8	Time Series
02-86-020	Elkin	Elkin Creek	0.87	Constant
01-80-010	Salisbury	Yadkin River	6	Time Series
02-85-010	King	Yadkin River	2	Constant
02-34-010-NW	Winston-Salem Northwest	Yadkin River	6.1	Time Series
02-86-010-S	Mount Airy, Stewarts Cr, F.G. Doggett	Stewarts Creek	2	Time Series
02-86-025	Pilot Mountain	Toms Creek	0.26	Constant
01-80-065	City of Kannapolis	Second Creek	1.4	Time Series
02-30-010	Mocksville	Hunting Creek	0.9	Constant
0057-0011	Duke Power Buck Steam Station (lake model application)	High Rock Lake	221	Time Series
02-99-010	Jonesville	Yadkin River	0.38	Constant
02-29-025	Davidson Water	Yadkin River	10	Time Series
01-97-025	Wilkesboro	Yadkin River	3	Constant
01-97-010	North Wilkesboro	Reddies River	0.97	Constant
01-02-015	Energy United Water	South Yadkin River	0.86	Constant
02-29-020	Thomasville	Lake Thom-A-Lex	3	Constant
02-29-010	Lexington	Lake Thom-A-Lex	3	Time Series

3.9 ATMOSPHERIC DEPOSITION

Atmospheric deposition may be a significant source of inorganic nitrogen loading. The atmospheric deposition of constituents was represented in the model as both wet and dry deposition. Wet deposition concentrations were obtained from the National Atmospheric Deposition Program (NADP) National Trends Network (NTN) (http://nadp.sws.uiuc.edu/) from Piedmont Research Station (NC34), which is located within the study area (Figure 3-10). The monthly average concentrations of nitrate and ammonium were converted to units of mg-N/L (Figure 3-11).

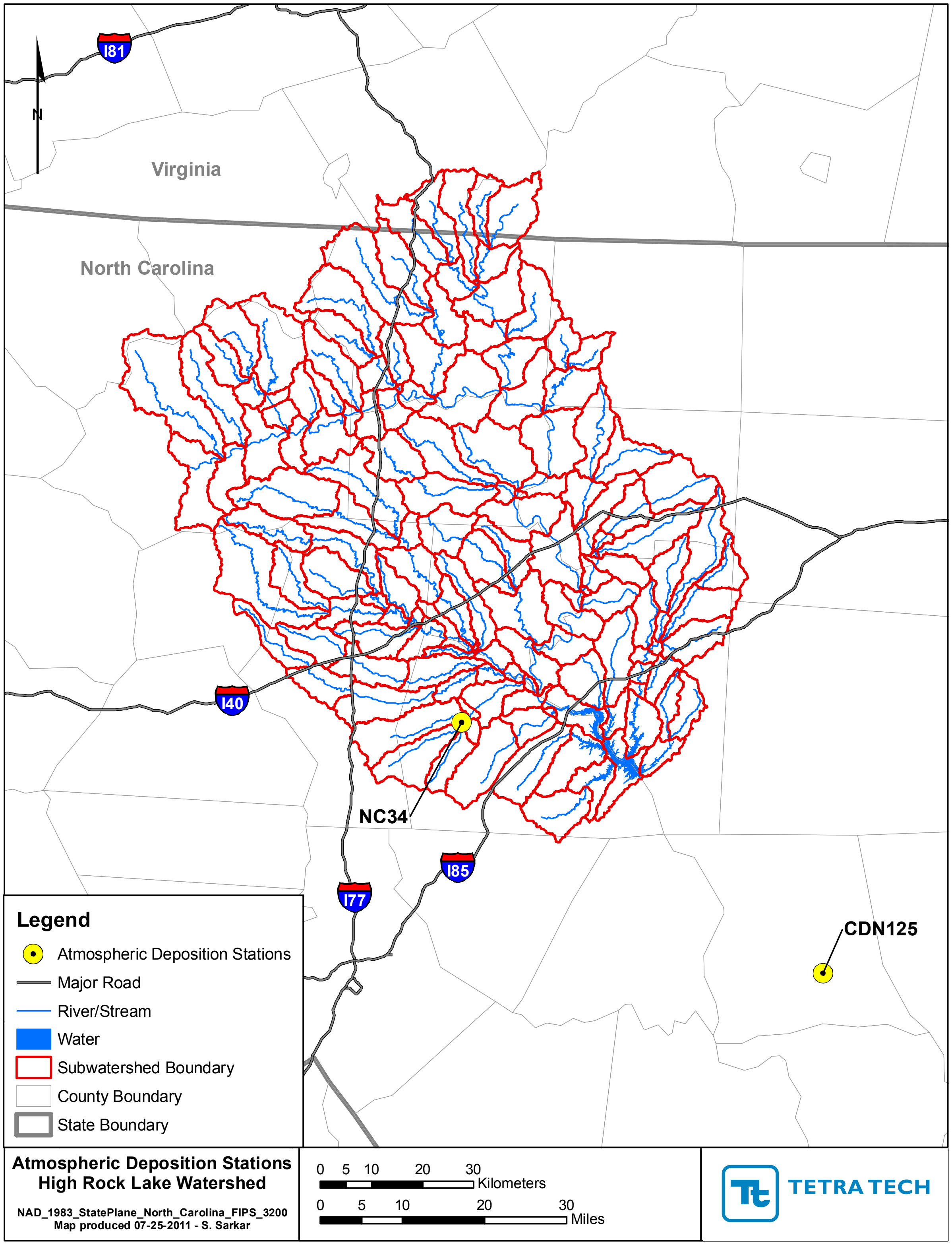

Figure 3-10. Atmospheric Deposition Station Locations

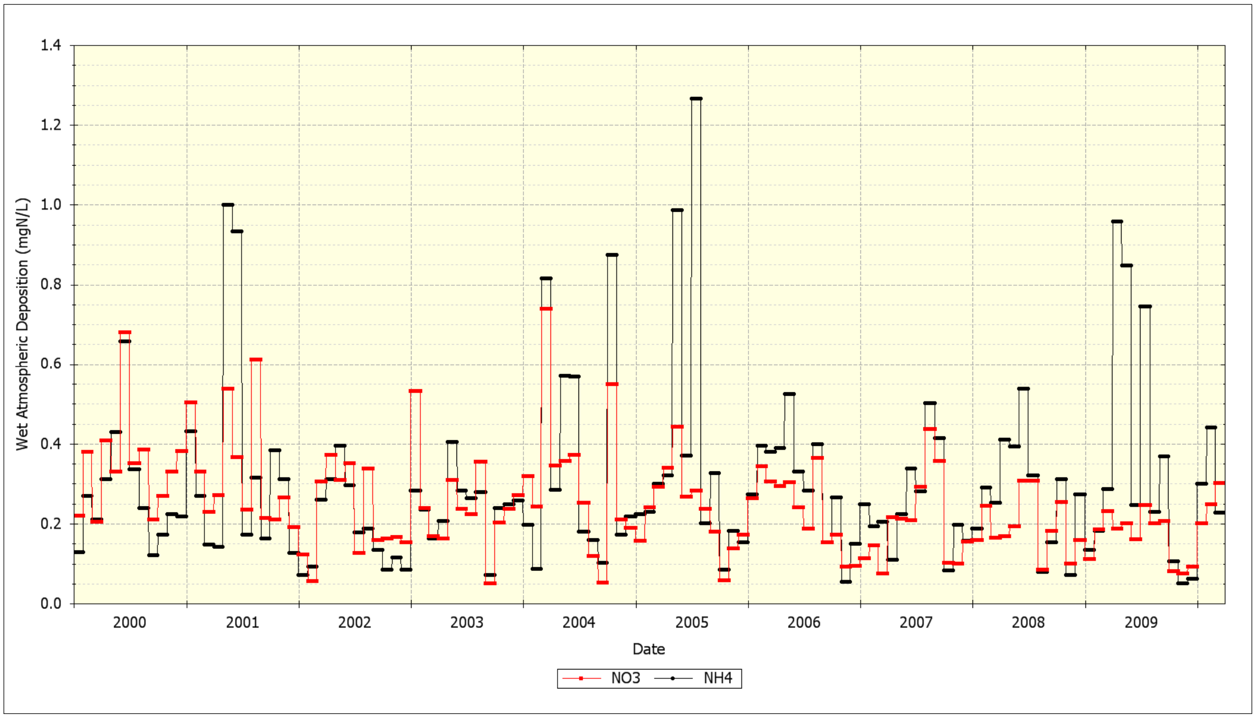

Figure 3-11. N Concentrations for Atmospheric Wet Deposition, Piedmont Research Station (NC34)

Seasonal dry deposition rates were obtained from the Clean Air Status and Trends Network (CASTNET) (http://java.epa.gov/castnet/) for station Candor (CND125), located about 30 miles south of the High Rock Lake watershed. The nitric acid (HNO_3), NO_3, and NH_4 were first converted to have units of N mass loading rates for assignment to the model (Figure 3-12).

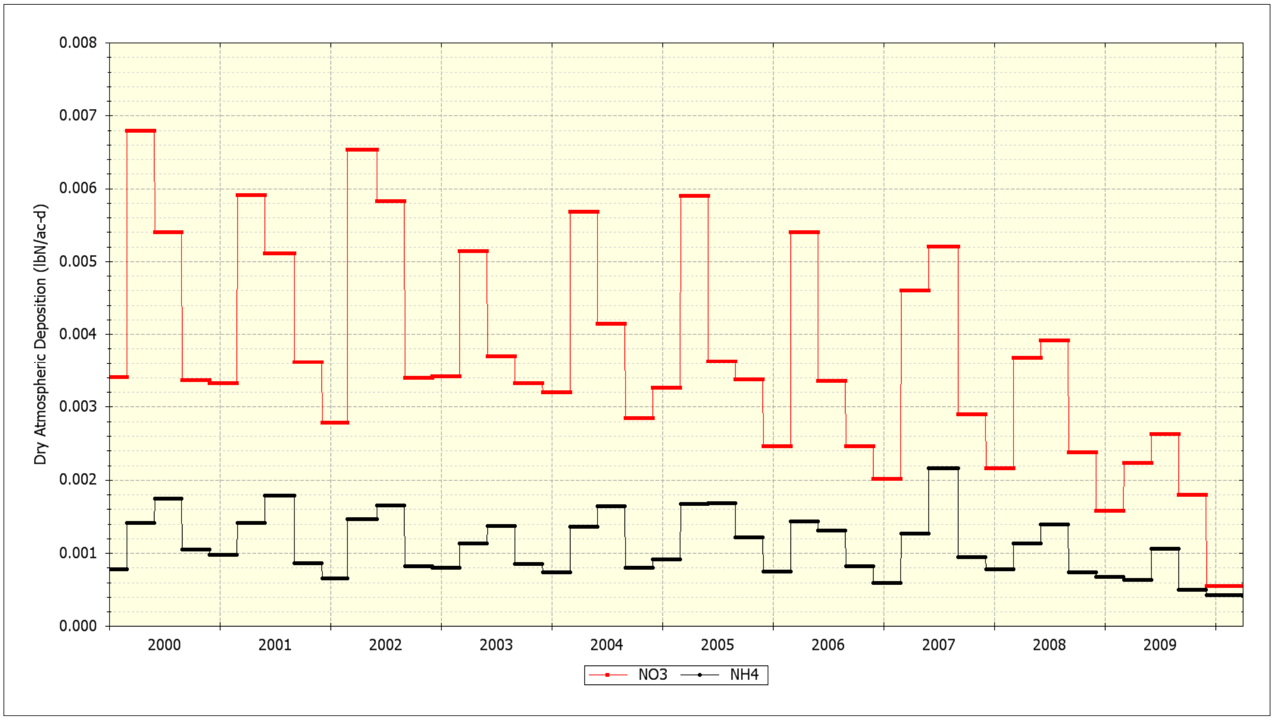

Figure 3-12. Dry Atmospheric Deposition Rates for N, Candor (CND125)

3.10 MONITORING DATA

Model calibration is conducted by comparing model output to monitored data for stream flow and water quality. This section summarizes the sources of data used for model calibration and validation.

3.10.1 Flow Monitoring

Daily average stream flow records were required to compare simulation output to observed data, assess wet and dry periods, and compute pollutant loading when combined with concentration observations. These data were obtained from the United States Geological Survey (USGS) for 11 stations in the study area (Figure 3-13).

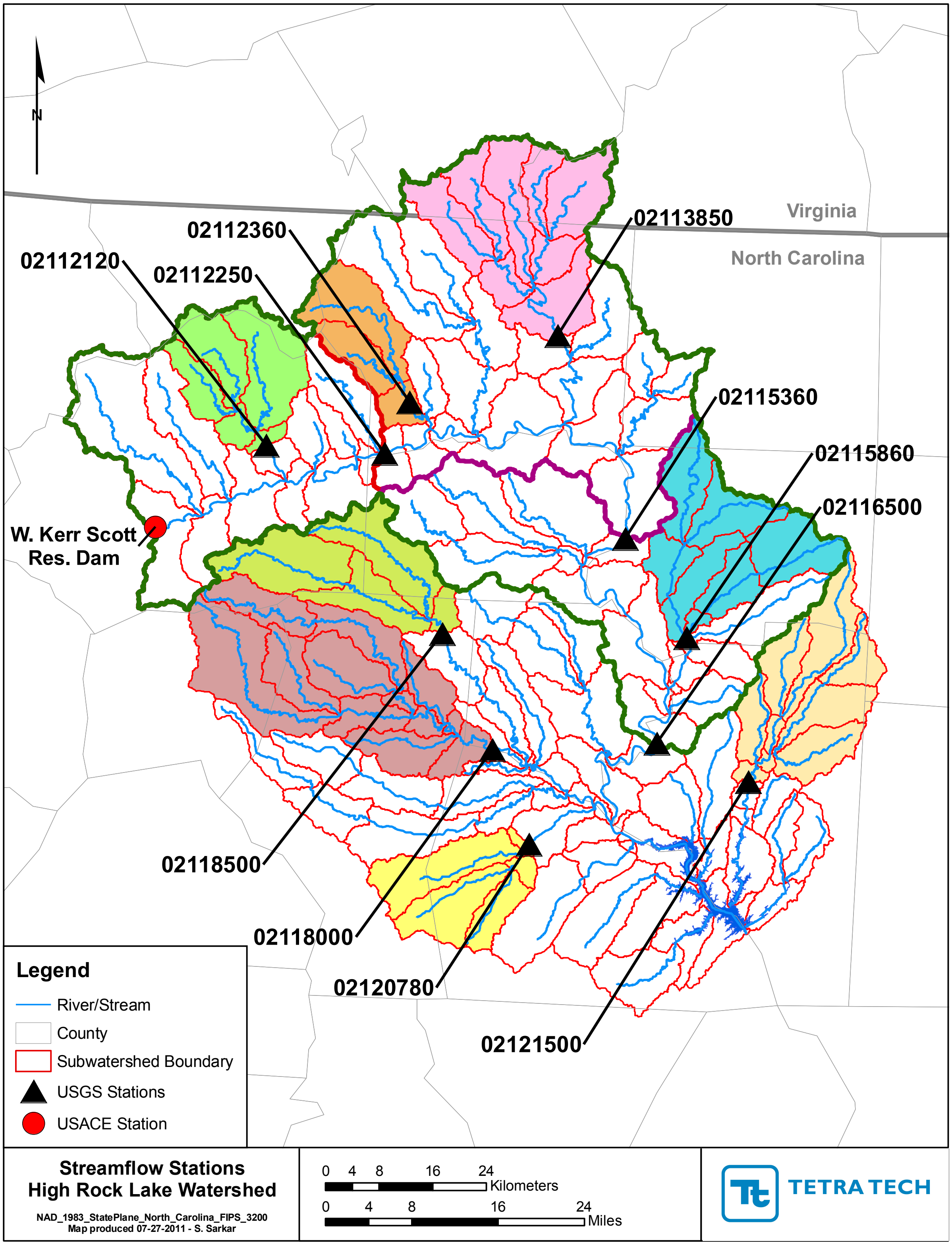

Figure 3-13. **Streamflow Gage Locations**

3.10.2 Water Quality Monitoring

High Rock Lake and the contributing watershed have been monitored since the 1970s. DWQ has collected water quality data within the reservoir since 1973 and has also collected monthly data on tributaries through the Ambient Surface Water Monitoring Program since 1974. Additional monitoring has been conducted by the Yadkin-Pee Dee River Basin Association (YPDRBA) since 1998 at 18 watershed sites. In preparation for the model development, a grant was awarded under Section 319 of the Clean Water Act to YPDRBA to conduct additional, more intensive monitoring (April 2008 through March 2010). DWQ was an active partner in this project and the TAC participated in the development of the monitoring plan. Of particular note in this monitoring effort is a focus on obtaining results for higher flow conditions. These conditions typically transport the majority of sediment and sediment-associated pollutants, but can be easily missed with fixed schedule sampling. The attention to capturing storm events provides a robust basis for model calibration by providing observations across a representative range of flows at most stations. Key water quality station locations located coincident to a streamflow observation station are shown in Figure 3-14.

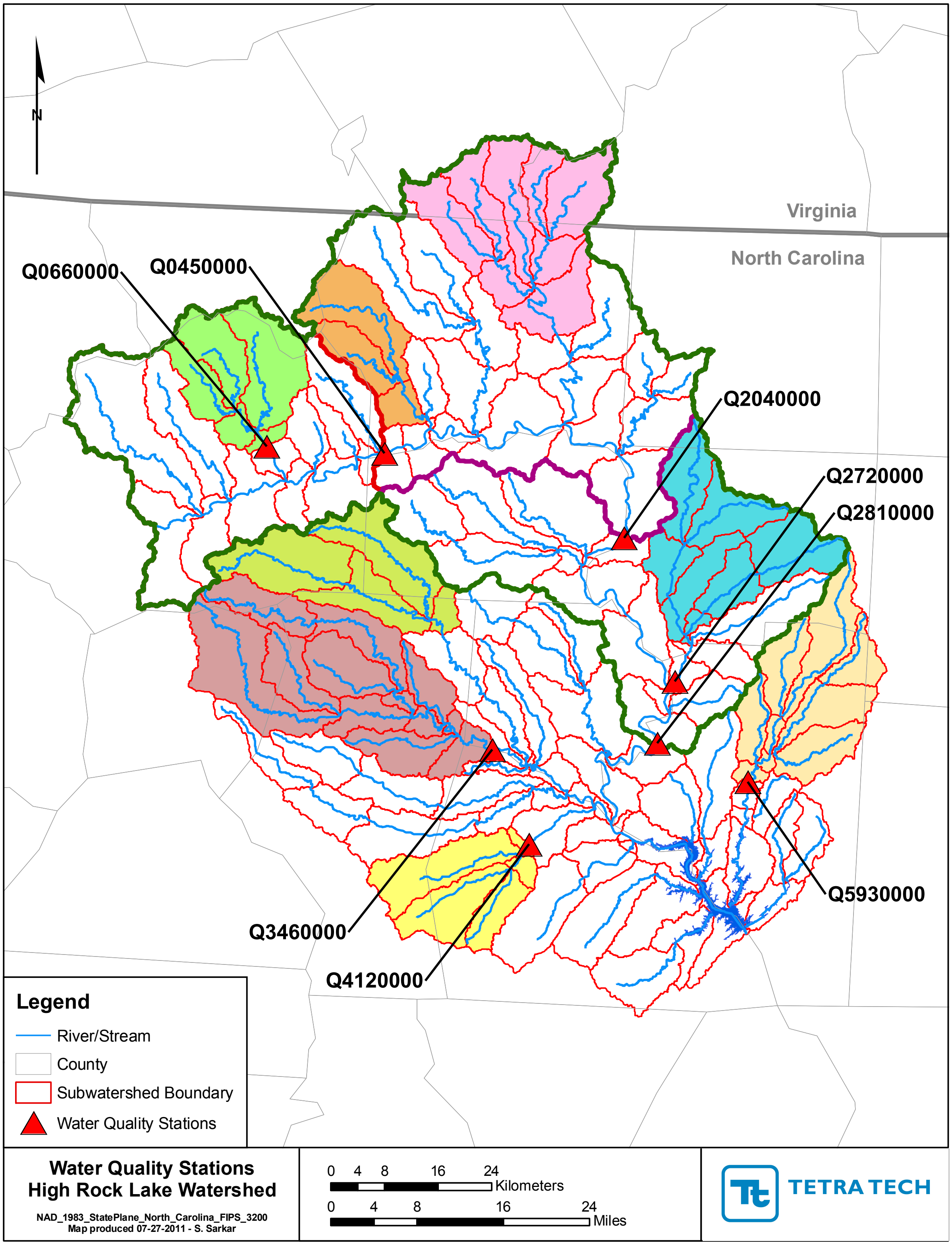

Figure 3-14. Water Quality Observation Stations Coincident to Streamflow Observation Stations

3.10.3 Upstream Boundary

This project did not include development of a separate lake model for W. Kerr Scott Reservoir, which substantially alters the amount and composition of nutrient and solids loads originating upstream. Therefore, the outflow from this reservoir is treated as a boundary condition for the High Rock Lake watershed model. The U.S. Army Corps of Engineers (USACE) – Wilmington district provided the daily average flow record for outflow from W. Kerr Scott Reservoir, which was used as a headwater assignment in the High Rock Lake watershed model application. Due to its size, and the lack of frequent water quality monitoring, the water quality of outflow from this reservoir is treated as approximately constant in time. The NC DWQ Intensive Survey Unit collected five monthly samples of water quality in the W. Kerr Scott Reservoir outflow in May through September 2009 (Whitaker, 2010). The High Rock Lake watershed model is thus forced by daily flows from W. Kerr Scott Reservoir, coupled with constant concentration assumptions shown in Table 3-18.

Table 3-18. Constant Concentration Assumptions for W. Kerr Scott Dam Boundary Conditions

Parameter	Concentration (mg/L)
Total Suspended Solids	11.0
Nitrate plus Nitrite Nitrogen	0.166
Ammonia Nitrogen	0.102
Total Phosphorus	0.042
Dissolved Oxygen	7.96

3.10.4 Water Resources Database

The Water Resources Database (WRDB) tool was used as the repository for project time series data (WRDB, 2011, www.wrdb.com). WRDB has been extensively developed and used for more than a decade in support of water resources needs. It provides a convenient location to house the data, perform calculations, generate summaries, prepare model input, and review data with graph options. The WRDB project files were iteratively developed and continually maintained to serve needs during the life of the project. Core data placed in the WRDB project files includes stream flow, W. Kerr Scott Reservoir outflow, water quality observations, point source flow and water quality, withdrawal flow, and atmospheric deposition.

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4 Model Calibration and Validation Process and Criteria

Calibration consists of the process of adjusting model parameters to provide a match to observed conditions. Calibration is necessary because of the semi-empirical nature of water quality models. Although these models are formulated from mass balance principles, most of the kinetic descriptions in the models are empirically derived. These empirical derivations contain a number of coefficients that are usually determined by calibration to data collected in the waterbody of interest.

Calibration tunes the models to represent conditions appropriate to the waterbody and watershed under study. However, calibration alone is not sufficient to assess the predictive capability of the model, or to determine whether the model developed via calibration contains a valid representation of cause and effect relationships. To help determine the adequacy of the calibration and to build confidence in results, the model is subjected to a corroboration or validation step. In the validation step, the model is applied to a set of data different from those used in calibration.

Simulation models are an imperfect approximation of reality. The appropriate question is not whether they are "right" in every detail, but whether they are useful for answering management questions. To answer management questions relevant to High Rock Lake, it is most important that the model provide a reasonable representation of the relative contributions of pollutant loads and their sources.

In light of these uses of the model, it is most informative to specify ranges of calibration objectives that characterize the model results as "very good," "good," "fair," or "poor." These characterizations inform appropriate uses of the model. When a model achieves a good or an excellent fit it can assume a strong role in evaluating management options. Conversely, when a model achieves only a fair or poor fit it should assume a less prominent role in the overall weight-of-evidence evaluation of management options. However, even a model that achieves only a fair fit to observations may still be useful to evaluate the relative differences between management strategies as long as the uncertainties in the analysis are identified and understood.

4.1 HYDROLOGIC CALIBRATION APPROACH

Calibration of the HSPF model is a sequential process, beginning with hydrology, followed by the movement of sediment, and chemical water quality. Hydrologic calibration for the High Rock Lake watershed used the standard operating procedures for the model described in Donigian et al. (1984) and Lumb et al. (1994). The general approach begins with replicating the total water balance, followed by adjustments to represent the division between high flows (due mostly to surface runoff) and low flows (due mostly to subsurface flow). Fine tuning is then used to adjust the seasonal balance. Calibration performance was tracked using Tetra Tech's HydroCal spreadsheet tool, which automatically retrieves model output and generates relevant statistics and graphical comparisons.

Initial values of hydrologic parameters were set in accordance with the ranges recommended in USEPA (2000) and adjusted during calibration. Key hydrologic parameters included the following:

LZSN: The LZSN parameter in HSPF is an index of the lower zone nominal soil moisture storage (inches), where the lower zone is operationally defined as the depth of the soil profile subject to evapotranspiration losses. LZSN is related, but not equivalent to the available water capacity (AWC) of a soil. It also reflects precipitation characteristics. USEPA (2000) recommends setting initial values at one-eighth of annual mean rainfall plus 4 inches in coastal, humid, and sub-humid regions, but also notes that this formula tends to yield "values somewhat higher than we typically see as final calibrated values…" The initial estimates (around 9.5) were adjusted downward during calibration to values ranging from 6 inches (in the western, mountainous portion of the watershed) to 7 inches (in the lower, eastern part of the watershed).

INFILT. INFILT is an index to mean soil infiltration rate (in/hr), which controls the overall division of the available moisture from precipitation (after interception) into surface and subsurface flows. INFILT is not a maximum infiltration rate, nor an infiltration capacity term. As a result, values of INFILT used in the model are expected to be much less than published infiltration rates or permeability rates shown in the soil survey (often on the order of 1 to 10 percent of soil survey values). USEPA (2000) shows acceptable ranges of INFILT for soil hydrologic groups, ranging from a minimum of 0.01 in/hr in group D soils to a maximum of 1.0 in/hr in group A soils. High Rock Lake watershed has dominantly C and B soils. The default range for C soils is 0.05 – 0.10 and the default range for B soils is 0.1 – 0.4. These initial values were adjusted during calibration to individual gages, resulting in lower values in the southern portion of the watershed. Slightly higher values were assigned to forest land cover due to forest canopy protection from surface sealing. Final values for C soils ranged from 0.042 to 0.079; final values for B soils ranged from 0.1 to 0.37.

AGWRC: The active groundwater recession coefficient was initially set based on baseflow separation and analysis of recession rates. Minor adjustments during calibration resulted in final values that ranged from 0.97 to 0.992, with higher values on B soils.

LZETP: The LZETP parameter is a coefficient to define the evapotranspiration opportunity from the soil lower zone and is a function of cover type. Monthly coefficients (MON-LZETP) were specified for all land uses, with a strong seasonal component for crops and forest cover and a weaker seasonal component for herbaceous cover.

The full set of parameters may be examined in the model user control input (*.UCI) file, provided electronically.

4.2 HYDROLOGIC CALIBRATION CRITERIA

For HSPF simulation of hydrology, a variety of performance targets have been specified, including Donigian et al. (1984), Lumb et al. (1994), and Donigian (2000). Based on these references and previous experience with similar models, hydrology performance targets were specified in the QAPP (Tetra Tech, 2009) and are summarized in Table 4-1.

