High Rock Lake Hydrodynamic and Nutrient Response Models

Draft Report Prepared by
Tetra Tech, Inc under EPA Contract
September 2012

Report Finalized by the
North Carolina Division of Water Resources
October 2016

Disclaimer

This final technical report documents the development and results of the High Rock Lake hydrodynamic and nutrient response models. It is a revised version of the draft report prepared by Tetra Tech in 2012 as part of their deliverables for a contract with the U.S. EPA (Contract EP-C-08-004, Task Order 036). The nutrient response model was later twice updated by U.S. EPA to address comments received from the High Rock Lake Technical Advisory Committee following the comment periods of September 27 to November 28, 2012 and May 5 to November 30, 2015. The Division of Water Resources further revised the model in October 2016 and updated the draft report originally prepared by Tetra Tech to incorporate results of the final model.

Contents

1 Introduction 1-1
1.1 Background 1-1
1.1.1 Description of Impairment 1-1
1.1.2 Technical Advisory Committee 1-6
1.2 Water Quality Monitoring Data 1-7
2 Lake Model Development 2-1
2.1 EFDC and WASP Model Description 2-1
2.1.1 EFDC 2-1
2.1.2 WASP 2-2
2.2 EFDC Model Configuration 2-3
2.2.1 Horizontal Grid 2-3
2.2.2 Bathymetry and Vertical Grid 2-5
2.2.3 Meteorological Forcing 2-8
2.2.4 EFDC Watershed Boundary Forcing (Flow) 2-9
2.2.5 EFDC Watershed Boundary Forcing (Temperature) 2-11
2.2.6 Point Sources and Withdrawals 2-12
2.2.7 Onsite Wastewater Systems 2-12
2.2.8 Dam Operation and Outflow 2-13
2.3 WASP Model Configuration 2-14
2.3.1 Linkage to Hydrodynamic Model 2-14
2.3.2 Linkage to Watershed Model 2-14
2.3.3 Point Source Loading 2-15
2.3.4 Direct Atmospheric Deposition 2-16
2.3.5 Representation of Sorbed and Dissolved Nutrient Fractions 2-16
2.3.6 Lake Sediment Fluxes 2-17
2.3.7 Algal Community Data 2-18
2.3.8 Light Extinction Data 2-20
3 Model Calibration/Validation 3-1
3.1 Calibration Process and Acceptance Criteria 3-1
3.2 Hydrodynamic Calibration and Validation (EFDC) 3-3
3.2.1 Water Balance and Flow Correction 3-4

3.2.2 Water Surface Elevation 3-6
3.2.3 Water Temperature Calibration 3-7
3.3 Water Quality Calibration and Validation (WASP) 3-14
3.3.1 Suspended Solids Calibration and Validation 3-14
3.3.2 Nutrients Calibration and Validation 3-19
3.3.3 Algae and Chlorophyll *a* Calibration and Validation 3-37
3.3.4 Dissolved Oxygen Calibration and Validation 3-43
4 Model Application 4-1
4.1 Limiting Factors on Algal Growth 4-1
5 Summary 5-1
6 References 6-1
Appendix A. Model Calibration and Validation Stations A-1

List of Figures

Figure 1-1. High Rock Lake Assessment Units 1-3
Figure 1-2. 2014 303(d) List - High Rock Lake Impairments 1-5
Figure 1-3. High Rock Lake Water Quality Sampling Stations 1-9
Figure 2-1. State Variables for the WASP Advanced Eutrophication Model 2-3
Figure 2-2. High Rock Lake EFDC Model Horizontal Grid 2-4
Figure 2-3. Number of Vertical Layers for the High Rock Lake Model Grid 2-6
Figure 2-4. Stage-Storage Curve for High Rock Lake (reproduced from APGI, 2002) 2-7
Figure 2-5. Comparison of Model Bathymetric Representation to APGI Stage-Storage Curve for High Rock Lake. 2-8
Figure 2-6. Box plots of observed Chlorophyll *a* concentrations and percent unit density of blue-green algae, diatoms, and green algae in different months. Data are combined from Stations HRL052, YAD1651A, YAD152C and YAD169B. 2-19
Figure 2-7. Relationship of Extinction Coefficient Calculated from PAR to Secchi Depth 2-21
Figure 3-1. Lake Model Calibration Sequence 3-1
Figure 3-2. High Rock Lake Flow Correction Time Series 3-6
Figure 3-3. Simulated and Observed Water Surface Elevation 3-7
Figure 3-4. Surface Water Temperature Time Series Comparison at HRL051 (2005 – 2010) 3-8
Figure 3-5. Surface Water Temperature Time Series Comparison at YAD152C (2005 – 2010) 3-9
Figure 3-6. Surface Water Temperature Time Series Comparison at YAD169F (2005 – 2010) 3-9
Figure 3-7. Water Temperature Profile Comparison at HRL051 (2008) 3-10
Figure 3-8. Water Temperature Profile Comparison at YAD152C (2008) 3-11
Figure 3-9. Water Temperature Profile Comparison at YAD169F (2008) 3-12
Figure 3-10. Water Temperature Profile Comparison at YAD169F (2009) 3-13
Figure 3-11. TSS (mg/l, log scale) calibration (2008-2010) and validation (2005-2006), main-stem stations in High Rock Lake. 3-16
Figure 3-12. TSS (mg/l, log scale) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake. 3-17
Figure 3-13. Total Phosphorus (TP, mg/l) calibration (2008-2010) and validation (2005-2006), main-stem stations in High Rock Lake 3-23
Figure 3-14. Total Phosphorus (TP, mg/l) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake 3-24
Figure 3-15. Phosphate (PO4, mg/l) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake 3-25

Figure 3-16. Phosphate (PO4, mg/l) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake 3-26
Figure 3-17. Total Nitrogen (mg/l) calibration (2008-2010) and validation (2005-2006), main-stem stations in High Rock Lake 3-29
Figure 3-18. Total Nitrogen (mg/l) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake 3-30
Figure 3-19. Nitrite+Nitrate Nitrogen (NOx, mg/l) calibration (2008-2010) and validation (2005-2006), main-stem stations in High Rock Lake 3-33
Figure 3-20. Nitrite+Nitrate Nitrogen (NOx, mg/l) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake 3-34
Figure 3-21. Ammonium Nitrogen (NH3, mg/l) calibration and validation, main-stem stations in High Rock Lake 3-35
Figure 3-22. Ammonium Nitrogen (NH3, mg/l) calibration and validation, arm stations in High Rock Lake 3-36
Figure 3-23. Chlorophyll *a* (Chl *a*, µg/l) calibration (2008-2010) and validation (2005-2006), main-stem stations in High Rock Lake 3-40
Figure 3-24. Chlorophyll *a* (Chl *a*, µg/l) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake 3-41
Figure 3-25. Chlorophyll *a* exceedance rate distributions in High Rock Lake 3-42
Figure 3-26. Dissolved Oxygen (DO, mg/l) calibration (2008-2010) and validation (2005-2006), main-stem stations in High Rock Lake 3-45
Figure 3-27. Dissolved Oxygen (DO, mg/l) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake 3-46
Figure 4-1. Factors Limiting Phytoplankton Growth in Upper High Rock Lake (HRL051) 4-1
Figure 4-2. Factors Limiting Phytoplankton Growth in Middle High Rock Lake (YAD152C) 4-2
Figure 4-3. Factors Limiting Phytoplankton Growth in Lower High Rock Lake (YAD169F) 4-2

List of Tables

Table 1-1. Description of High Rock Lake Assessment Units and 2014 List of Impairments 1-4
Table 1-2. North Carolina Waterbody Classifications Applicable to High Rock Lake.........................1-6
Table 1-3. Observation Stations for High Rock Lake Intensive Monitoring (2008 – 2010)..............1-10
Table 1-4. Summary of Observation Stations from Scoping Monitoring (2005 – 2006)..................1-10
Table 1-5. Parameter Summary from Scoping Monitoring (2005 – 2006) for all Stations 1-11
Table 2-1. Summary of Calculated Weather Elements 2-8
Table 2-2. Numerical Interpretation of Sky Condition Observation 2-9
Table 2-3. USGS Area Weighted Flow Forcing Assignments for EFDC..2-11
Table 2-4. Point Source Discharges to and Withdrawals from High Rock Lake 2-12
Table 2-5. Connection of Water Quality State Variables between HSPF and WASP 2-15
Table 2-6. Range of Dissolved Nutrient Fractions for the Lake Model 2-17
Table 2-7. Nutrient Sediment Flux Data...2-18
Table 2-8. Algal Community Data Monitoring Stations 2-19
Table 2-9. PAR-Based Light Extinction Coefficients (k) in High Rock Lake 2-20
Table 2-10. Observed Secchi Depths (m) in High Rock Lake 2-21
Table 2-11. Light Extinction Coefficients (k, 1/m) Derived from Secchi Depths...............................2-22
Table 3-1. Reference Calibration Guidelines for “Good” Model Fit in Estuaries[1].............................3-3
Table 3-2. Analysis of Water Surface Elevation Calibration (2005 – 2010) 3-7
Table 3-3. Calibration Statistics for Surface Water Temperature (2008-2010)..............................3-13
Table 3-4. Validation Statistics for Surface Water Temperature (2005-2006) 3-14
Table 3-5. Calibration Statistics for Total Suspended Solids (2008-2010) 3-15
Table 3-6. Validation Statistics for Total Suspended Solids (2005-2006) 3-18
Table 3-7. Selected Kinetic Parameters for High Rock Lake Eutrophication Model 3-19
Table 3-8. Key parameters for the two phytoplankton groups 3-20
Table 3-9. Calibration Statistics for Total Phosphorus (2008 – 2010)...3-21
Table 3-10. Validation Statistics for Total Phosphorus (2005 – 2006)...3-22
Table 3-11. Calibration Statistics for Total Nitrogen (2008 – 2010) 3-27
Table 3-12. Validation Statistics for Total Nitrogen (2005 – 2006)..3-28
Table 3-13. Calibration Statistics for Nitrite+Nitrate Nitrogen (2008 – 2010)..................................3-31
Table 3-14. Validation Statistics for Nitrite+Nitrate Nitrogen (2005 – 2006) 3-32
Table 3-15. Calibration Statistics for Chlorophyll *a* (2008 – 2010) 3-38
Table 3-16. Validation Statistics for Chlorophyll *a* (2005 – 2006) 3-39
Table 3-17. Calibration Statistics for Dissolved Oxygen (2008 – 2010) 3-43
Table 3-18. Validation Statistics for Dissolved Oxygen (2005 – 2006)..3-44

[This page intentionally left blank]

1 Introduction

1.1 Background

High Rock dam was constructed in 1927 and is currently owned by Alcoa Power Generating, Inc. (APGI). High Rock Lake was filled by April, 1928 (APGI, 2006a). The normal pool elevation is 623.9 feet (190.2 m. NGVD), which corresponds to a surface area of 15,180 acres and a volume of 239,672 acre-feet. The dam and lake originally supplied power to support aluminum manufacturing power generation, however now the primary use is for generation and sale of hydroelectric power. Due to peaking power generation, the water level in the lake fluctuates on an intraday basis.

1.1.1 Description of Impairment

The State of North Carolina Division of Water Resources (DWR) assesses the support of designated uses in waterbodies of the state in accordance with the Federal Clean Water Act. High Rock Lake has been identified as failing to support its designated uses for water supply, recreation, and support of aquatic life 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.

Water quality standards consist of three parts: an antidegradation policy, designated uses, and water quality 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)*

DWR uses 14 different assessment units (AUs) to characterize water quality in High Rock Lake. These assessment units are shown in Figure 1-1.

The identified impairments (Clean Water Act Section 303(d) listings) in High Rock Lake were obtained from the 2014 Integrated Report (NCDENR, 2014). The relevant impaired assessment units in the study area are listed in Table 1-1 and shown in Figure 1-2. 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. The pH listings are due to elevated pH, typically associated with excess algal growth that depletes the bicarbonate ion from the water column. Descriptions of the associated designated uses for the assessment units of High Rock Lake are provided in Table 1-2.

Two assessment units of the lake are not listed as impaired for any of the three constituents: 12-(108.5)b1, which is the uppermost assessment unit on the mainstem, and 12-117-(1), which is on the Second Creek Arm. On the mainstem, one assessment unit is impaired for all three constituents, two assessment units are impaired for chlorophyll *a* and turbidity, one is impaired for chlorophyll *a* and pH, and one is impaired for chlorophyll *a* only. All of the assessment units (with the exception of 12-117-(1)) on the arms of the lake are impaired for chlorophyll *a* and one assessment unit (on the Second Creek Arm) is impaired for both chlorophyll *a* and pH.

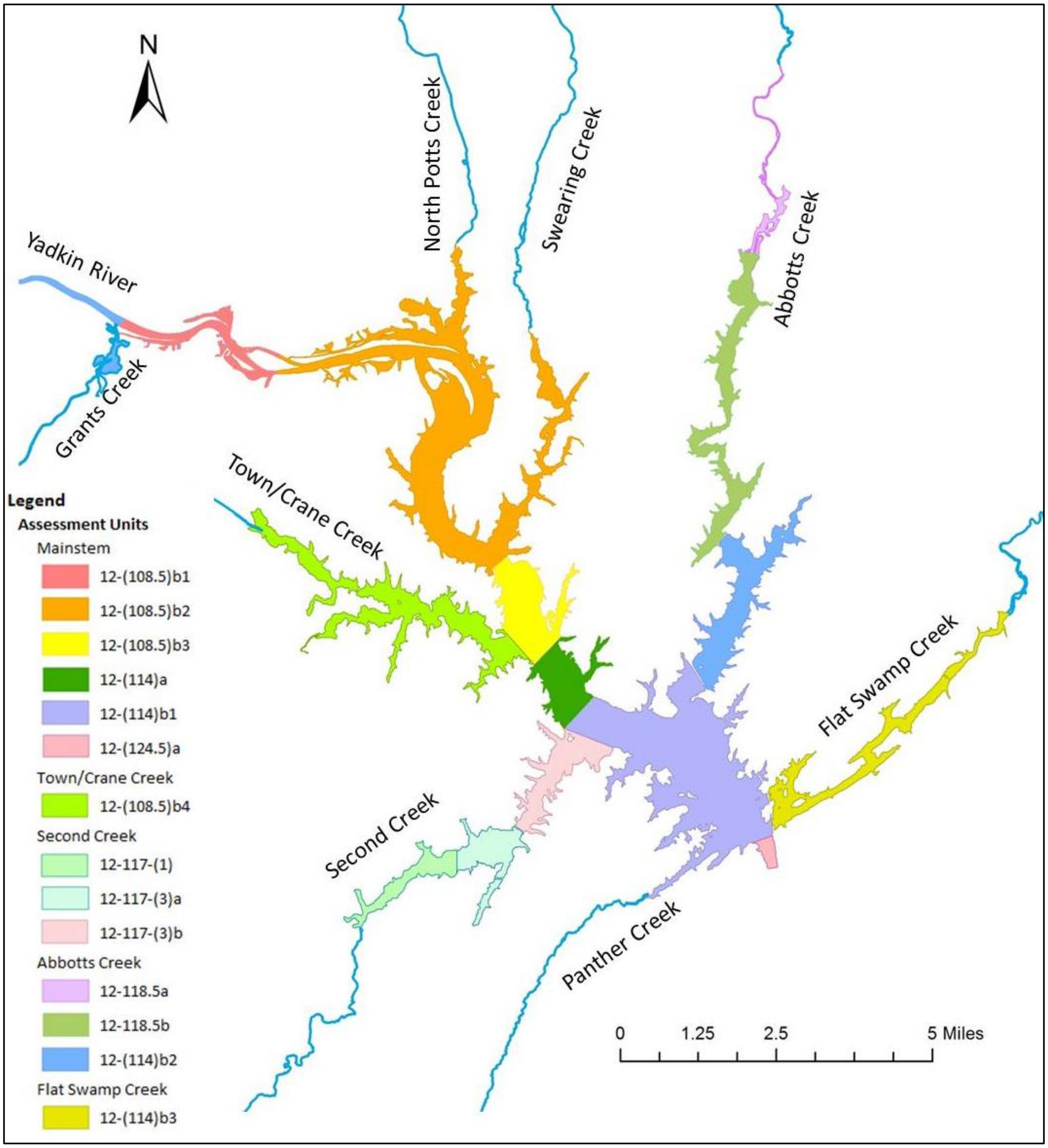

Figure 1-1. High Rock Lake Assessment Units

Table 1-1. Description of High Rock Lake Assessment Units and 2014 List of Impairments

Description	Segment ID	Classi-fication	Listed for chlorophyll *a*	Listed for turbidity	Listed for pH
Mainstem					
Yadkin River from mouth of Grants Creek to Buck Steam Station	12-(108.5)b1	WS-V			
Yadkin River from Buck Steam Plant to a line across High Rock Lake at the downstream side of Swearing Creek arm	12-(108.5)b2	WS-V	X	X	
Yadkin River from downstream side Swearing Creek arm to downstream side of Crane Creek arm	12-(108.5)b3	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)b1	WS-IV, 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		
Town/Crane Creek Arm					
Crane Creek Arm of High Rock Lake	12-(108.5)b4	WS-V	X		
Second Creek Arm					
Second Creek arm of High Rock Lake from source to a point 1.7 miles downstream of Rowan County SR 1004	12-117-(1)	WS-V, B			
Second Creek arm of High Rock Lake from a point 1.7 miles downstream of Rowan County SR 1004 to SR 1002	12-117-(3)a	WS-IV, B	X		
Second Creek arm of High Rock Lake from SR 1002 to High Rock Lake	12-117-(3)b	WS-IV, B	X		X
Abbotts Creek Arm					
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		
Lower Abbotts Creek Arm above NC 8	12-(114)b2	WS-IV, B	X		
Flat Swamp Creek Arm					
Lower Flat Swamp Creek Arm above railroad bridge	12-(114)b3	WS-IV, B	X		

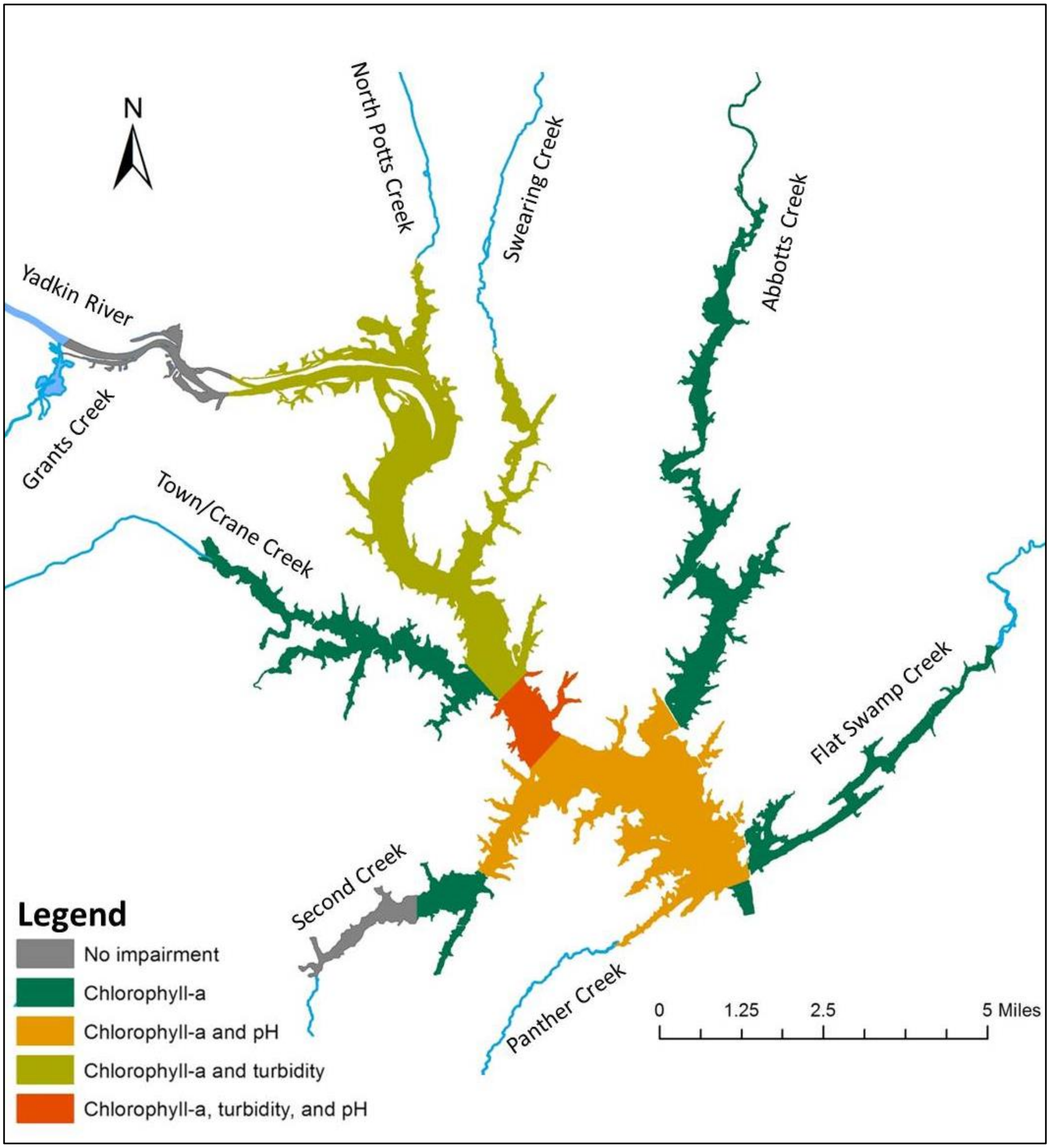

Figure 1-2. 2014 303(d) List - High Rock Lake Impairments

Table 1-2. North Carolina Waterbody Classifications 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) (NCDENR, 2007)

1.1.2 Technical Advisory Committee

In August 2005, the Division of Water Quality (DWQ, which was merged with DWR in 2013) convened a Technical Advisory Committee (TAC) to assist with development of monitoring plans, watershed and receiving water models, and data analysis tools that can be used to aid in the management of nutrients, algae (chlorophyll *a*) and turbidity in High Rock Lake. Membership to the TAC was open on a voluntary basis.