Table 4-1. Performance Targets for HSPF Hydrologic Simulation (Magnitude of Annual and Seasonal Relative Mean Error (RE); Daily NSE)

Model Component	Very Good	Good	Fair	Poor
1. Error in total volume	≤ 5%	5 - 10%	10 - 15%	> 15%
2. Error in 50% lowest flow volumes	≤ 10%	10 - 15%	15 - 25%	> 25%
3. Error in 10% highest flow volumes	≤ 10%	10 - 15%	15 - 25%	> 25%
4. Error in storm volume	≤ 10%	10 - 15%	15 - 25%	> 25%
5. Winter volume error	≤ 15%	15 - 30%	30 - 50%	> 50%
6. Spring volume error	≤ 15%	15 - 30%	30 - 50%	> 50%
7. Summer volume error	≤ 15%	15 - 30%	30 - 50%	> 50%
8. Fall volume error	≤ 15%	15 - 30%	30 - 50%	> 50%
9. Nash-Sutcliffe coefficient of model fit efficiency (NSE) daily values	> 0.80	> 0.70	> 0.40	≤ 0.40

It is important to clarify that these performance target ranges are intended to be applied to mean values, and that individual events or observations may show larger differences and still be acceptable (Donigian, 2000).

Adequacy of daily flow predictions was also evaluated using the Nash-Sutcliffe coefficient of model fit efficiency (NSE). NSE is a commonly used model performance measure and extensive information is available on reported values from various studies. It is recommended for use by ASCE (1993), Legates and McCabe (1999), and Moriasi et al. (2007). The NSE ranges from minus infinity to one and is given by the following formula:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean} \right)^2} \right],$$

where Y_i^{obs} is the ith observation, Y_i^{sim} is the paired simulated value, Y^{mean} is the mean of the observed values, and n is the number of observations. The NSE is thus a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information").

An NSE value of 1 indicates perfect prediction, while a value of zero indicates that the model does no better than the long-term average in explaining variability among individual observations. An NSE value of 0.7 or better is generally accepted as a measure of excellent model fit; however, the ability to obtain high NSE values is limited by the accuracy and representativeness of precipitation data. Moriasi et al.

(2007) recommend an NSE of 0.50 or better (applied to monthly sums) as an indicator of adequate hydrologic calibration when accompanied by a relative error of 25 percent or less.

Based on the recommendations of Moriasi et al. (2007), two additional performance measures were added to those specified in the QAPP – the Relative Error (RE, also known as %BIAS, which is the average error divided by the mean, and RSR, which is the root mean squared error (RMSE) normalized to the standard deviation of the observations (STD_{obs}), as shown in Table 4-2 A number of additional statistics were also calculated.

Table 4-2. Performance Rating for Selected Statistics (Moriasi et al., 2007)

Category	Relative Error (RE or %BIAS)	$RMSE/STD_{obs}$ (RSR)	NSE
Very Good	RE ≤ ±10%	RSR ≤ 0.50	NSE ≥ 0.75
Good	±10% < RE ≤±15%	0.50 < RSR ≤ 0.60	0.60 ≤ NSE < 0.75
Satisfactory	±15% < RE ≤±25%	0.60 < RSR ≤ 0.70	0.5 ≤ NSE < 0.60
Unsatisfactory	RE ≥ ±25%	RSR > 0.70	NSE < 0.50

Note: RMSE is the root mean squared error, STDobs is the standard deviation of the observed data, and RE or %BIAS is the percent error calculated as observed minus simulated and normalized to the average observed value.

4.3 WATER QUALITY CALIBRATION APPROACH

Unlike flow, water quality is not observed continuously. The calibration must therefore rely on comparison of continuous model output to point-in-time-and-space observations of concentration. This creates a situation in which it is not possible to fully separate error in the model from variability inherent in the observations. For example, a model could provide an accurate representation of an event mean or daily average concentration in a reach, but an individual observation at one time and one point in a reach itself may differ significantly from the average. For this reason, it is important to use statistical tests of equivalence that are relevant to the principal study questions in the evaluation of the water quality calibration.

The High Rock Lake watershed model is calibrated and validated for suspended sediment, total phosphorus, and total nitrogen. Sediment is calibrated first, as nutrient transport (particularly phosphorus transport) is strongly influenced by sediment transport. The HSPF watershed model represents land-based and channel-based sediment. Three classes of sediment are simulated in HSPF: sand, silt, and clay. Silt and clay are simulated as cohesive sediment classes. The land and channel parameters were set to default values to begin the modeling process. The point source dischargers were assigned their effluent TSS values which were assumed to be all clay.

The sediment simulation depends on the hydrologic calibration. The nutrient simulation depends on both the hydrologic and sediment calibration, along with the specification of loading from point sources. Errors and uncertainties in the hydrology and sediment simulation will propagate into the nutrient simulation. In addition, the lack of detailed time series for loading from point sources intrinsically limits the accuracy of the nutrient simulation as the model cannot account for day to day changes in WWTP loads.

The approach for sediment calibration generally follows the guidance of Donigian and Love (2003), with some enhancements. Suspended sediment concentrations observed in-stream are the result of both upland and channel processes, so there are multiple sets of parameters that control results. The general strategy for sediment calibration consists of the following steps:

- Specify initial upland parameter values based on external information (e.g., soils data).
- Adjust upland sediment erosion to reproduce calibration targets available from other studies or literature.
- Adjust instream/channel parameters to match observed total suspended solids (TSS) concentrations and loads.

Although not a primary focus of the modeling effort, water temperature simulation is important in the High Rock Lake watershed model for several reasons: water temperature affects many biologically mediated processes that influence water quality in the streams, and the temperature of the water determines how it will mix when it enters the lake.

Daily average water temperature in shallow flowing streams is largely controlled by air temperature. Temperature cycles within the day, however, may be strongly affected by heat gain from incoming solar radiation and heat loss due to longwave back radiation. Both of these effects are controlled by the extent of cover and shading on the stream in addition to meteorological variables such as solar radiation and cloud cover.

A detailed diurnal simulation of stream water temperature is a complex undertaking. The timing and magnitude of heat fluxes are controlled by a variety of factors such as stream orientation and vegetative and topographic shading angles that are not considered in HSPF. For example, a stream oriented east-west is likely to be exposed to unshaded solar radiation for a longer part of the day than a stream oriented north-south. Stream shading varies over the course of the year as canopy density changes, and may also change over time as trees grow, are cut, or fall due to ice storms. HSPF approximates all these complex details through the assignment of a temporally constant "surface exposed" (CFSAEX) factor that represents the average fraction of tree-top solar radiation reaching the water surface.

Given these issues, the stream temperature calibration was checked for reasonableness, but not constrained to achieve specific statistical targets.

Loading of nutrients that may support excess algal growth in High Rock Lake is a primary concern for management planning. The major nutrients controlling algal growth are phosphorus and nitrogen. Both are simulated in detail in the High Rock Lake watershed model. Minor nutrients (e.g., silica, iron) may also play a role in determining algal response but are not simulated in the watershed model as they are not believed to be limiting factors on algal growth.

In forested watersheds, much of the nutrient load moves as a constituent of organic matter (including leaf litter, other debris, and dissolved organic compounds, such as humic acids), while stream concentrations of inorganic nutrients remain low in these watersheds. In contrast, agriculture and fertilized lawns may export significant amounts of nutrients in inorganic forms.

The approach taken is to simulate three components in loading from the land surface as general quality constituents (GQUALs): inorganic nitrogen (nitrate, nitrite, and ammonia), inorganic phosphorus (total orthophosphate), and organic matter. Each of these constituents is then partitioned at the point of entry into the stream network:

- Inorganic nitrogen is partitioned into dissolved nitrate, dissolved ammonium, and sorbed ammonium. Fractions of the dissolved constituents are set to reproduce observed data in the Yadkin River after additional instream kinetic reactions, while sorption of ammonium is simulated using equilibrium partitioning assumptions (the model connects inorganic N from the land surface to dissolved N in the stream reach, but equilibrium partitioning to the sorbed form occurs instantaneously). Assignment of total inorganic nitrogen from the land surface to nitrate and ammonium at the point of entry to the stream is represented by a constant ratio throughout the model, but differs for agricultural land and impervious surfaces. Partitioning of ammonium between dissolved and sorbed forms depends on local suspended sediment concentrations. A small portion of the inorganic N is routed directly to organic N to represent uptake by heterotrophic organisms in low order streams (a process not explicitly simulated by the model).

- Inorganic phosphorus is partitioned into dissolved and sorbed fractions using equilibrium partitioning assumptions. As with ammonium, the fraction that becomes sorbed depends on the local suspended sediment concentration,
- Organic matter (biomass) is partitioned into labile and refractory organic carbon, organic nitrogen, and organic phosphorus components. Initial specifications were based on expected stoichiometry of forest litter, and then revised during calibration to achieve agreement with observed concentrations. Final C:N:P ratios derived during calibration reflect a reduction in carbon relative to N and P, and a reduction of N relative to P, with a C:N ratio of 3.83 and a C:P ratio of 12.6.

All three upland components (inorganic nitrogen, inorganic phosphorus, and organic matter) may be loaded through either surface flow or subsurface flow (interflow and groundwater discharge). The HSPF GQUAL algorithms do not maintain a full mass balance of subsurface constituents (which would require a groundwater quality model); rather, the user specifies concentration values, which may vary monthly, for interflow and groundwater. Surface washoff loading is considered from both pervious and impervious surfaces.

Inorganic phosphorus loading from pervious surfaces is simulated as a sediment-associated process because of the strong affinity of orthophosphate for soil particles. Surface loading of inorganic phosphorus is thus determined by a potency factor applied to sediment load, which may vary on a monthly basis to reflect changes in surface soil concentration associated with the annual growth cycle. (While this reflects the physical basis of surface loading of inorganic phosphorus, it does mean that any errors in the simulation of sediment loading will also affect estimates of inorganic phosphorus loading.) Subsurface flow pathways are assumed to primarily load small amounts of dissolved inorganic phosphorus. Organic matter is also simulated as a sediment-associated load from pervious surfaces, as this primarily represents the erosion of humus, leaf litter, and other detritus.

In contrast to phosphorus, inorganic nitrogen is highly soluble, and loading in surface runoff may occur independent of sediment movement (particularly where fertilizer is applied). Further, much of the nitrate load in surface runoff represents input from atmospheric deposition. Therefore, inorganic nitrogen loading from pervious surfaces is represented via a buildup-washoff process in which the user specifies a rate of accumulation, an accumulation limit, and a flow rate sufficient to remove 90 percent of the accumulated material.

4.4 WATER QUALITY CALIBRATION CRITERIA

For both sediment and nutrients, it is unreasonable to propose that the model predict all temporal variations in concentration and load. The model should, however, provide an accurate representation of long-term and seasonal trends in concentration and load, and correctly represent the relationship between flow and load. To ensure this, it is important to use statistical tests of equivalence between observed and simulated concentrations, rather than relying on a pre-specified model tolerance on difference in concentrations.

Ideally, average errors and average absolute errors should both be low, reflecting a lack of bias and high degree of precision, respectively. In many cases, the average error statistics will be inflated by a few highly discrepant outliers. It is therefore also useful to compare the median error statistics.

General performance targets for water quality simulation with HSPF are also provided by Donigian (2000) and are shown in Table 4-3. These are calculated from observed and simulated daily concentrations, and should only be applied in cases where there are a minimum of 20 observations.

Table 4-3. Performance Targets for HSPF Water Quality Simulation (Magnitude of Annual and Seasonal Relative Average Error (*RE*) on Daily Values)

Model Component	Very Good	Good	Fair	Poor
1. Suspended Sediment	≤ 20%	20 - 30%	30 - 45%	> 45%
2. Nutrients	≤ 15%	15 - 25%	25 - 35%	> 35%

Evaluation of water quality simulations presents a number of challenges because, unlike flow, water quality is generally not monitored continuously. Grab samples at a point in space and time may not be representative of average conditions in a model reach on a given day due to either spatial or temporal uncertainty (i.e., an instantaneous measurement in time may deviate from the daily average, especially during storm events, while a point in space may not be representative of average conditions across an entire model reach). Where constituent concentrations are near reporting levels, relative uncertainty in reported results is naturally high. Accurate information on daily variability in point source loads is also rarely available.

Evaluation of relative average error is recommended, but averages are prone to biasing by one or a few extreme outliers. Therefore, it is also useful to examine median relative errors, which are less influenced by outliers.

The performance targets for water quality simulation may be applied to either concentrations or loads. Concentrations provide the most natural metric, but error magnitude may be unduly influenced by variability at low flow conditions that has little effect on cumulative loading to the lake. Loads are more meaningful for lake impacts but are not directly observed and need to be estimated from flow and concentration – both uncertain. Tests on loads are performed in two ways: on paired data (observed and simulated daily average concentration multiplied by flow) and on complete time series of monthly loads. For the latter approach, “observed” monthly loads are estimated for sediment and phosphorus using a stratified rating curve regression approach and for nitrogen using a stratified averaging estimator approach, as nitrogen concentration is less likely to be strongly correlated with flow. The stratified rating curve regression consists of a broken-line (two- part) regression of the natural logarithm of load versus the natural logarithm of flow. The breakpoint between the two regression strata is assigned visually, but is typically set at about 1.5 times the median flow. NSE values are calculated on the monthly load series, and Moriasi et al. (2007) recommend an NSE of 0.50 or better on monthly loads as indicative of adequate model fit; however, this is dependent on the quality of the estimates of continuous load that can be inferred from scattered monitoring data.

Additional statistical tests are also applied as part of a weight-of-evidence examination of the water quality calibration. Two-sample *t*-tests are reported on the differences in mean concentration and mean load, with a target that there should be less than an 80 percent probability that the means differ (i.e., a probability value greater than 0.20). Higher probability values are desirable—and were obtained in many cases—but are not always achievable. A problem with the *t*-test is that the test is on a null hypothesis that the mean difference is exactly equal to zero, not whether the difference is physically meaningful. Therefore, a low value on the *t*-test (rejection of the null hypothesis) is considered of practical significance only when the mean difference is greater than 10 percent. Additional graphical tests are also performed to ensure that errors in the prediction of load and concentration do not exhibit strong correlations relative to flow magnitude and season.

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5 Model Calibration and Validation

5.1 HYDROLOGY

The watershed hydrology was calibrated and validated by comparing simulation output to 11 daily-average USGS flow gaging stations in the study area. Ten of these stations have complete daily records for the simulation period (2000 – 2010); the remaining one, Muddy Creek, has a partial record. Figure 5-1 shows the location of these flow gages with the contributing drainage area either shaded or indicated with a thick outline. Table 5-1 lists the stations along with the corresponding model reach number (RCHRES ID). The distribution of land uses upstream of each gage is shown in Table 5-2. Forest on hydrologic soil group B is the dominant land use category in most of the study area; Roaring River (73 percent) and Mitchell River (70 percent) have the greatest percentage of area in forest. Abbotts Creek (36 percent) and Muddy Creek (61 percent) have the most NCDOT, urban, and MS4 model land units. Second Creek (52 percent) and South Yadkin River (44 percent) have the most crop and pasture area. Table 5-3 indicates the presence of upstream permitted discharges and withdrawals upstream of each gage.

Table 5-1. Hydrology Calibration and Validation Stations

USGS ID	Name	Calibration/Validation	Drainage Area (mi^2)	Corresponding RCHRES ID
02112120	Roaring River near Roaring River	Calibration	128	82
02113850	Ararat River at Ararat	Calibration	231	101
02118500	Hunting Creek near Harmony	Calibration	155	45
02118000	S. Yadkin River near Mocksville	Calibration	306	31
02120780	Second Creek near Barber	Calibration	118	13
02121500	Abbotts Creek at Lexington	Calibration	174	133
02112250	Yadkin River at Elkin	Validation	869	89+73
02112360	Mitchell River near State Road	Validation	78.8	91
02115360	Yadkin River at Enon	Validation	1,694	67
02116500	Yadkin River at Yadkin College	Validation	2,280	56
02115860	Muddy Creek near Muddy Creek	Validation	186	117

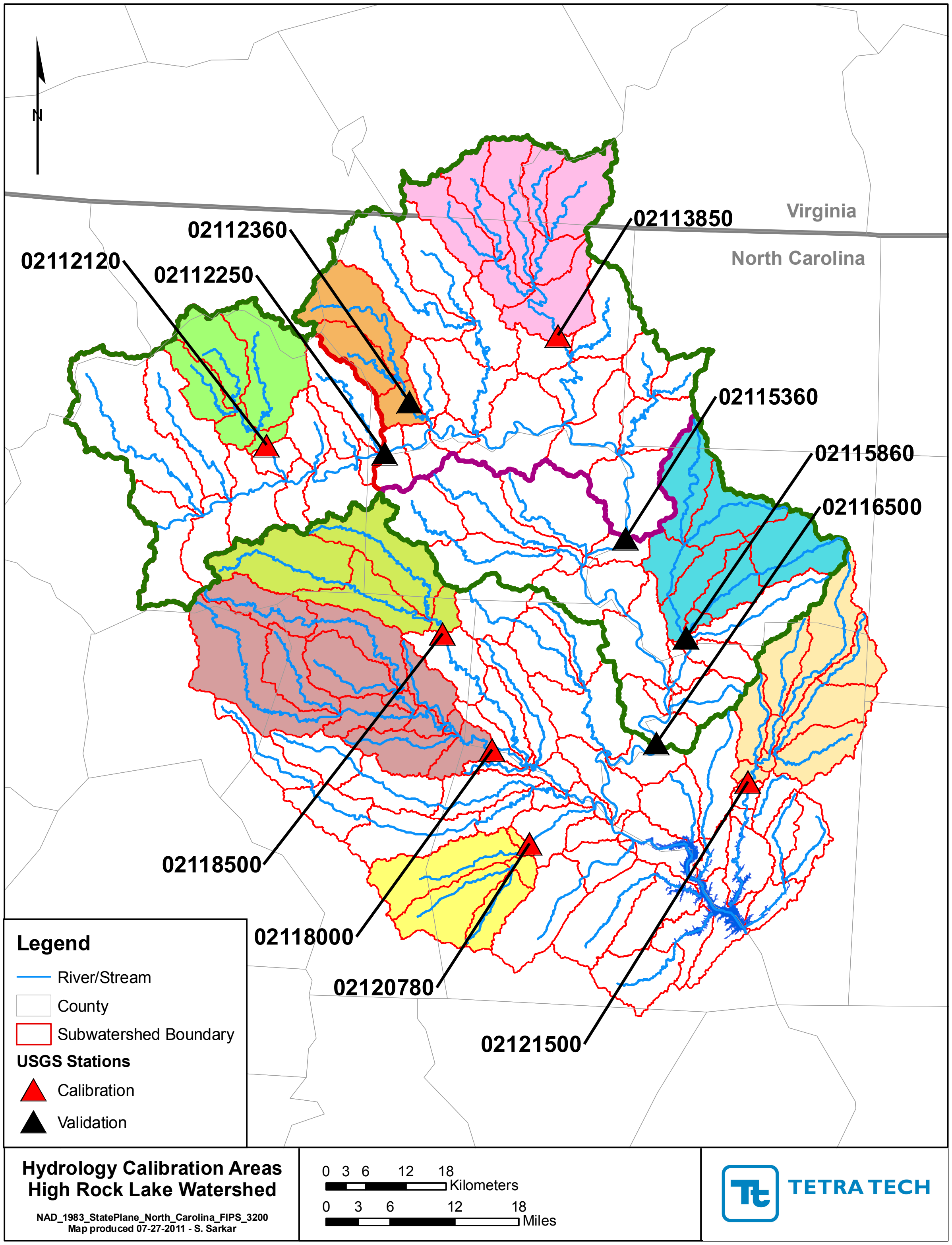

Figure 5-1. Hydrology Calibration/Validation Gage Locations and Drainage Areas

Table 5-2. Percent Distribution of Model Land Uses by Station

Station Name	Crop B	Crop C	Forest B	Forest C	Pasture B	Pasture C	NCDOT Imp	NCDOT Pervious	Urban Imp	Urban Pervious	MS4 Impervious	MS4 Pervious
Roaring R. near Roaring R. (02112120)	1%	0%	69%	4%	16%	1%	0%	1%	1%	6%	0%	0%
Ararat R. at Ararat (02113850)	2%	0%	46%	10%	22%	2%	1%	1%	2%	11%	1%	2%
Hunting Cr. near Harmony (02118500)	6%	0%	47%	1%	32%	1%	1%	1%	1%	8%	0%	0%
S. Yadkin R. near Mocksville (02118000)	5%	0%	42%	1%	38%	1%	1%	1%	2%	9%	0%	0%
Second Cr. near Barber (02120780)	9%	3%	22%	7%	33%	7%	1%	1%	1%	2%	12%	1%
Abbotts Cr. at Lexington (02121500)	2%	1%	23%	12%	16%	8%	2%	1%	3%	3%	15%	4%
Yadkin R. at Elkin (02112250)	1%	0%	58%	3%	21%	2%	0%	1%	1%	2%	8%	1%
Mitchell R. near State Rd (02112360)	3%	0%	67%	3%	19%	1%	1%	1%	1%	5%	0%	0%
Yadkin R. at Enon (02115360)	3%	1%	52%	5%	23%	1%	1%	1%	2%	9%	1%	1%
Yadkin R. at Yadkin Col. (02116500)	4%	1%	44%	6%	22%	2%	1%	2%	2%	10%	2%	4%
Muddy Cr. near Muddy Cr. (02115860)	0%	0%	22%	6%	7%	2%	0%	4%	3%	16%	15%	24%

Table 5-3. Upstream Point Source Discharges and Withdrawals by Station

Station Name	Major Point Source	Minor Point Source	Withdrawal
These stations are upstream of Yadkin River at Yadkin College and are listed in downstream order.			
Roaring R. near Roaring R. (02112120)	-	-	W-S Neilson
Yadkin R. at Elkin (02112250)	Louisiana Pacific ABT N. Wilkesboro WWTP Wilkesboro WWTP	-	Elkin Jonesville Wilkesboro N. Wilkesboro
Mitchell R. near State Rd (02112360)	-	-	-
Ararat R. at Ararat (02113850)	Mt. Airy WWTP	-	Mt. Airy Lovills Mt. Airy Stewarts
Yadkin R. at Enon (02115360)	Interface Fabric Elkin WWTP Pilot Mtn. WWTP	Boonville WWTP Dobson WWTP Jonesville WWTP	King W-S Northwest Pilot Mtn
Muddy Cr. near Muddy Cr. (02115860)	W-S Archie Elledge WWTP	Lucent Tech Salem Bus Park	W-S Thomas
Yadkin R. at Yadkin Col. (02116500)	Yadkinville WWTP W-S Muddy Cr WWTP	Bermuda WWTP Heater Util WWTP	W-S Neilson Yadkinville Davie County
The following stations are independent drainages.			
Hunting Cr. near Harmony (02118500)	-	-	-
S. Yadkin R. near Mocksville (02118000)	-	-	Energy United Water
Second Cr. near Barber (02120780)	Invista Salisbury	Salisbury-Rowan Util WWTP	Kannapolis
Abbotts Cr. at Lexington (02121500)	Thomasville WWTP High Point WWTP	-	Thomasville Lexington

In general, a period of 10 years or more is recommended for hydrologic calibration to allow stabilization of persistent signals, such as groundwater levels and soil moisture, and to present the model with a range of meteorological conditions. Because of concerns over changes in land use, population, and land management practices over time, a spatial validation approach was selected rather than a temporal validation. In this approach, the available stations were divided into calibration and validation sites, rather than testing the calibration through application to a time period separate from that used for calibration. Six of the stations were selected for calibration. These were more headwater drainages and had a complete monitoring record for the simulation period. The remaining five stations were used for model validation. Three of the five validation stations are on the main stem. The remaining two validation stations are Muddy Creek (which has a partial record) and Mitchell River.

Hydrologic calibration endeavored to provide a simultaneous fit to all the different metrics describing daily, annual, seasonal, and high and flows, as specified in Table 4-1. Calibration began by focusing on the overall water balance (most sensitive to soil storages, evapotranspiration, and groundwater losses), followed by simulation of peak flows (most sensitive to infiltration), the seasonal flow balance, and low flow hydrology.

The full comparison of simulated and observed flow is presented in figures and tables in Appendix E. A summary of daily and monthly NSE statistics, along with the total relative error on flow volume, is shown in Table 5-4. This section recapitulates key statistics across all calibration and validation stations. The NSE values are for the period of simulation (January 2000-March 2010) except for Muddy Creek which is for 2007-2010. The stations are grouped to indicate either calibration or validation. All of the calibration stations except Roaring River (0.563) resulted in daily NSE values greater than 0.6 with South Yadkin River and Second Creek above 0.7. Arguably the most important validation station with respect to input to the lake, Yadkin River at Yadkin College, which measures the majority of the flow from the watershed, resulted in a daily NSE value of 0.761 and a monthly NSE of 0.98.

Table 5-4. Summary Statistics for Hydrology Calibration and Validation (2000-2010)

USGS ID	Name	Calibration/ Validation	Daily NSE	Monthly NSE	Total Volume Error
02112120	Roaring River at Roaring River	Calibration	0.563	0.927	5.22%
02113850	Ararat River near Ararat	Calibration	0.621	0.913	-3.58%
02118500	Hunting Creek near Harmon	Calibration	0.626	0.922	4.25%
02118000	South Yadkin River near Mocksville	Calibration	0.716	0.904	1.38%
02121500	Abbotts Creek near Lexington	Calibration	0.620	0.916	6.55%
02120780	Second Creek near Barber	Calibration	0.722	0.931	0.48%
02112250	Yadkin River at Elkin	Validation	0.841	0.954	-1.48%
02112360	Mitchell River near State Road	Validation	0.574	0.930	2.23%
02115360	Yadkin River at Enon	Validation	0.715	0.953	2.37%
02115860 (2007-2010)	Muddy Creek near Muddy Creek	Validation	0.597	0.736	4.89%
02116500	Yadkin River at Yadkin College	Validation	0.761	0.938	8.23%

Monthly NSEs for all stations are greater than 0.9, except for the short period of gage record on Muddy Creek. This indicates that the general water balance is simulated well. Total volume errors for all stations are less than 10 percent. As shown in Appendix E, seasonal objectives for the hydrologic calibration are also met.

In general, the model provides a good fit to long-term hydrology, representing both high and low flow regimes and the seasonal distribution of flows within the tolerances recommended by Lumb et al. (1994). The potential accuracy of the model fit is limited by the necessity of using daily summary precipitation station records that may not accurately reveal the intraday intensity of rainfall events and may not be representative of precipitation totals across broader watershed areas. Other factors include the presence of small ponds, either naturally occurring or human created, that are not explicitly simulated, uncertainty regarding time series of discharges and withdrawals, and year to year variability in land management practices. In addition, while Lake Thom-A-Lex is represented in the model, its hydraulic behavior is described in a simplistic fashion as engineering data were not available to fully describe stage-area-volume-discharge relationships.

The simulation for Abbotts Creek provides a good example of the general quality of model fit. As shown in Appendix E, error statistics on total volume, flows in the lower 50th percentile, flows above the 10th percentile, and seasonal flows are all within the criteria for a good or very good model fit, with the exception of the daily NSE, which is fair (in the range of 0.4 to 0.7), while the monthly NSE is above 0.9. Discrepancies in the model fit at a daily time step are most likely due to the incomplete coverage provided by point rainfall stations and the influence of un-simulated ponds on flow. For the Roaring River gage, where the monthly NSE is high but the daily NSE is relatively low, it appears likely that disaggregation of daily rainfall data provides a suboptimal representation of the intensity of individual precipitation events on the watershed, but provides a good representation of longer-term average response (resulting in a high monthly NSE, low total volume error, and seasonal error statistics that are within criteria for a “very good” model fit).

The statistical comparisons for hydrology discussed above are those specified in the QAPP (Tetra Tech, 2009). A variety of additional calibration statistics for flow were also computed to help assess model performance with respect to the hydrologic simulation, including the evaluation criteria recommended by Moriasi et al. (2007) and summarized above in Table 4-2. These are shown in Table 5-5.