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 provided recommendations for monitoring, model development, and performance criteria. The TAC helped shape many aspects of the modeling process and provided:

- Feedback on monitoring plans
- Information on effluent discharge quantity and quality
- Information on water withdrawal amounts
- Collaboration on accounting of septic systems
- Technical review of draft models and reports

In December 2008, the U.S. Environmental Protection Agency (EPA) issued a task order to Tetra Tech to develop watershed and lake response models for High Rock Lake. The watershed loading model was developed using EPA's Hydrologic Simulation Program – FORTRAN (HSPF) framework and is documented in a companion report (Tetra Tech, 2012) located here: https://deq.nc.gov/about/divisions/water-resources/planning/modeling-assessment/special-studies#HRL. This report documents only the lake response model; the reader is referred to the companion report for details on the watershed and its representation in a simulation model.

An initial draft of this report and accompanying model files were provided to TAC members for a 60-day review and comment period in September 2012. A subgroup of TAC members (NC Department of Transportation (DOT) and the Yadkin Pee Dee River Basin Association (YPDRBA)) contracted with a third party, LimnoTech, Inc (LTI), to perform the review on their behalf. Comments were also submitted by the Yadkin Riverkeeper, Alcoa Power Generating, Inc. (APGI), and the Piedmont Triad Regional Council (PTRC). Responses to comments and descriptions of resulting model revisions are described in the supplemental document titled "High Rock Lake Technical Advisory Committee Draft Lake Response Models Review Comments and Responses, March, 2013" (Tetra Tech, 2013).

One of the primary concerns identified by the TAC review was the lack of multiple algal groups in the draft lake nutrient response model. The original water quality model that was developed by Tetra Tech utilized the conventional eutrophication module of the Water Quality Simulation Program (WASP Version 7.5). The eutrophication module can simulate only one homogeneous algal group. High Rock Lake experiences late fall and early spring algal blooms that were not being accounted for in the model simulations due to the limitation of a single algal group. WASP has an advanced eutrophication module that can simulate up to three algal groups that Tetra Tech could not use for High Rock Lake because of model memory limitations associated with the large gridded network.

Following the TAC review, EPA modified the WASP model to address the memory limitation issue and applied the modified advanced eutrophication module to High Rock Lake to account for multiple algal groups. The revised model was provided to TAC on May 5, 2015.

LTI then reviewed the revised model on behalf of TAC members DOT and YPDRBA, and submitted further comments to DWR on November 30, 2015. The Yadkin-Pee Dee Riverkeeper also contracted Drs. Scott Wells and Chris Berger of Portland State University and provided their comments on the revised model on November 30, 2015.

Upon receiving the second round of model review comments, EPA further revised the model to address some comments raised. DWR further revised the model in October 2016 to correct errors in the WASP model input files and updated the draft report originally prepared by Tetra Tech to incorporate results of the final model. Responses to comments and descriptions of resulting model revisions are described in the supplemental document titled "High Rock Lake Technical Advisory Committee Draft Lake Response Models Review Comments and Responses, October 27, 2016" (DWR, 2016). This report provides the results of the updated final model.

1.2 WATER QUALITY MONITORING DATA

Water quality monitoring used for model development and calibration comes from two separate sampling studies – an intensive monitoring effort in 2008 – 2010 explicitly designed to support the modeling effort, and an earlier scoping monitoring program conducted in 2005 – 2006.

To help support the model development process, an intensive monitoring effort was undertaken from April 2008 through March 2010 with the guidance of the High Rock Lake TAC. Monitoring was supported by a Clean Water Act (CWA) Section 319 grant to YPDRBA with APGI, DWQ, and LimnoTech serving as partners. This effort included 10 monitoring stations within the lake (Figure 1-3 and Table 1-3). Physical and chemical observations were collected year-round with increased frequency during the summer months, for a total of 45 sampling dates. Details of this sampling effort are provided in LimnoTech (2010), which can be found here: http://portal.ncdenr.org/c/document_library/get_file?uuid=901501d5-6df3-4815-8747-a24401782703&groupId=38364.

An earlier scoping monitoring program was conducted by DWQ from 2005 through 2006. Twelve lake stations (Table 1-4, key stations shown in Figure 1-3) were sampled and reported 74,389 observations. The observations were primarily focused on physical and chemical eutrophication related parameters and sediment (Table 1-5). The scoping monitoring for water quality was conducted on a monthly basis, but also included continuous temperature monitoring at several stations.

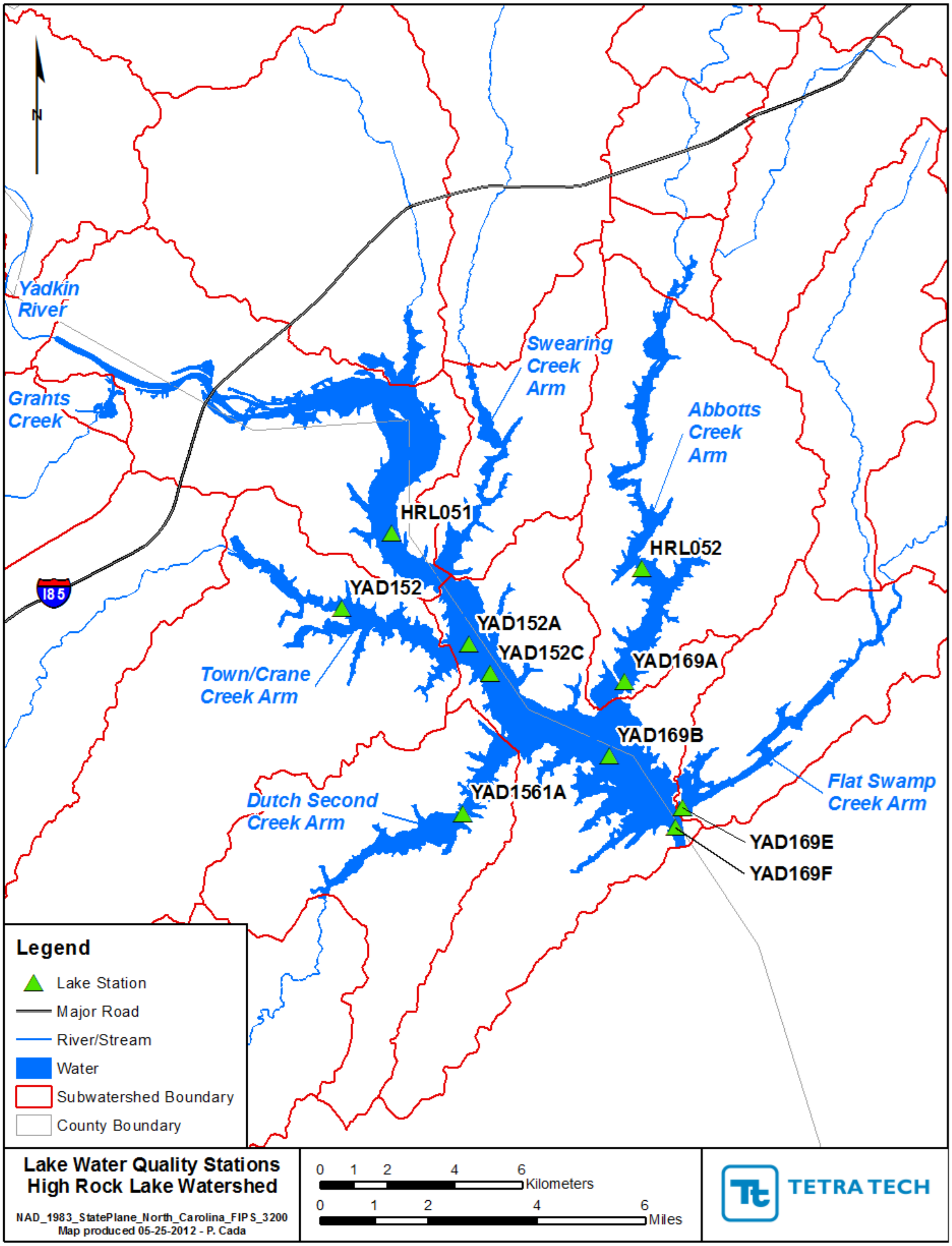

Figure 1-3. High Rock Lake Water Quality Sampling Stations

Table 1-3. Observation Stations for High Rock Lake Intensive Monitoring (2008 – 2010)

Station	Station Name
HRL051	Upper HRL above Swearing Creek
HRL052	Upper Abbotts Creek Arm
YAD152	Town/Crane Creek Arm
YAD152A	Middle HRL at Town/Crane Creek
YAD152C	Middle HRL below Town/Crane Creek
YAD1561A	Second Creek Arm
YAD169A	Lower Abbotts Creek Arm
YAD169B	Lower HRL below Abbotts Creek
YAD169E	Flat Swamp Creek Arm
YAD169F	Lower HRL at forebay

Table 1-4. Summary of Observation Stations from Scoping Monitoring (2005 – 2006)

Station	Station Name	Start	End	No. Obs.
HRL051	Upper HRL above Swearing Creek	3/29/2005	8/1/2006	478
HRL052	Upper Abbotts Creek Arm	3/29/2005	8/1/2006	735
YAD1391A*	HRL Upstream of S Potts Creek	3/29/2005	1/19/2006	290
YAD152	Town/Crane Creek Arm	2/8/2006	8/1/2006	233
YAD152A	Middle HRL at Town/Crane Creek	3/29/2005	8/1/2006	639
YAD152C	Middle HRL below Town/Crane Creek	3/22/2005	8/1/2006	20534
YAD1561A	Second Creek Arm	2/9/2006	8/2/2006	272
YAD156A	Second Creek at mouth near Granite Quarry	3/29/2005	8/2/2006	822
YAD169A	Lower Abbotts Creek Arm	3/29/2005	8/1/2006	1004
YAD169B	Lower HRL below Abbotts Creek	3/29/2005	8/2/2006	957
YAD169E	Flat Swamp Creek Arm	3/29/2005	8/2/2006	1090
YAD169F	Lower HRL at forebay	3/22/2005	8/2/2006	47335

* Station discontinued and not used in model calibration.

Table 1-5. Parameter Summary from Scoping Monitoring (2005 – 2006) for all Stations

PCode	Parameter Name	Units	No. Obs.	Mean	Min	Max
BOD5	Biochemical Oxygen Demand (5-Day)	mg/L	172	3.479	2	15
CHLA	Chlorophyll *a*	µg/L	146	30.63	3	71
COND	Specific Conductance	µmho/cm	1491	99.36	8	209
DO	Dissolved Oxygen	mg/L	1491	7.298	0	15.1
NH3	Total Ammonia as N	mg-N/L	185	0.04	0.01	0.2
NH3SEDFLUX	Ammonia Sediment Flux as N	g-N/m^2/day	2	0.055	0.019	0.091
NO2+NO3	Nitrite+Nitrate (as N)	mg-N/L	185	0.421	0.01	1
NOXSEDFLUX	Nitrite+Nitrate Sediment Flux as N	g-N/m^2/day	2	-0.035	-0.059	-0.01
PH	pH	Standard units	1491	7.483	5.2	10
PO4	Orthophosphate as P	mg-P/L	186	0.029	0.01	1
SECCHIDPTH	Secchi Depth	meters	174	0.639	0.1	4
SOD_COR	Sediment Oxygen Demand, corrected	g/m^2/day	2	-1.59	-1.99	-1.19
TDS	Total Dissolved Solids/Residue	mg/L	175	73.223	32	139
TIN	Total Inorganic Nitrogen	mg-N/L	96	0.437	0.02	1.05
TKN	Total Kjeldahl Nitrogen as N	mg-N/L	185	0.582	0.1	1.2
TKNSEDFLUX	Total Kjeldahl Nitrogen Sediment Flux as N	g-N/m^2/day	2	0.064	0.016	0.112
TOC	Total Organic Carbon as C	mg-C/L	186	4.845	2.4	33.8
TON	Total Organic Nitrogen	mg-N/L	106	0.489	0.05	0.95
TP	Total Phosphorus as P	mg-P/L	185	0.105	0.03	0.96
TPSEDFLUX	Total Phosphorus Sediment Flux as P	g-P/m^2/day	2	0.009	0.001	0.017
TS	Total Solids/Residue	mg/L	183	100.732	57	270
TSS	Total Suspended Solids (residue, total nonfilterable)	mg/L	184	14.428	4	119
TURBIDITY	Turbidity	NTU	185	21.683	1	290
WTEM	Water Temperature	º C	67277	18.453	3.32	37.1

2 Lake Model Development

The lake model application consists of fully linked EFDC (Environmental Fluid Dynamics Code) and WASP (Water Quality Analysis Simulation Program) models. The three-dimensional EFDC model provides the simulation of the movement of water (hydrodynamics) and water temperature. The WASP model provides the simulation of sediment transport, nutrient transport and transformations, and the responses of algae, dissolved oxygen, and organic matter to environmental conditions within the lake. Both models are described in this section. Both simulation models are supported by EPA and are frequently used for TMDL applications.

2.1 EFDC and WASP Model Description

2.1.1 EFDC

EFDC (https://www.epa.gov/exposure-assessment-models/efdc) is a hydrodynamic and water quality modeling package for simulating one-dimensional, two-dimensional, and three-dimensional flow and transport in surface water systems including: rivers, lakes, estuaries, reservoirs, wetlands, and nearshore to shelf scale coastal regions. The EFDC model was originally developed at the Virginia Institute of Marine Science for estuarine and coastal applications and is considered public domain software (Hamrick, 1992, 1996).

The physics of the EFDC model, and many aspects of the computational scheme, are equivalent to the widely used Blumberg-Mellor model (Blumberg & Mellor, 1987) and the U.S. Army Corps of Engineers' CH3D or Chesapeake Bay model (Johnson, et al., 1993). The EFDC model solves the three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motion for a variable density fluid. Dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity, and temperature are also solved. The two turbulence parameter transport equations implement the Mellor-Yamada level 2.5 turbulence closure scheme (Mellor & Yamada, 1982; Galperin et al., 1988).

The EFDC model uses Cartesian or curvilinear, orthogonal horizontal coordinates. The numerical scheme employed in EFDC to solve the equations of motion uses second order accurate spatial finite differencing on a staggered grid. The model's time integration employs a second order accurate three-time level, finite difference scheme with an internal-external mode splitting procedure to separate the internal shear, or baroclinic mode, from the external free surface gravity wave, or barotropic mode.

The external mode solution is semi-implicit, and simultaneously computes the two-dimensional surface elevation field by a preconditioned conjugate gradient procedure. The external solution is completed by the calculation of the depth average barotropic velocities using the new surface elevation field. The model's semi-implicit external solution allows large time steps that are constrained only by the stability criteria of the explicit central difference, or high order upwind advection scheme (Smolarkiewicz and Margolin, 1993) used for the nonlinear accelerations. Horizontal boundary conditions for the external mode solution include options for simultaneously specifying the surface elevation only, the characteristic of an incoming wave (Bennett and McIntosh, 1982), free radiation of an outgoing wave (Bennett, 1976; Blumberg and Kantha, 1985) or the normal volumetric flux on arbitrary portions of the boundary.

The EFDC model's internal momentum equation solution, at the same time step as the external, is implicit with respect to vertical diffusion. The internal solution of the momentum equations is in terms of the vertical profile of shear stress and velocity shear, which results in the simplest and most accurate form of the baroclinic pressure gradients and eliminates the over-determined character of alternate internal mode formulations. Time splitting inherent in the three time level scheme is controlled by periodic insertion of a second order accurate two time level trapezoidal step.

2.1.2 WASP

The water quality simulation of High Rock Lake was completed with WASP version 7.52, released on November 15, 2013 (https://www.epa.gov/exposure-assessment-models/water-quality-analysis-simulation-program-wasp).

The Water Quality Analysis Simulation Program is an enhancement of the original WASP (Di Toro et al., 1983; Connolly and Winfield, 1984). WASP is an EPA-supported, general-purpose modeling system for assessing the fate and transport of conventional and toxic pollutants in surface waterbodies, including nutrients, dissolved oxygen, and pathogens. The model simulates time-varying processes of advection and dispersion, considering point and diffuse mass loading, and boundary exchange and is not limited in its ability to simulate transport in response to reversing flows. WASP has been used in the development of hundreds of TMDLs and is actively supported by EPA Region 4.

The WASP model helps users interpret and predict water quality responses to natural phenomena and man-made pollution for various pollution management decisions. WASP can be run in either eutrophication or toxicant transport mode (with eutrophication mode applied for High Rock Lake). WASP 7.52 is a dynamic compartment-modeling program for aquatic systems, including both the water column and the underlying benthos. WASP allows the user to investigate 1, 2, and 3 dimensional systems, and a variety of pollutant types. WASP also can be linked with hydrodynamic models that can provide flows, depths velocities, temperature, and salinity.

The state variables for WASP in advanced eutrophication mode are shown in Figure 2-1.

Version 7.52 of the WASP model includes the ability to simulate up to three solids state variables during eutrophication simulation. The solids variables are subject to advective and diffusive transport, as well as settling. Due to resource constraints, only a single solids class is included in the model; for lakes this typically represents the finer, slower-settling clay fraction of influent sediment. Organic detritus is simulated separately.

Version 7.52 of the WASP model also includes the ability to simulate up to three separate algal groups during eutrophication simulation. Two groups are included in the High Rock Lake model to represent warm-water and cold water algae, discussed in further detail below in Section 2.3.7. Information about model parameters used for the two algal groups is provided under section 3.3.2.

WASP version 7.52 does not have a separate user manual at this time. The user's manual for version 6 (Wool et al., 2001) remains the primary documentation for the model.

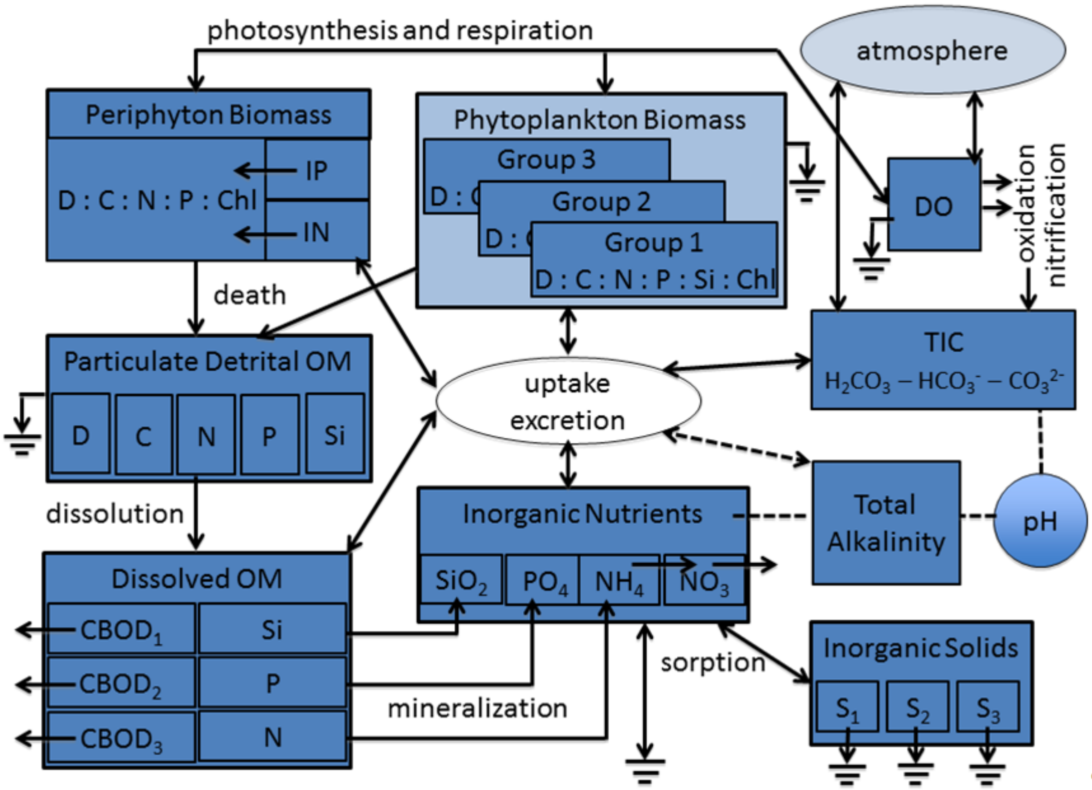

Figure 2-1. State Variables for the WASP Advanced Eutrophication Model

2.2 EFDC Model Configuration

2.2.1 Horizontal Grid

The horizontal extent of High Rock Lake is represented in the model with a curvilinear orthogonal grid that approximates the actual shoreline yet allows conversion to a corresponding orthogonal basis for computations. Selection of grid cell size is a tradeoff between a variety of factors, with more and smaller cells providing a closer fit to the true shoreline and potentially greater accuracy in hydrodynamic simulation but requiring a shorter time step to achieve numeric stability.

The horizontal grid generally approximates the normal pool shoreline of High Rock Lake. The upstream boundary of the lake model was placed at the confluence of the Yadkin River and South Yadkin River. This represents a compromise between the desire to represent this section in EFDC and the difficulties caused by higher flow velocities in flowing river reaches than in lacustrine reaches that present challenges for maintaining model stability, requiring a very short time step and/or large grid size.

The final High Rock Lake model grid contains 538 horizontal grid cells (Figure 2-2). These range in size from 5 to 221 acres with a median value of 19 acres. The average dimension of the grid cells is approximately 100 – 300 meters. In aggregate, the model grid has a surface area of 13,568 acres (21.2 square miles). All the cells within the model contain water throughout the simulation of operating conditions and the model capability to simulate drying cells (which adds considerably to run times) is not used. This means that during high flow events the surface area of the lake remains fixed and additional storage in flat areas near the lake shore is not simulated.

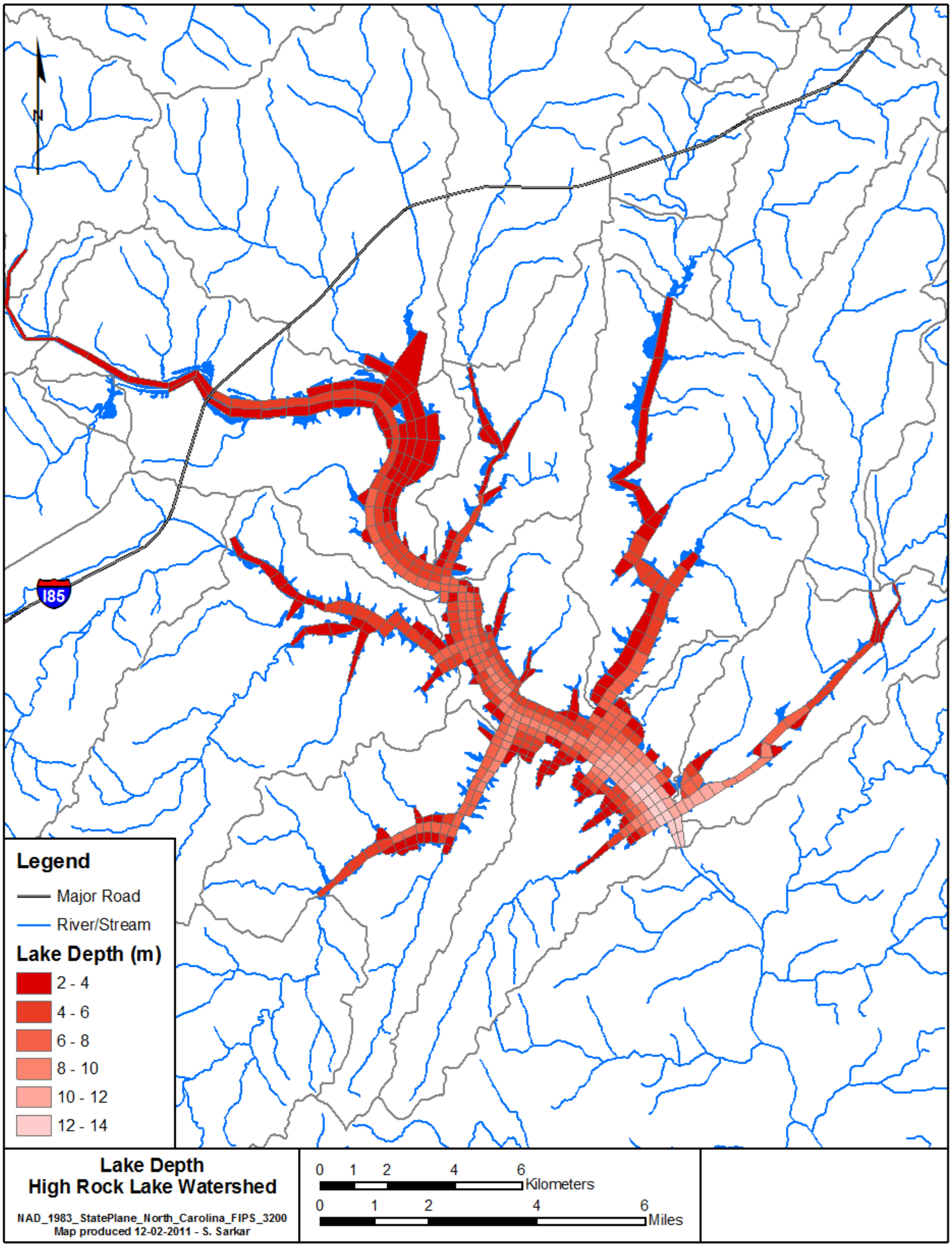

Figure 2-2. High Rock Lake EFDC Model Horizontal Grid

2.2.2 Bathymetry and Vertical Grid

The EFDC model can use either a stretched (sigma) vertical coordinate or a hybrid sigma and generalized vertical coordinate (GVC or Z) option. The EFDC model was originally formulated with a sigma or stretched vertical coordinate. In the sigma coordinate formulation, the number of vertical layers is the same at all horizontal locations in the model grid. Although this formulation is widely accepted, conceptually attractive, and adequate for a large range of applications, it may be subject to internal pressure gradient errors, particularly where there is steep bottom topography (Mellor et al., 1994, 1998). The sigma formulation can also result in layers becoming very thin in shallow water, potentially introducing stability problems for the water quality simulation.

For deeper reservoirs with rapid lateral bathymetric changes, such as High Rock Lake, a traditional Z or fixed layer vertical grid is preferable to a sigma grid for simulating shallow-water processes. A somewhat different approach has been taken in EFDC to arrive at a hybrid or generalized vertical grid (Tetra Tech, 2006). The approach allows the horizontal model domain to be partitioned into sigma regions and what can be referred to as laterally constrained, localized sigma regions (LCL sigma). In the LCL region, the number of active vertical layers is variable, while in the sigma region, the number of vertical layers is constant. Although the LCL transformation includes the sigma transformation as a special case, the vertical grid behavior has strong similarities with the traditional Z vertical grid, with the advantage of the free surface being a constant coordinate surface. Therefore, the High Rock Lake model is constructed with a hybrid Z grid with a minimum of two layers for the shallower sections and a maximum of five layers (Figure 2-3). There are 538 surface layer cells and a total of 1,524 cells in this system.

According to APGI (2002), the available storage capacity of High Rock Lake is 234,100 acre feet at a full pool elevation of 623.9 feet (190.16 m) and a surface area of 15,180 acres. The reservoir has an average depth of 17 feet and a maximum depth of 62 feet. An elevation-storage curve for High Rock Lake is provided in APGI (2002) and reproduced in Figure 2-4. This represents *available* storage above the minimum turbine input invert elevation; additional dead storage exists below this level.

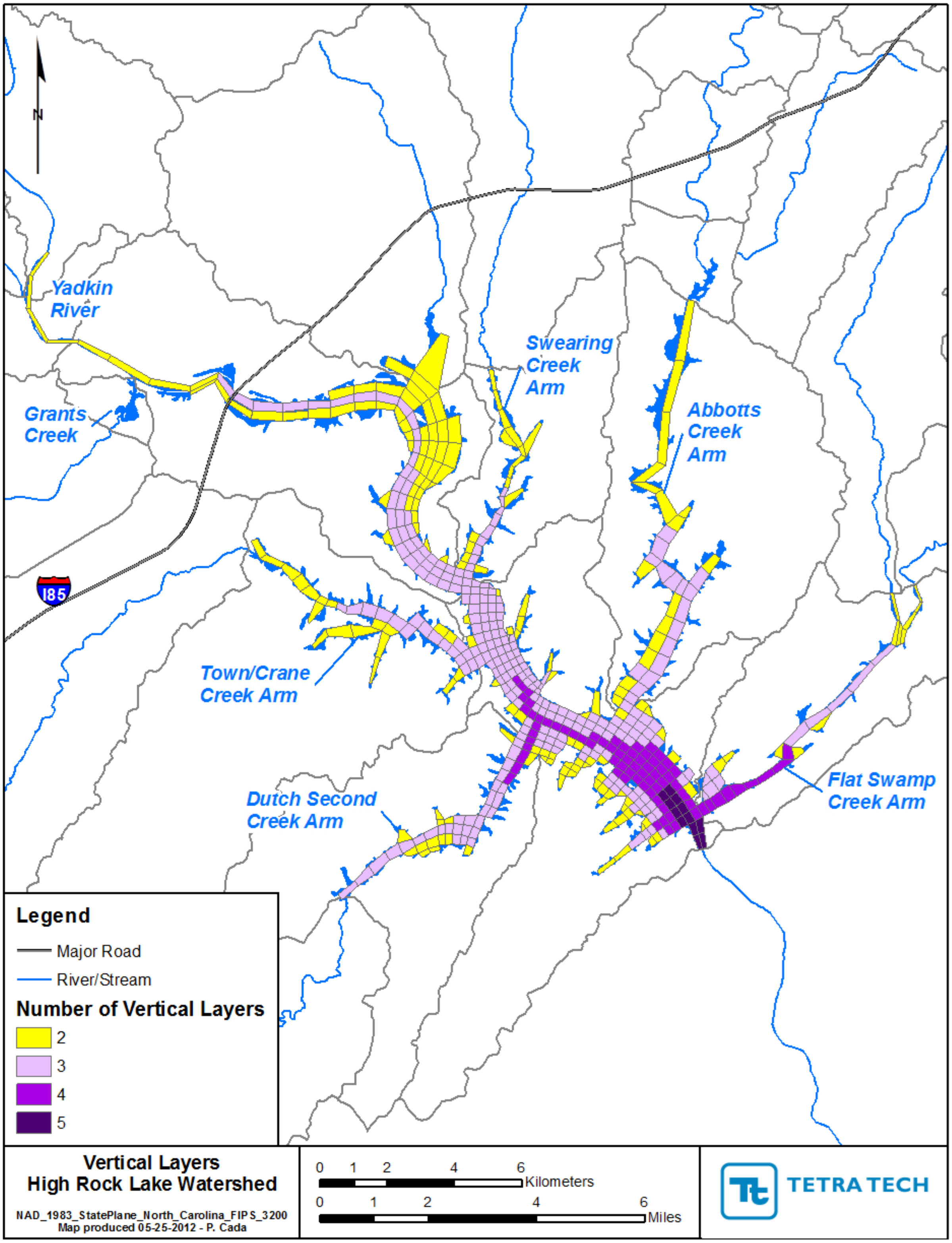

Figure 2-3. Number of Vertical Layers for the High Rock Lake Model Grid

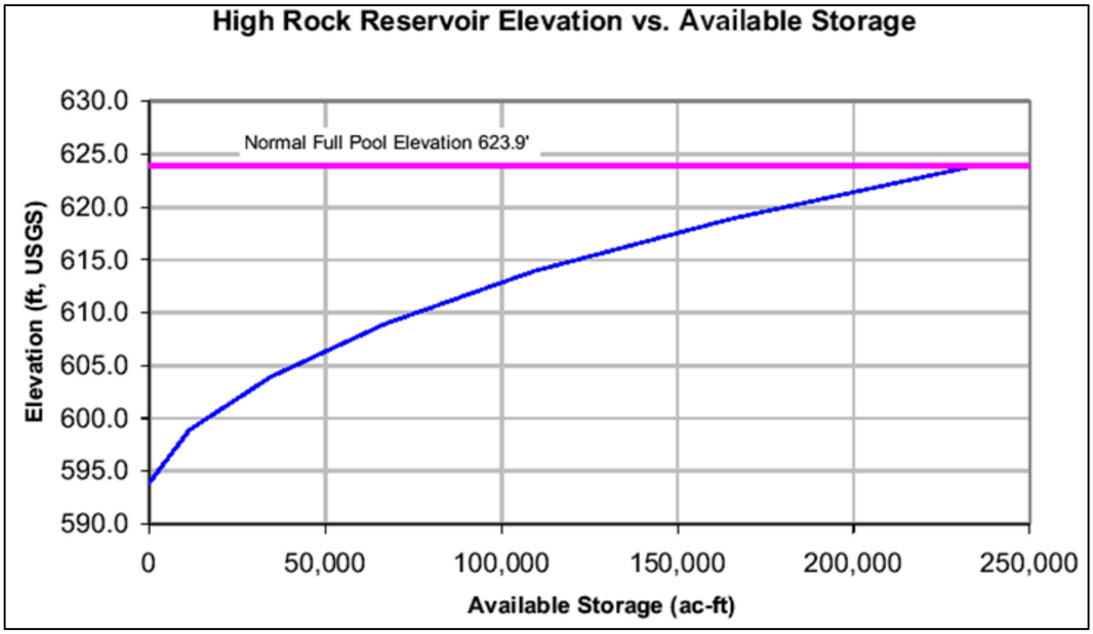

Figure 2-4. Stage-Storage Curve for High Rock Lake (reproduced from APGI, 2002)

The bathymetry, or bottom elevation, for the model grid was estimated from multiple sources. A single unified source of lake bathymetry was not available to prescribe the bottom elevation. The following sources were used to estimate model grid bottom elevation:

- NC DWR cross section soundings during monitoring trips
- APGI contour line coverage
- APGI cross section survey in the upper reaches of the lake
- APGI detailed drawings of the dam and forebay
- City of Salisbury HEC6 study

The resulting strategy to approximate the bottom elevation for the model grid was to consider two elevations as anchors, one at the dam forebay (priority) and the other near the confluence of Yadkin River and South Yadkin River. Intermediate break points were estimated based on the NC DWR cross section soundings during monitoring trips to determine relative longitudinal slopes. The NC DWR cross section soundings were also used to estimate the lateral position of the thalweg, the lowest portion of a given cross section. Once the thalweg elevations were determined for the longitudinal dimension of the main body of the lake, the lateral estimation of bottom elevation was performed at each cross section. After the bottom elevation of a cross section was estimated the bottom elevation of the intermediate longitudinal cells was estimated by linear interpolation. The resulting model grid has a static plan view area but a dynamic volume. The process was iterated as necessary in comparison with the reported stage-volume relationship (Figure 2-5) until a satisfactory comparison was achieved.