Table 5-5. Supplemental Statistical Measures for High Rock Lake Watershed Model Hydrology, Calibration Stations (cfs)

Statistical Measure	Abbotts Cr near Lexington 02121500	Second Cr near Barber 02120780	Hunting Cr near Harmony 02118500	S. Yadkin R. near Mocksville 02118000	Ararat R. at Ararat 02113850	Roaring R. near Roaring R. 02112120
Count	3743	3743	3743	3743	3743	3743
Mean Absolute Error (MAE)	85.4	35.9	54.1	93.3	70.9	39.0
Average Error	11.4	0.4	6.8	3.7	-9.9	7.6
RMSE	276.7	110.2	170.2	254.0	188.0	107.6
R^2	0.63	0.74	0.63	0.72	0.65	0.64
STD$_{obs}$	448.8	209.2	278.3	476.4	305.5	162.8
RMSE/STD$_{obs}$	0.62	0.53	0.61	0.53	0.62	0.66
RE	-6.55%	-0.48%	-4.25%	-1.37%	3.58%	-5.22%
NSE	0.620	0.722	0.626	0.716	0.621	0.564
RMSE/OBS$_{avg}$	1.59	1.28	1.07	0.950	0.681	0.737
MAE/OBS$_{avg}$	0.489	0.417	0.339	0.349	0.257	0.267
RMSE – MAE	191.4	74.3	116.1	160.7	117.1	68.6
Overall Rating	Good	Good - Very Good	Good	Good - Very Good	Good	Good

Notes: RMSE is the root mean squared error; R^2 is the squared correlation coefficient, STDobs is the standard deviation of observations, RE is the percent error calculated as observed minus simulated and normalized to the average observed value and is also known as %BIAS, NSE is the Nash-Sutcliffe coefficient of model fit efficiency, and OBSavg is the average of observed data. The overall ratings in this table are based on the criteria provided for Relative Error, RMSE/STD$_{obs}$, and NSE by Moriasi et al. (2007) and shown above in Table 4-2.

The overall rating for the calibration based on the criteria of Moriasi et al. (2007) ranges from good to very good. The statistical measures other than RE, RMSE/STDobs, and NSE presented in Table 5-5 are not directly used to determine the overall ratings, but provide additional insights. For example, the absolute error measures (MAE, RMSE) provide assessment of the difference between observed and predicted values (in the same unit) and MAE/OBS_{avg} can be used to assess error relative to the mean of the observed values. The difference (RMSE - MAE) can be used as an indicator of the extent to which outliers (or variance in the differences between the simulated and observed values) exist in the data.

Similar results for the validation stations are shown in Table 5-6. Once again, the quality of model fit ranges from good to very good. The model is thus assessed as adequately calibrated for hydrology

Table 5-6. Supplemental Statistical Measures for High Rock Lake Watershed Model Hydrology, Validation Stations (cfs)

Statistical Measure	Yadkin R. at Yadkin Col. 02116500	Muddy Cr. Near Muddy Cr. 02115860	Yadkin R. at Enon 02115360	Mitchell R. near State Rd 02112360	Yadkin R. at Elkin 02112250
Count	3743	1005	3743	3743	3743
Mean Absolute Error (MAE)	580.7	68.8	415.5	27.2	188.2
Average Error	201.6	10.1	47.5	2.3	-14.1
RMSE	1265.8	242.3	1015.5	68.2	367.9
R^2	0.78	0.65	0.73	0.68	0.87
STD_{obs}	2590.6	381.5	1903.0	104.4	922.0
$RMSE/STD_{obs}$	0.49	0.64	0.53	0.65	0.40
RE (%BIAS)	-8.23%	-4.88%	-2.37%	-2.23%	1.30%
NSE	0.761	0.596	0.715	0.574	0.841
$RMSE/OBS_{avg}$	0.52	1.62	0.51	0.65	0.34
MAE/OBS_{avg}	0.237	0.331	0.208	0.260	0.173
RMSE – MAE	685.1	173.5	600.1	41.0	179.8
Overall Rating	Very Good	Good	Good - Very Good	Good	Very Good

Notes: RMSE is the root mean squared error; R^2 is the squared correlation coefficient, STDobs is the standard deviation of observations, RE or %BIAS is the percent error calculated as observed minus simulated and normalized to the average observed value, NSE is the Nash-Sutcliffe coefficient of model fit efficiency, and OBSavg is the average of observed data. The overall ratings in this table are based on the criteria provided for RE/%BIAS, RMSE/STDobs, and NSE by Moriasi et al. (2007) and shown above in Table 4 2.

5.2 SEDIMENT CALIBRATION

Sediment transport depends on, and is calibrated after hydrology. As noted in Section 4.3, the general strategy for sediment calibration follows the procedure described in Donigian and Love (2003) and consists of the following steps:

- Specify initial upland parameter values based on external information (e.g., soils data).
- Adjust upland sediment erosion to reproduce calibration targets available from other studies or literature.
- Adjust instream/channel parameters to match observed total suspended solids (TSS) concentrations and loads.

Initial values of sediment parameters were set in accordance with the ranges recommended for application of HSPF sediment transport models by Donigian and Love (2003) and adjusted during calibration.

The upland parameters for sediment were related to soil and topographic properties. The HSPF model does not use the Universal Soil Loss Equation (USLE) for sediment simulation. However, some of the parameters used in HSPF are similar to those in the USLE and HSPF erosion parameters for pervious land covers were estimated based on a theoretical relationship between HSPF algorithms and documented soil parameters, ensuring consistency in relative estimates of erosion based on soil type and cover. HSPF calculates the detachment rate of sediment by rainfall (in tons/acre) as

$$DET = (1 - COVER) \cdot SMPF \cdot KRER \cdot P^{JRER}$$

where *DET* is the detachment rate (tons/acre), *COVER* is the dimensionless factor accounting for the effects of cover on the detachment of soil particles, *SMPF* is the dimensionless management practice factor, *KRER* is the coefficient in the soil detachment equation, *JRER* is the exponent in the soil detachment equation, which is recommended to be set to 1.81, and *P* is precipitation depth in inches over the simulation time interval. Actual sediment storage available for transport (*DETS*) is a function of accumulation over time and the reincorporation rate, *AFFIX*. The equation for *DET* is formally similar to the USLE equation (Wischmeier and Smith, 1978) where *RE* is the rainfall erosivity, *K* is the soil erodibility factor, *LS* is the length-slope factor, *C* is the cover factor, and *P* is the practice factor,

$$RE \cdot K \cdot LS \cdot C \cdot P.$$

USLE predicts sediment loss from one or a series of events at the field scale, and thus incorporates local transport as well as sediment detachment. For a large event with a significant antecedent dry period, it is reasonable to assume that *DET≈DETS* if *AFFIX* is greater than zero. Further, during a large event, sediment yield at the field scale is assumed to be limited by supply, rather than transport capacity. Under those conditions, the USLE yield from an event should approximate *DET* in HSPF.

With these assumptions, the HSPF variable *SMPF* may be taken as fully analogous to the USLE P factor. The complement of *COVER* is equivalent to the USLE C factor (i.e., (1 - *COVER*) = *C*). This leaves the following equivalence (given *JRER* = 1.81):

$$KRER \cdot P^{JRER} \quad = \quad RE \cdot K \cdot LS \text{, or}$$

$$KRER = {RE \cdot K \cdot LS}\big/{P^{1.81}}$$

The empirical equation of Richardson et al. (1983) as further tested by Haith and Merrill (1987) gives an expression for *RE* (in units of MJ-mm/ha-h) in terms of precipitation:

$$RE \quad = \quad 64.6 \cdot a_t \cdot R^{1.81}$$

where *R* is precipitation in cm and a_t is an empirical factor that varies by location and season. As shown in Haith et al. (1992), the expression for *RE* can be re-expressed in units of metric tonnes/ha as:

$$RE \quad = \quad 0.132 \cdot 64.6 \cdot a_t \cdot R^{1.81}$$

This relationship suggests that the HSPF exponent on precipitation, *JRER*, should be set to 1.81.

The remainder of the terms in the calculation of *RE* must be subsumed into the *KRER* term of HSPF, with a units conversion. Writing *RE* in terms of tons/acre and using precipitation in inches:

$$RE\,(tons\ /\ ac) \quad = \quad [0.132 \cdot 64.6 \cdot a_t] \cdot P\,(in)^{1.81} \cdot (2.54\ cm\ /\ in)^{1.81} \cdot (1\ ton\ /\ ac)\,/\,(2.24\ tonnes\ /\ ha)$$

The average value for a_t for this part of North Carolina (USLE Region 28) is 0.225 (Selker et al., 1990), yielding

$$RE = 4.629 \cdot P^{1.81}$$

The power term for precipitation can then be eliminated from the equation for *KRER*, leaving the following expression (English units) in terms of the USLE K factor:

$$KRER \;=\; 4.629 \cdot K \cdot LS$$

The *K* factor is available directly from soil surveys, while the *LS* factor can be estimated from slope, using the expression of Wischmeier and Smith (1978):

$$LS = (0.045\, L)^b \cdot \left(65.41 \sin^2 \theta_k + 4.56 \sin \theta_k + 0.065\right), \text{ where}$$

$\theta = \tan^{-1}(S/100)$, *S* is the slope in percent, *L* is the slope length (in meters), and *b* takes the following values: 0.5 for $S \geq 5$, 0.4 for $3.5 \leq S < 5$, 0.3 for $1 \leq S < 3$, and 0.2 for $S < 1$.

This approach establishes values for *KRER* that are consistent with USLE information. Sediment calibration is then pursued primarily by modifying the transport coefficient, *KSER.* It should be noted that Donigian and Love (2003) recommend setting *KRER* directly equal to the USLE *K* factor. As was seen from the discussion above, this is theoretically incorrect, although *KRER* will be proportional to *K*, depending on slope. Because a different approach is used here, the "typical" ranges for *KRER* and *KSER* cited by Donigian and Love are not applicable.

Once KRER is established, the primary upland calibration parameter for sediment is KSER, which determines the ability of overland flow to transport detached sediment. Sediment yield varies as a function of erodibility, slope, and hydrology. Therefore, values reported in the literature on typical sediment yields by land use are of limited value for comparison. As expected, the sediment loading rates show a wide range for a given land use due to differences in soils and slopes. The simulated average upland unit-area sediment yields by model land use type are shown in Figure 5-2 as a check to confirm that reasonable values are predicted. The simulated values generally compare well with the range of values from literature. For example, Simmons (1993) reports an average TSS load of 0.828 tons/ac/yr for Piedmont NC "rural area affected by nonagricultural and agricultural activities" and an average of 0.070 tons/ac/yr for forest.

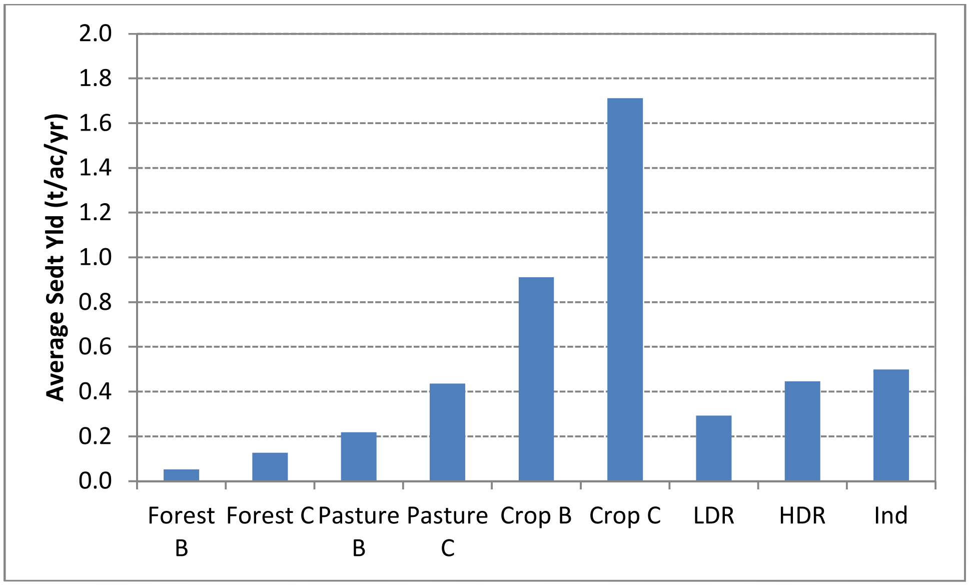

Figure 5-2. Simulated Average Unit Area Sediment (TSS) Yield

Note: Results for LDR (low density residential), HDR (high density residential) and Ind (industrial) are composites of pervious and impervious area loading rates.

Tetra Tech originally intended to treat unpaved rural roads as a separate land use class as these can potentially be a significant source of sediment load. However, the majority of the unpaved roads in the watershed are privately owned and no comprehensive coverage of their extent was available. As a result, unpaved roads are primarily represented as part of the general load from rural land uses. NCDOT (2009b) identified a total of 480 miles of unpaved roads maintained by them in Alexander, Davidson, Davie, Forsyth, Iredell, Rowan, Surry, Wilkes, and Yadkin Counties and conducted a series of RUSLE2 analysis (USDA, 2003) of potential sediment yields on an approximately 10 percent subset. This resulted in estimated loading rates for unpaved roads ranging from 0.29 to 1.83 tons/ac/yr with a median of 0.81 tons/ac/yr. It is more likely, however, that abandoned or poorly maintained private unpaved roads are major sources of sediment load.

NCDOT provided a variety of studies on suspended solids event mean concentration in runoff from DOT right-of-ways (Line, 2006; luell et al., 2010, Skipper, 2008, Winston et al., 2011; Wu and Allan, 2001; Wu and Allan, 2006; Wu and Allan, 2009). These studies show median EMCs for solids ranging from 49 to 415 mg/L and 85th percentile EMCs ranging from 49 to 415 mg/L, and thus do not provide an exact target. In addition, it is likely that larger loads arise from a limited population of problem sites and occasional extreme storm events that may not be well represented in the cited studies. Nonetheless, the EMCs produced by the model should s how approximate consistency. To analyze this, Tetra Tech undertook a direct comparison by converting model simulated storm-event loads from DOT right-of-ways to EMCs. The resulting model simulations yield road land use EMCs that have a median of 68 mg/L and 85th percentile of 161 mg/L, consistent with the ranges in the cited studies.

HSPF simulates total sediment load from upland land segments. The total sediment load must be partitioned into sand, silt, and clay classes before being passed to the stream reach simulation. The sediment size class fractions in delivered load were estimated from calculations based on soil properties and an assumed clay enrichment value.

The next step in calibration was to assess the mass balance of the three sediment classes in each stream reach across the period of the simulation. This reach-by-reach assessment is laborious but useful to ensure reasonable behavior of the reach sediment simulation. The final step was to compare the simulated concentrations and loads to the observations at water quality monitoring stations.

Key parameters controlling sediment transport within streams and rivers are as follows (Donigian and Love (2003) :

KSER: The coefficient in the soil washoff or transport equation represents an attempt to combine the effects of slope, overland flow length, sediment particle size, and surface roughness on the sediment transport capacity of overland flow into a single parameter. Consequently, calibration is the major method of evaluating KSER. This parameter was set between of 0.01 and 2.5.

KSAND: Sand transport is represented with a power function based on velocity. KSAND, the coefficient in the sand load power function, was set to 0.1 to start calibration and adjusted to improve the comparison between simulated and observed sand concentrations.

TAUCD: The critical bed shear stress for deposition (lb/ft^2) represents the energy level below which cohesive sediment (silt and clay) begins to deposit to the bed. Values of TAUCD for silt and clay were estimated on a reach-by-reach basis by examining graphs of the cumulative distribution function of simulated shear stress and setting the parameter to a lower percentile of the distribution in each reach segment, as recommended by Donigian and Love. The 5th percentile was used for clay and the 10th percentile for silt.

TAUCS: The critical bed shear stress for scour (lb/ft^2) represents the energy level above which scour of cohesive sediment begins. Initial values of TAUCS were set, as recommended, at upper percentiles of the distribution of simulated shear stress in each reach (the 85th percentile for clay and the 90th percentile for silt). Values for some individual reaches were subsequently modified during calibration.

M: The erodibility coefficient of the sediment (lb/ft^2-d) determines the maximum rate at which scour of cohesive sediment occurs when shear stress exceeds TAUCS. This coefficient is a calibration parameter. It was initially set to 0.01 and adjusted during calibration. The maximum value used was 0.04.

One constraint applied to the reach sediment calibration was to keep the simulated bed sediment conditions near a dynamic steady state over the course of the simulation, while allowing some net channel degradation in headwaters and developing reaches and sediment aggradation in impounded or backwater reaches. This constraint means that model parameters are selected so that aggradation or degradation of the bed by tens of feet is not allowed, as this is inconsistent with observations. Significant scour can still occur in high flow events, but this is largely balanced by subsequent deposition during moderate flow events. The reach-by-reach calibration also endeavored to maintain an approximately constant bed composition (sand, silt, and clay) over time. Collection of data on channel morphology and form evolution of individual stream reaches could be used to further improve this portion of the model.

Phosphorus simulation is strongly dependent on the sediment simulation, as much of the total phosphorus load moves in association with sediment. Therefore, the sediment calibration was further adjusted during the phosphorus calibration. In some cases, reduction in the apparent quality of fit for sediment was required to improve the fit for phosphorus.

The sediment simulation depends directly on the hydrologic simulation and it is useful to specify calibration and validation locations and time frames differently for the sediment and hydrologic calibrations and validations. This also ensures that the sediment calibration tests local conditions at each of the monitoring points while also providing for a validation test. To ensure a robust model fit, the sediment validation was performed on a temporal basis (as opposed to a spatial basis), with observed time series separated into calibration validation periods. Direct comparison of model simulated concentrations to observations of total suspended solids was performed at eight monitoring locations listed in Table 5-7. The period with more observed data was 2005-2010 due to the scoping and intensive monitoring programs and this period was selected for model calibration. The earlier 2000-2004 period was used for model validation.

Table 5-7. Water Quality Calibration Station Locations

Station ID	Name	Coincident USGS ID	Model Subbasin (RCHRES ID)
Q0660000	Roaring River at Roaring River	02112120	82
Q0450000	Yadkin River at Elkin	02112250	73
Q2040000	Yadkin River at Enon	02115360	67
Q2720000	Muddy Creek at Muddy Creek	02115860	115
Q2810000	Yadkin River at Yadkin College	02116500	56
Q3460000	South Yadkin River near Mocksville	02118000	31
Q4120000	Second Creek near Barber	02120780	13
Q5930000	Abbotts Creek near Lexington	02121500	133

Note: Muddy Creek has an insufficient number of samples for full calibration; however, results for this station are included in Appendix F.

Appendix F presents detailed tables and figures for the sediment calibration and validation for all stations, including both concentration and load comparisons. Additional detail is presented here on Abbotts Creek as an example of the sediment calibration process.

Upland sediment loading rates (in Abbotts Creek and elsewhere) were first set based on the USLE and average annual load analysis, as described above. Channel sediment transport parameters for Abbotts Creek were then set to allow some degradation in this urban watershed, with the exception of the reach containing Lake Thom-A-Lex, which was assumed to be aggrading. Additional sediment calibration focused on the adjustment of the channel scour and deposition parameters. As a first, step, power plots of load and concentration versus flow were examined to ensure that load-flow and concentration-flow relationships were similar between observations and predictions. The agreement is generally good, except that there are a few observations coincident with high simulated flows that show unexpectedly lower concentrations (Figure 5-3). These primarily represent occasions where the flow was not well simulated, likely due to the available rainfall record. For example, on April 22, 2008 the simulated flow was 1100 cfs and the observed TSS concentration was 14 mg/L; however, the actual measured flow was only 122 cfs, consistent with the low TSS observation.

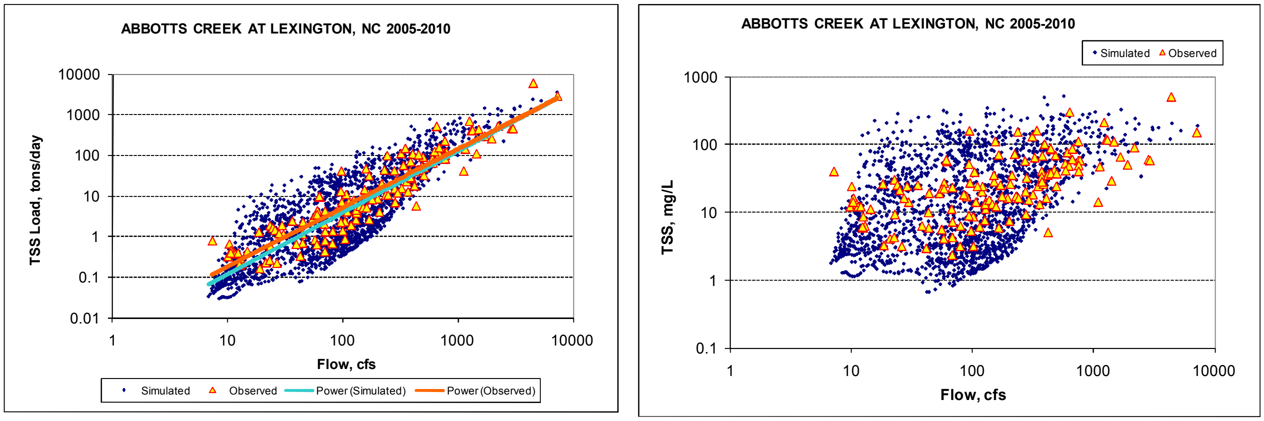

Figure 5-3. Power Plots for Total Suspended Solids Calibration, Abbotts Creek

Standard time series plots and statistics also appear to show a relatively good fit (Figure 5-4). Direct graphical comparison of two time series can, however, be misleading. Therefore, plots of error (simulated minus observed) versus flow and month were examined to ensure that strong biases relative to flow and season are not present (Figure 5-5).

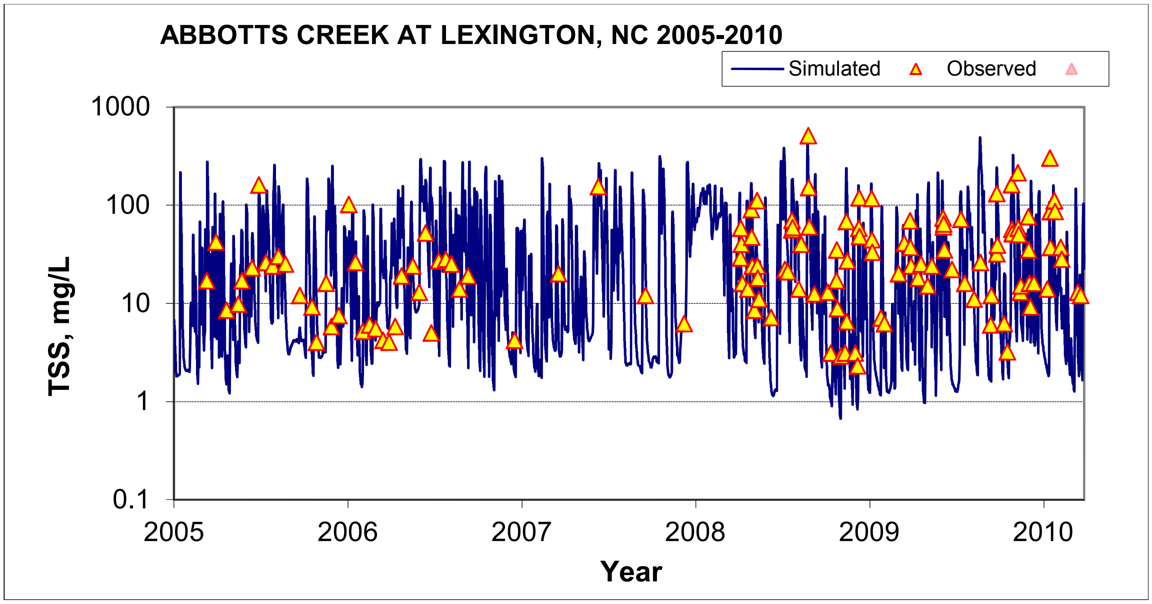

Figure 5-4. Time Series Comparison, Total Suspended Solids Calibration, Abbotts Creek

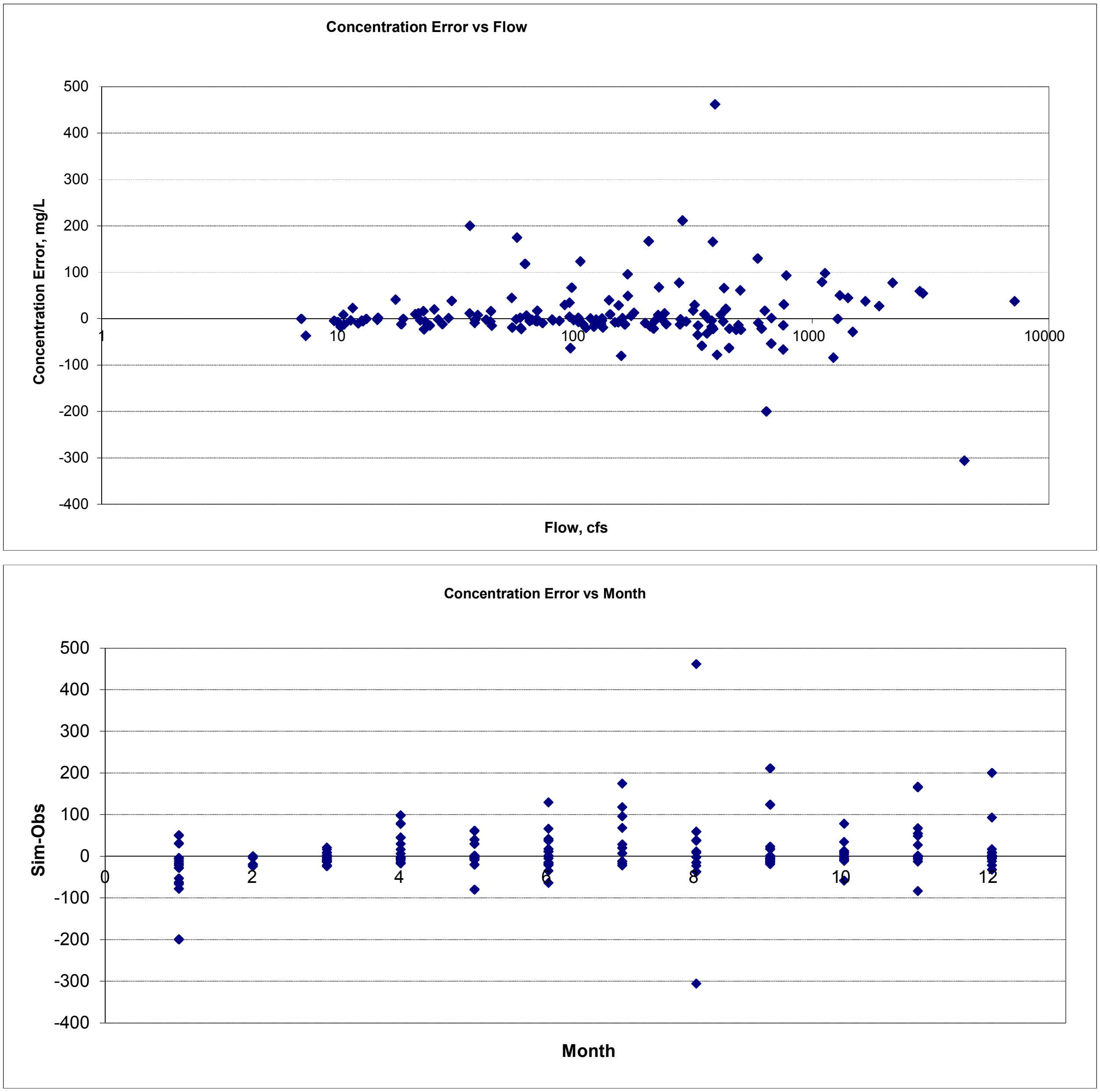

Figure 5-5. Error Bias Plots, Total Suspended Solids Calibration, Abbotts Creek

The calibration was followed by a validation check against earlier data. This provided reasonable fits to both concentration and paired load estimates. Finally, model performance was evaluated against estimated monthly load series. The average relative error or %BIAS during the calibration period is small (4.8 percent), and the fit appears reasonable (Figure 5-6); however, the NSE for the calibration period is low (0.18) as some months seem to be over-predicted and others under-predicted. (Remember that this may reflect deficiencies in the interpolation of monthly load from observations as well as discrepancies in the model). The NSE is based on squared errors and is sensitive to outliers; thus low NSE does not necessarily imply bad model performance. Examination of the NSE for the validation period reveals a much higher NSE (0.60), and, given the good fit obtained on other statistics, the TSS calibration and validation is judged to be acceptable on weight of evidence.