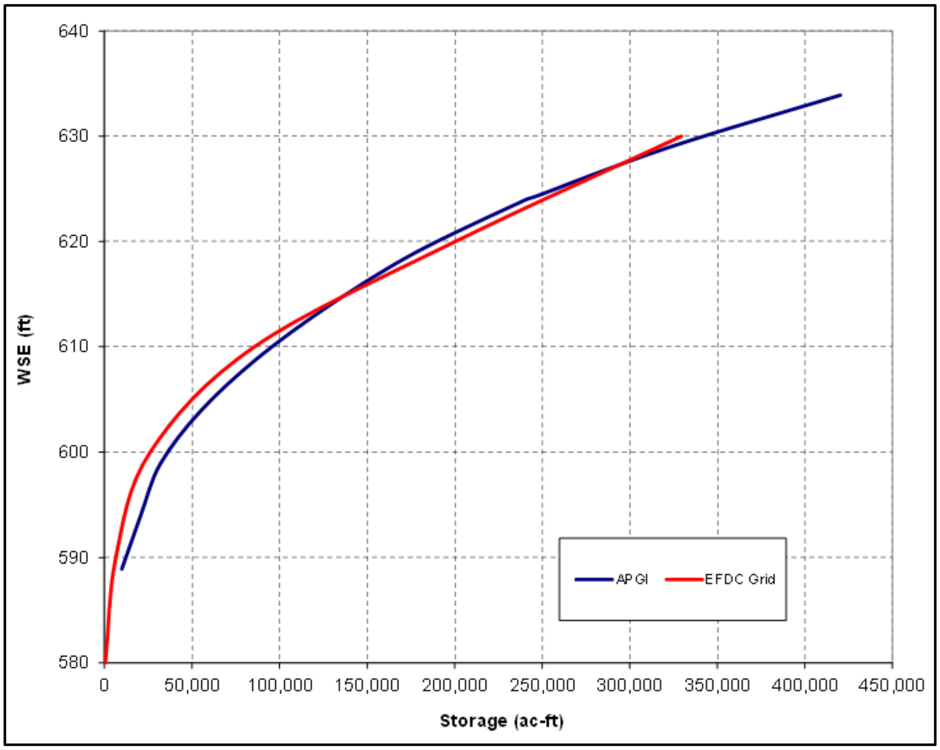

Figure 2-5. Comparison of Model Bathymetric Representation to APGI Stage-Storage Curve for High Rock Lake.

2.2.3 Meteorological Forcing

A variety of weather data are required to drive the thermal and algal response simulation components of the lake model. Hourly time series for precipitation, air temperature, dewpoint, relative humidity, wind, and atmospheric pressure were obtained for Winston-Salem Reynolds Airport (WBAN 93807) available from the National Climatic Data Center. Table 2-1 summarizes additional weather time series that must be calculated from reported data.

Table 2-1. Summary of Calculated Weather Elements

Calculated Series	Observed Data Source
Cloud Cover	Hourly, estimated from sky condition
Potential Evapotranspiration	Hourly, calculated from air temperature, dewpoint, temperature, wind, solar radiation, and coefficients
Solar Radiation	Hourly, calculated from latitude, date-time, and cloud cover

The processing of precipitation and temperature data and the development of potential evapotranspiration series for High Rock Lake watershed are described in the watershed modeling report (Tetra Tech, 2012) and are not repeated here. However, temperature from Winston-Salem Reynolds Airport, located approximately 30 miles north-northeast of High Rock Lake, is not fully appropriate to conditions at the lake surface, particularly during hot summer weather when lake evaporation results in temperatures that are cooler than over land. This microclimate effect was approximated by a small reduction in summer air temperatures: specifically, summer temperatures greater than 22 degrees C were multiplied by a factor of 0.93, which was determined through model calibration.

Hourly dewpoint temperature, relative humidity, wind observations, and atmosphere pressure series were also reviewed for outliers, missing, or aggregated data and revised accordingly. The revisions were performed by either averaging a before and after value if a missing period were short, or by inserting a long-term average value.

Cloud cover was estimated from sky condition reports at Winston-Salem Reynolds Airport. Table 2-2 presents the assumptions used to estimate numerical cloud cover for model input from sky condition observations. The cloud cover parameter is used as input forcing to both the watershed and lake models as it affects long-wave back-radiation from water; it is also used in the calculation of incident surface solar radiation at the land/water surface.

Table 2-2. Numerical Interpretation of Sky Condition Observation

Description	Abbreviation	NWS Suggested Numerical Range (Eighths)	Numerical Assignment for Model Input (Tenths)
Clear Sky	CLR	0	0
Few	FEW	1 – 2	1.25
Scattered	SCT	3 – 4	4.38
Broken	BKN	5 – 7	7.5
Variable	VV	8	10
Overcast	OVC	8	10

An hourly solar radiation time series was also estimated at Winston-Salem Reynolds Airport station. The incident solar radiation calculation routine from CE-QUAL-W2 (Cole and Buchak, 1995) was used to develop the time series. The routine uses cloud cover, latitude, elevation, and date-time to perform the computations.

2.2.4 EFDC Watershed Boundary Forcing (Flow)

Gaged flows, rather than watershed model (HSPF) simulated flows, were used to drive the lake model during calibration and validation to minimize errors propagated from the watershed model. This was done because, while the watershed model has been shown to be, on average, unbiased and provides a good fit to observed flow in the Yadkin River at Yadkin College (less than 10 percent errors on total flow, high flows above the 90th percentile, and dry weather flows below the median) and other gaged tributaries (Tetra Tech, 2012), there are some discrepancies in the magnitude and timing of individual events. Given that dam operations most strongly influence retention time in the lake, using the gaged flows ensures the timing and magnitude of all inflow events are synchronized with records of dam releases.

The vast majority of inflows to High Rock Lake enter through the Yadkin River and South Yadkin River. Both of these are gaged, although adjustments are needed to account for additional drainage area between the Yadkin River gage and the lake. Abbotts Creek is also gaged. The remaining small tributaries that enter the lake are not gaged. These inflows were represented by scaling the gage record from nearby Second Creek.

The assignments of USGS stream gage records to the EFDC lateral grid, along with associated area adjustments, are shown in Table 2-3. Tributary inflows are assigned equally to all vertical layers present in the lake model at the inflow point. Because a hybrid grid is used and the model grid extends to the shallow edge of the lake, the inflow points typically contain only two layers in the lake model, so the problems associated with distributing inflows to all layers of a sigma grid are avoided.

A comparison of the use of gaged flow and the watershed model flow output was carried out to determine the impact of the boundary flow input used in the Lake Response model. Overall, the watershed model output and the lake model input based on area-weighted gage flows agree within 4 percent, which is within the error of the watershed model fit over the 2005-2010 lake model simulation period. For comparison, the calibrated and gaged flows for Yadkin River at Yadkin College differ by 8 percent. For all three of the partially gaged inputs (Yadkin River, South Yadkin River, and Abbotts Creek) the difference is less than 8 percent.

For the smaller ungaged tributaries, the true amount of flow cannot be known. The watershed model output and estimates extrapolated from other gages are within 15 percent for Grants, Swearing, and Flat Swamp Creek, and within 25 percent for South and North Potts Creek. Larger discrepancies are seen for Town/Crane (48 percent) and Second Creek (45 percent), for both of which extrapolation from the Second Creek gage leads to consistently higher flows than are predicted by the watershed model. These represent a small portion of the total drainage area (3.4 percent), and so have little impact on the overall flow balance. Both Town/Crane and Second Creek are simulated in the watershed model on the basis of precipitation records from Salisbury (317615), but the adequacy of the simulation of runoff responses in this part of the watershed model is not known because there are no flow gages. The series extrapolated from the gage records use the Second Creek flow gage, which will differ to some unknown extent from the actual flow response in Town/Crane and Dutch Second. Thus, actual error associated with flow estimates for these locations cannot be calculated.

Table 2-3. USGS Area Weighted Flow Forcing Assignments for EFDC

Name	Drainage Area (mi^2)	Percent of Total Drainage Area	EFDC Cell (I,J)	Referenced USGS Station(s)	Area Adjustment Factor
Yadkin River	2,456	63.2%	31-44	02116500 (Yadkin River at Yadkin College)	1.077261
South Yadkin River	908	23.4%	32-44	Sum of 02118000 (S. Yadkin River nr. Mocksville), 02118500 (Hunting Cr nr Harmony), and 02120780 (Second Cr nr Barber)	(02118000 * 1.737634) + (02118500 * 1.516574) + (02120780 * 1.19644)
Grants Creek	68	1.7%	36-44	02120780 (Second Creek near Barber)	0.574219
Swearing Creek	49	1.3%	63-63		0.417797
South and North Potts Creek	28	0.7%	46-47		0.239115
Town/Crane Creeks	77	2.0%	79-56		0.653377
Second Creek	54	1.4%	52-40		0.455641
Flat Swamp Creek	49	1.3%	85-08		0.412553
Abbotts Creek	196	5.0%	81-31	02121500 (Abbotts Creek at Lexington)	1.127530

2.2.5 EFDC Watershed Boundary Forcing (Temperature)

Regarding temperature inputs, the lake models also require continuous time series of water temperature, while only limited observed temperature data are available from the tributaries. The HSPF model watershed simulation was used to estimate water temperature of inflows to the EFDC and WASP lake model applications. The calibrated watershed model enables estimation of a continuous temperature input series based on physical principles that is consistent with the observed data.

2.2.6 POINT SOURCES AND WITHDRAWALS

A review of all NPDES permits for wastewater discharges in the High Rock Lake watershed is provided in the watershed model report, in which 177 dischargers were considered for model input. Five of these discharges go directly to the lake or the portion of the watershed covered by the lake model. All of the discharges and withdrawal were located in the upper portion of the lake, upstream of Swearing Creek. Table 2-4 shows the discharges and withdrawals included in the lake model. For each of these discharges, time series of flow and pollutant loads were developed using the same methods as were applied in the watershed model (Tetra Tech, 2012).

The Duke Energy Buck Steam Station has two outfalls and one withdrawal intake from High Rock Lake. Duke Power stated that the withdrawal of cooling water from High Rock Lake was approximately equal to the discharge back to the lake. The withdrawal rate was thus set equal to the cooling water discharge in the model.

Table 2-4. Point Source Discharges to and Withdrawals from High Rock Lake

NPDES ID	Name	Flow (MGD)	EFDC (I-J-K)
	Duke Energy Buck Steam Station Withdrawal	Average: 207	41-43-05
NC0004774-001	Duke Energy Buck Steam Station Cooling Water Discharge	Average: 207	42-43-05
NC0004774-002	Duke Energy Buck Steam Station Ash Pond Discharge	Average: 3.4	42-44-05
	Salisbury Withdrawal	Average: 7	*
NC0023884	Salisbury Rowan WWTP	Limit: 20	34-44-05
NC0029246-011	Norfolk Southern Linwood Yard	Limit: 0.32	47-47-05
NC0004626	PPG Industries Fiberglass	Limit: 0.6	47-48-05

* The Salisbury withdrawal is located in EFDC cell 32-44-04, the same location as the upstream extent of the model at the point of discharge of the South Yadkin River. To simplify model boundary conditions, the Salisbury withdrawal is subtracted from the Salisbury discharge slightly downstream at cell 34-44-05.

2.2.7 ONSITE WASTEWATER SYSTEMS

Nutrient loads derived from onsite wastewater systems located near the edge of the lake were represented using the same assumptions as was done in the watershed model (see Section 3.7 in Tetra Tech, 2012). This representation, worked out in conjunction with staff from the North Carolina Department of Public Health Onsite Water Protection Branch (NCDPH OWPB) represents loads of various strengths associated with surface failing systems, direct pipe systems, direct pipe discharges of gray water, surface discharge of gray water, and nonfailing systems located within 61 meters (200 feet) from the edge of the waterbody. Properly operating systems more than 61 m from a waterbody are assumed to provide no load in excess of background. Other types of systems are assigned the concentrations shown in Table 3-16 of Tetra Tech (2012) and an effluent flow rate of 68.6 gal/person/d.

Populations using onsite wastewater disposal are estimated by intersecting the 2000 census blocks and areas outside public sewer service boundaries.

The vast majority of onsite wastewater systems in the High Rock Lake watershed are accounted for in the watershed model. Those not accounted for in the watershed model are associated with watershed stream reaches 1, 4, 6, 128, and 130 – the nominal reaches that provide linkage through the lake surface. Onsite systems in these areas are estimated to serve 19,213 people, with systems serving 2,128 people within 61 m of the lake.

These systems were aggregated into three groups for representation in the model and assigned to three locations in the upper, middle, and lower portion of High Rock Lake at the following grid cell locations (I,J,K):

- Upper lake near Potts Creek – (46,44,05)
- Middle High Rock Lake – (37, 44, 05)
- High Rock Lake forebay – (65, 12, 05)

Together, these systems are estimated by the approach described in Tetra Tech (2012) to contribute 7.0 kg/d of NH_4-N, 9.0 kg/d of NO_3-N, 2.5 kg/d of PO_4-P, and 98.7 kg/d of CBOD.

2.2.8 Dam Operation and Outflow

APGI (2002) describes High Rock Dam as 936 feet long, with a maximum height of 101feet. The dam has a gate-controlled spillway with an integral powerhouse intake. The dam is currently operated in a store and release mode according to an operational rule curve established in 1968. The rule curve is written in terms of power generation as a function of elevation, and generally maintains higher lake levels from mid-May to mid-September. The pool is drawn down in the fall, and then refilled during winter rains. The annual maximum drawdown averages 12 feet in winter and 5 feet in summer. The normal daily fluctuation in water level is 1 foot, with a maximum daily fluctuation of 2 to 4 feet.

Water is discharged from the lake via hydropower turbines and the gated spillway. Turbine flow is controlled by wicket gates on the units. Spillway discharge occurs through a 550-foot long spillway. The spillway gates are vertical lift or underflow gates with an invert at elevation 593.9 feet (National Geodetic Vertical Datum (NGVD) 29). The primary outflow of the lake is through the turbines to generate power. The intake for the turbines is subsurface. As needed during infrequent high flow events, excess water is released over the dam spillway gates in accordance with a gate operating procedure. The procedure specifies that gates are opened on increasing inflow to maintain headwater at or near full pond until gates are full open at approximately 290,000 cfs. Hourly estimates of flow through the turbines and spillway gates were provided by APGI as well as the description of when the spillway gates were used. These data were aggregated to daily values for use in the model and assigned as time series to the subsurface model layers representing the turbines and the spillway.

Because the EFDC model uses a sigma vertical grid, the depth associated with individual layers stretches or shrinks with water surface elevation and layers do not correspond to fixed elevations. Further, the spatial scale of the whole lake model is such that the model represents the average depth of the forebay, rather than the maximum depth immediately adjacent to the turbine intake. There are two lateral model grid cells representing the forebay at High Rock Dam. One was used to represent the spillway flow and the other was used for discharge through the turbines. The turbine outflow is evenly divided between EFDC vertical layers 2 and 3 of 5 (counting from the bottom), while the underflow gate entrance to the spillway is placed in vertical layer 3, in agreement with APGI's analysis.

2.3 WASP Model Configuration

2.3.1 Linkage to Hydrodynamic Model

The WASP water quality model application is built on the EFDC hydrodynamic model using linkage features built into EFDC. EFDC is used to write a binary "hyd" file, which is read by WASP to establish time series of segment volumes and fluxes. The EFDC grid cells and WASP model segments are thus identical, although the two models use different numbering schemes.

2.3.2 Linkage to Watershed Model

As noted above, the calibrated hydrodynamic model uses the USGS gage scaling method using measured flow rather than watershed model simulated tributary flows for the Yadkin River and other key inputs. In contrast, watershed model simulated pollutant concentrations are used to drive the lake water quality model. The combination of observed flows and simulated loads has the potential to introduce timing discrepancies. For instance, an unreasonably high concentration transient might be simulated in the lake model if the timing was off between gaged flows and simulated loads, such that the simulated load arrived prior to the gaged flow. To protect against this issue, water quality constituents are linked to the WASP model as concentration boundary conditions on inflows rather than being directly specified as loading time series. Specifically, daily flow-weighted concentrations are specified, calculated as the total simulated load from the watershed model divided by the total simulated flow for each day. The WASP model then provides a smoothed, linear interpolation between concentrations specified at the midpoint of each day.

The connection of water quality constituents is relatively straightforward, but must take into account some differences between the models in the representation of state variables:

- HSPF simulates three sediment size classes (sand, silt, and clay), while, due to resource limitations, the High Rock Lake WASP model simulates a single sediment variable. This presents some problems as heavier sediment fractions progressively settle out after flow from streams and rivers enters the lake. Observed concentrations of inorganic solids in the lake appear to be greater than the tributary concentrations of clay alone, but less than the sum of silt plus clay as simulated in the watershed model. As a compromise, the single inorganic solids state variable in WASP was represented as 85 percent of the sum of silt and clay concentrations predicted by the watershed model.

  This presents some uncertainty with regards to using the model to evaluate the turbidity impairment within High Rock Lake, a concern shared by the TAC during draft model review. As a result, DWR will only apply the High Rock Lake WASP model to address the chlorophyll *a* impairment at this time.

- HSPF simulates the sorption of ammonium and orthophosphate to three separate size classes of sediment, while WASP simulates these constituents as a whole, with user-specified dissolved fraction (see Section 2.3.5 for the specification in WASP).
- HSPF simulates labile organic nutrients by ratio to CBODu, whereas WASP represents organic nutrients as state variables. HSPF simulates dead refractory organic nutrients separately, while WASP has state variables for organic N and organic P. In addition, the fraction that is practically considered as refractory in the short-residence time of transport through the stream network can ultimately break down after longer residence in the lake. Accordingly, the concentrations of organic nutrients in WASP represent the sum of the "refractory" organic component simulated

by HSPF plus the labile fraction represented by the stoichiometric relationship to CBODu (see Tetra Tech, 2012).

- HSPF simulates one algal group, while WASP represents two algal groups: warm-water algae and cold-water algae. As discussed below in section 2.3.7, bluegreens dominate (at or above 75% in unit density) during warm seasons, while diatoms and green algae are the main algal groups during winter and spring. Ideally, the percentage of individual algal groups at lake boundaries should be a function of time or water temperature, but time-varying ratio for algae partition is not practical in WASP. A constant partition ratio of 75% (algal group 1) and 25% (algal group 2) was assumed for boundary conditions to account for higher algal growth rate during warm seasons. Model sensitivity test runs show that the model simulated total algae was not sensitive to the partition of algal groups at the lake boundaries.

The resulting connections between HSPF and WASP state variables are summarized in Table 2-5.

Table 2-5. Connection of Water Quality State Variables between HSPF and WASP

<table>
<tr><th>HSPF</th><th>WASP (version 7.52)</th></tr>
<tr><td rowspan="2">Chlorophyll a</td><td>Algal group 1 Chlorophyll a</td></tr>
<tr><td>Algal group 2 Chlorophyll a</td></tr>
<tr><td>DO</td><td>DO</td></tr>
<tr><td>Dissolved Nitrate N</td><td>Nitrate N</td></tr>
<tr><td>Dissolved Ammonium N</td><td rowspan="2">Ammonium N</td></tr>
<tr><td>Sorbed Ammonium N (on sand, silt, clay)</td></tr>
<tr><td>Refractory Organic N</td><td rowspan="2">Organic N</td></tr>
<tr><td rowspan="3">CBODu</td></tr>
<tr><td>CBODu</td></tr>
<tr><td rowspan="2">Organic P</td></tr>
<tr><td>Refractory Organic P</td></tr>
<tr><td>Sorbed Ortho P</td><td rowspan="2">Ortho P</td></tr>
<tr><td>Dissolved Ortho P</td></tr>
<tr><td>Silt</td><td rowspan="2">Inorganic Solids</td></tr>
<tr><td>Clay</td></tr>
</table>

2.3.3 Point Source Loading

Water quality loading time series were developed for each of the point source discharges to the lake listed above in Table 2-4. The approach to processing the point source effluent data into load estimates for model input is described in Section 3.6 of the watershed model report (Tetra Tech, 2012).

The flow records were typically the most complete. Gaps were addressed 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 a gap.

For both the watershed and lake model applications, point source inputs were developed for the following water quality parameters.

- NH_3, ammonia as N
- NOx, nitrite+nitrate as N
- OrgN, organic nitrogen as N
- PO_4, orthophosphate as P
- OrgP, organic phosphorus as P
- CBODu, carbonaceous biochemical oxygen demand, ultimate
- DO, dissolved oxygen
- Water temperature

2.3.4 Direct Atmospheric Deposition

Atmospheric deposition can be a significant source of inorganic nitrogen loading to open water surfaces. WASP represents the atmospheric deposition of total inorganic nitrogen as constant areal loading rates of nitrate N and ammonium N, representing the sum of wet and dry deposition.

Wet deposition flux estimates for nitrate and ammonium were obtained through 2010 from the National Atmospheric Deposition Program (NADP) National Trends Network (NTN) (http://nadp.sws.uiuc.edu/) from Piedmont Research Station (NC34), located within the High Rock watershed. Seasonal dry deposition data were obtained through 2009 from the Clean Air Status and Trends Network (CASTNET) (http://java.epa.gov/castnet/) for station Candor, NC (CND125), located about 30 miles south of the High Rock watershed. Both were converted to mass loading rates as N.

The dry deposition rates show a decreasing trend due to air emission controls, while wet deposition rates vary with changes in annual precipitation. The 2008 – 2009 average deposition rates were 0.802 $mg/m^2/d$ of oxidized N (HNO_3-N and NO_3-N) and 0.927 $mg/m^2/d$ of reduced N (ammonium nitrogen). Averages for 2000 – 2009 are slightly higher for the oxidized fraction (1.01 $mg/m^2/d$) and lower for the reduced fraction (0.840 $mg/m^2/d$). Oxidized N deposition rate of 0.802 $mg/m^2/d$ and reduced N deposition rate of 0.927 $mg/m^2/d$ were used in the model.

The assigned deposition rates were checked against rates calculated from EPA's Watershed Deposition Tool (WDT; Schwede et al., 2009). The WDT summarizes deposition rates from EPA/NOAA's regional-scale, multi-pollutant Community Multiscale Air Quality Model (CMAQ) and is intended to provide deposition estimates for TMDLs.

The WDT contains output from CMAQ runs for 2002 through 2006. The 2006 run predicts fluxes of oxidized nitrogen (HNO_3-N and NO_3-N) and reduced nitrogen (ammonium nitrogen) over the area of High Rock Lake of 1.93 and 0.96 $mg/m^2/d$, respectively. The reduced nitrogen load rates are in general agreement with the estimates from CASTNET and NADP monitoring, but the oxidized nitrogen estimates are higher.

2.3.5 Representation of Sorbed and Dissolved Nutrient Fractions

The WASP model distinguishes between sorbed and dissolved forms of nutrients. This is an important distinction as it is the dissolved fractions that are bioavailable, while the sorbed fractions are subject to settling and deposition. This application uses specified dissolved fractions, primarily because the WASP model does not represent progressive fining of sediments as inflows proceed into the lake. Instead, sorption of nutrients (ammonium, orthophosphate, and organic nutrients) was represented by assigning progressively larger dissolved fractions away from inflow points during model calibration. Values were set to be generally consistent with the ratio of dissolved to total nutrient concentrations observed from in-lake monitoring data. For example, the observed mean dissolved fraction of total phosphorus increases from 50 percent at HRL051, the most upstream mainstem station, to 63 percent at YAD169F, at the dam forebay.

In general, lower dissolved nutrient fractions were appropriate at the upstream ends of coves where nutrients are more likely to be associated with larger organic detritus that is more prone to settling. The typical values of dissolved nutrient fractions for the lake model is shown below in Table 2-6.

Table 2-6. Typical values of Dissolved Nutrient Fractions for the Lake Model

	HRL near Forebay	Upstream Cove Arms
Nitrate N	100%	97%
Organic N	85%	60%
Ortho P	60%	50%
Organic P	60%	50%

2.3.6 Lake Sediment Fluxes

Exchanges with lake-bottom (benthic) sediments are potentially important to the balance of constituents in the water column. Flux out of the sediment is typically important under reducing, hypoxic conditions. These exchanges are difficult to measure, requiring deployment of specialized chambers, and likely to show significant spatial heterogeneity. The limited available data were used to initialize the model.

Benthic exchange sampling occurred at two lake locations, once each, during the scoping monitoring: at a middle lake station (YAD152C) located near the confluence of Town/Crane Creek with the mainstem on May 25, 2005, and at the lower station (YAD169A) in Abbotts Creek arm on June 01, 2005. Five parameters were reported from each sampling event: ammonia nitrogen, nitrite+nitrate nitrogen, total Kjeldahl nitrogen, total phosphorus, and sediment oxygen demand. The sampling indicated a small, but net positive contribution from the sediment to the water column for ammonia, total Kjeldahl nitrogen, and total phosphorus at each station. The gain in reduced forms of nitrogen was offset by a loss of nitrite+nitrate nitrogen and oxygen from the water column. On average, ammonia constituted about 85 percent of the total Kjeldahl nitrogen, with the remainder present as organic nitrogen (Table 2-7).

Table 2-7. Nutrient Sediment Flux Data

Nutrient Sediment Flux	YAD152C May 25, 2005	YAD169A June 01, 2005	Average
Ammonia (g-N/m^2/d)	0.091	0.019	0.055
Nitrite+Nitrate (g-N/m^2/d)	-0.059	-0.010	-0.035
Total Kjeldahl Nitrogen (g-N/m^2/d)	0.112	0.016	0.064
Total Phosphorus (g-P/m^2/d)	0.017	0.001	0.009
Sediment Oxygen Demand (g-O_2/m^2/d)	-1.994	-1.195	-1.595

Note: Reported ammonia greater than Total Kjeldahl Nitrogen on 6/1/05 is apparently an artifact of method precision

There is considerable variability between the two sampling events. The WASP 7.52 model allows the user to prescribe benthic flux values for ammonia, orthophosphate, and sediment oxygen demand. The average measured flux rates were selected as initial values for the model application and applied to all lake bottom segments. The net total phosphorus benthic flux observation was assumed to be as orthophosphate. These initial values were adjusted in the calibration process. Specifically, the observed average phosphorus benthic flux was assumed to apply only from April 1 through October 31 (the period in which bottom hypoxia is most likely). The average measured ammonia flux was applied from April 1 through October 31 and was reduced to 60 percent during other days.

2.3.7 Algal Community Data

Algal community information was developed by DWQ from composite, photic-zone water samples collected monthly at four sites in High Rock Lake during the intensive monitoring study (April 2008 to March 2010). The sites are noted in Table 2-8 and the locations can be seen in Figure 1-3. Algal community information included algal group, cell density (cells/ml), unit density (units/ml), and biovolume (mm^3/m^3).

Cyanobacteria (commonly referred to as blue-green algae) are typically the dominant algal community group in terms of unit density (as well as biovolume, not shown) during the period from July to October, as shown below in Figure 2-6. Diatoms and greens are more active in the winter period and the early growing season period. A natural break-out of the algal groups contains:

- Warm-water algae which are dominated by blue-greens (cyanobacteria)
- Cold-water algae which are dominated by diatoms (bacillariophytes) and greens (chlorophyta)

As a result, the model is set-up to represent two groups as described above. Algal growth parameters and temperature, light, and nutrient requirements are likely to differ for the warm-water blue-green algae and the cold-water eukaryotic algae such as diatoms. In addition, blue-green algae often have a lower chlorophyll *a* to biovolume ratio than do diatoms and other algal groups. Information about model parameters used for the two algal groups is provided under section 3.3.2.

Table 2-8. Algal Community Data Monitoring Stations

Station ID	Name	Description
HRL052	Abbotts Creek arm	Upper portion of Abbotts Creek arm near Holloway Church Road
YAD1561A	Second Creek arm	Near Bringle Ferry Road
YAD152C	Middle HRL	Middle lake, downstream of Town/Crane Creek and upstream of Second Creek
YAD169B	Lower HRL	Lower lake, downstream of Abbots Creek and upstream of the forebay

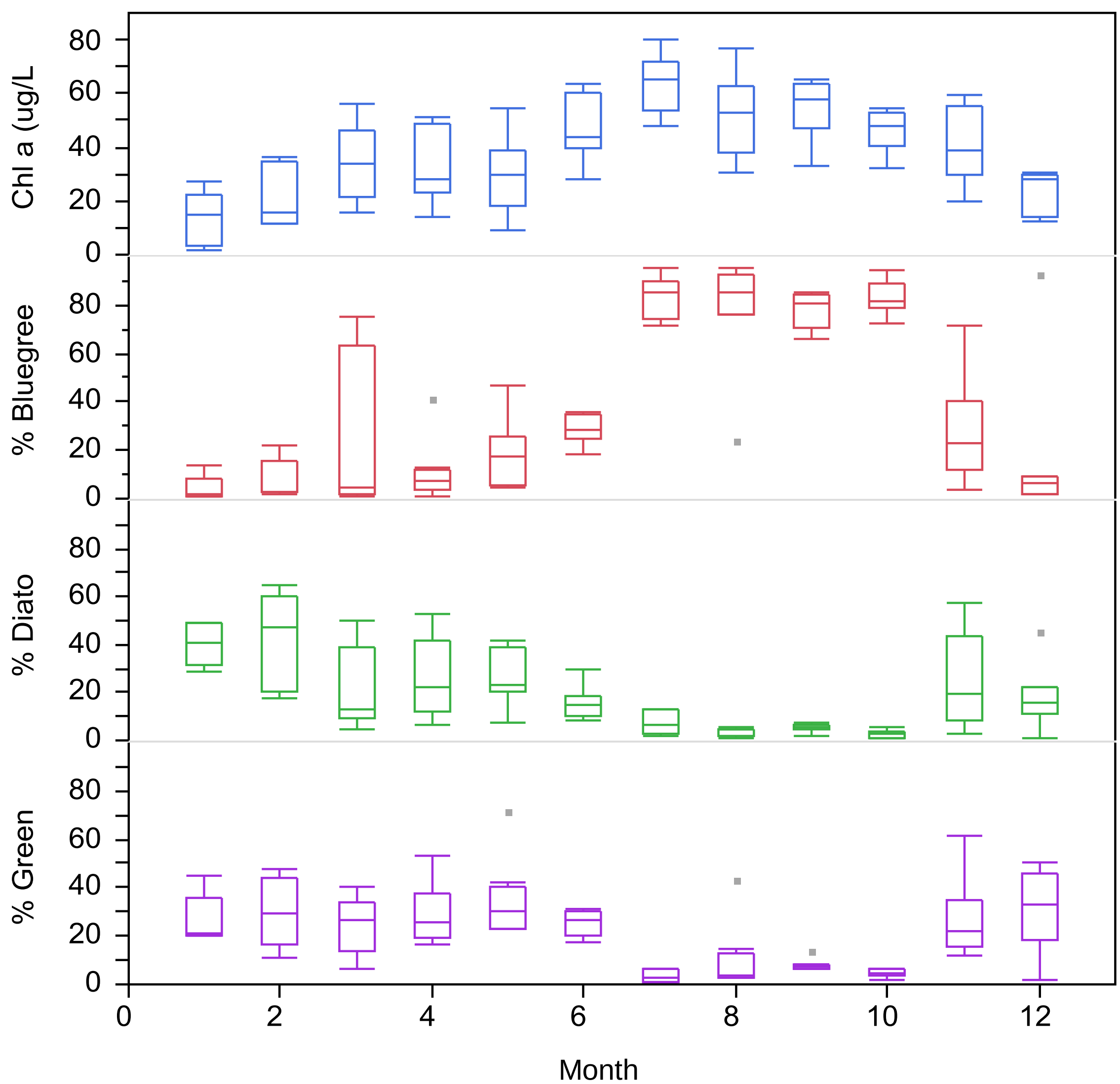

Figure 2-6. Box plots of observed Chlorophyll *a* concentrations and percent unit density of blue-green algae, diatoms, and green algae in different months. Data are combined from Stations HRL052, YAD1651A, YAD152C and YAD169B.

2.3.8 LIGHT EXTINCTION DATA

Algal growth is principally governed by temperature, nutrients, and the availability of light to drive production. As described in the WASP manual, frameworks developed by Di Toro et al. (1971) and Smith (1980), and rooted in formulations by Steele (1962), account for the effects of light availability and attenuation of light through the water column.

Light attenuation or extinction with depth in water is described by the Beer-Lambert equation:

$$I_z = I_0 * e^{-kz}$$

where k is the light extinction coefficient, I_z is the light intensity at depth z, and I_0 is light intensity just below the water surface. The extinction coefficient, k, is a result of suspended solids (including inorganic sediment, detritus, and algae), dissolved material, and the optical properties of water.

Light extinction coefficients were calculated for High Rock Lake using both direct photosynthetically active radiation (PAR) measurements in µmol/m^2/s and more numerous observations of Secchi depths. PAR was measured at four stations during the intensive monitoring study. Secchi depth was collected across 2005 through 2010 and at a greater number of stations.

Light extinction coefficients developed from PAR were calculated using the slope method by taking the natural log of the Beer-Lambert equation and rearranging it into a linear form that solves for slope (Kirk, 1994). Values range from 1.2 to 5.9 m^{-1}. The overall average was 2.2 m^{-1} with a decreasing trend from uplake to downlake (Table 2-9).

Table 2-9. PAR-Based Light Extinction Coefficients (k) in High Rock Lake

Station	Average	Count
HRL052	2.34	32
YAD152C	2.49	30
YAD1561A	2.24	32
YAD169B	1.89	32
Grand Total	2.23	126

In the absence of measured PAR, Secchi depth can be used to approximate light extinction (k). An often-cited relationship to approximate k from Secchi depth (Z_{sd}, m) is k=1.7/Z_{sd} (Wetzel, 2001). However this relationship does not hold up well in High Rock Lake upon comparison of paired values based Secchi depth and PAR-based k. Instead, a power relationship was fit (Figure 2-7). Using this relationship, k values were calculated from Secchi data collected at 12 stations from 2005 through March 2010 (Table 2-10). The results are summarized in Table 2-11.

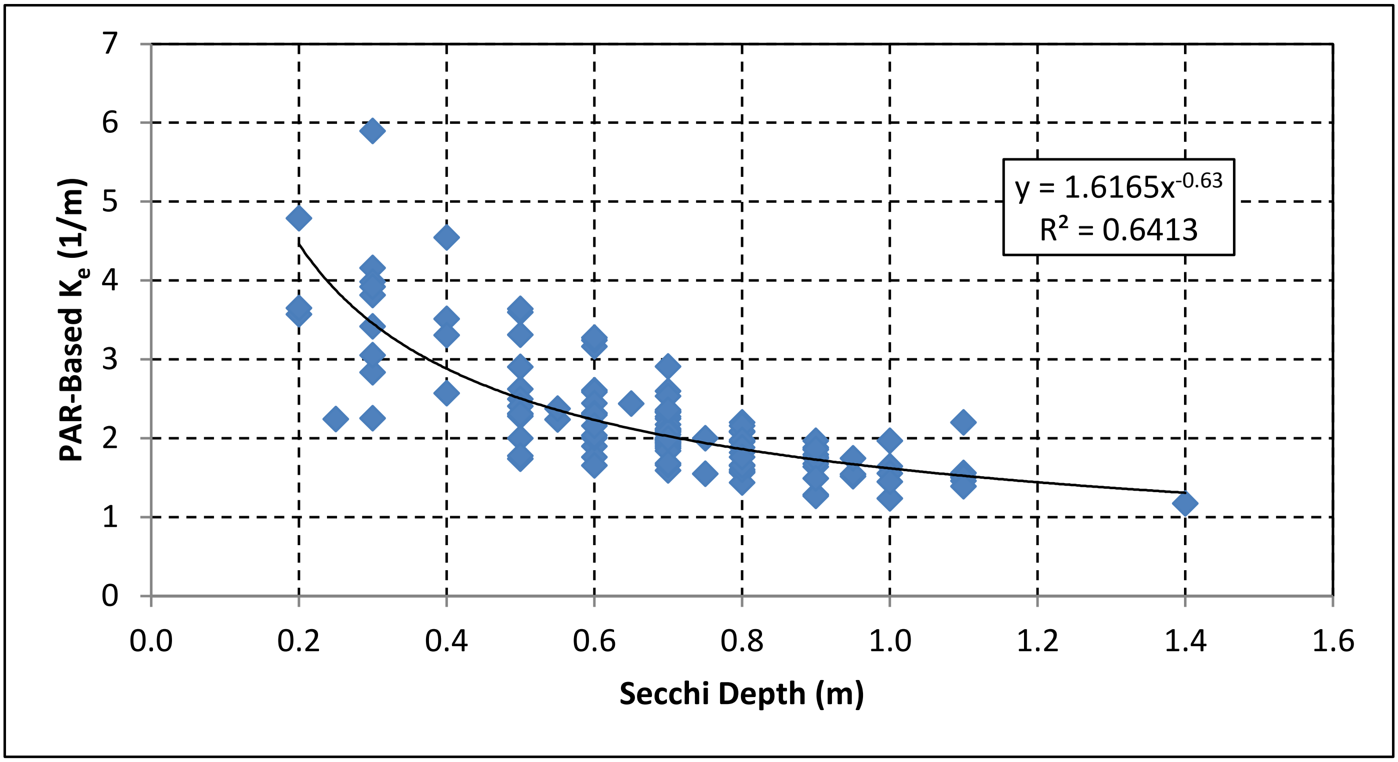

Figure 2-7. Relationship of Extinction Coefficient Calculated from PAR to Secchi Depth

Table 2-10. Observed Secchi Depths (m) in High Rock Lake

Station	Average	Count	Min	Max
HRL051	0.47	61	0.1	4
HRL052	0.70	58	0.2	1.4
YAD1391A	0.40	10	0.1	0.5
YAD152	0.63	53	0.2	1.35
YAD152A	0.54	62	0.1	0.9
YAD152C	0.61	60	0.1	1
YAD1561A	0.71	52	0.3	1.4
YAD156A	0.63	17	0.2	1
YAD169A	0.76	61	0.2	1.2
YAD169B	0.77	62	0.2	1.23
YAD169E	0.88	62	0.2	1.35
YAD169F	0.88	62	0.2	1.4
Grand Total	0.69	620	0.1	4

Table 2-11. Light Extinction Coefficients (k, 1/m) Derived from Secchi Depths

Station	Average	Count	Min	Max
HRL051	3.08	61	0.67	6.90
HRL052	2.18	58	1.31	4.46
YAD1391A	3.19	10	2.50	6.90
YAD152	2.28	53	1.34	4.46
YAD152A	2.63	62	1.73	6.90
YAD152C	2.43	60	1.62	6.90
YAD1561A	2.09	52	1.31	3.45
YAD156A	2.31	17	1.62	4.46
YAD169A	2.04	61	1.44	4.46
YAD169B	2.05	62	1.42	4.46
YAD169E	1.87	62	1.34	4.46
YAD169F	1.89	62	1.31	4.46
Grand Total	**2.27**	**620**	**0.67**	**6.90**

Observed light extinction is a function of inorganic and organic suspended solids concentration, algal concentration, and dissolved organic compounds. Because the WASP simulation of suspended sediment (which addresses only a single particle size class) does not provide an accurate representation of the spatial gradient in light extinction due to suspended inorganic solids under variable hydrologic conditions, the background light extinction function was used to represent the typical light extinction within different areas of the lake, with incremental contributions from simulated inorganic solids and chlorophyll *a* concentrations. Specifically, the background light extinction rate was set equal to the observed light extinction after backing out contributions from algae and suspended inorganic sediment as simulated by the model. The model output was checked to ensure that simulated light extinction time series were consistent with the range obtained from observed Secchi depth and PAR measurements.