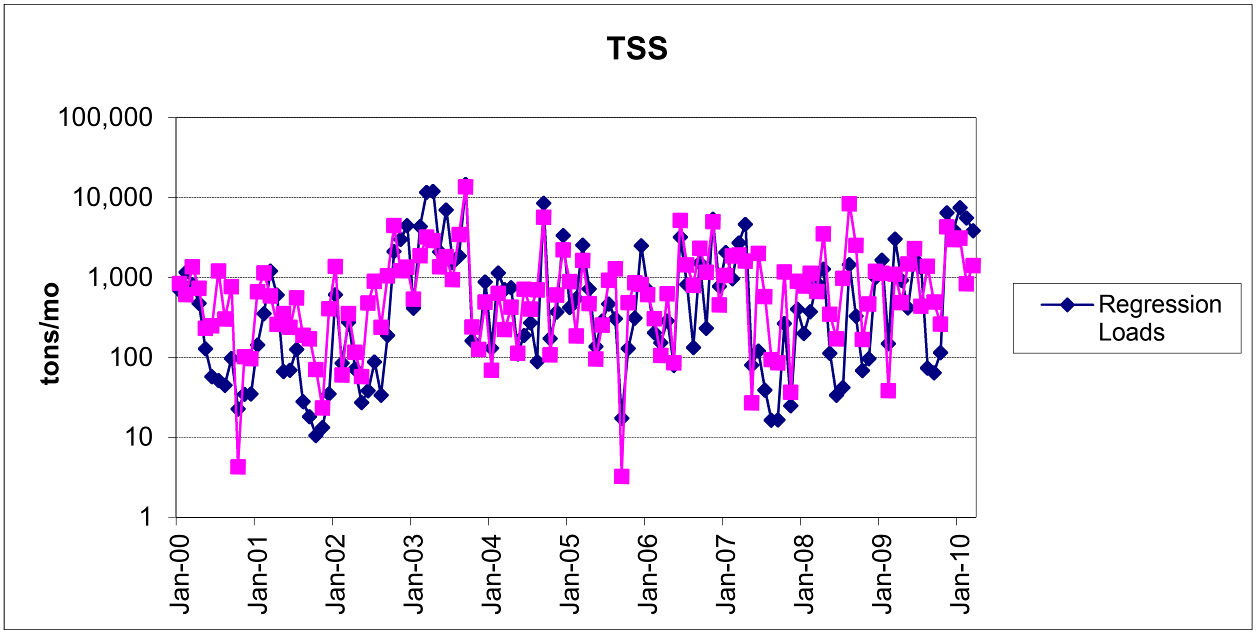

Figure 5-6. Monthly Load Series Comparison for TSS, Abbotts Creek

Summary statistics for the suspended sediment calibration and validation across all stations are shown in Table 5-8. Complete details and figures are provided in Appendix F.

Table 5-8. Summary Statistics for TSS Calibration and Validation

Station	Calibration (2005-2010)			Validation (2000-2004)		
	Concentration Relative Error	Paired Load Relative Error	NSE, Monthly Load Series	Concentration Relative Error	Paired Load Relative Error	NSE, Monthly Load Series
Roaring River at Roaring River	-14,6 % (-1.3%)	11.1% (-0.2%)	0.31	-14.0% (-11.2%)	182.9% (-11.1%)	0.68
Yadkin River at Elkin	-36.2% (-0.1%)	-40.5% (-0.0%)	0.63	-10.7% (-1.2%)	-5.2% (-0.9%)	0.40
Yadkin River at Enon	16.3% (-3.1%)	46.7% (-0.7%)	0.40	29.4% (-2.7%)	10.3% (-0.7%)	0.28
Yadkin River at Yadkin College	-0.4% (-2.1%)	37.2% (-0.4%)	0.60	-7.5% (-.5%)	-22.8% (-1.5%)	0.43
South Yadkin River near Mocksville	29.8% (-0.6%)	139% (-0.1%)	0.73	-31.7% (-12.5%)	-32.1% (-2.6%)	0.26
Second Creek near Barber	-38.9 % (-0.9%)	-5.5% (0.0%)	0.35	-34.1% (0.5%)	-2.1% (0.1%)	0.32
Abbotts Creek near Lexington	26.1% (-2.4%)	-0.1% (-0.1%)	0.18	15.5% (-18.8%)	-20.2% (-6.4%)	0.59

Note: Error statistics show the average relative error (simulated minus observed) followed by the median relative error (in parentheses).

Examination of the table shows several cases in which the average errors are inflated by one or a few extreme outliers, as is the case for paired loads in Roaring River during the validation period. In such cases, the relative median error, which is not unduly influenced by outliers, is a better indicator of model performance. Note that outliers also affect the NSE and the regression-based calculations of long-term monthly load.

In most cases, model fit based on both concentration and paired load relative average error falls into the "good" or "fair" category. Model fit based on relative median error is in the "excellent" category for all stations. The model over-predicts the estimated load in Yadkin River at Yadkin College by about 35 percent (Figure 5-7); however, this is mostly due to a few outliers, and the general trend is captured well. NSE values for monthly loads are in some cases low, but may reflect uncertainties in application of the stratified regression estimate of observed loads.

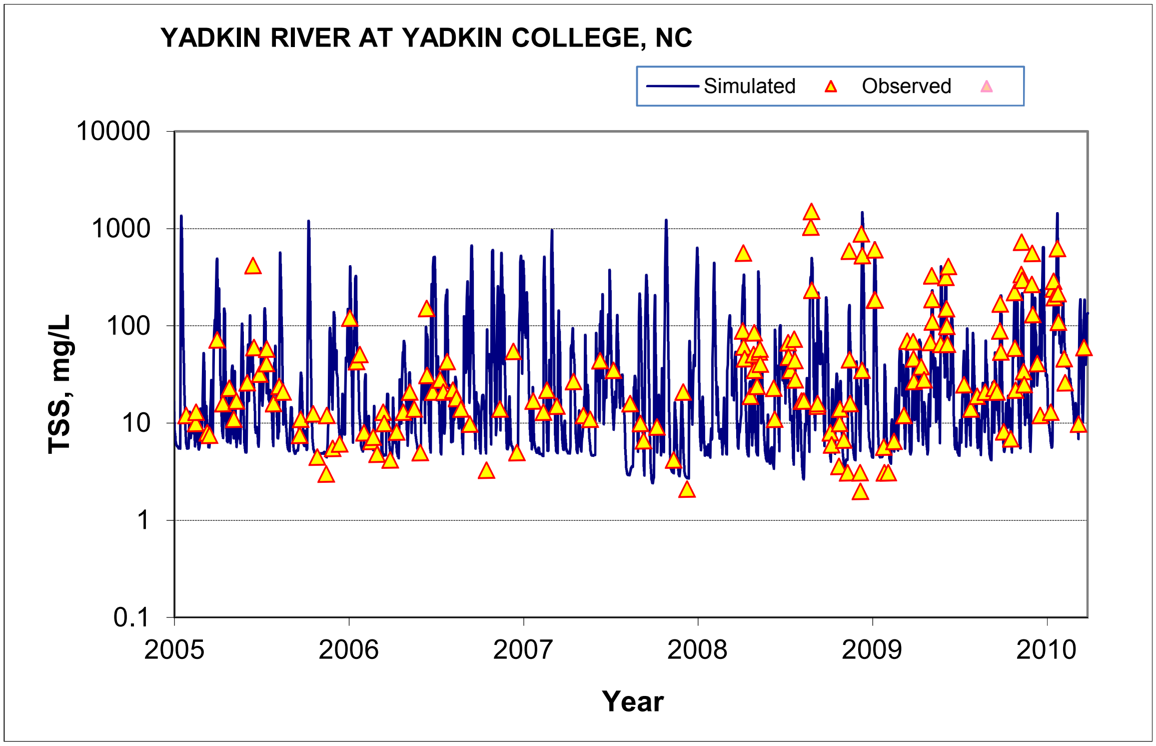

Figure 5-7. Calibration Time Series for TSS, Yadkin River at Yadkin College

5.3 WATER TEMPERATURE

As noted in Section 4.3, water temperature simulation is not a primary objective of the High Rock Lake watershed model; however, a reasonable representation of water temperature is important because it affects many biologically mediated processes that influence water quality transformations in the stream and river network.

The time series comparison of water temperature simulation is presented at four stations at the end of Appendix F and indicates acceptable agreement with observed data.

5.4 NUTRIENT CALIBRATION

5.4.1 Nutrient Calibration Setup

As described in 4.3, the nutrient simulation for the uplands represents inorganic nitrogen, inorganic phosphorus, and organic matter as three distinct constituents. Inorganic phosphorus and organic matter on pervious surfaces are simulated using a sediment potency approach, while inorganic nitrogen on pervious surfaces and all three constituents on impervious surfaces are represented as a buildup/washoff process. Concentrations associated with subsurface flows are also included.

Within the stream reaches the model represents individual nutrient species (ammonia, nitrate, nitrite, organic nitrogen, orthophosphate, organic phosphorus, and organic carbon/BOD). The stream reach module is implemented with full nutrient simulation, including uptake by and release from plankton and benthic algae, decay of organic matter, oxidation of ammonium to nitrite and nitrite to nitrate nitrogen, bed exchanges of dissolved and sorbed nutrients, and ammonia volatilization. The calibration was constrained to provide a reasonable representation of individual nutrient species within the stream reaches; however, the focus of calibration is on representing total phosphorus and total nitrogen as the primary purpose of the model is to represent loads delivered to High Rock Lake.

The key parameters controlling the upland nutrient simulation are listed below:

MON-ACCUM: The monthly varying assignment of the build-up or accumulation of a constituent on a particular surface (lb/ac-d). The values were around 10^{-2} for inorganic nitrogen.

MON-SQOLIM: The monthly varying upper limit value beyond which a constituent can no longer accumulate on a surface (lb/ac). The values were around 10^{-1} for inorganic nitrogen.

MON-IFLW-CONC and **MON-GRND-CONC**: These parameters are used to assign the interflow and groundwater constituent concentrations on a monthly basis. The values for these parameters were estimated from the observed data with consideration of flow regime and then calibrated as necessary.

MON-POTFW: The monthly varying specification of constituent mass per sediment mass (lb/ton). For organic matter the assigned values were around 10^0 to 10^1. The seasonal assignment for organic matter reflects the annual cycle of growth and then litter. This assignment was held constant for inorganic phosphorus as this is primarily a characteristic of soils, with values ranging from approximately 10^{-2} to 10^{-1}.

The sediment potency and build-up/wash-off parameters were initialized based on past experience and revised as needed during the calibration process. The first step was to verify that unit area loading rates were reasonable compared to literature values. Next, calibration to instream observations was carried out to refine the simulation through adjustment of organic matter settling rates, bottom sediment concentrations of phosphorus and ammonium, and the growth of periphyton/macrophytes. Plant growth has an important effect on nutrient balances during low flow conditions; therefore, nitrogen and phosphorus must be calibrated simultaneously.

As with TSS, a graphical comparison of unit-area loading rates is used to assess the general reasonableness of the upland nutrient simulation. Table 5-9 shows literature ranges for typical nutrient loading rates for various land use categories used to assess the reasonableness of land-based generation of nutrients in the High Rock Lake watershed model application. The simulated average unit area loads in Figure 5-8 and Figure 5-9 are in toward the higher end of the reported literature ranges. However, the literature values are largely based on surface runoff, whereas the model results include additional load (particularly for TN) by subsurface pathways.

Table 5-9. Typical Nutrient Yield Ranges from Literature

Land Use	TN (lb-N/ac/y)	TP (lb-P/ac/y)	Source
Low Density Residential, Medium Density Residential	4 - 8	0.4 – 1.4	Table 8-2 and 8-3, Novotny and Olem, 1994
High Density Residential, Commercial	1.6 – 11	0.1 - 3	Table 8-2 and 8-3, Novotny and Olem, 1994; Lin 2004
Medium-High Intensity Industrial	2 – 14	0.8 - 4	Table 8-2 and 8-3, Novotny and Olem, 1994; Lin, 2004
Forested	1 – 6	0.01 – 0.8	Lin, 2004;Table 28.2, Chapra, 1997
Agriculture	0.4 - 44	0.09 - 4	Table 28.2, Chapra, 1997
Urban	0.9 - 18	0.1 - 9	Table 28.2, Chapra, 1997

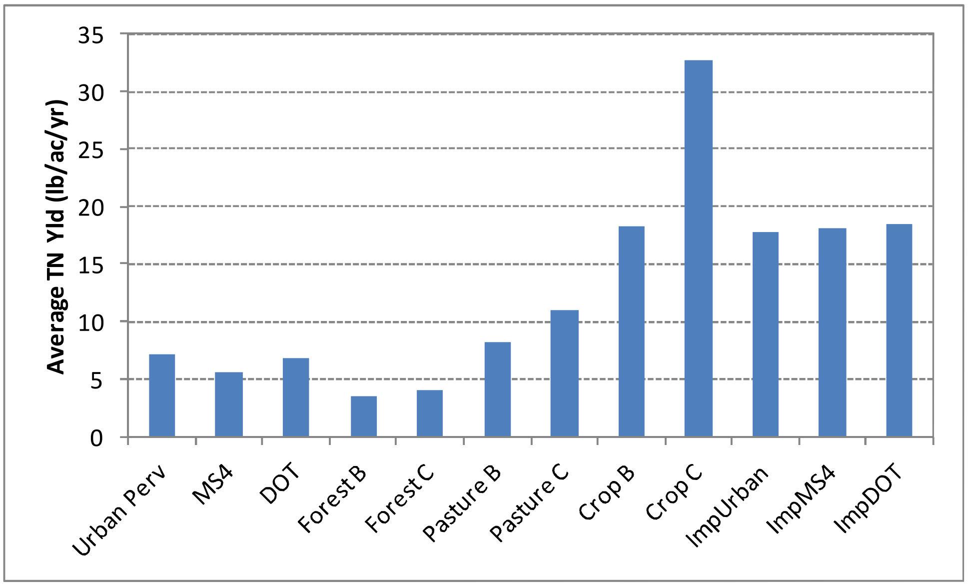

Figure 5-8. Simulated Average Unit-Area Total Nitrogen Yield (2000-2010)

Note: Results for LDR (low density residential), HDR (high density residential) and Ind (industrial) are composites of pervious and impervious area loading rates.

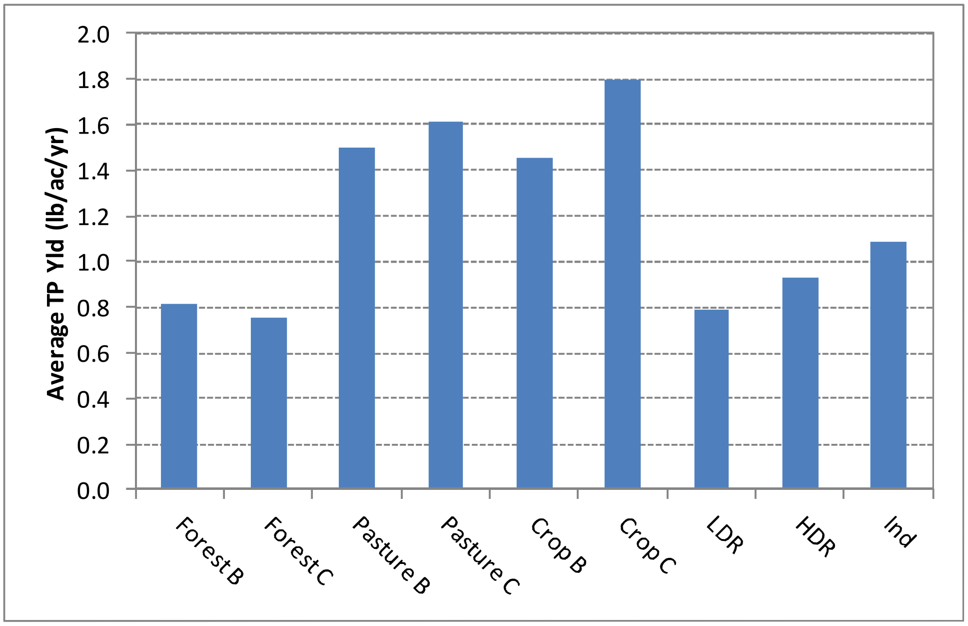

Figure 5-9. Simulated Average Unit Area Total Phosphorus Yield (2000-2010)

Note: Results for LDR (low density residential), HDR (high density residential) and Ind (industrial) are composites of pervious and impervious area loading rates.

Few studies have been undertaken within the High Rock watershed, but studies in nearby watersheds yield generally similar loading rates. Harned (1995) reported for agriculture in northeastern Guilford Co. TN loading rates of 11-14 lb/ac/yr and TP loading rates of about 3.5 lb/ac/yr for agriculture, while forest loading rates were reported as 3.3 lb/ac/yr for TN and 0.44 lb/ac/yr for TP. Line et al. (2010) reported somewhat lower loading rates for nutrients (but based on only 1-2 years of data from four sites during a relatively dry period) of about 5.2 – 7.5 lb/ac/yr TN and 2.5 – 4.7 lb/ac/yr TP for pasture land uses and 5.4 – 5.8 lb/ac/yr TN and 0.29 – 0.33 lb/ac/yr TP for crop land uses. TP yields are highly variable and reflect local soils. Swartley et al. (2010) report loads from forest land uses in the headwaters of the Neuse River Basin of 1.1 -3.6 lb/ac/yr TN and 0.14 – 0.32 lb/ac/yr TP for 2009. Instream monitoring suggests that loading rates for nutrients are higher in the High Rock Lake watershed than in the Jordan Lake watershed due to soils characteristics.

5.4.2 Total Phosphorus Calibration

Phosphorus calibration to concentrations observed in streams was undertaken using a weight-of-evidence approach, similar to the sediment calibration, with checks for biases relative to flow and season. As with sediment, comparison was also made to monthly load series estimated via a stratified regression approach. While nonpoint loading of phosphorus is generally associated with sediment, one major difference from the suspended sediment calibration is that the phosphorus balance in some streams in the High Rock watershed is dominated by point source discharges. The accuracy with which the time series of point source loading are known imposes a fundamental limitation on the calibration in these areas.

Appendix G presents detailed concentration and loading statistics and comparison figures for total phosphorus at all stations along with details on the prediction of organic and inorganic phosphorus at selected downstream stations. Relative error statistics on concentration and paired load, along with the NSE coefficients for the monthly load series are summarized in Table 5-10. For many stations these are similar to the suspended sediment statistics, as nonpoint loading of phosphorus is largely driven by sediment loading. As with sediment, most of the average relative error statistics are in the good to fair range, while most of the median relative error statistics are in the excellent range. Monthly load NSEs are greater than 0.5 during calibration at all stations except Roaring River, where the concentrations are low and show very little correlation to flow, and Abbotts Creek, which has a large point source load.

Table 5-10. Summary Statistics for Phosphorus Calibration and Validation

	Calibration (2005-2010)			Validation (2000-2004)		
Station	Concentration Relative Error	Paired Load Relative Error	NSE, Monthly Load Series	Concentration Relative Error	Paired Load Relative Error	NSE, Monthly Load Series
Roaring River at Roaring River	-14.1% (25.3%)	-21.8% (6.4%)	0.39	-17.2% (7.8%)	-0.3% (7.6%)	0.85
Yadkin River at Elkin	-16.3% (7.1%)	-33.7% (3.2%)	0.79	-6.4% (5.7%)	-5.9% (4.5%)	0.72
Yadkin River at Enon	2.7% (8.4%)	22.6% (4.1%)	0.70	-21.5% (0.4%)	-20.8% (0.3%)	0.57
Yadkin River at Yadkin College	-30.1% (2.3%)	9.6% (1.3%)	0.51	-27.6% (-5.2%)	-15.4% (-2.9%)	0.62
South Yadkin River near Mocksville	-1.2% (3.6%)	60.0% (0.5%)	0.75	-6.6% (25.7%)	-18.2% (21.8%)	0.34
Second Creek near Barber	-31.1 % (5.1%)	-16.5% (0.6%)	0.57	-28.7% (-20.8%)	39.7% (-14.0%)	0.63
Abbotts Creek near Lexington	-6.3% (-1.7%)	-2.4% (-0.5%)	0.36	-12.2% (-4.9%)	-19.0% (-8.3%)	0.82

Note: Error statistics show the average relative error (simulated minus observed) followed by the median relative error (in parentheses).

For stations dominated by point sources, such as Abbotts Creek, the fit for total phosphorus is good (Figure 5-10), except for a scattering of individual points for which estimates of point source loads may be inaccurate. At the downstream station at Yadkin College the model does an excellent job of reproducing the central tendency (median) of total phosphorus concentration, but does not reproduce the observed variability – which may be due to a combination of point source influences from upstream and analytical uncertainty. Note that the observed time series at Yadkin College (Figure 5-11) includes two extreme observations, just less than 10 mg-P/L, which inflate the error statistics.

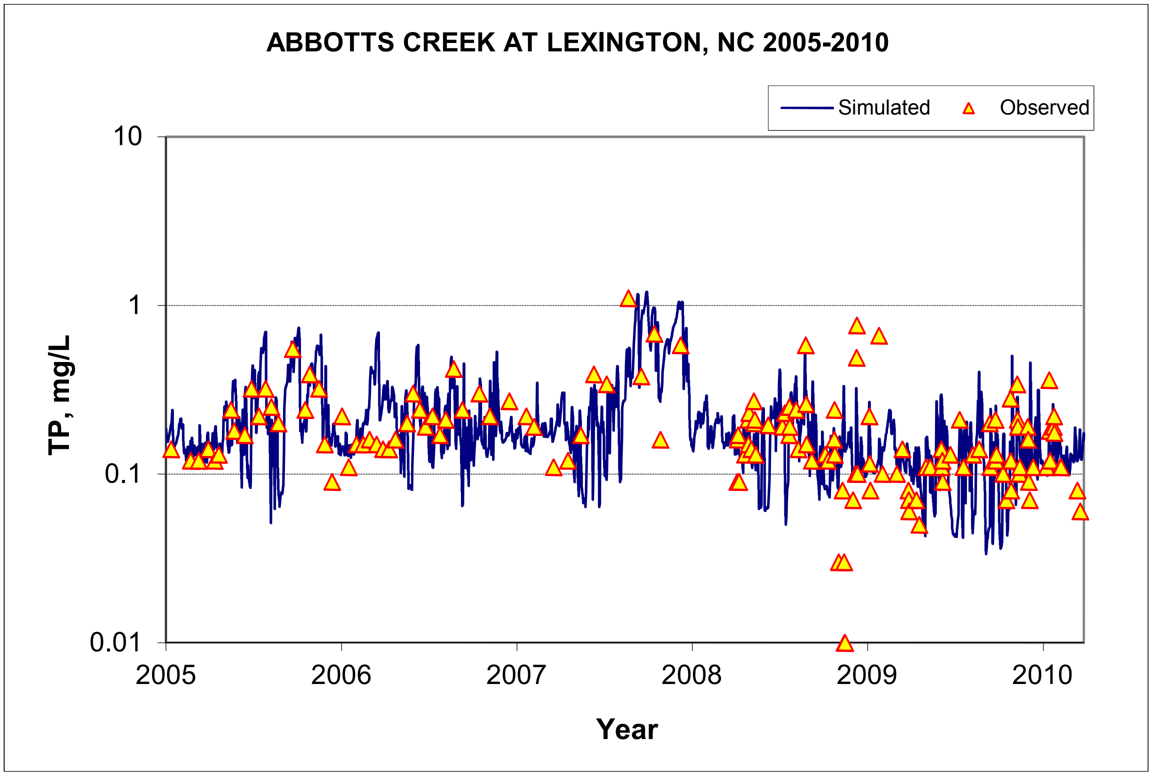

Figure 5-10. Total Phosphorus Calibration, Abbotts Creek

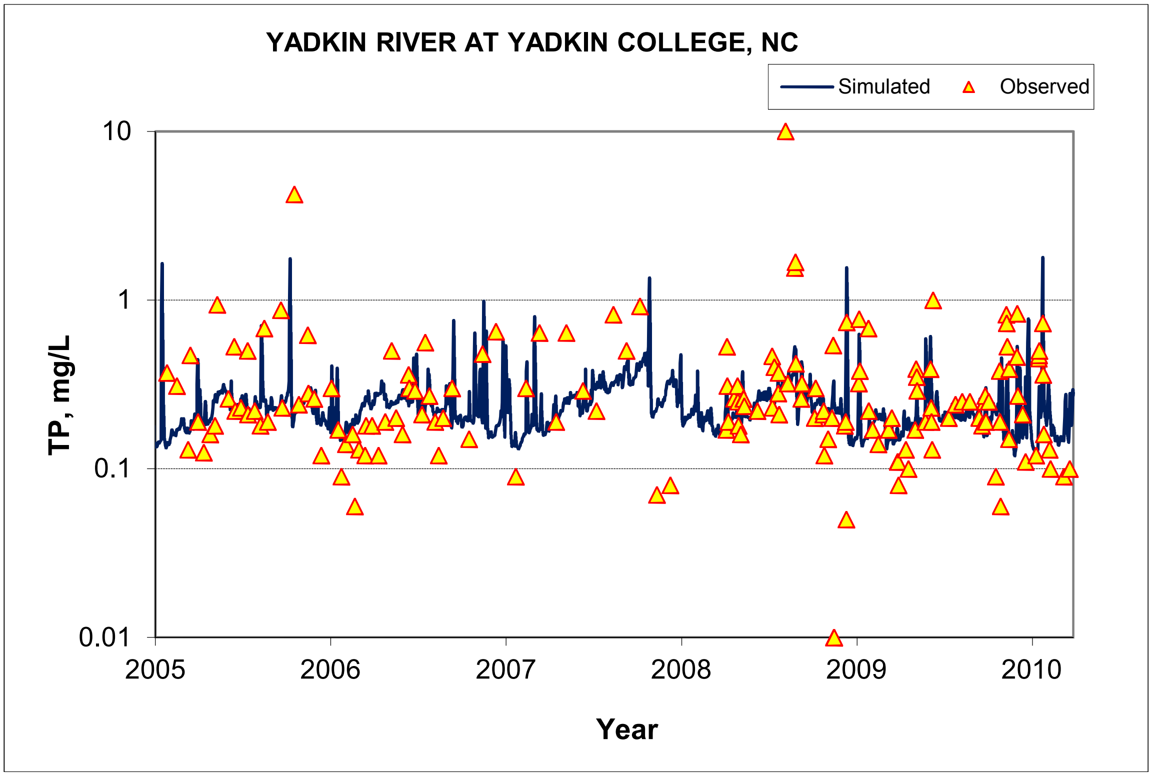

Figure 5-11. Total Phosphorus Calibration, Yadkin River at Yadkin College

Overall, the phosphorus calibration is judged to be acceptable in light of the performance targets specified in Section 4.4. However, the imprecision in predicting individual concentration observations should be recognized. In large part this imprecision, particularly at low flows, may be due to variability in point source loads that is not captured in the available discharge monitoring records. In addition, uncertainty in the hydrologic and sediment calibration propagates into the TP simulation.