3 Model Calibration/Validation

Calibration consists of the process of adjusting model parameters to provide a match between model-simulated values and 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 evaluate the uncertainty associated with the calibration, the model is subjected to a validation step. In the validation step, the model is applied to a set of data different from those used in calibration.

High Rock Lake presents an inherently difficult case for calibration because residence time is relatively short, ranging from 4 to 50 days (APGI, 2006b). As a result, conditions within the lake are strongly affected by boundary conditions (loads from the watershed), which are imprecisely known, and less determined by in-lake reaction parameters that are typically adjusted during calibration.

Calibration of the lake model focused on the 2008 – 2010 time period. Validation used earlier data collected in 2005-2006 (see Section 1.3). The cell numbers used for calibration and validation for EFDC and WASP are provided in Appendix A. The EFDC model was calibrated and validated to water surface elevations and lake temperature profiles. The WASP water quality model was then calibrated/ validated at all ten observation stations sampled during the 2008 – 2010 monitoring, including stations on the main axis of the lake and in arms of the lake (see Table 1-3 above). The water quality calibration focused on chlorophyll *a*, nutrients (totals and individual species), dissolved oxygen, and total suspended solids.

3.1 Calibration Process and Acceptance Criteria

Model calibration proceeded sequentially, beginning with EFDC hydrodynamics and ending with WASP water quality. The hydrodynamic calibration focused on reproducing observed water surface elevations and the vertical distribution of temperature, as dye studies and velocity measurements were not available. The general strategy for the calibration of the two models involves repeated iterations and feedback to achieve acceptable representation of all components. The calibration sequence is summarized in Figure 3-1, including potential feedback loops.

EFDC	Water Balance
	Water Surface Elevation
	Thermal Profile
WASP	Suspended Solids
	Nutrient Balance
	Algae and Eutrophication

Figure 3-1. Lake Model Calibration Sequence

Hydrodynamic and water quality models are often evaluated through visual comparisons, which plot the simulated result against observed data for the same location and time, and visually judge if the model is able to mimic the trend and overall magnitude of the observed condition. If the model predicted results follow the general trend and reproduce the overall magnitude of the observed data, the model is said to represent the dynamics of the system well. The limitation of this method is that it relies on the subjective judgment of modelers, and lacks quantitative measures to differentiate among sets of calibration results.

An alternative approach aimed at overcoming the limitations of the visual comparison method is to quantify the goodness of fit using a series of statistical measures. Ideally, if there is a large amount of data and most of the data are accurate, a quantitative approach can be very reliable in judging a model's performance. However, in reality, the amount of water quality data is generally limited and the available data often contains errors and uncertainties. Therefore, the validity of the quantitative statistical method is often compromised by uncertainties in the observed data (Zou and Lung, 2004). Also, the statistical method is further compromised because the comparison is between a water sample collected from one point to an entire cell. Cells range in size from 5 to 221 acres with a median value of 19 acres. Finally, there is no widely accepted target range of error statistics defined for water quality predictions in lake models.

In this study, a two-stage approach is adopted to guide the calibration of the lake models. In the first stage, the model calibration is guided by the visual comparison approach, which allows the calibration effort to focus on reproducing the trend and overall dynamics of the lake. The first stage is a global search process for a water quality calibration which prevents a calibration from being trapped at suboptimal solutions associated with a local maximum for model fit statistics but incorrect overall representations. After the model has been calibrated to the trend and overall dynamics, the second stage involves fine tuning the parameters and then calculating various error statistics in order to find the most appropriate calibration within the range of state spaces that were found in stage one. The second stage is thus a local search process for a water quality calibration. Constrained by the stage-one global search, the error statistics can be interpreted together with the general fit to trend and magnitude. After the model is calibrated, it is applied to the validation period to further evaluate the degree of generalization of the model.

While quantitative performance targets for reservoir simulation models are not well established in the literature, a model needs to be reliable enough to provide appropriate and pertinent insights into potential management strategies. For example, the model needs to be able to provide insights into the degree to which reductions in a source of watershed nutrient loads will provide improvements in lake water quality. Ideally, the models should attain tight calibration to observed data; however, a less precise calibration can still provide useful information for management decisions.

In light of these uses of the models, it is most informative to specify performance target ranges in a qualitative manner. These characterizations inform appropriate uses of the model. Where a model achieves a good fit it can assume a strong role in evaluating management options. Conversely, where a model achieves only a fair or poor fit it should assume a much less prominent role in the overall weight-of-evidence evaluation of management options.

While there are not widely accepted quantitative measures of "good" model fit specific to reservoir models, EPA (1990) has provided guidance on error statistics for calibrating estuarine water quality models, which are similar in many respects. The general guidance for a "good" fit for such estuarine models is summarized by the calibration targets shown in Table 3-1. Similar targets are appropriate for reservoir models, except that chlorophyll *a* concentrations are likely to be even more variable in reservoirs than in estuaries. Based on past experience with Piedmont reservoirs, a chlorophyll *a* relative error target of ±25 percent is suggested as an indicator of good model fit. Validation results will typically be somewhat less precise.

Models should be deemed fully acceptable when they achieve a "good" level of fit. In the event that this level of quality cannot be achieved on some or all measures the model may still be useful; however, a detailed description of the models potential range of applicability should be provided.

Table 3-1. Reference Calibration Guidelines for "Good" Model Fit in Estuaries[1]

	Hydrodynamic	Chemical Water Quality	Chlorophyll *a*
Relative Error (RE)	±30%	±45%	±16% (±25%)[2]
Coefficient of Variation (CV)	≤10%	≤90%	≤70%
Correlation Coefficient (r)	≥0.94	≥0.60	≥0.70

1. From EPA, 1990
2. For chlorophyll *a* the target of ±25% is suggested for High Rock Lake; ±16% is suggested in the estuarine guidance.

In addition to these recommendations, the Root Mean Square Error (RMSE) and Relative Absolute Error (RAE) are also calculated and reported. The statistics are calculated as follows:

$$RE = \frac{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)}{\overline{O}},$$

$$RAE = \frac{\frac{1}{n}\sum_{i=1}^{n}\left|S_i - O_i\right|}{\overline{O}},$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2},$$

$$CV = \frac{RMSE}{\overline{O}},$$

$$r = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{S_i - \overline{S}}{\sqrt{\frac{1}{n}\left(S_i - \overline{S}\right)^2}}\right)\left(\frac{O_i - \overline{O}}{\sqrt{\frac{1}{n}\left(O_i - \overline{O}\right)^2}}\right)$$

In these equations, *S* is a simulated value, *O* is an observed value, *n* is the count of simulated-observed pairs, and the overbar indicates the mean.

3.2 Hydrodynamic Calibration and Validation (EFDC)

The EFDC hydrodynamic model simulates the three-dimensional movement and mixing of water within High Rock Lake. Direct measurements of hydrodynamic details such as water velocities or dye studies are not available. Therefore, the EFDC calibration must rely on reproducing the general water balance and water surface elevation (both measures of hydrology rather than hydrodynamics) and reproducing the net impacts of water movement. The latter calibration target is addressed primarily through model fit to the observed water temperature vertical and spatial gradients in High Rock Lake, but was also revisited in light of chemical concentration distributions in the lake. In essence, it is necessary to have an accurate representation of the movement and mixing of water (hydrodynamics) in order to reproduce observed water temperature profiles.

3.2.1 WATER BALANCE AND FLOW CORRECTION

Application of the lake model with specified inflows and outflows begins with an evaluation of the water mass balance. Conservation of mass requires change in storage must equal inputs minus outputs. Inputs include stream flow, point source discharge, direct precipitation, and groundwater inflow, while outputs include releases at the dam, evaporation, withdrawals, and losses to groundwater, including underflow at the dam. The various components of the hydrologic balance are known with differing degrees of certainty. On the input side, stream flow is continuously measured for major gaged tributaries (although the gage records themselves depend on converting measured depth to flow using rating curves, which can change between recalibration efforts due to shifting sand deposits in a river), but is more uncertain for extrapolation to ungaged tributaries. Direct precipitation is measured, and, while total amounts integrated across the lake surface may differ from point measurements, is unlikely to contribute significantly to mass balance errors. Direct groundwater inflow is not measured or known; however, the contribution is expected to be relatively small because (1) regional groundwater flow systems are of limited extent in the Piedmont, and (2) the watershed model is fit without a significant component of "deep" groundwater losses that do not show up at stream gages.

On the output side, APGI has provided time series of dam releases. However, these may be incomplete as they do not account for potential seepage around the dam. Losses from the lake to groundwater and potential underflow at the dam are not measured and unknown.

The observed stream flow records are not all located at the pour points of tributaries to the lake. Therefore uncertainty is introduced by the incremental drainage area joining the gaged area to the lake input location. Point source discharge flow rates were represented on a daily basis, however domestic wastewater treatment plants typically have sub-daily variability based on morning and evening use patterns. The dam outflow occurs through turbines and spillway overflow. The dam outflow data were provided on an hourly basis but required processing to separate the turbine and spillway components. There is uncertainty in the rating curve used for the turbines as it changes across the life of the turbines through use. Collectively, these uncertainties and others make it necessary to provide some flow correction to the model application in order to achieve water mass balance in the lake.

Given all these factors, there is a fair amount of uncertainty in the overall water mass balance for the lake. To compensate for this a flow correction was used, in which additional distributed gains or losses of water are assigned to the lake to ensure that an overall mass balance is attained and a reasonable simulation of water surface elevations (Section 3.2.2) is achieved.

The preliminary runs of the High Rock Lake EFDC model indicated that the inflow estimates (as described in Section 2.2.4) exceeded the reported outflows and thus the simulated water surface elevation continued to rise across the simulation period. This likely occurs due to a combination of net seepage losses from the lake, uncertainty in the estimation of spillway discharge based on head and gate opening, uncertainty in the extrapolation of gaged flows to ungaged areas, and uncertainty in the estimated releases through the turbines due to gradual declines in turbine efficiency over time. For the period from 1/1/2005 through 4/1/2010, the estimated average unaccounted outflow appears to be about 14 cubic meters per second (cms), with some variability over time and with season. A two stage iterative approach was developed to incorporate a flow correction in the model. In the first stage, model-simulated water surface elevation was compared to the observed water surface elevation and the difference was used to calculate a daily flow discrepancy. These daily terms are both positive (representing an apparent need for additional inflow) and negative (representing additional outflow). In many cases, large negative discrepancies immediately follow large positive discrepancies, indicating small errors in timing. The longer term trends in flow mass balance need to be filtered out of these short-term timing errors. This was accomplished in the second stage by fitting a LOESS curve (locally weighted scatterplot smoothing; Cleveland and Devlin, 1988) to the daily disturbance terms, using an alpha value of 0.1. The LOESS approach fits a least-squares solution to local subsets of the data, and thus captures both the overall magnitude and localized trends in the data. The resulting daily flow correction term varies gradually from -1.93 to -23.29 cms and enforces approximate consistency between observed and simulated water surface elevations without imposing sudden shocks on the system (Figure 3-2).

The flow correction was applied as an additional outflow located at the dam forebay. The average flow correction value is equivalent to about 15 percent of the reported dam outflow. APGI in draft model review comments suggested that their calculations indicate that the turbine efficiency issue accounts for a flow correction on the order of 5 – 6 percent. Examination of individual daily discrepancies in WSE prediction without flow correction indicates that the magnitude of the average required correction is greatest in the high flow years of 2005 and 2009 and smallest in the low flow year of 2008, suggesting that a significant part of the needed flow correction may be associated with the extrapolation of gaged flows and/or the estimation of flow from the gated spillway, which accounts for a larger proportion of releases in wet years. Given these various sources of uncertainty, the magnitude of the proposed flow correction is believed to be reasonable.

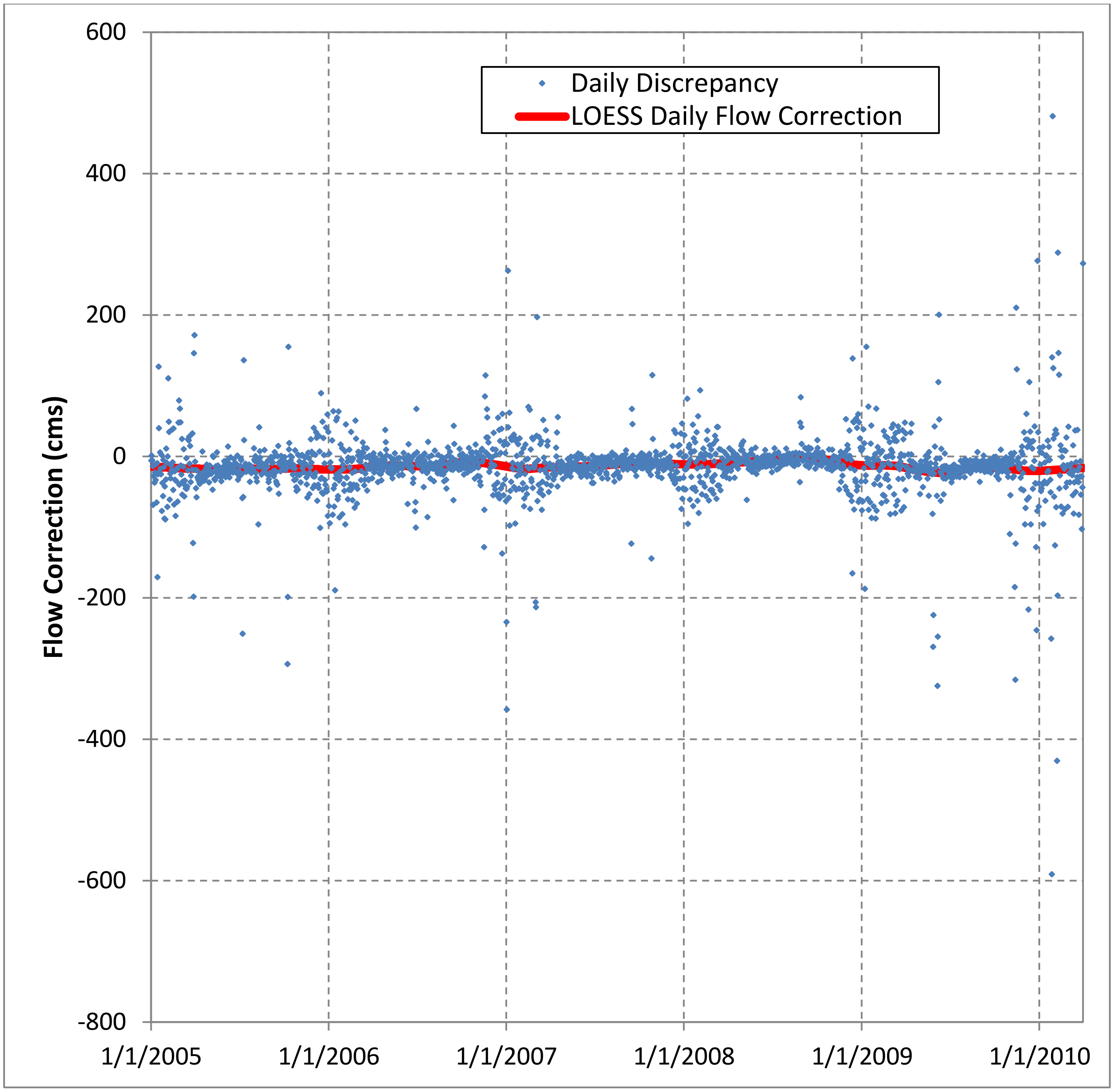

Figure 3-2. High Rock Lake Flow Correction Time Series

3.2.2 Water Surface Elevation

Water surface elevation is regularly measured in High Rock Lake and provides the basis for adjusting the hydrologic mass balance. It should, however, be noted that this check of mass balance can only be as accurate as the accuracy of the stage – storage relationships for the lake and their representation in the model. As was noted in Section 2.2, there is a fair amount of uncertainty regarding the details of the bathymetry of High Rock Lake, and thus of the stage-storage relationship, while the model grid of necessity represents an approximation to this relationship.

The water surface elevation comparison of the model was performed on a daily basis (Figure 3-3). The observed record is from the forebay area of High Rock Lake dam. As a smoothed daily flow correction approach was used, the residual error is generally small except for a few transients that result in temporary discrepancies of up to about 1 m. Such discrepancies are expected during high flow events due to small errors in timing of inflows (especially inflows from ungaged areas) and the fact that the model grid does not represent lateral expansion of the lake surface into low-lying nearshore areas when the water surface elevation exceeds normal pool elevation of 190.2 m. The average error is 0.031 m and the Nash-Sutcliffe coefficient of model fit efficient is 0.889 (equivalent to r=0.943), indicating an excellent fit overall (Table 3-2).

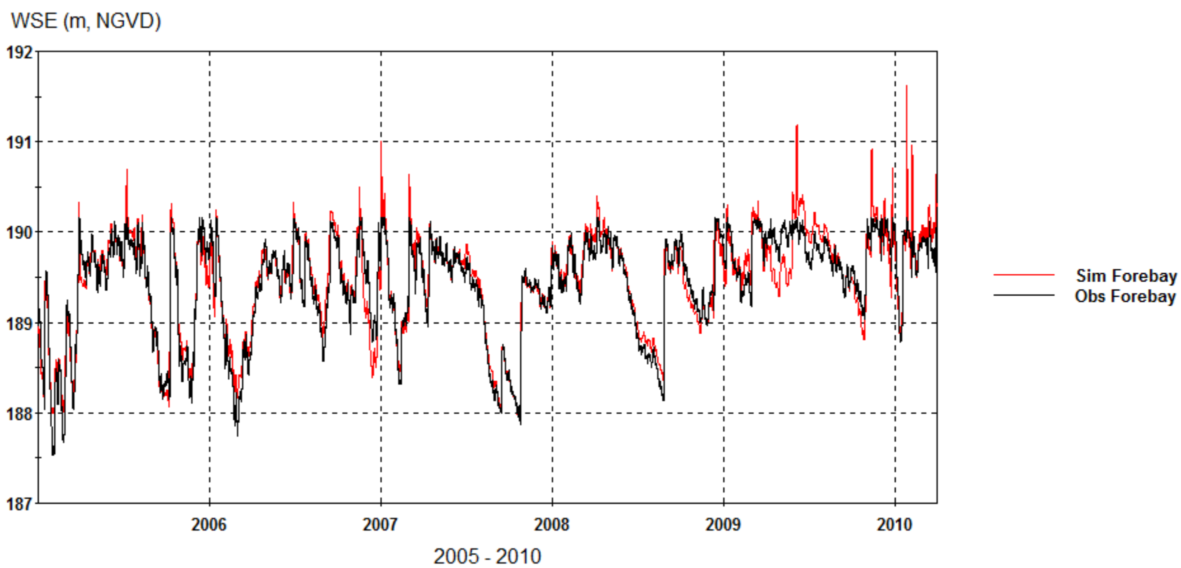

Figure 3-3. Simulated and Observed Water Surface Elevation

Table 3-2. Analysis of Water Surface Elevation Calibration (2005 – 2010)

Average Observed (m)	Average Simulated (m)	Average Error	Average Absolute Error	Root Mean Square Error	Nash-Sutcliffe Model Fit Efficiency
189.415	189.446	0.031	0.135	0.187	0.889

3.2.3 Water Temperature Calibration

Water temperature simulation is important in the High Rock Lake model as it is the primary indicator of the ability of the model to represent vertical, and, to a lesser degree, lateral mixing. In addition, water temperature affects many biologically mediated processes that influence water quality in the lake. Accordingly, the High Rock Lake model is calibrated to both spatial data on surface water temperature and vertical temperature profile data at specific locations.

The EFDC hydrodynamic model of High Rock Lake represents the movement of water as a function of inflows, outflows, momentum, and buoyancy components. Buoyancy is affected by both salinity and temperature. Within High Rock Lake there are not significant salinity gradients; however, temperature is important in the setup of (usually temporary) thermal stratification. EFDC includes a full simulation of water temperature, which is affected by influent temperature, short-wave, long-wave, and sensible heat exchange with the atmosphere, energy exchanges associated with evaporation or condensation, and thermal exchanges with the lake bed.

The water temperature in the lake is driven by three types of inputs: tributary and discharge heat loads, meteorological inputs (solar input and heat exchanges with the atmosphere), and thermal interaction with the sediment bed. The HSPF simulation of the watershed was used to set the tributary water temperature assignments. The light attenuation coefficient, which determines the vertical distribution of shortwave solar radiation, and the parameters controlling heat exchange with the bed in EFDC were the primary calibration adjustments used to achieve fit to observed temperature profiles. The solar radiation attenuation coefficient (SWRATNF, 1/m) in the meteorology input file was set to 1.7 during calibration, within the range of measured light extinction coefficients near the forebay discussed in Section 2.3.8.

The temperature simulation was calibrated at three stations along the main axis of the lake. Simulated water temperatures compare well to observations both in terms of time series (Figure 3-4 to Figure 3-6) and vertical profiles (Figure 3-7 to Figure 3-10). The profile information confirms that vertical thermal stratification in the lake is limited due to the dynamic flow-through nature of the lake; thus observed water temperatures are primarily a function of boundary conditions. Predicted water temperatures at these stations meet or exceed the targets for relative error, CV, and correlation coefficient during both the calibration and validation periods (Table 3-3 and Table 3-4).

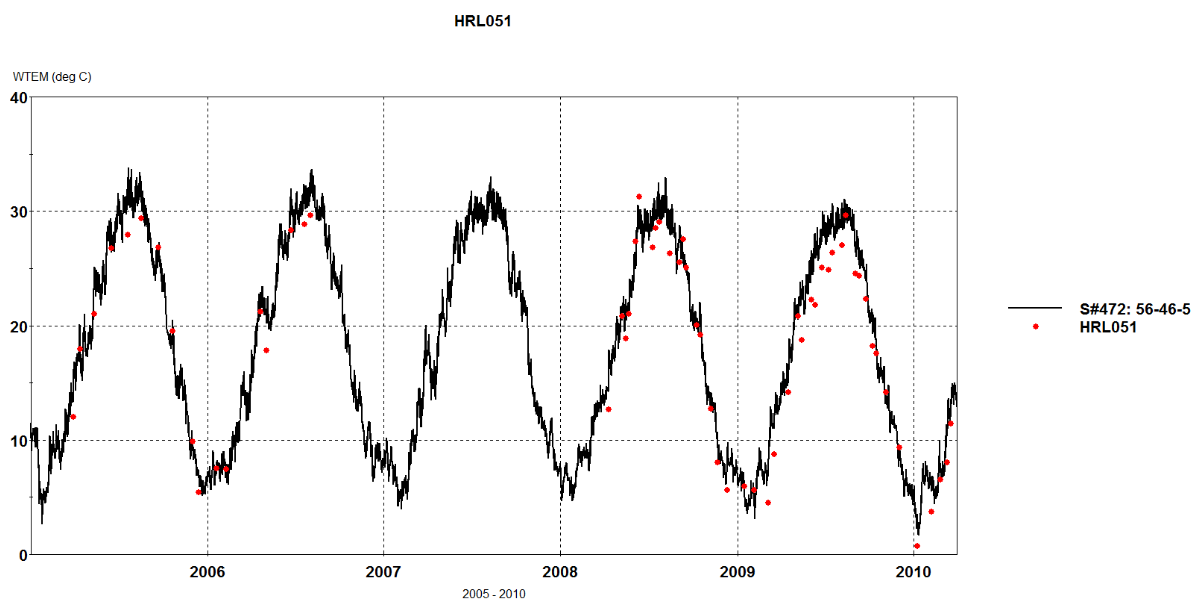

Figure 3-4. Surface Water Temperature Time Series Comparison at HRL051 (2005 – 2010)

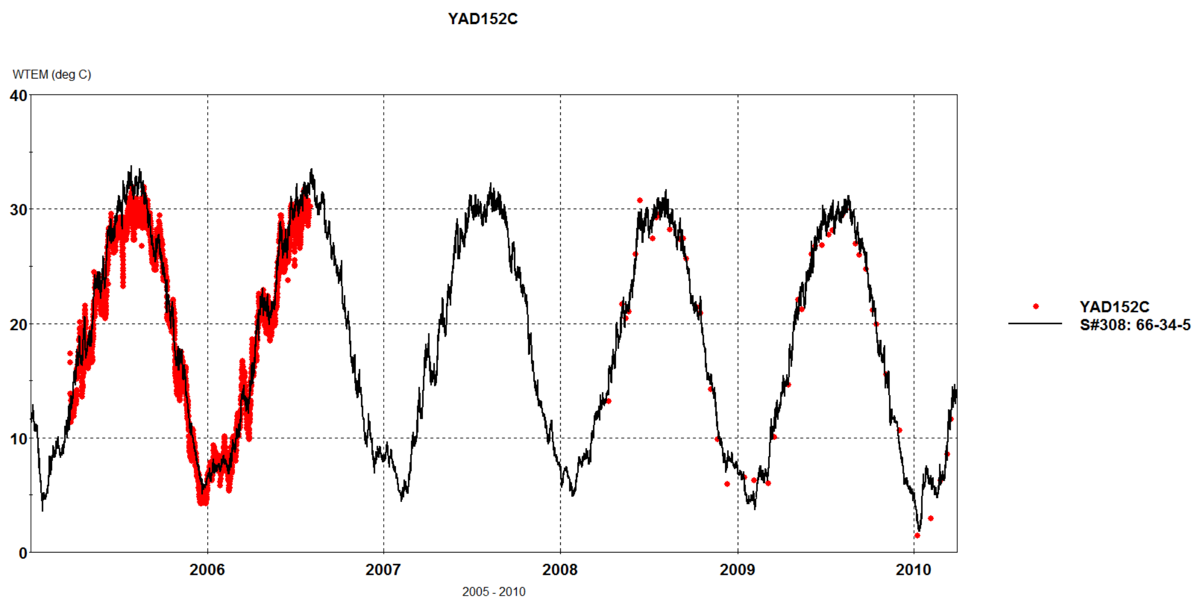

Figure 3-5. Surface Water Temperature Time Series Comparison at YAD152C (2005 – 2010)

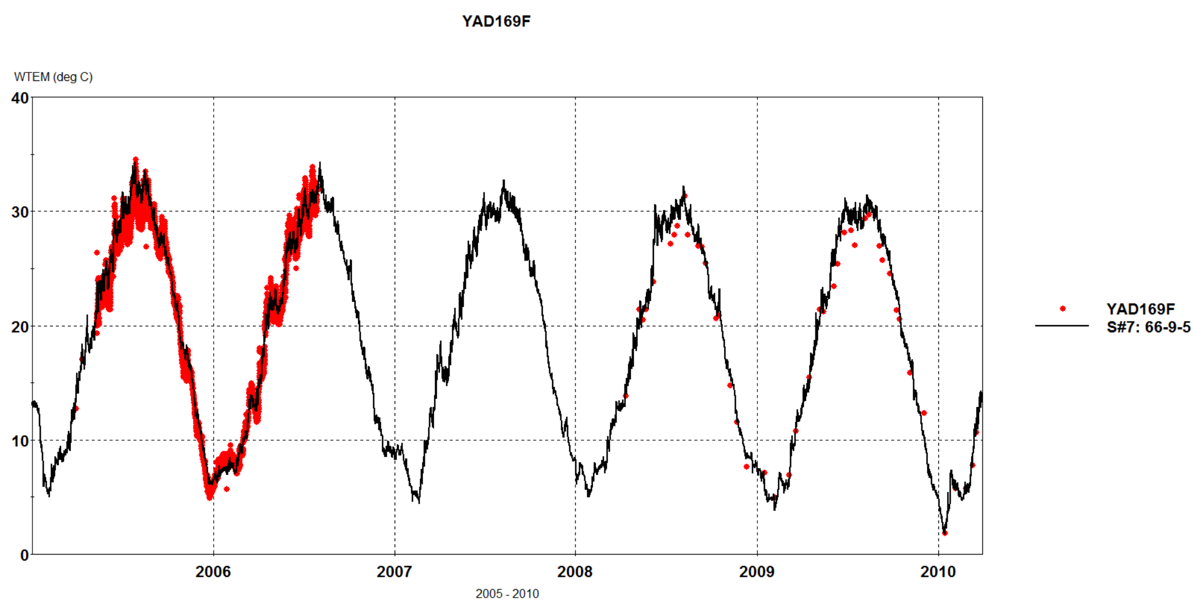

Figure 3-6. Surface Water Temperature Time Series Comparison at YAD169F (2005 – 2010)

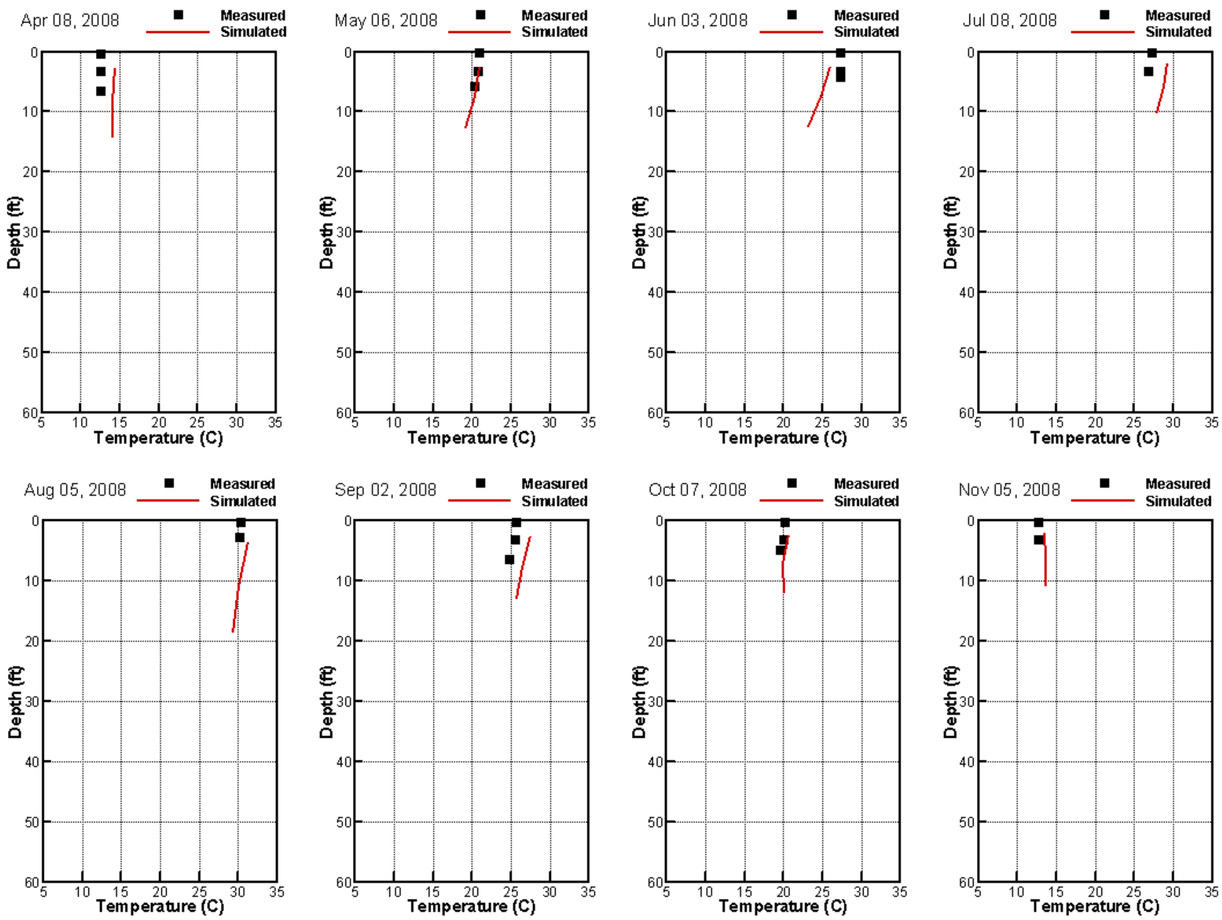

Figure 3-7. Water Temperature Profile Comparison at HRL051 (2008)

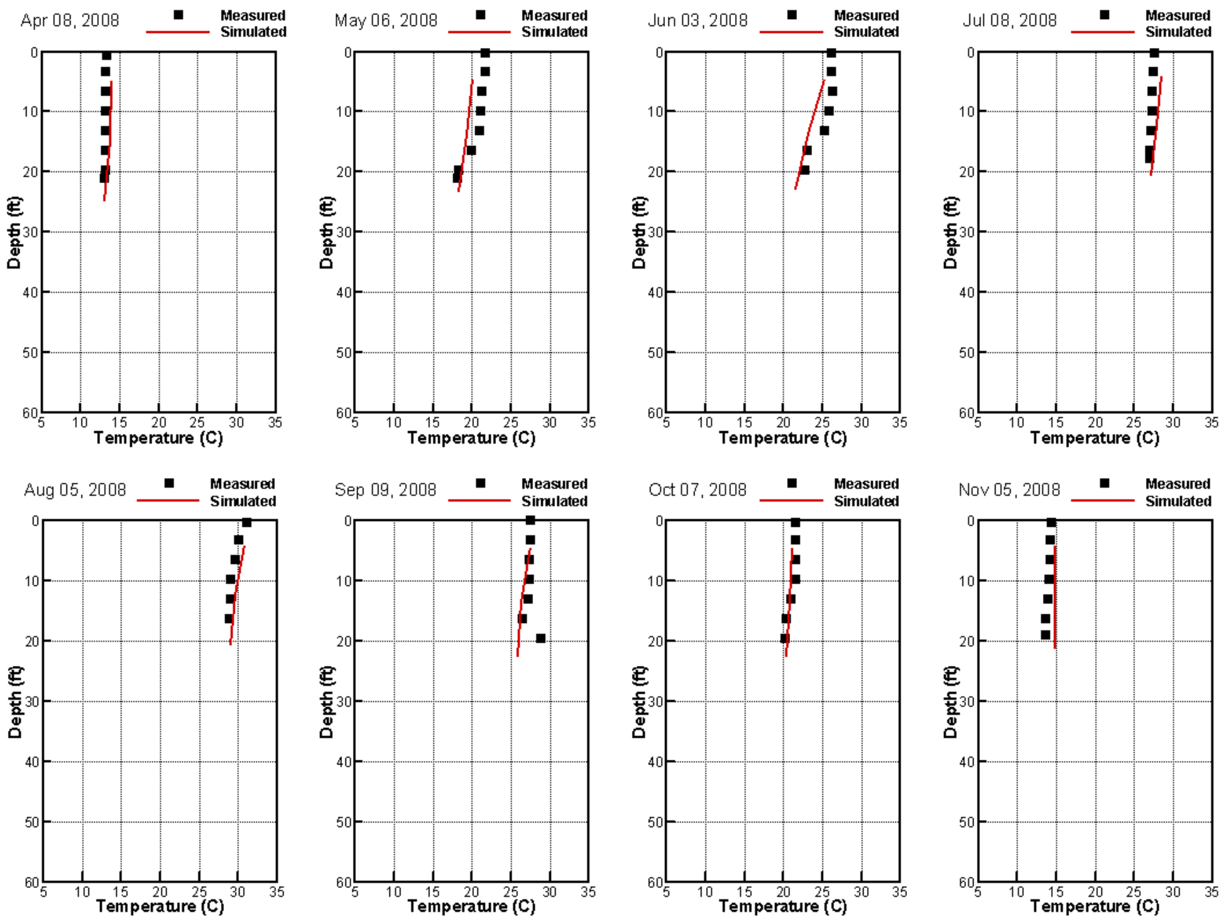

Figure 3-8. Water Temperature Profile Comparison at YAD152C (2008)

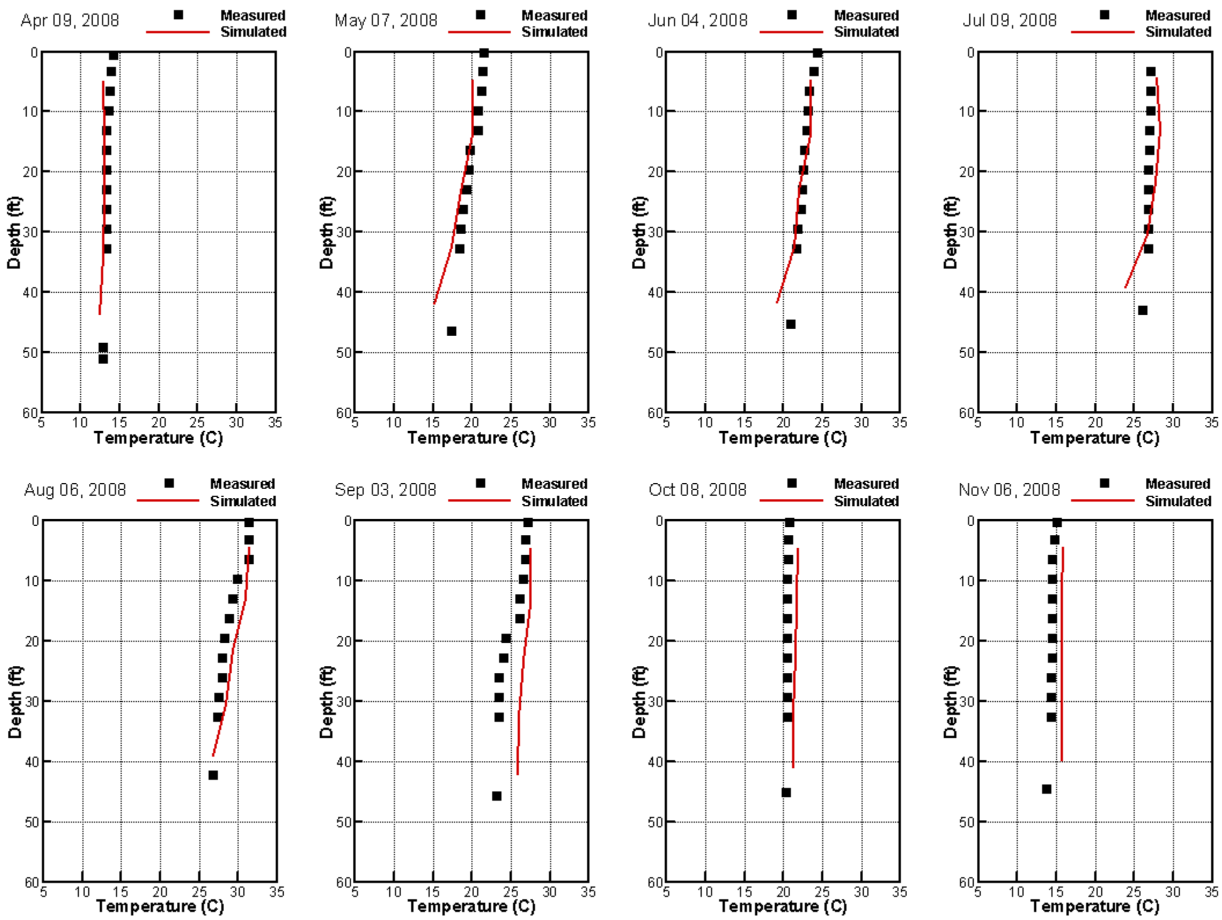

Figure 3-9. Water Temperature Profile Comparison at YAD169F (2008)