5.4.3 Total Nitrogen Calibration

The total nitrogen calibration uses the same general approach described above, but is much more dependent on the specification of subsurface concentrations. These were set as monthly patterns by land cover. Similar to phosphorus, the low flow nitrogen concentration in some area streams is dominated by point source discharges.

The nitrogen calibration is more complex than that for phosphorus, as three major groups (nitrate N, ammonia N, and organic N) are simulated. The calibration endeavored to optimize fit to total N while also maintaining an accurate representation of the relative magnitude of these components.

Average relative error results for concentration and load are within 15 percent for the calibration period. Relative error results and NSE statistics on load are more variable (Table 5-11). Appendix G presents a complete set of tables and figures comparing simulated and observed total nitrogen concentrations and loads, along with details on nitrogen species representation at key stations.

Table 5-11. Summary Statistics for Nitrogen Calibration and Validation

Station	Calibration (2005-2010)			Validation (2000-2004)		
	Concentration Relative Error	Paired Load Relative Error	NSE, Monthly Load Series	Concentration Relative Error	Paired Load Relative Error	NSE, Monthly Load Series
Roaring River at Roaring River	-3.1 % (6.6%)	-5.7% (1.6%)	0.42	-21.1% (-1.1%)	-14.5% (-0.9%)	0.79
Yadkin River at Elkin	-13.3% (1.5%)	-20.4% (0.7%)	0.77	2.1% (-1.8%)	4.2% (-1.4%)	0.75
Yadkin River at Enon	8.0% (-0.1%)	26.3% (0.0%)	0.21	8.5% (14.1%)	9.3% (11.3%)	0.56
Yadkin River at Yadkin College	-8.3% (-5.7%)	14.3% (-3.3%)	0.63	-12.0% (-5.8%)	-11.1% (-3.6%)	0.67
South Yadkin River near Mocksville	7.0% (-4.1%)	56.7% (-1.1%)	0.75	13.3% (7.7%)	13.0% (5.3%)	0.37
Second Creek near Barber	-6.5 % (-7.4%)	26.9% (-1.3%)	0.41	-6.8% (-17.1%)	12.9% (-8.2%)	0.49
Abbotts Creek near Lexington	-8.1% (3.3%)	4.5% (1.0%)	0.25	-46.7% (-23.0%)	-9.6% (-26.1%)	0.77

Note: Error statistics show the average relative error (simulated minus observed) followed by the median relative error (in parentheses).

Evaluated against the performance targets discussed in Section 4.4, the relative errors for total nitrogen concentration are mostly in the “good” range. On the other hand, a number of the NSE values on monthly loads are less than the desired target of 0.5 or better. In general, these discrepancies seem to be driven by a relatively small number of outliers that have a strong impact on the squared error statistics. For example Figure 5-12 shows the observed and simulated total N results for Abbotts Creek. Most individual observations, seasonal patterns, and the reduction in N discharges following 2008 are well captured; however, some individual observations are underestimated by a large amount, deflating the NSE.

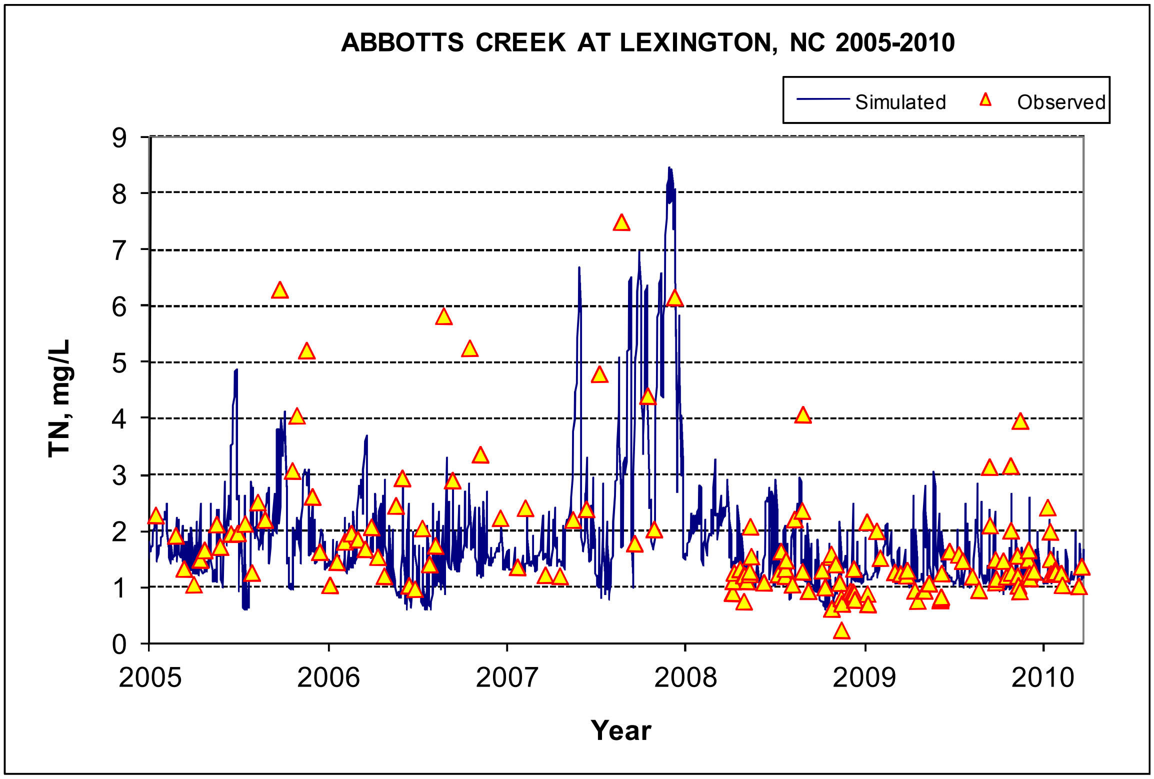

Figure 5-12. Total Nitrogen Calibration for Abbotts Creek

5.4.4 Nutrient Species

As noted above, while calibration focused on total N and total P, the calibration also endeavored to provide an appropriate representation of inorganic and organic nutrient species. This is not the primary focus of the calibration because most of the point source discharge records do not provide a full accounting of nutrient species and various important transformation processes (such as uptake and conversion to organic forms of nutrients by bacteria and fungi in wetlands and low order streams) are not explicitly represented in the model. Nonetheless, a reasonable representation of nutrient species is obtained. Detailed graphical and statistical results for three downstream stations (Yadkin River at Yadkin College, Abbotts Creek, and South Yadkin River) are provided in Appendix G. The results for Yadkin River at Yadkin College are summarized graphically in Figure 5-13.

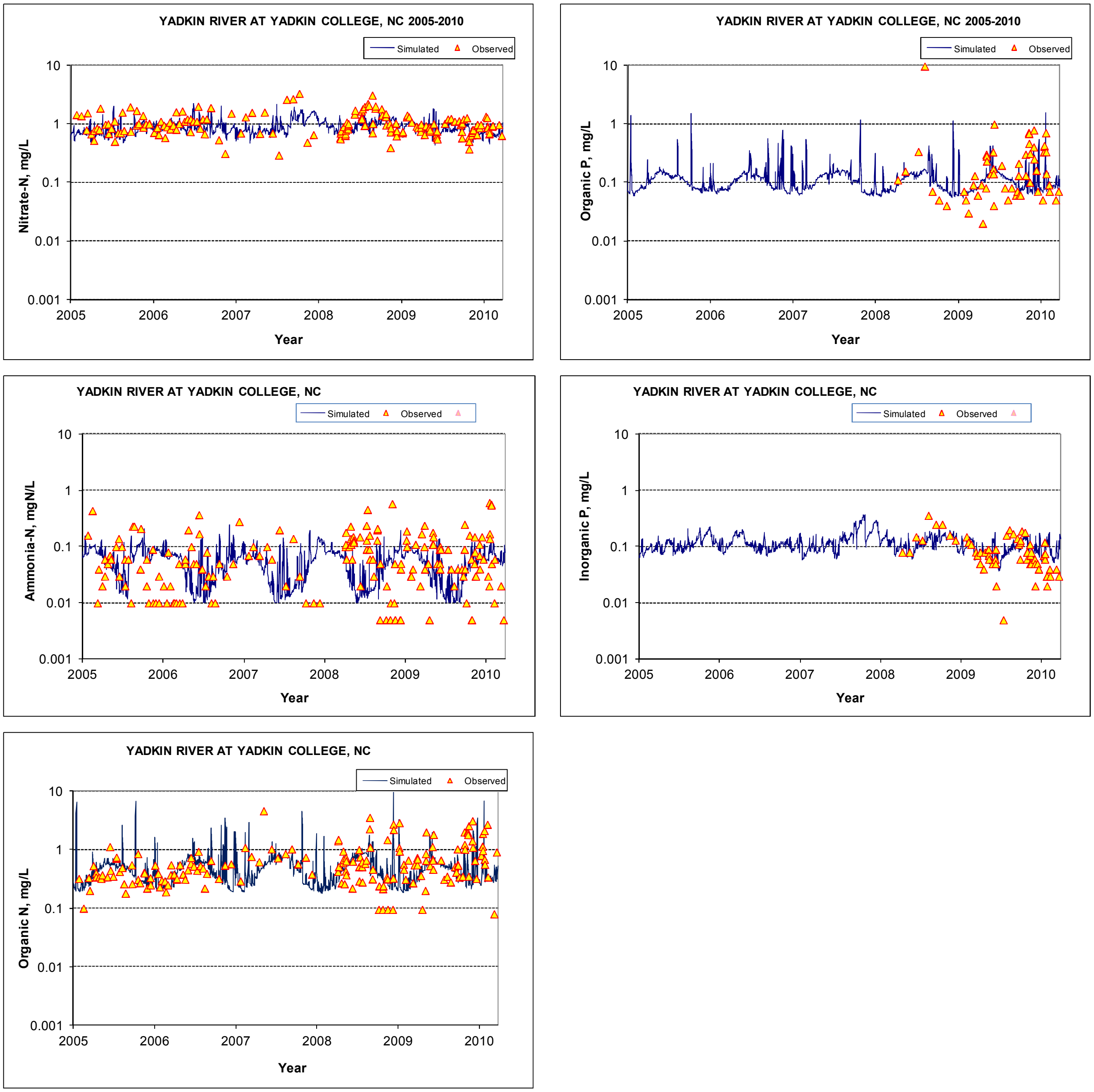

Figure 5-13. Nutrient Species Simulation, Yadkin River at Yadkin College

5.4.5 Algal Simulation

The instream calibration for nutrients was adjusted based on comments to provide a reasonable representation of algal growth in the streams and rivers. Only a limited amount of monitoring data is available, and most data on chlorophyll *a* in the watershed is either for small lakes or from backwater areas where tributaries enter High Rock Lake. It is, however, known that periodic algal blooms occur in slower-moving river sections (as is confirmed by limited sampling in the Yadkin River at NC 150 near Spencer, station Q4660000), and this is reproduced in the model. In addition, it was confirmed that chlorophyll *a* concentrations simulated by the model in Lake Thom-A-Lex (the only upstream lake in the watershed that is explicitly simulated) are consistent with the observed growing season range of 20 – 60 μg/L.

5.5 DISSOLVED OXYGEN AND BOD

Dissolved oxygen (DO) and biochemical oxygen demand (BOD) were not expected to be a concern in the riverine portion of the High Rock Lake watershed and are not a focus of model calibration. A reasonable simulation of DO is, however, needed as the occurrence of hypoxia affects a variety of stream nutrient transformation processes. Time series comparisons of DO and BOD simulated values and observations are presented in Appendix G and indicate a reasonable fit.

The simulation period included a significant drought, which did result in lower observed values of DO. The pronounced drought period was 2000-2002, which is not within the period used to drive the lake model. However, the 2007 drought is within the 2005-2010 period, thus a significant low flow event with lower watershed DO is included in the lake model applications.

6 Analysis of Pollutant Loading

6.1 POLLUTANT LOAD DELIVERED TO HIGH ROCK LAKE

The majority of flow and pollutant loads reach High Rock Lake via the Yadkin River. On average, the Yadkin River inflow accounts for about 70 percent of the flow, 62 percent of the sediment, 71 percent of the phosphorus, and 68 percent of the nitrogen reaching the lake. Model predictions of average annual loading for the simulation period of 2000-2009 are shown in Table 6-1. This includes the total watershed loads going into High Rock Lake, including unmonitored areas. It does not include direct atmospheric deposition onto the lake surface or point sources that discharge directly to the lake. The spatial distribution of loading is shown graphically in Figure 6-1. After the Yadkin River, the next largest sources are South Yadkin River and Abbotts Creek, which contribute 20 and 5 percent, respectively, of the flow, and 18 and 5 percent, respectively, of the total phosphorus reaching High Rock Lake.

Table 6-1. Annual Average Watershed Flow and Pollutant Loads Delivered to High Rock Lake

Watershed	Flow (AF/yr)	TSS (t/yr)	TP (t/yr)	TN (t/yr)
Yadkin River	1,951,767 (69.5%)	326,964 (62.5%)	685 (71.3%)	4,092 (67.5%)
South Yadkin River	558,544 (19.9%)	151,858 (29.0%)	178 (18.5%)	1,286 (21.2%)
Grants Creek	38,740 (1.4%)	8,284 (1.6%)	014 (1.4%)	101 (1.7%)
Abbotts Creek	148,500 (5.3%)	18,624 (3.6%)	049 (5.1%)	347 (5.7%)
Flat Swamp Creek	21,671 (0.8%)	3,625 (0.7%)	009 (0.9%)	053 (0.9%)
Dutch Second Creek	18,409 (0.7%)	3,452 (0.7%)	007 (0.8%)	052 (0.9%)
Town/Crane Creek	26,001 (0.9%)	4,576 (0.9%)	009 (0.9%)	065 (1.1%)
Swearing Creek	27,808 (1.0%)	5,916 (1.1%)	009 (1.0%)	070 (1.1%)
North and South Potts Creek	18,605 (0.7%)	3,856 (0.7%)	008 (0.8%)	053 (0.9%)
Total	2,810,045	523,299	960	6,066

Note: Minor direct drainages are aggregated with the adjacent larger watershed. Total for Grants Creek does not include Salisbury Rowan WWTP as this discharge is entered directly into the lake model.

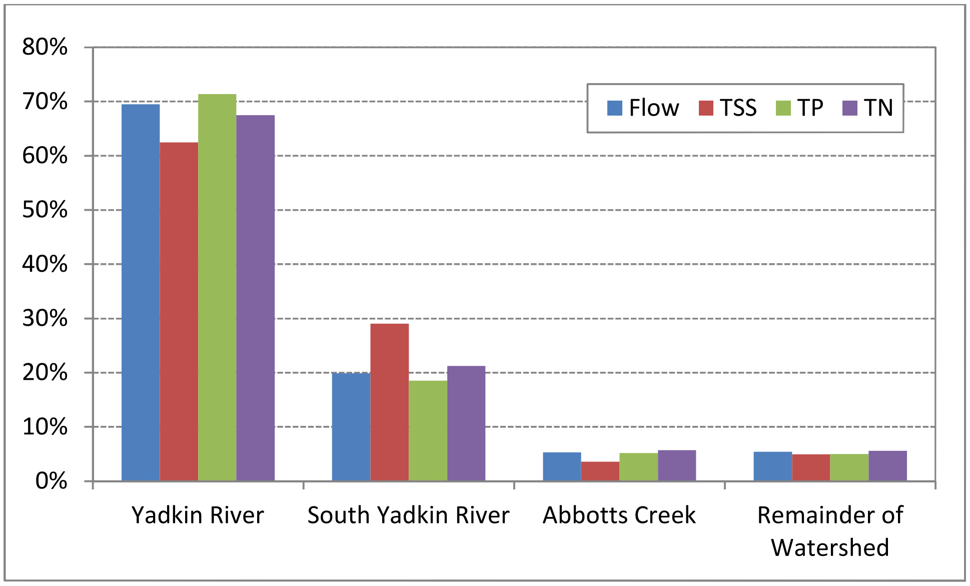

Figure 6-1. Spatial Distribution of Flow and Pollutant Loading to High Rock Lake

6.2 LOAD SOURCES

The delivered loads shown in Table 6-1 arise from a variety of point and nonpoint sources and are further altered by net losses (or gains) during transport through the stream network. Pollutant loads at the source are summarized in Table 6-2 through Table 6-9 for locations corresponding to the flow gages and water quality stations. Each table shows the source loading from the entire upstream area, and the total source loads are generally greater than the delivered amounts. For instance, the total phosphorus inputs upstream of Abbotts Creek at Lexington amount to 72 tons/yr, but the total delivered to High Rock Lake through Abbotts Creek is 35 tons/yr. The difference is largely due to sedimentation losses, including retention in Lake Thom-A-Lex. In contrast, the gage on South Yadkin River is well upstream and the delivered load from the South Yadkin also includes the load from the gaged portion of Second Creek and Hunting Creek as well as additional area downstream of both the South Yadkin and Second Creek gages.

The table of load sources does not include atmospheric deposition of nitrogen as a separate category, although this can be an important contributor to the total N load. Direct atmospheric deposition onto streams is a minimal fraction of the total N load because the stream surface area is small relative to the watershed as a whole. Atmospheric deposition onto pervious and impervious land surfaces is more important, but its contribution is difficult to tabulate in the model. This is because the model adds atmospheric load to the total store on the land surface that may either be washed off or removed (by volatilization, plant uptake, street sweeping, or incorporation into the medium). The atmospheric contribution is thus embedded within the nonpoint source categories.

Table 6-2. Annual Average Load (ton/year and percent of total) by Source, Yadkin River at Yadkin College

Category	TSS(t/y)	TP(t/y)	TN(t/y)	TSS (%)	TP (%)	TN (%)
Water	0	0	26	0%	0%	0%
Urban (non-MS4)	75,777	95	656	26%	9%	11%
Urban MS4	36,369	37	285	12%	4%	5%
NC DOT	18,427	20	160	6%	2%	3%
Forest	32,381	271	1,450	11%	27%	25%
Pasture	62,424	243	1,288	21%	24%	22%
Crop	69,698	53	706	24%	5%	12%
Point Source	730	280	1,112	0%	28%	19%
Septic System	0	11	75	0%	1%	1%
Total	295,806	1010	5,758	-	-	-

Table 6-3. Annual Average Load (ton/year and percent of total) by Source, South Yadkin River near Mocksville

Category	TSS(t/y)	TP(t/y)	TN(t/y)	TSS (%)	TP (%)	TN (%)
Water	0	0	3	0%	0%	0%
Urban (non-MS4)	11,867	13	85	23%	12%	13%
Urban MS4	347	0	2	1%	0%	0%
NC DOT	2,908	3	21	6%	2%	3%
Forest	7,713	31	166	15%	28%	25%
Pasture	18,948	54	298	37%	50%	45%
Crop	9,388	7	76	18%	6%	12%
Point Source	0	0	0	0%	0%	0%
Septic System	0	1	8	0%	1%	1%
Total	51,171	109	659	-	-	-

Table 6-4. Annual Average Load (ton/year and percent of total) by Source, Abbotts Creek at Lexington

Category	TSS(t/y)	TP(t/y)	TN(t/y)	TSS (%)	TP (%)	TN (%)
Water	0	0	5	0%	0%	1%
Urban (non-MS4)	6,487	8	72	21%	11%	13%
Urban MS4	9,136	7	67	30%	10%	12%
NC DOT	2,601	3	23	9%	4%	4%
Forest	2,524	14	78	8%	19%	14%
Pasture	6,617	21	115	22%	29%	21%
Crop	2,873	2	32	9%	3%	6%
Point Source	190	15	141	1%	21%	26%
Septic System	0	2	11	0%	3%	2%
Total	30,428	72	544	-	-	-

Table 6-5. Annual Average Load (ton/year and percent of total) by Source, Second Creek near Barber

Category	TSS(t/y)	TP(t/y)	TN(t/y)	TSS (%)	TP (%)	TN (%)
Water	0	0	2	0%	0%	1%
Urban (non-MS4)	3,719	5	32	18%	12%	13%
Urban MS4	1,086	1	6	5%	2%	2%
NC DOT	704	1	5	3%	2%	2%
Forest	1,352	6	31	6%	16%	12%
Pasture	6,580	20	100	31%	52%	39%
Crop	7,623	5	73	36%	14%	29%
Point Source	17	0	1	0%	0%	0%
Septic System	0	1	4	0%	2%	1%
Total	21,081	39	254	-	-	-

Table 6-6. Annual Average Load (ton/year and percent of total) by Source, Muddy Creek near Muddy Creek

Category	TSS(t/y)	TP(t/y)	TN(t/y)	TSS (%)	TP (%)	TN (%)
Water	0	0	4	0%	0%	1%
Urban (non-MS4)	4,910	8	68	16%	6%	10%
Urban MS4	20,940	22	172	70%	15%	25%
NC DOT	1,895	2	20	6%	2%	3%
Forest	644	11	59	2%	8%	9%
Pasture	947	5	31	3%	4%	5%
Crop	548	1	7	2%	0%	1%
Point Source	206	93	317	1%	65%	46%
Septic System	0	1	8	0%	1%	1%
Total	30,090	143	686	-	-	-

Table 6-7. Annual Average Load (ton/year and percent of total) by Source, Roaring River at Roaring River

Category	TSS(t/y)	TP(t/y)	TN(t/y)	TSS (%)	TP (%)	TN (%)
Water	0	0	0	0%	0%	0%
Urban (non-MS4)	5,813	6	37	32%	12%	12%
Urban MS4	0	0	0	0%	0%	0%
NC DOT	752	1	5	4%	1%	2%
Forest	5,966	33	171	33%	58%	57%
Pasture	4,840	16	77	26%	28%	26%
Crop	939	1	8	5%	1%	3%
Point Source	0	0	0	0%	0%	0%
Septic System	0	0	2	0%	0%	1%
Total	18,310	57	300	-	-	-

Table 6-8. Annual Average Load (ton/year and percent of total) by Source, Yadkin River at Elkin

Category	TSS(t/y)	TP(t/y)	TN(t/y)	TSS (%)	TP (%)	TN (%)
Water	0	0	3	0%	0%	0%
Urban (non-MS4)	21,581	25	164	32%	9%	12%
Urban MS4	4,494	4	31	7%	2%	2%
NC DOT	4,490	5	36	7%	2%	3%
Forest	11,916	91	493	18%	34%	37%
Pasture	18,427	65	345	28%	24%	26%
Crop	5,510	4	57	8%	2%	4%
Point Source	123	71	196	0%	26%	15%
Septic System	0	3	17	0%	1%	1%
Total	66,541	268	1342	-	-	-

Table 6-9. Annual Average Load (ton/year and percent of total) by Source, Yadkin River at Enon

Category	TSS(t/y)	TP(t/y)	TN(t/y)	TSS (%)	TP (%)	TN (%)
Water	0	0	13	0%	0%	0%
Urban (non-MS4)	57,729	70	444	29%	11%	13%
Urban MS4	11,089	11	79	6%	2%	2%
NC DOT	12,468	13	104	6%	2%	3%
Forest	26,177	225	1,201	13%	35%	34%
Pasture	46,141	183	958	23%	29%	27%
Crop	44,830	33	438	23%	5%	12%
Point Source	228	98	258	0%	15%	7%
Septic System	0	7	46	0%	1%	1%
Total	198,662	640	3,541	-	-	-

As shown above in Table 6-1, the bulk of pollutant loads are delivered from the Yadkin River and South Yadkin River. Load sources at these locations are shown graphically (using a common scale) in Figure 6-2 through Figure 6-25.

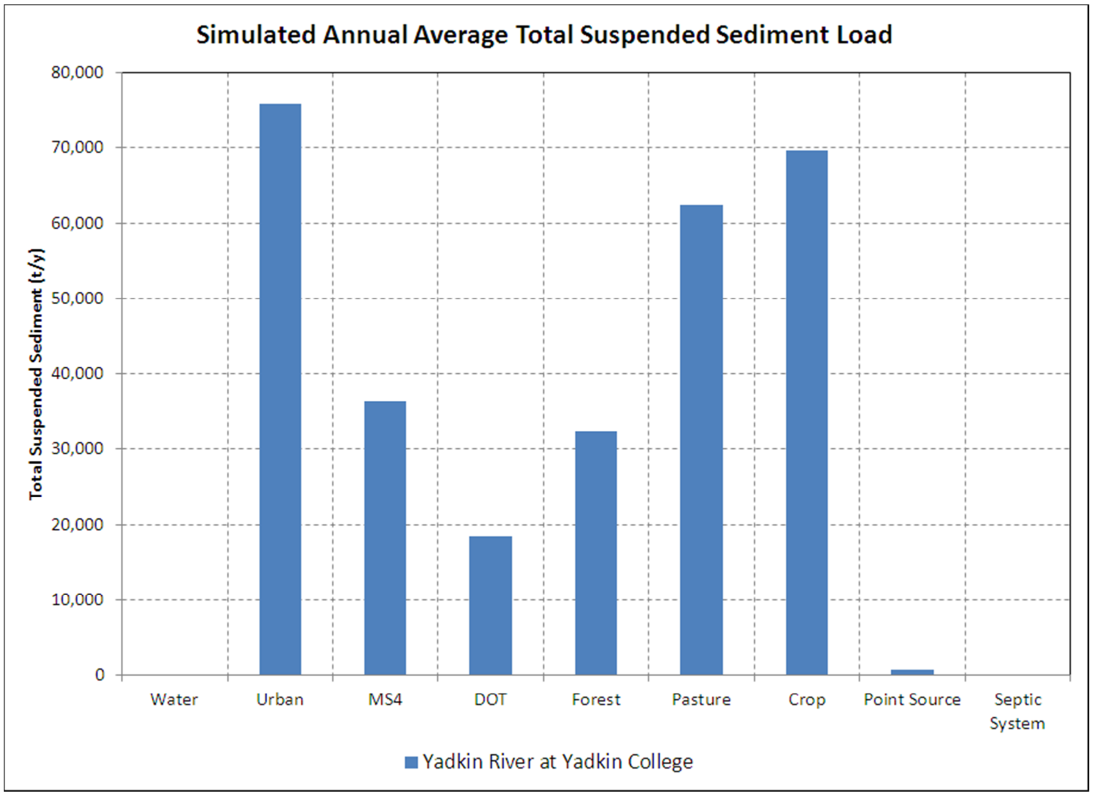

Figure 6-2. Annual Average Sediment Source Loads, Yadkin River at Yadkin College

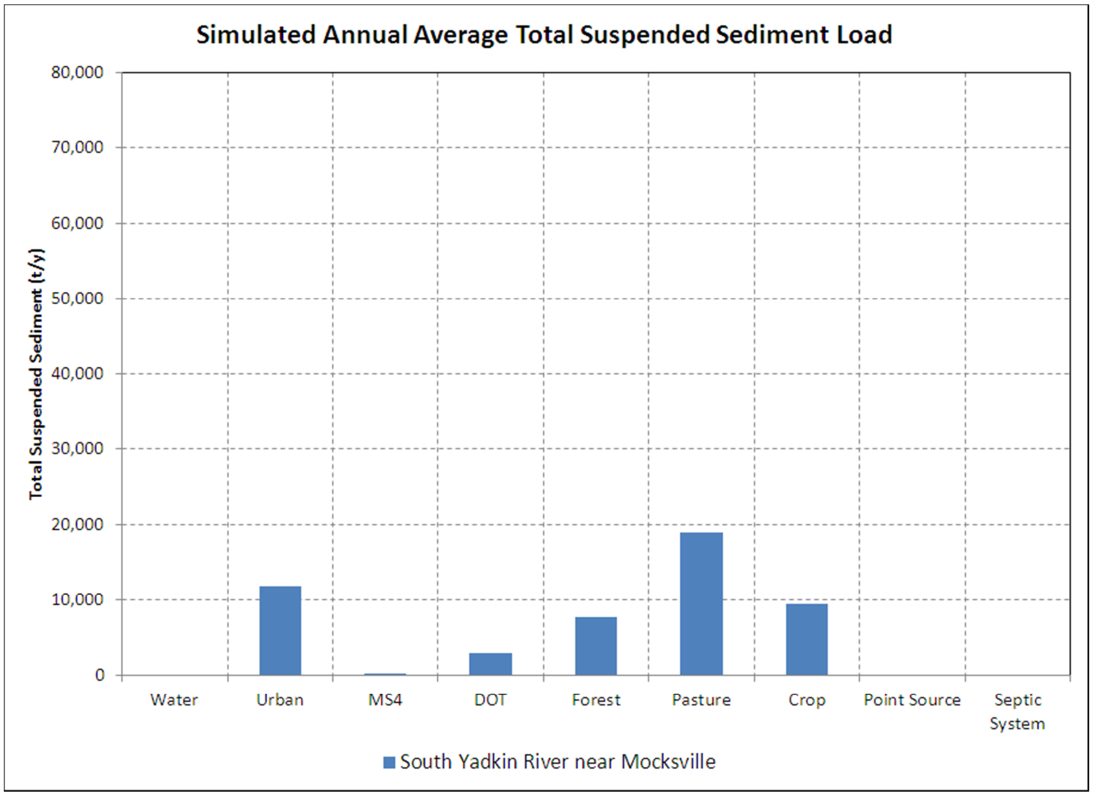

Figure 6-3. Annual Average Sediment Source Loads, South Yadkin River near Mocksville

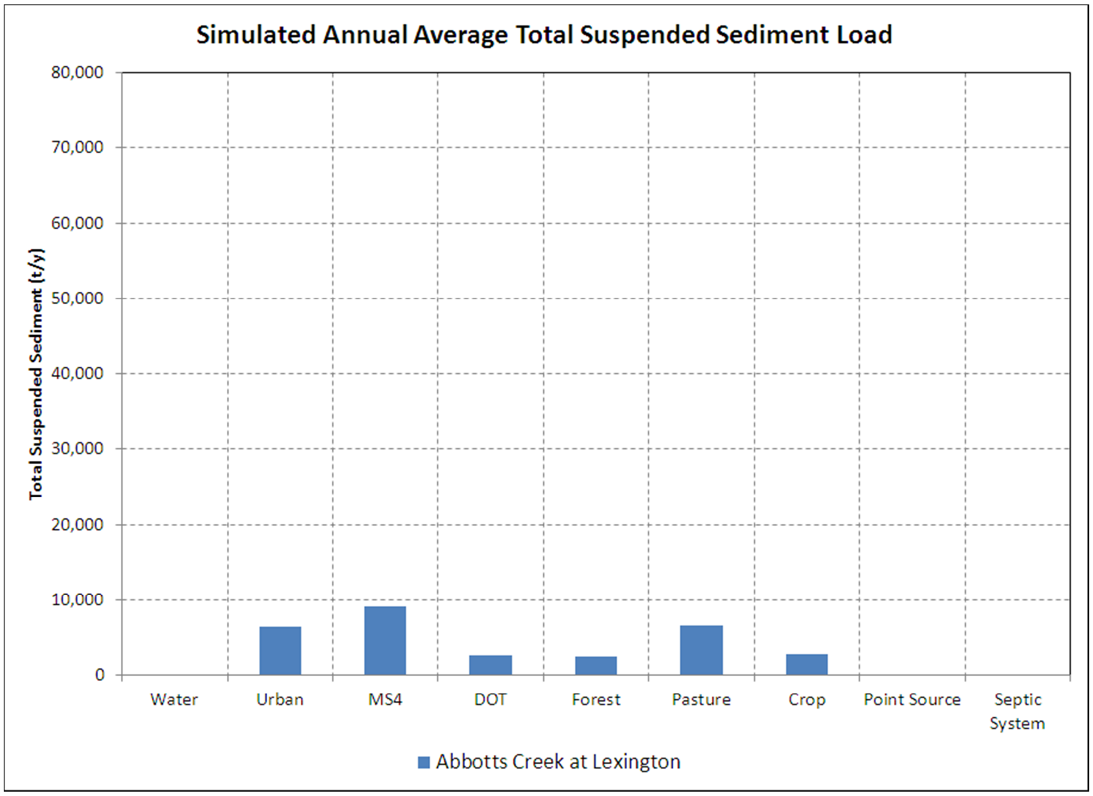

Figure 6-4. Annual Average Sediment Loads, Abbotts Creek at Lexington

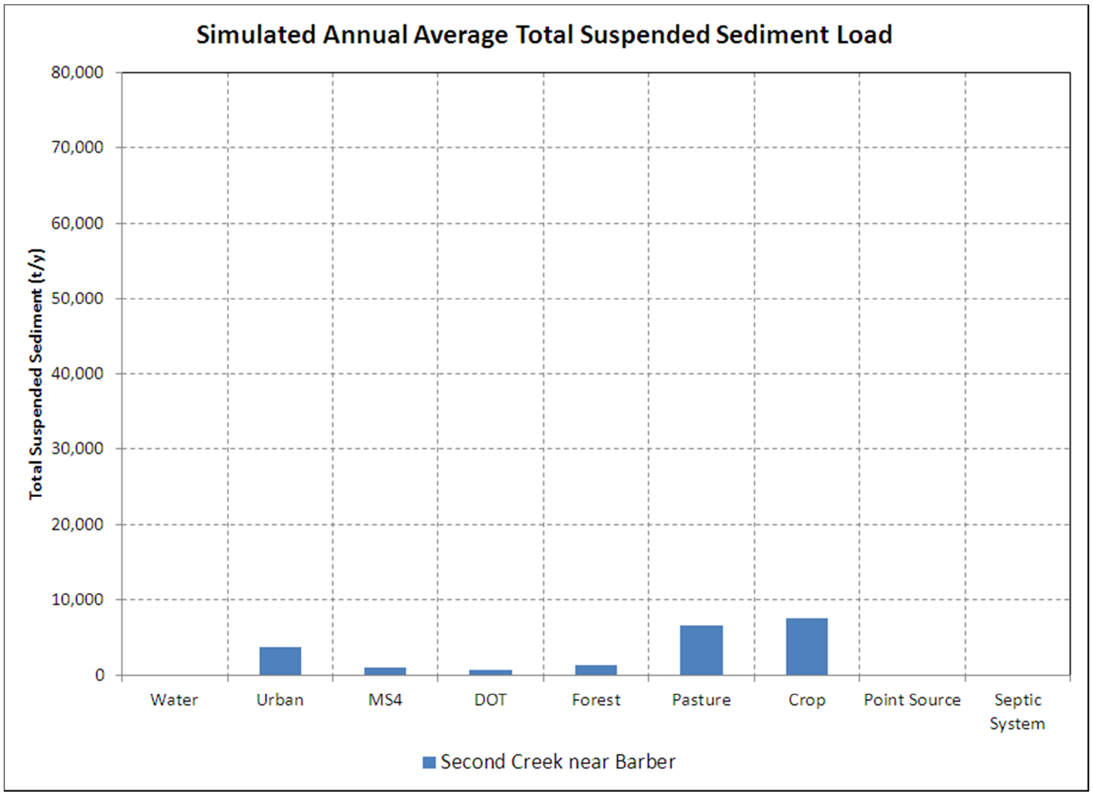

Figure 6-5. Annual Average Sediment Source Loads, Second Creek near Barber

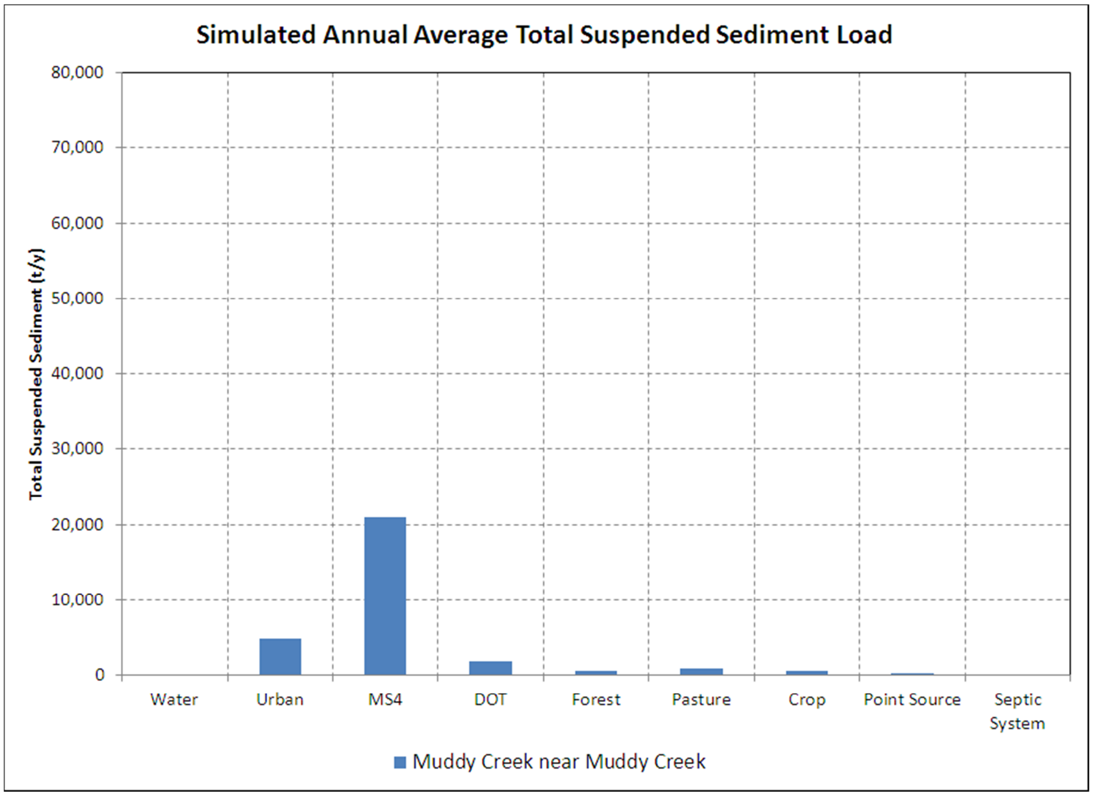

Figure 6-6. **Annual Average Sediment Source Loads, Muddy Creek near Muddy Creek**

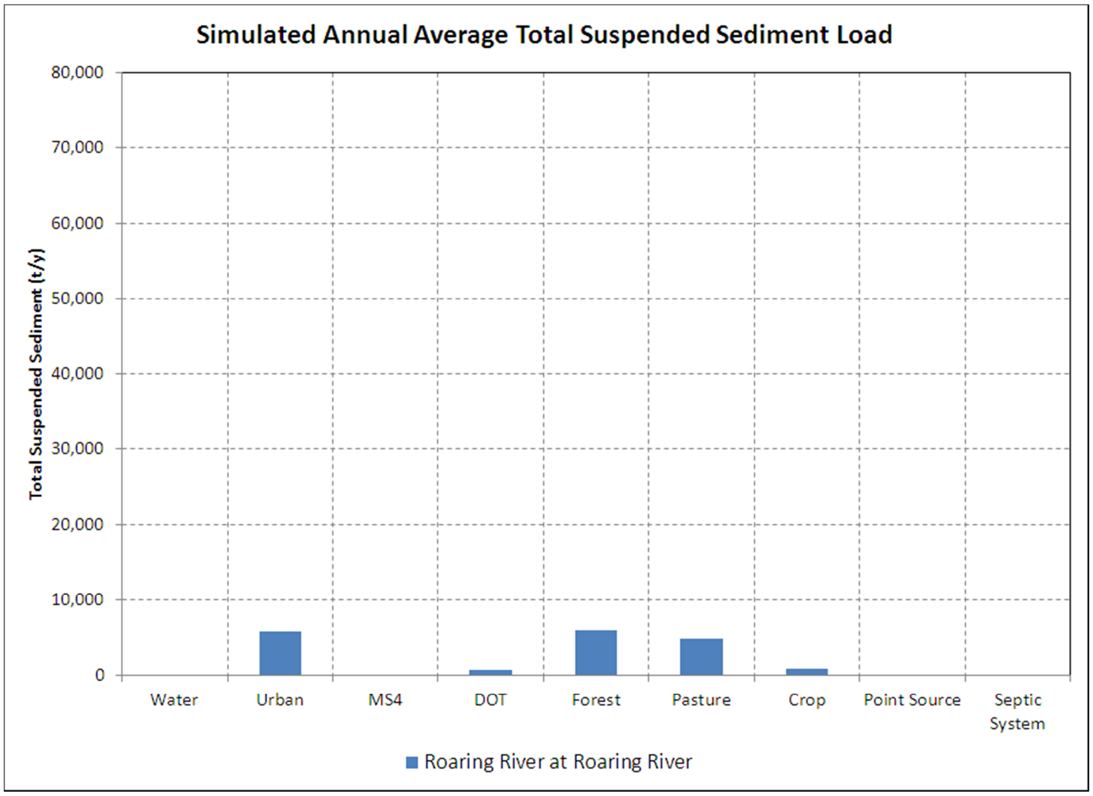

Figure 6-7. **Annual Average Sediment Source Loads, Roaring River at Roaring River**

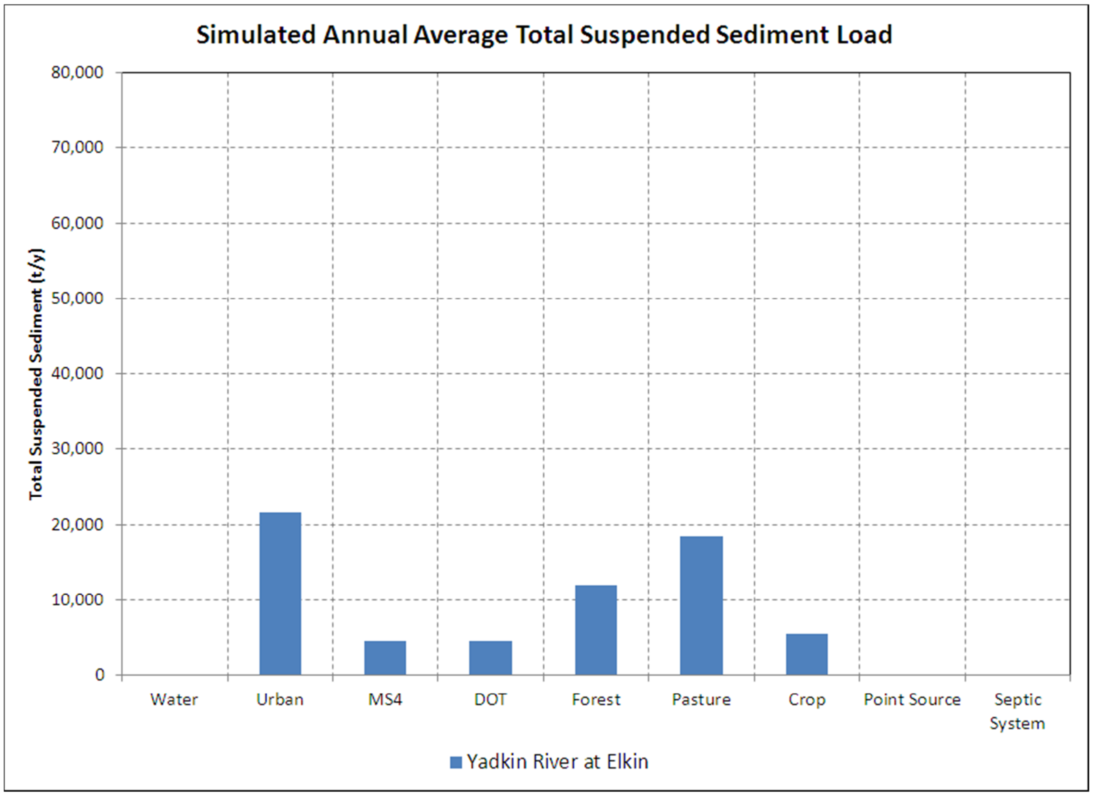

Figure 6-8. Annual Average Sediment Source Loads, Yadkin River at Elkin

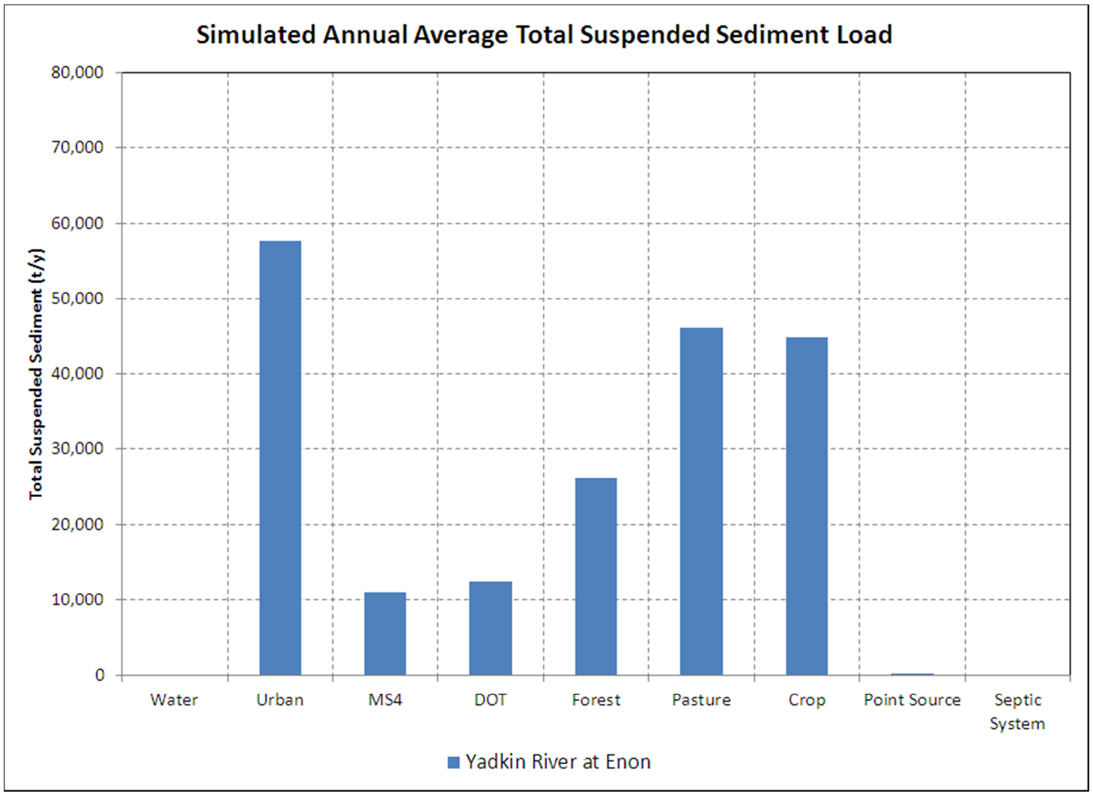

Figure 6-9. Annual Average Sediment Loads, Yadkin River at Enon

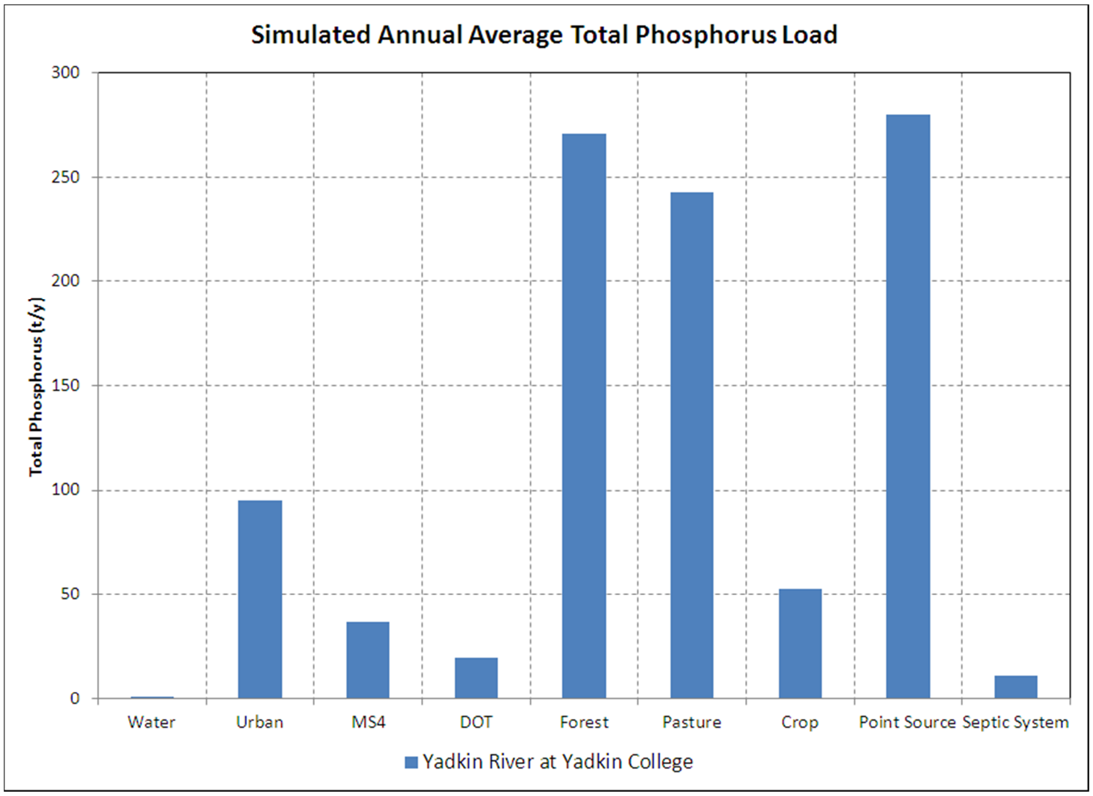

Figure 6-10. Annual Average Phosphorus Source Loads, Yadkin River at Yadkin College

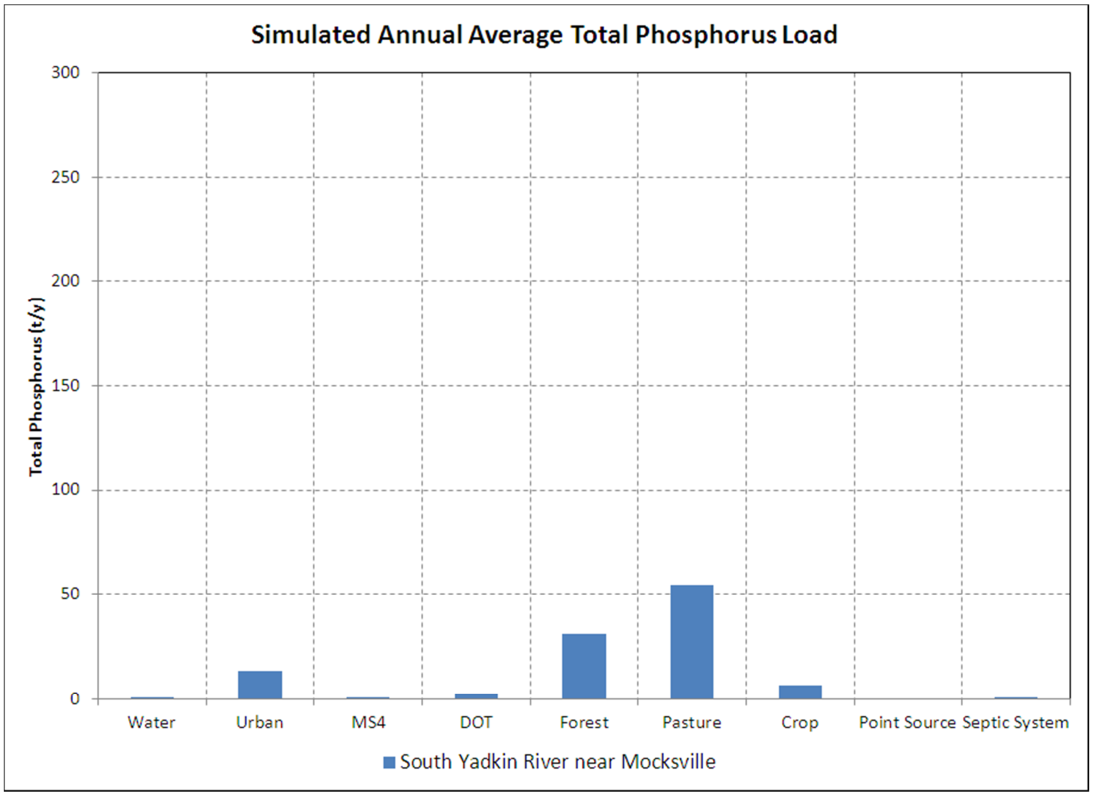

Figure 6-11. Annual Average Phosphorus Source Loads, South Yadkin River near Mocksville

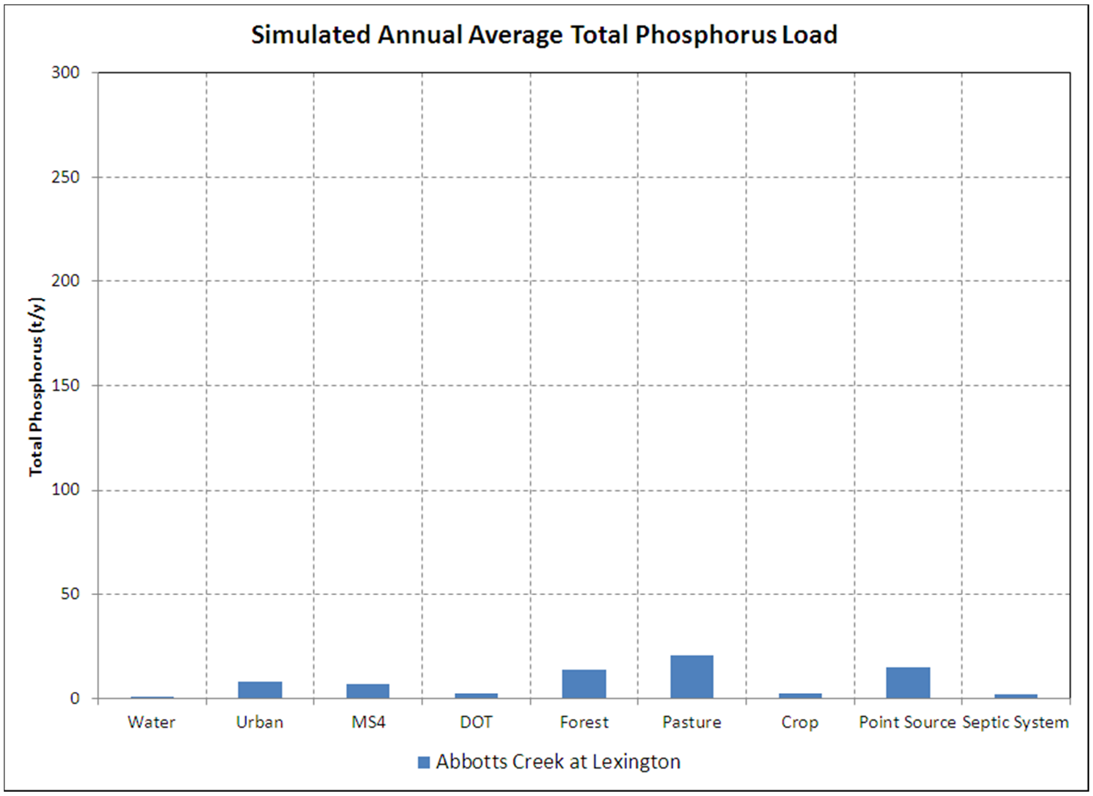

Figure 6-12. Annual Average Phosphorus Source Loads, Abbotts Creek at Lexington

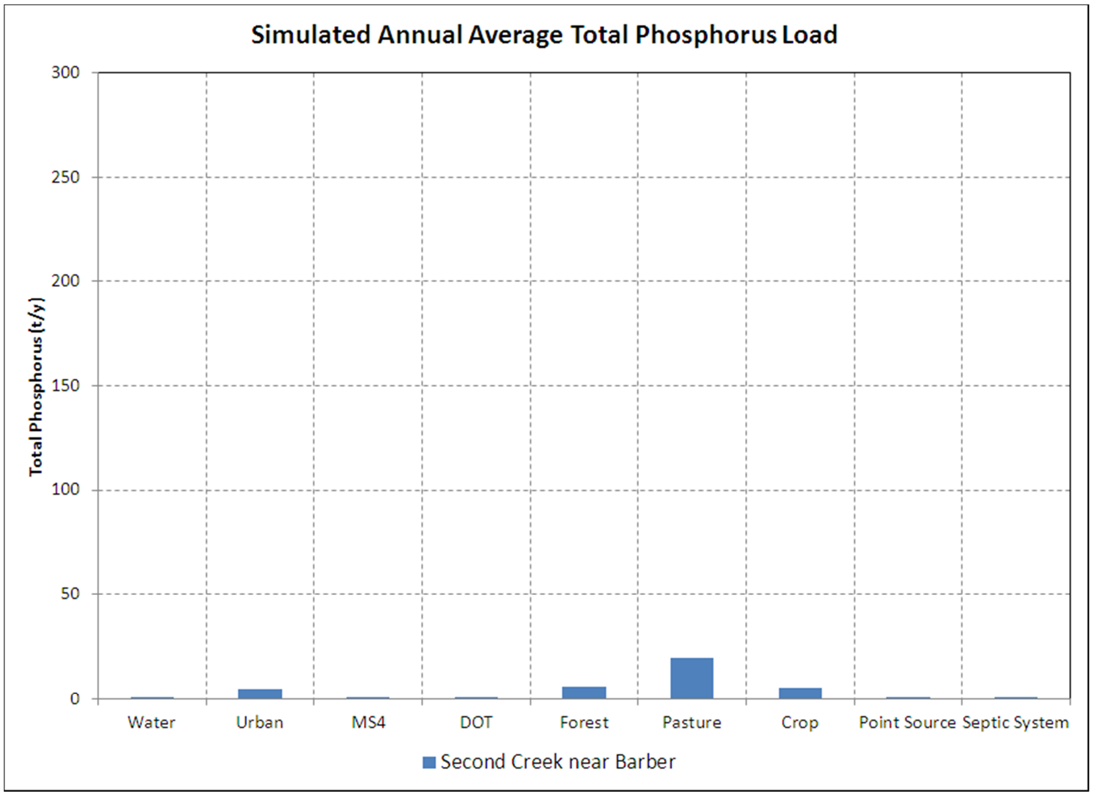

Figure 6-13. Annual Average Phosphorus Source Loads, Second Creek near Barber

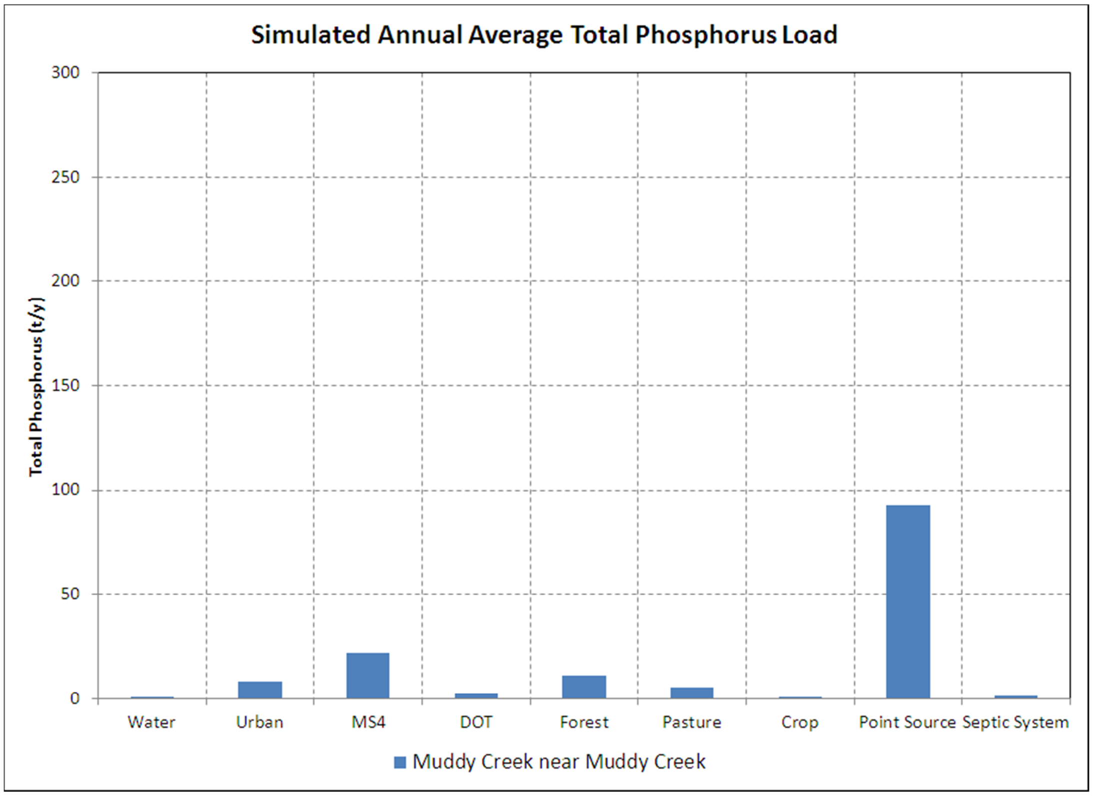

Figure 6-14. Annual Average Phosphorus Source Loads, Muddy Creek near Muddy Creek

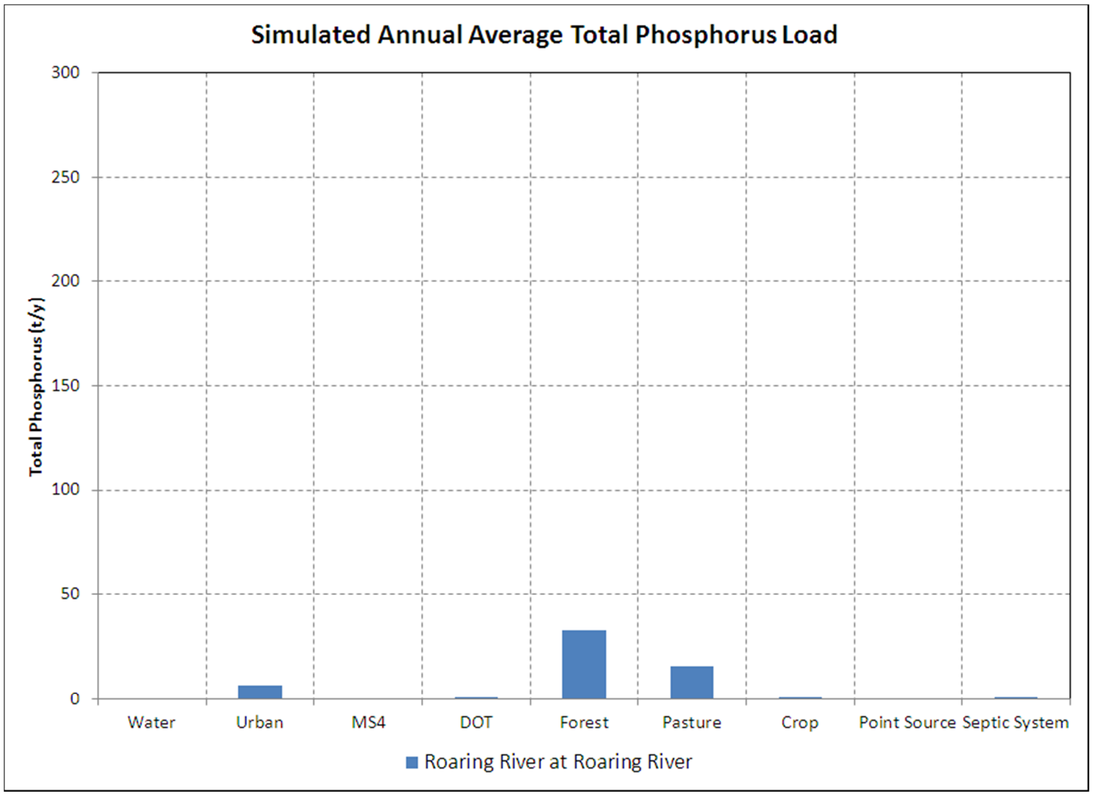

Figure 6-15. Annual Average Phosphorus Source Loads, Roaring River at Roaring River

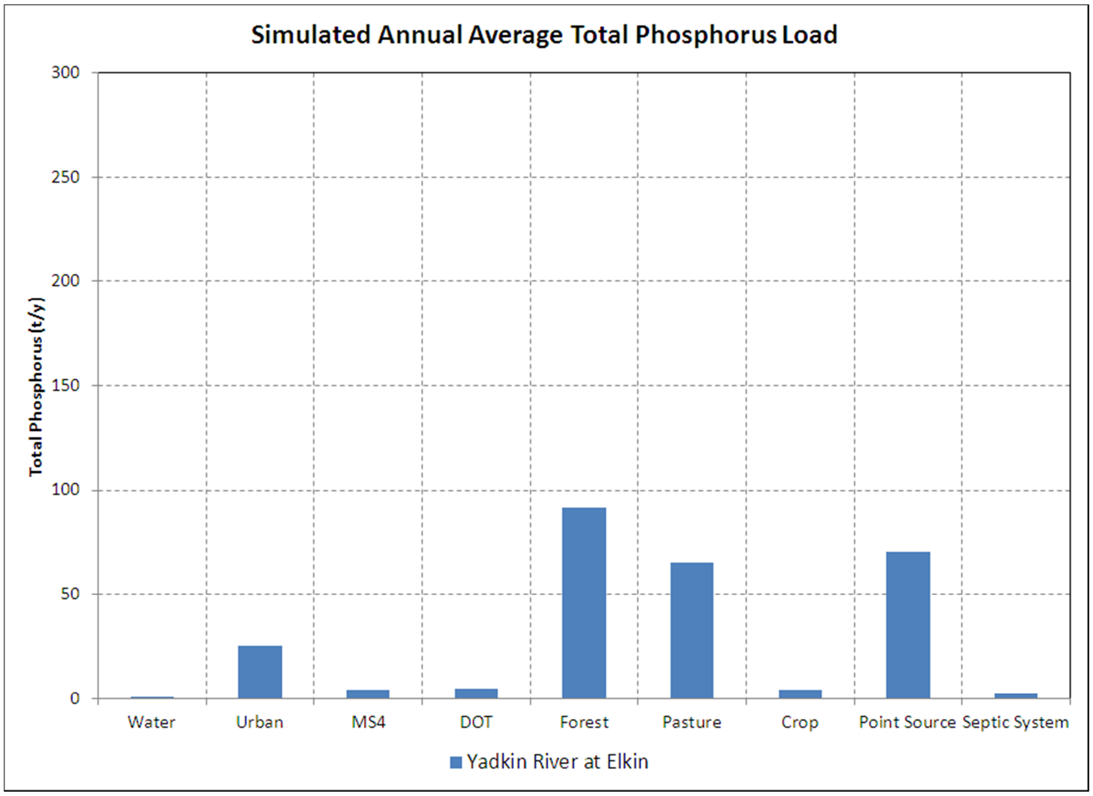

Figure 6-16. Annual Average Phosphorus Source Loads, Yadkin River at Elkin

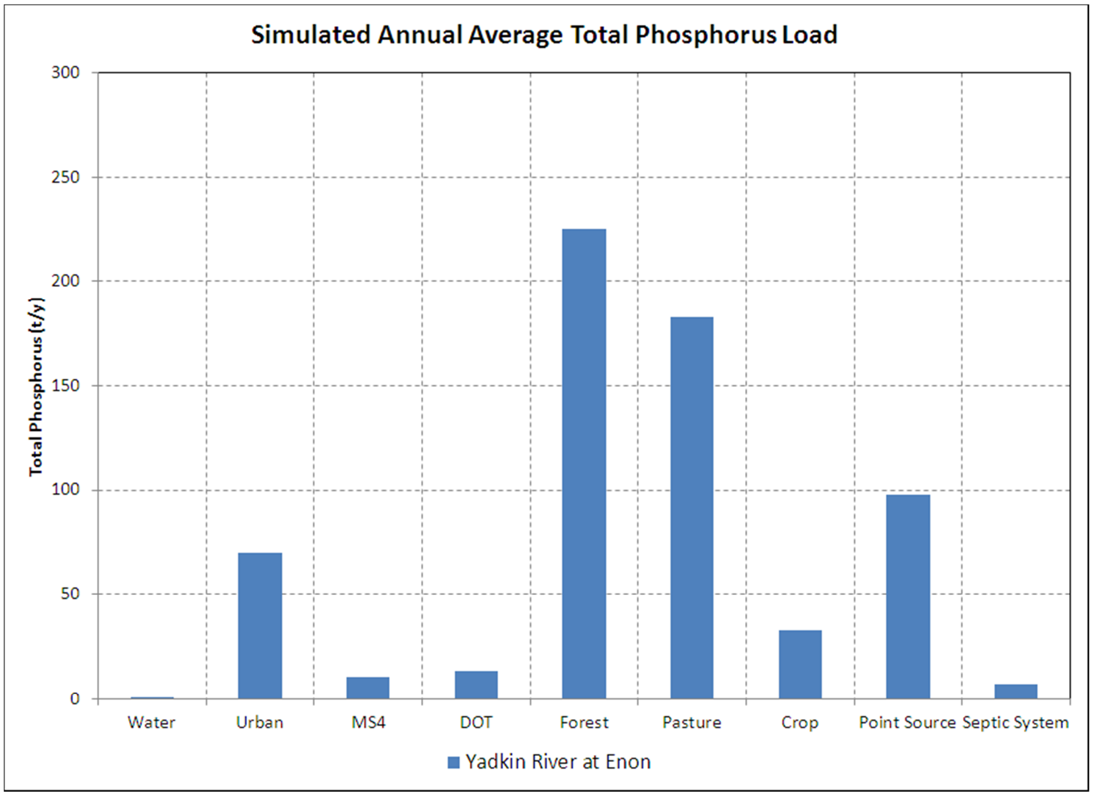

Figure 6-17. Annual Average Phosphorus Source Loads, Yadkin River at Enon

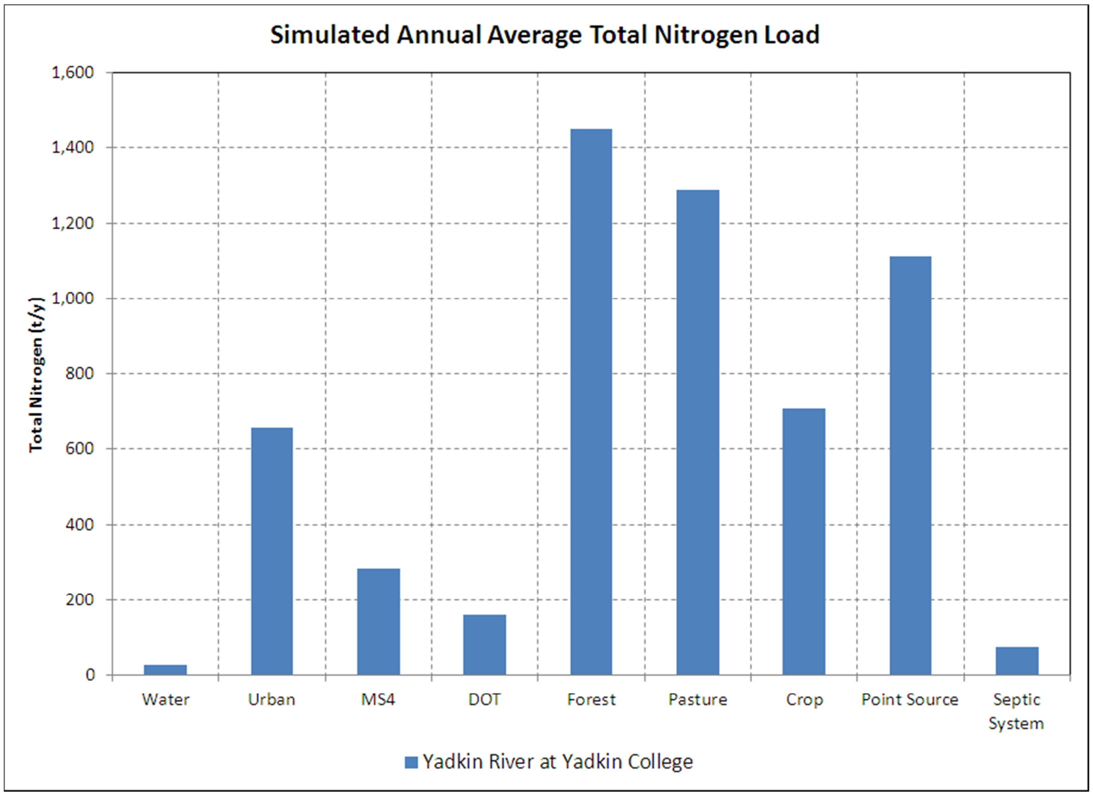

Figure 6-18. Annual Average Nitrogen Source Loads, Yadkin River at Yadkin College

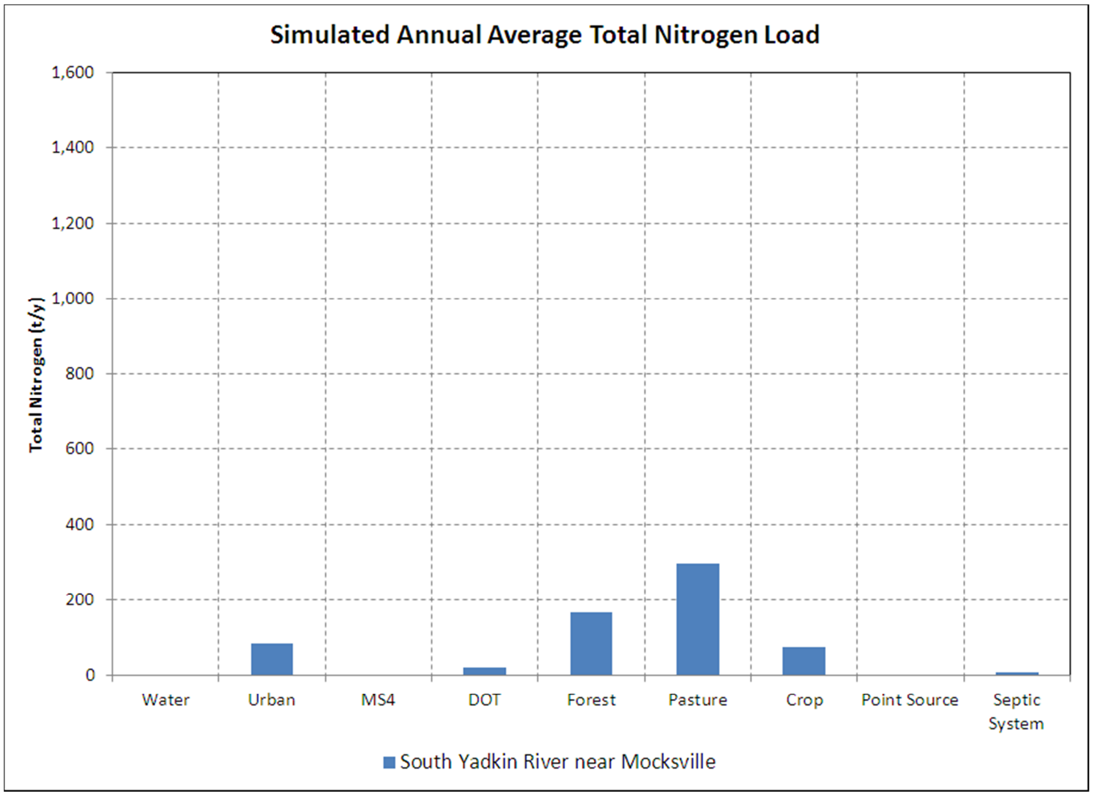

Figure 6-19. Annual Average Nitrogen Source Loads, South Yadkin River near Mocksville

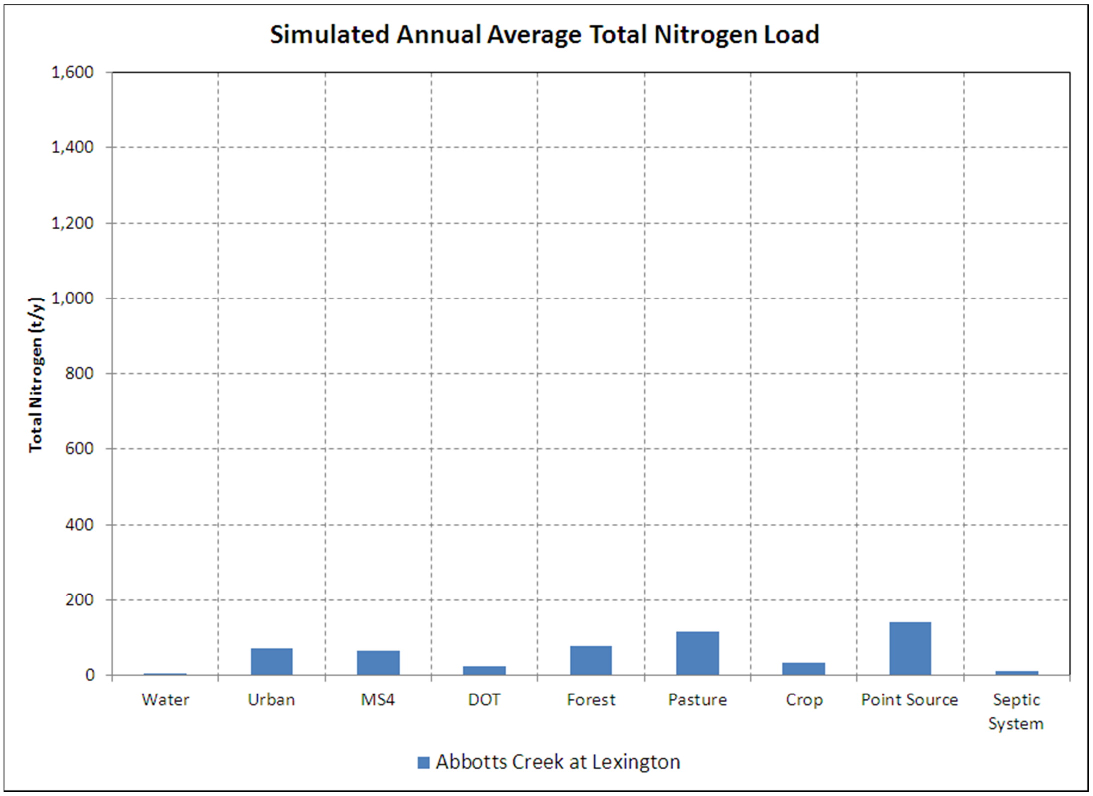

Figure 6-20. Annual Average Nitrogen Source Loads, Abbotts Creek at Lexington

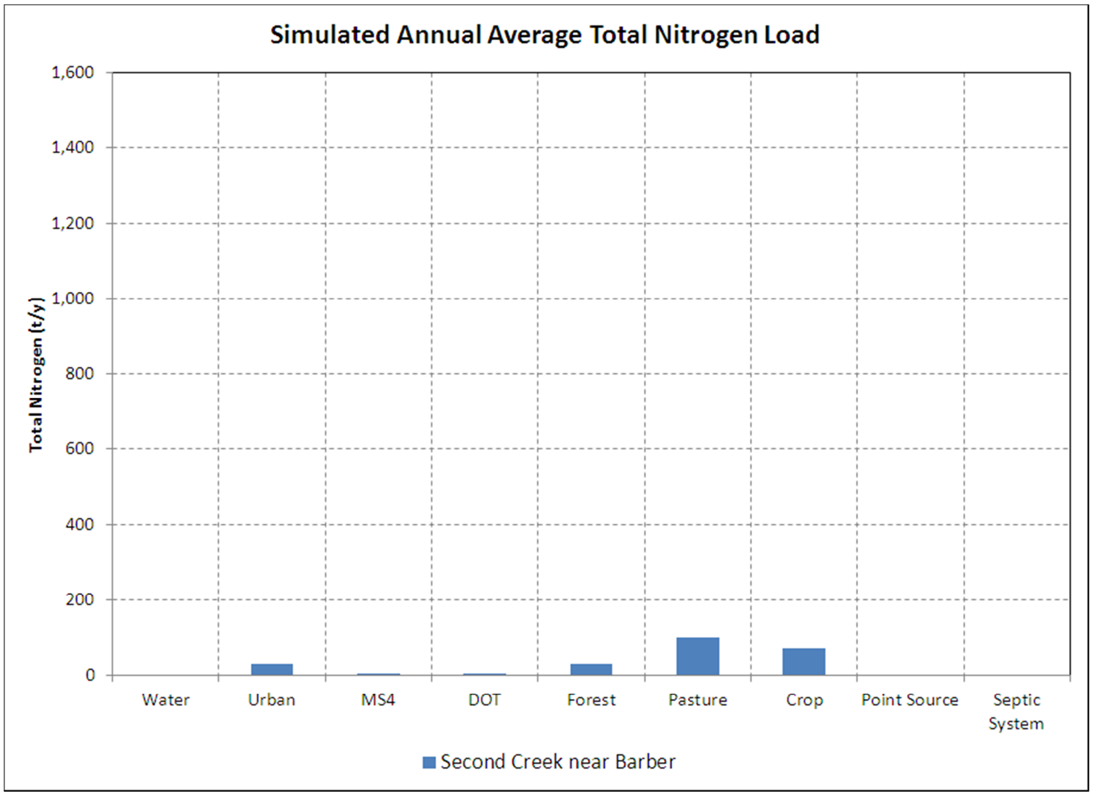

Figure 6-21. Annual Average Nitrogen Source Loads, Second Creek near Barber

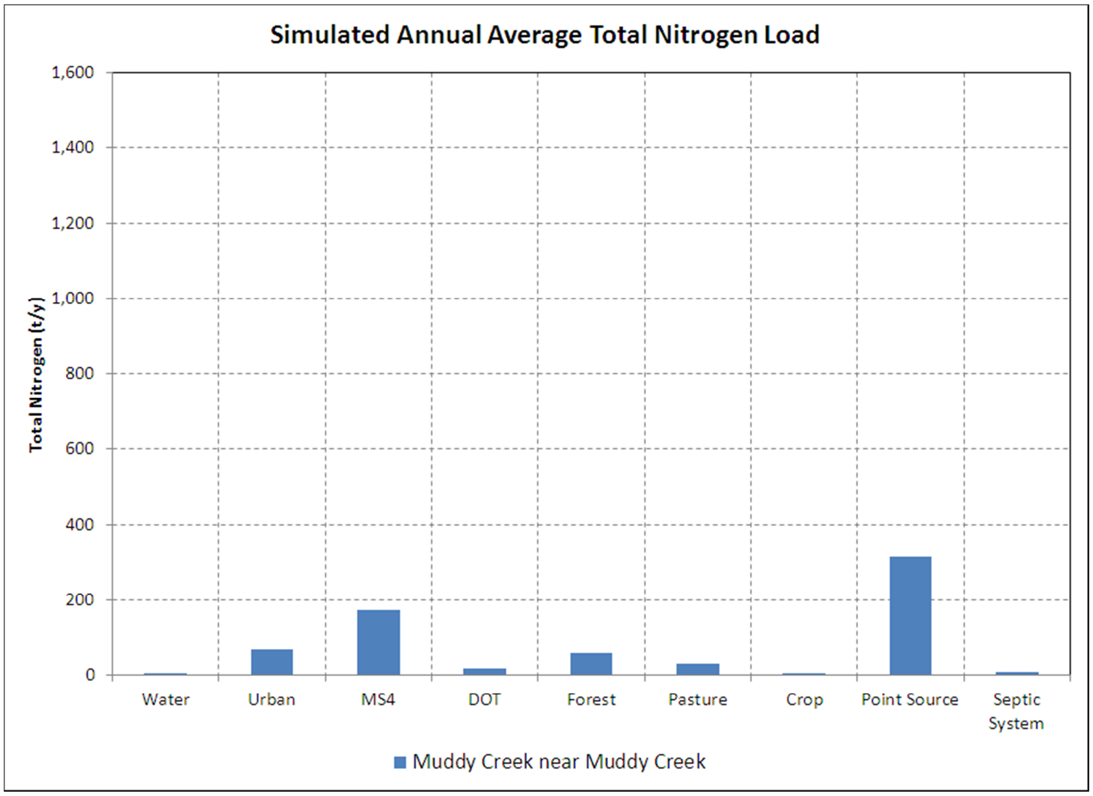

Figure 6-22. Annual Average Nitrogen Source Loads, Muddy Creek near Muddy Creek

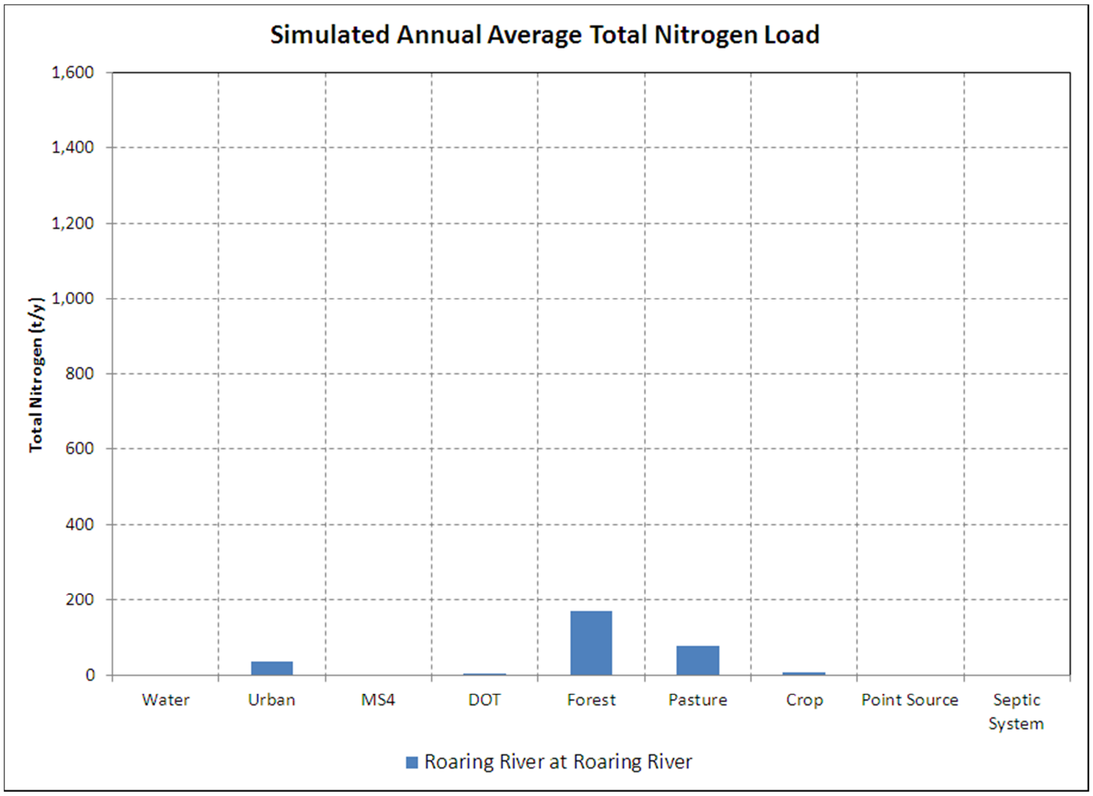

Figure 6-23. Annual Average Nitrogen Source Loads, Roaring River at Roaring River

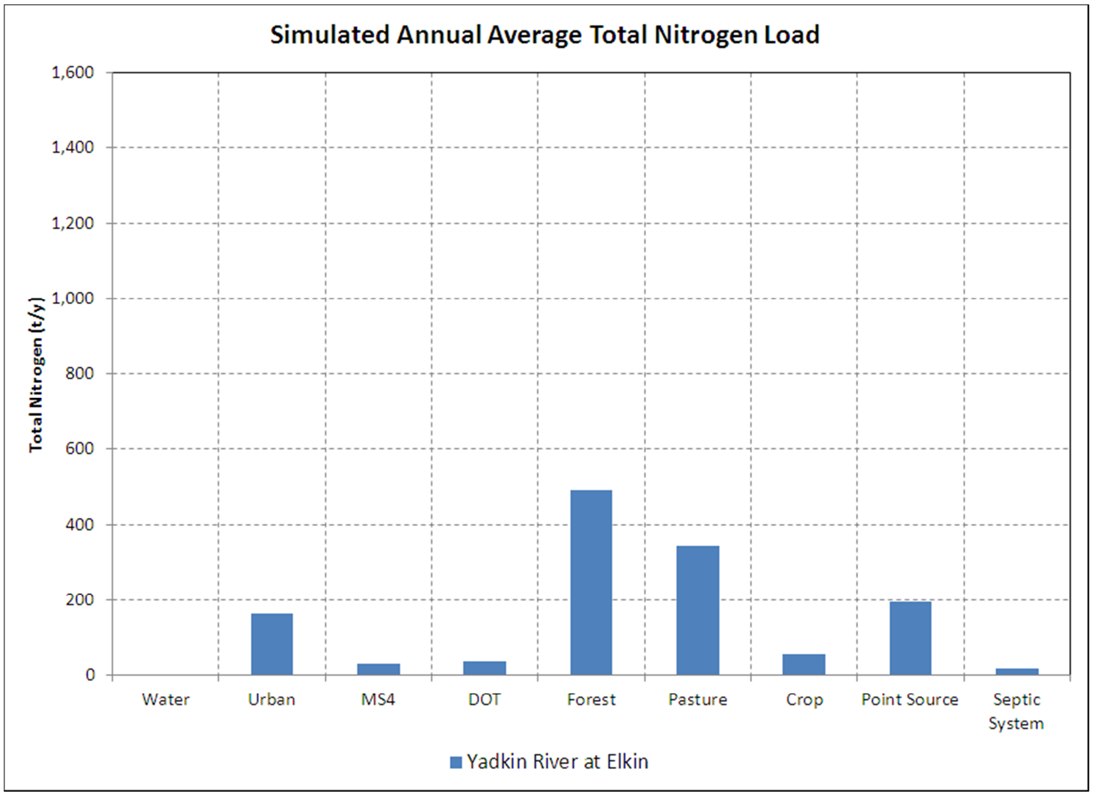

Figure 6-24. Annual Average Nitrogen Source Loads, Yadkin River at Elkin

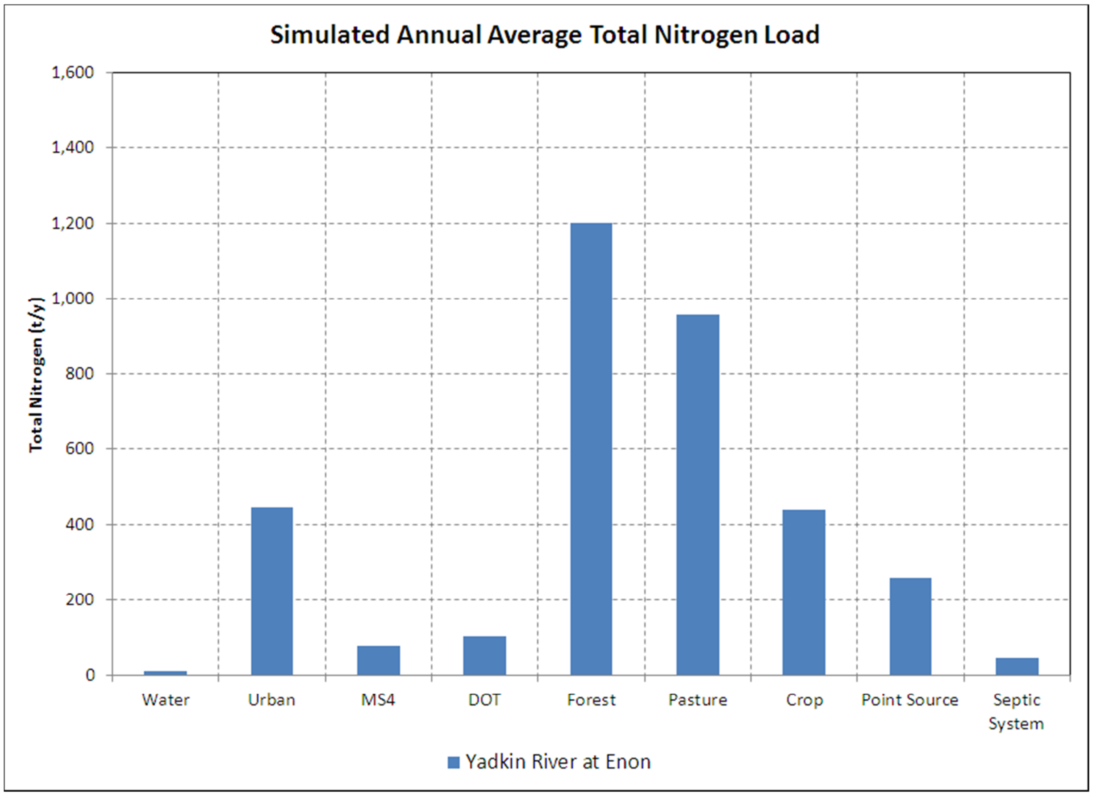

Figure 6-25. Annual Average Nitrogen Source Loads, Yadkin River at Enon

Table 6-10 presents a summary of the three largest sources of load for a given constituent upstream of the five downstream stations nearest to the lake. Point sources tend to dominate the nutrient loads in Abbotts and Muddy Creek. Despite lower unit area loading rates, forest is a significant source of total load due to its large land area. Pasture lands dominate loads in several of the more rural watersheds. Urban categories were the largest contributor of sediment for the more highly developed Muddy Creek and Abbotts Creek watersheds.

Table 6-10. Largest Sources of Pollutant Load by Constituent and Location

Constituent	Location	Largest Contributor	Second Largest Contributor	Third Largest Contributor
Total Suspended Solids	Yadkin River at Yadkin College	Urban (non-MS4)	Crop	Pasture
	South Yadkin River near Mocksville	Pasture	Urban (non-MS4)	Crop
	Abbotts Creek at Lexington	Urban MS4	Pasture	Urban (non-MS4)
	Second Creek near Barber	Crop	Pasture	Urban (non-MS4)
	Muddy Creek near Muddy Creek	Urban MS4	Urban (non-MS4)	NC DOT
Total Phosphorus	Yadkin River at Yadkin College	Point Source	Forest	Pasture
	South Yadkin River near Mocksville	Pasture	Forest	Urban (non-MS4)
	Abbotts Creek at Lexington	Pasture	Point Source	Forest
	Second Creek near Barber	Pasture	Forest	Urban (non-MS4)
	Muddy Creek near Muddy Creek	Point Source	Urban MS4	Forest
Total Nitrogen	Yadkin River at Yadkin College	Forest	Pasture	Point Source
	South Yadkin River near Mocksville	Pasture	Forest	Urban (non-MS4)
	Abbotts Creek at Lexington	Point Source	Pasture	Forest
	Second Creek near Barber	Pasture	Crop	Urban (non-MS4)
	Muddy Creek near Muddy Creek	Point Source	Urban MS4	Urban (non-MS4)

6.3 SUMMARY

Process-based models are used in water resources applications as a tool to assist in planning and evaluating management decisions. The overall objective of this modeling project is to determine the loads of nutrients and sediment that High Rock Lake can receive while still attaining water quality standards for DO, chlorophyll *a*, and turbidity. Management strategies for both point and nonpoint sources of pollutant loads may need to be developed to support the attainment of water quality standards and designated uses for High Rock Lake. The HSPF watershed model provides a linkage between the loading received by the lake and sources of loads on the land surface, from atmospheric deposition, and from point source discharges.

HSPF was selected for this study because it is a physically-based model appropriate to the dynamic simulation of a large watershed with varying land cover and management conditions. The model was applied to the High Rock Lake watershed to estimate flow, suspended solids, phosphorus, and nitrogen loads delivered to the lake from both point and nonpoint sources. The watershed land area is subdivided into 16 land cover types. These were further subdivided by soil hydrologic group to produce hydrologic response units for use in the model. These were simulated within areas associated with 14 precipitation stations to produce results for 145 model subbasins. The model subbasins drive a simulation of flow and transport through the reach network at an hourly time step to provide a detailed and sophisticated representation of watershed contributions to the lake.

The model is calibrated for flow, TSS, total P, and total N at multiple stations covering each of the major subwatersheds in the system. The calibration was achieved using a unified parameter data set that successfully explains the differences in observations between sites as a function of land use, soils, slopes, and meteorology. Following calibration, the performance of the model was validated through application to additional periods of observations. Generally, the model water quality calibration covered years 2005 through 2010. Model performance was validated using data from 2000 through 2004. (Note that there were drought conditions present during both the calibration and validation periods, including 2000 - 2002 and 2007).

The model calibration and validation for hydrology is rated as “good” to “very good.” The water quality simulations show more variability, but meet the majority of the calibration targets and successfully explain most of the spatial and temporal variability observed in gaging and monitoring data. The watershed model is, of necessity, a simplified representation of reality, but provides a physically based, mechanistic description of the key processes that determine flow and pollutant load generation, transport, and delivery. This provides a foundation for assessing the relative importance of different pollutant sources and evaluating the efficacy of potential management strategies

While every attempt was made to accurately represent all major sources of sediment and nutrients in the mode, there are various data limitations. These include: coarser than daily point source water quality reporting, estimation of septic system contributions, lack of site-scale runoff studies to better parameterize model land units, lack of channel erosion data, and sparse coverage of subdaily rainfall data.

Given these limitations, the High Rock Lake watershed model simulates well the hydrology and water quality observed throughout the watershed. The error statistics associated with model prediction are generally low, suggesting a good agreement between the simulated and observed values. It is Tetra Tech’s opinion that the calibrated model is demonstrated to be an appropriate tool to assist with decision-making for the purpose of developing a TMDL or nutrient management strategy for the High Rock Lake watershed. Applications of the model for decision purposes and interpretation of the model results should take into consideration the level of accuracy documented for the model predictions in this report.

7 References

APGI. 2006. Yadkin Hydroelectric Project FERC No. 2197, Application for License, Volume I. Alcoa Power Generating, Inc.

ASCE. 1993. Criteria for evaluation of watershed models. *Journal of Irrigation Drainage Engineering*, 119(3): 424 - 442.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, Jr., T.H. Jobes, and A. S. Donigian, Jr. 2001. Hydrological Simulation Program - FORTRAN, Version 12, User's Manual for Version 12. Aqua Terra Consultants, Mountain View, CA.

Brunner, G.W. 2010. HEC-RAS River Analysis System User's Manual, Version 4.1. CPD-68. U.S. Army Corps of Engineers Hydrologic Engineering Center, Davis, CA.

Chapra, S.C. 1997. *Surface Water-Quality Modeling*. McGraw-Hill. Boston, MA.

Donigian, A.S., Jr., B.R. Bicknell, L.C. Linker, J. Hannawald, C. Chang, and R. Reynolds. 1990. Chesapeake Bay Program Watershed Model Application to Calculate Bay Nutrient Loadings: Preliminary Phase I Findings and Recommendations. Prepared by AQUA TERRA Consultants for U.S. EPA Chesapeake Bay Program, Annapolis, MD.

Donigian, A.S. Jr., and A.S. Patwardhan. 1992. Modeling nutrient loadings from croplands in the Chesapeake Bay Watershed. In: Proceedings of Water Resources sessions at Water Forum '92. Baltimore, Maryland. August 2-6, 1992. p. 817-822.

Donigian, A.S., Jr. 2000. HSPF Training Workshop Handbook and CD. Lecture #19. Calibration and Verification Issues. EPA Headquarters, Washington Information Center, 10-14 January, 2000. Prepared for U.S. EPA, Office of Water, Office of Science and Technology, Washington, DC.

Donigian, A.S., Jr., J.C. Imhoff, B.R. Bicknell, and J.L. Kittle, Jr. 1984. Application Guide for Hydrological Simulation Program – FORTRAN (HSPF). EPA-600/3-84-065. Office of Research and Development, U.S. Environmental Protection Agency, Athens, GA.

Donigian, A.S., Jr., and J.T. Love. 2003. Sediment Calibration Procedures and Guidelines for Watershed Modeling. Aqua Terra Consultants, Mountain View, CA.

DSWC. 2007a. Upper Yadkin River Watershed: 03040101 Cooperative Conservation Partnership Initiative Rapid Watershed Assessment. North Carolina Division of Environment and Natural Resources, North Carolina Soil and Water Conservation. Raleigh, NC.

DSWC. 2007b . South Yadkin River Watershed: 03040102 Cooperative Conservation Partnership Initiative Rapid Watershed Assessment. North Carolina Division of Environment and Natural Resources, North Carolina Soil and Water Conservation. Raleigh, NC.

DSWC, 2007c. Lower Yadkin River Watershed: 03040103 Cooperative Conservation Partnership Initiative Rapid Watershed Assessment. North Carolina Division of Environment and Natural Resources, North Carolina Soil and Water Conservation. Raleigh, NC.

EarthInfo. 2009. http://www.earthinfo.com/.

Haith, D.A. and D.E. Merrill. 1987. Evaluation of a daily rainfall erosivity model. *Transactions of the American Society of Agricultural Engineers*, 28(6): 1916-1920.

Haith, D.A., R. Mandel, and R.S. Wu. 1992. GWLF - Generalized Watershed Loading Functions, Version 2.0 - User's Manual. Department of Agricultural Engineering, Cornell University, Ithaca, NY.
Harned, D.A. 1995. Effects of Agricultural Land-Management Practices on Water Quality in

Northeastern Guilford county, North Carolina, 1985-90. Water Supply Paper 2435. U.S. Geological Survey.

Hicks, C.N. 1985. Continuous Simulation of Surface and Subsurface Flows in Cypress Creek Basin, Florida, Using Hydrological Simulation Program - FORTRAN (HSPF). Water Resources Research Center, University of Florida, Gainesville, FL.

HSPF. http://water.epa.gov/scitech/datait/models/basins/index.cfm.

Legates D.R. and G.J. McCabe Jr. 1999. Evaluating the use of "Goodness-of-Fit" Measures in Hydrologic and Hydroclimatic Model Validation. *Water Research,* 35(1):233-241.

Lin, J. 2004. Review of Published Export Coefficient and Event Mean Concentration (EMC) Data. ERDC TN-WRAP-04-3. Wetlands Regulatory Assistance Program, U.S. Army Corps of Engineers.

Line, D. E. 2006. Evaluating BMPs for Treating Stormwater and Wastewater from NCDOT's Highways, Industrial Facilities, and Borrow Pits. Final report for Research Project 2001-07. North Carolina State University, NC Cooperative Extension Service, Raleigh, NC.

Line, D.E. and D.L. Osmond. 2010. Final Report: Lake Jordan Paired Watershed Study, a 319(h) Project Sponsored by NCDENR – Division of Water Quality. Biological and Agricultural Engineering Dept., N.C. State University, Raleigh, NC.

Luell, S. K., R. J. Winston, and W. F. Hunt. 2010. Retrofitting with Bioretention and a Swale to Treat Bridge Deck Stormwater Runoff. Draft report for Research Project 2009-29. NorthCarolina State University, NC Cooperative Extension Service, Raleigh, NC.

Lumb. A.M., R.B. McCammon, and J.L. Kittle, Jr. 1994. User's Manual for an Expert System (HSPEXP) for Calibration of the Hydrological Simulation Program – FORTRAN. Water-Resources Investigation Report 94-4168. U.S. Geological Survey, Reston, VA.

McCray, J.E., S.L. Kirkland, R.L. Siegrist, and G.D. Thyne. 2005. Model parameters for simulating fate and transport of on-site wastewater nutrients. *Ground Water*, 43(4):628-639.

Moriasi, D.N., J.G. Arnold, M.W. Van Liew, R.L. Bingner, R.D. Harmel, and T.L. Veith, 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE*, 50(3): 885-900.

NCDEH. 2000. Report on the Proper Maintenance of Septic Tank Systems in Accordance with Section 13.5 of HB 1160 (Clean Water Act of 1999). Submitted by the NC Commission for Health Services to the Environmental Review Commission, North Carolina General Assembly. Division of Environmental Health, NC Department of Environment and Natural Resources. Raleigh, NC.

NCDNR. 2007. Administrative Code Section 15A NCAC 2B .0100. North Carolina Department of Environment & Natural Resources, Division of Water Quality. Raleigh, NC.

NCDNR. 2010. NC 2010 Integrated Report Category 5-303(d) List Approved by EPA August 31, 2010. North Carolina Department of Environment & Natural Resources, Division of Water Quality. Raleigh, NC.

NCDOT. 2009a. Letter from NCDOT to DWQ. North Carolina Department of Transportation. Raleigh, NC.

NCDOT. 2009b. RUSLE2 Calculations for Gravel Roads within the High Rock Lake Drainage Basin for TMDL Study.

Novotny, V. and H. Olem. 1994. *Water Quality: Prevention, Identification, and Management of Diffuse Pollution*. Van Nostrand Reinhold. New York, NY.

Richardson, C.W., G.R. Foster, and D.A. Wright. 1983. Estimation of erosion index from daily Rainfall amount. *Transactions of the American Society of Agricultural Engineers*, 26(1): 153-157, 160.

Ross, M. A., R.D. Tara, J.S. Geurink, and M.T. Stewart. 1997. FIPR Hydrologic Model, User's Manual and Technical Documentation. FIPR-OFR-88-03-085. Florida Institute of Phosphate Research, Barton, Florida.

Selker, J.S., D.A. Haith, and J.E. Reynolds. 1990. Calibration and testing of daily rainfall erosivity model. *Transactions of the American Society of Agricultural Engineers*, 33(5): 1612-1618.

Simmons, C.E. 1993. Sediment Characteristics of North Carolina Streams, 1970 – 1979. U.S. Geological Survey Water-Supply Paper 2364. Washington, DC.

Skipper, G. 2008. Watershed-Scale Stormwater Monitoring of a Mixed Land Use Watershed in the North Carolina Piedmont. PhD thesis, North Carolina State University, Raleigh, NC.

Swartley, B., D. Jones, J. Boggs, G. Sun, and S. McNulty. 2010. BMP Effectiveness Monitoring Study, Phase II: Grant Final Report. A 319(h) project sponsored by NCDENR – Division of Water Quality. N.C. Division of Forest Resources, Forestry Nonpoint Source Branch, Raleigh, NC.

Tetra Tech. 2009. Quality Assurance Project Plan for Total Maximum Daily Load (TMDL) Model Development for High Rock Lake, NC. Prepared for USEPA Region 4 by Tetra Tech, Inc., Research Triangle Park, NC.

Tetra Tech. 2012. High Rock Lake Technical Advisory Committee Watershed Model Review Comments and Responses. Prepared for USEPA Region 4 by Tetra Tech, Inc., Research Triangle Park, NC.

Thomann, R.V. and J.A. Mueller. 1987. *Principles of Surface Water Quality Modeling and Control*. Harper Collins Publishers, Inc. New York, NY.

Tsihrintzis, V.A., H.R. Fuentes and R. Gadipudi. 1996. Modeling prevention alternatives for nonpoint source pollution at a wellfield in Florida. *Water Resources Bulletin*, 32(2):317-331.

USDA. 1986. Urban Hydrology for Small Watersheds TR-55. United States Department of Agriculture, Natural Resources Conservation Service, Conservation Engineering Division, Washington, DC.

USDA. 2003. User's Guide, Revised Universal Soil Loss Equation Version 2: RUSLE2. USDA Agricultural Research Service, Washington, DC.

USEPA. 2000. Estimating Hydrology and Hydraulic Parameters for HSPF. BASINS Technical Note 6. EPA-823-R00-012. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. 2002. Onsite Wastewater Treatment Systems Manual. EPA/625/R-00/008. Office of Water, Office of Research and development, United States Environmental Protection Agency, Washington, DC.

WERF. 2007. Influent Constituent Characteristics of the Modern Waste Stream from Single Sources: Literature Review. Report # 04-DEC-1a. Water Environment Research Foundation, Alexandria, VA.

Whitaker, S. 2010. W. Kerr Scott Reservoir Discharge Study Results. Memorandum from Sam Whitaker, Intensiver Survey Unit, Enironmental Sciences Section, NC Division of Water Quality to Kathy Stecker, June 15, 2010.

Winston, R. J., W. F. Hunt, S.G. Kennedy, and J.D. Wright. 2011. Evaluation of Permeable Friction Course (PFC), Roadside Filter Strips, Dry Swales, and Wetland Swales for Treatment of Highway Stormwater Runoff. Final report for NCDOT Research Project 2007-21. NC Department of Transportation, Hydraulics Unit, Raleigh, NC.

Wischmeier, W.H. and D.D. Smith. 1978. Predicting Rainfall Erosion Losses – A Guide to Conservation Planning. Agricultural Handbook 537. U.S. Department of Agriculture, Washington, DC.

Wu, J. S. and C. J. Allan. 2001. Sampling and Testing of Stormwater Runoff from North Carolina Highways. Final report for Research Project 1999-06. FHWA/NC/2001-002. U.S. Department of Transportation, Research and Special Programs Administration, Washington, DC.

Wu, J. S. and C. J. Allan. 2006. Evaluation and Implementation of BMPs for NCDOT's Highway and Industrial Facilities, Final Report for Research Project 2003-19. North Carolina Department of Transportation, Raleigh, NC.

Wu, J. S. and C. J. Allen. 2009. Evaluation of Nutrient Loading Rates and Effectiveness of Roadside Vegetation Connectivity for Managing Runoff from Secondary Roadways. Draft report for Research Project 2007-04. North Carolina Department of Transportation, Raleigh, NC.

Appendix A. Weather Data

The appendix is provided in the companion document.

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Appendix B. Point Source Nitrogen and Phosphorus

The appendix is provided in the companion document.

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Appendix C. County Septic Systems Information

The appendix is provided in the companion document.

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Appendix D. Animal Operations

The appendix is provided in the companion document.

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Appendix E. Hydrology Calibration/Validation

The appendix is provided in the companion document.

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Appendix F. Sediment and Water Temperature Calibration/Validation

The appendix is provided in the companion document.

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Appendix G. Nutrients and DO/BOD Calibration/ Validation

The appendix is provided in the companion document.

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