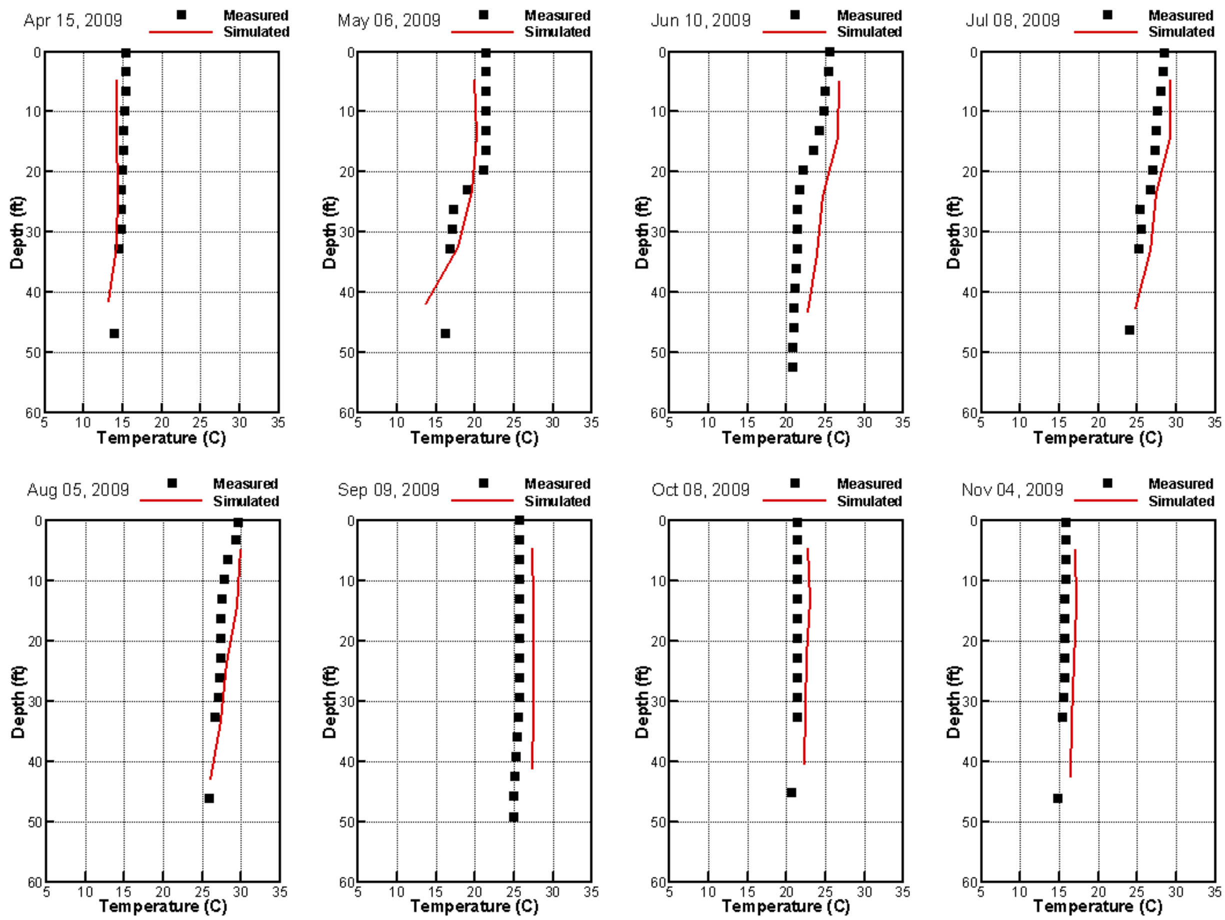

Figure 3-10. Water Temperature Profile Comparison at YAD169F (2009)

Table 3-3. Calibration Statistics for Surface Water Temperature (2008-2010)

Station	RE	RAE	CV	r	RMSE	Count
HRL051 (Upper HRL above Swearing Cr)	7.1%	8.8%	10.5%	0.99	1.91	44
YAD152C (Middle HRL below Town/Crane Cr)	1.4%	4.0%	5.0%	0.99	0.98	45
YAD169F (Lower HRL at forebay)	2.7%	4.7%	5.5%	0.99	1.1	45

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

Table 3-4. Validation Statistics for Surface Water Temperature (2005-2006)

Station	RE	RAE	CV	r	RMSE	Count
HRL051 (Upper HRL above Swearing Cr)	5.5%	7.0%	8.5%	0.99	1.69	17
YAD152C (Middle HRL below Town/Crane Cr)	4.0%	5.7%	7.1%	0.99	1.39	5939
YAD169F (Lower HRL at forebay)	2.3%	4.3%	5.3%	0.99	1.04	7295

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

3.3 Water Quality Calibration and Validation (WASP)

WASP 7.52 was implemented in full eutrophication simulation (EUTRO) mode. EUTRO represents transport and transformations of nutrients, algae, CBOD, and DO. In addition, this version of WASP allows the simulation of suspended solids within the EUTRO module.

As noted in Section 3.1, water quality calibration began with suspended solids and proceeded through nutrients and algae, with several feedback loops. Parameter values were initialized at recommended values (Wool et al., 2001) and improved through visual comparison of time series and evaluation of statistics. The PEST automated parameter estimation software (Watermark Numerical Computing, 2002) was also used as an aid in calibration; however, its usefulness was somewhat limited due to long model run times.

3.3.1 Suspended Solids Calibration and Validation

Total suspended solids (TSS) calibration proved difficult due in part to the dynamic setting of the system. Sediment settling and resuspension are normally affected by sediment composition, sediment size, flow speed, and bottom properties. The representation of the above mentioned processes are limited in WASP. Inflows to the lake typically carry coarser particles during high flow events and the influent load becomes progressively finer through deposition as flow slows within the lake. Large amounts of sediment deposition are known to occur between the confluence of the Yadkin and South Yadkin Rivers and the I-85 bridge (Normandeau, 2004; Copeland, 2007), within the domain of the lake model. This effect was approximated by assigning high rates of solids deposition in this part of the model grid; however, WASP is not able to fully account for the variable, lower deposition velocity of fine sediment. In addition, TSS measurements are inherently subject to a degree of sampling uncertainty, while point-in-time grab samples can be unrepresentative of spatial and temporal averages simulated by the model.

Calibration statistics for all monitoring stations (2008 – 2010) are provided in Table 3-5. The statistics compare WASP model predictions for the surface layer to values of composite samples over twice the Secchi depth. Time series plots from all stations are shown in Figure 3-11 through Figure 3-12. In general, the model reproduces the central tendency of the observed data (as evidenced by relative error values that are mostly less than the criteria of 45% cited in Table 3-1), but does not provide precise representation of individual observations. This is evident in the time series comparison plots, which suggest that the model appear to over-estimate TSS during large inflow events and tends to under-estimate observed TSS during some of the more quiescent periods when influent TSS is dominated by fine silt and clay.

Table 3-5. Calibration Statistics for Total Suspended Solids (2008-2010)

Station	Count	Observed Mean (mg/L)	RE	RAE	CV	r	RMSE
HRL051 (Upper HRL above Swearing Cr)	45	28.8	-5.6%	94.4%	1.48	0.20	42.53
YAD152A (Middle HRL at Town/Crane Cr)	45	18.9	10.0%	101.2%	2.15	0.20	40.67
YAD152C (Middle HRL below Town/Crane Cr)	45	13.5	38.7%	123.4%	2.71	0.15	36.61
YAD169B (Lower HRL below Abbotts Cr)	45	9.2	42.2%	109.8%	2.84	0.42	26.10
YAD169F (Lower HRL at forebay)	45	8.2	41.5%	106.1%	2.63	0.73	21.60
YAD152 (Town/Crane Cr Arm)	45	12.2	-15.6%	54.7%	0.72	0.40	8.83
YAD1561A (Second Cr Arm)	45	10.7	-9.7%	72.3%	1.12	0.60	11.97
HRL052 (Upper Abbotts Cr Arm)	45	11.0	25.5%	80.6%	1.19	0.13	13.13
YAD169A (Lower Abbotts Cr Arm)	44	9.4	26.9%	85.3%	1.58	0.55	14.83
YAD169E (Flat Swamp Cr Arm)	45	7.7	57.0%	125.1%	3.33	0.84	25.49

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

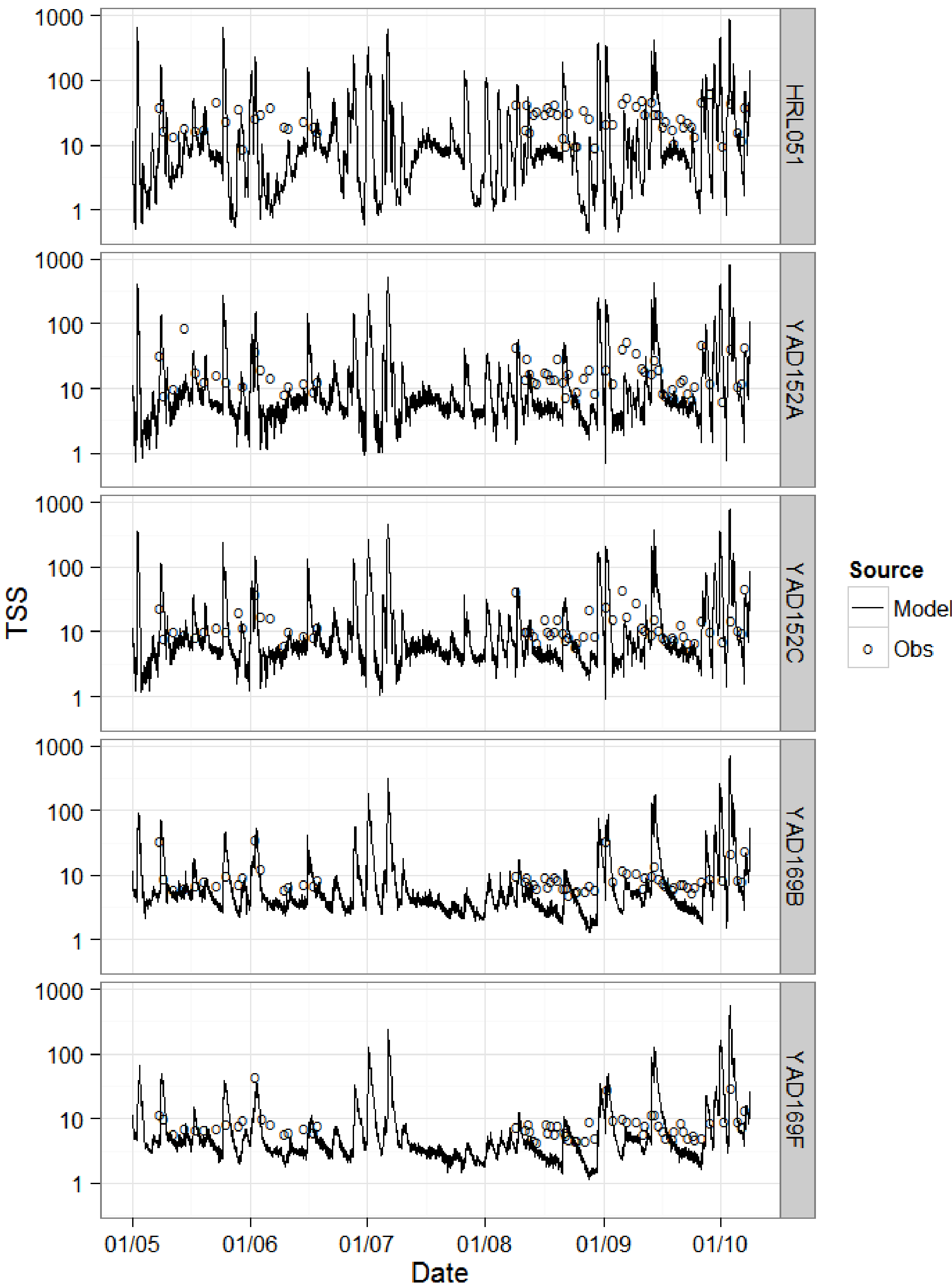

Figure 3-11. TSS (mg/l, log scale) calibration (2008-2010) and validation (2005-2006), main-stem stations in High Rock Lake.

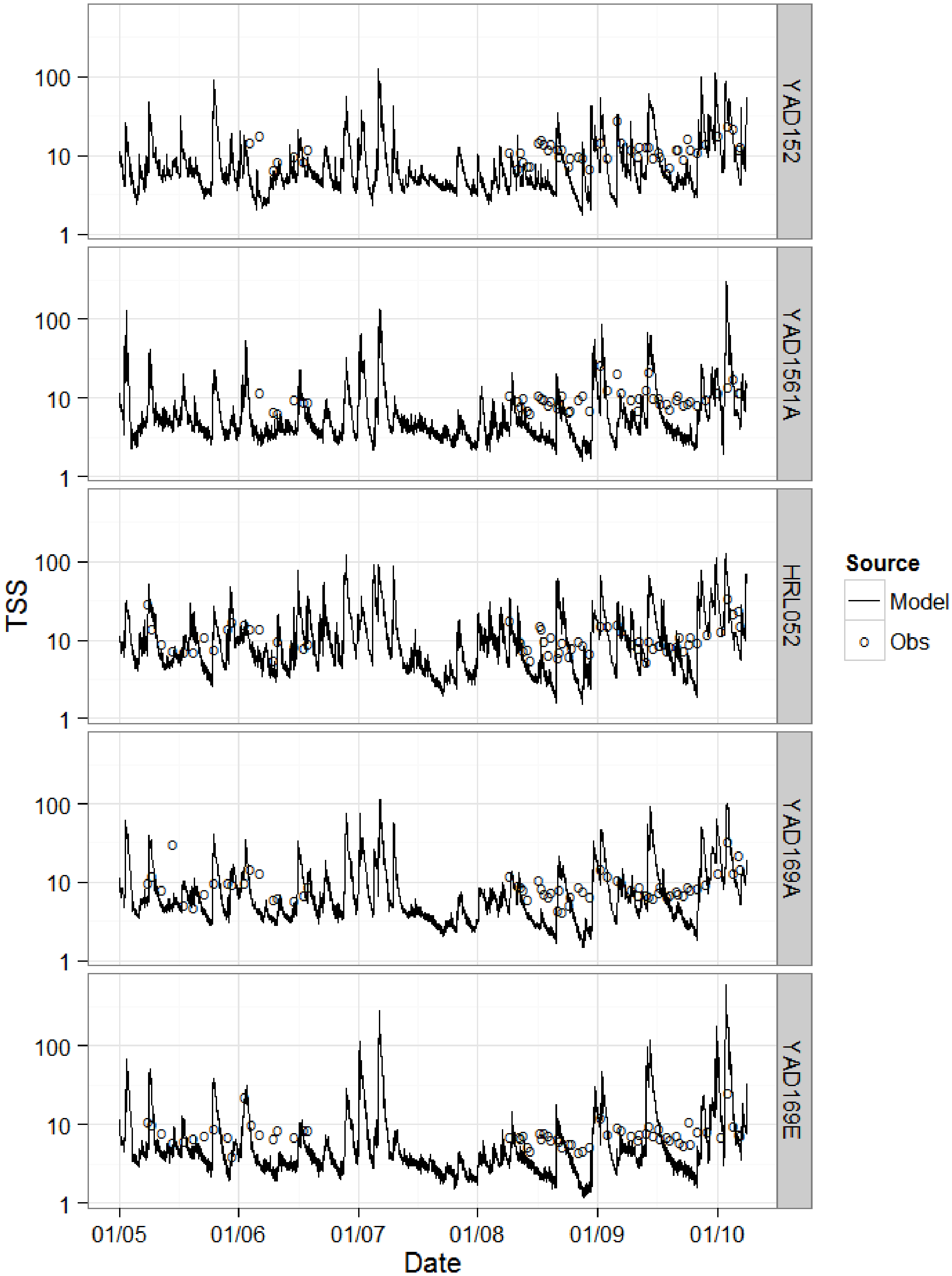

Figure 3-12. TSS (mg/l, log scale) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake.

Table 3-6. Validation Statistics for Total Suspended Solids (2005-2006)

Station	Count	Observed Mean (mg/L)	RE	RAE	CV	*r*	RMSE
HRL051 (Upper HRL above Swearing Cr)	18	24.33	0.0%	96.5%	1.51	0.25	36.76
YAD152A (Middle HRL at Town/Crane Cr)	17	19.85	19.0%	99.0%	1.77	0.31	35.06
YAD152C (Middle HRL below Town/Crane Cr)	18	13.47	41.3%	93.9%	1.63	0.80	21.91
YAD169B (Lower HRL below Abbotts Cr)	17	11.15	0.3%	34.6%	0.45	0.92	5.00
YAD169F (Lower HRL at forebay)	18	9.88	-17.6%	53.1%	0.73	0.61	7.22
YAD152 (Town/Crane Cr Arm)	7	11.21	-49.4%	49.4%	0.67	-0.69	7.47
YAD1561A (Second Cr Arm)	6	8.78	-43.3%	43.3%	0.52	-0.13	4.54
HRL052 (Upper Abbotts Cr Arm)	18	11.57	27.2%	58.1%	0.75	0.53	8.71
YAD169A (Lower Abbotts Cr Arm)	18	10.02	-7.8%	62.2%	0.84	-0.02	8.44
YAD169E (Flat Swamp Cr Arm)	18	8.66	-5.6%	52.5%	0.65	0.66	5.62

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

The model parameters established during calibration were applied without further adjustment to the validation period (2005 – 2006). The quality of fit is similar to the calibration period, although the data are limited (Table 3-6 and Figure 3-11 through Figure 3-12).

Impacts of uncertainty in the fit for TSS are mitigated in the lake model by two strategies. First, light extinction is simulated in part with a background extinction coefficient that accounts for light availability, after accounting for algal shading, during typical conditions with a relatively small increment from simulated TSS. Second, WASP simulates the losses of nutrients and algae to settling independent of the TSS simulation. Thus, uncertainty in the TSS simulation will have only a minor effect on the simulation of nutrients and algae.

3.3.2 Nutrients Calibration and Validation

The WASP model simulates a full range of nutrient species. Inorganic nutrients are most important for algal growth, but, in the case of inorganic phosphorus in High Rock Lake concentrations are often near practical quantitation limits. Therefore, the calibration focuses on total phosphorus and total nitrogen along with nitrite+nitrate and ammonium nitrogen, the two major inorganic species of nitrogen. Calibration began with recommended default parameters, which were then modified within accepted ranges to obtain better visual and statistical fit. Nutrient calibration is carried out on a full-year basis using all observations. A summary of selected eutrophication kinetic parameters is provided below in Table 3-7. Key parameters for the kinetic processes of the two phytoplankton groups are provided in Table 3-8.

As with suspended sediment, calibration results for nutrients are presented for all stations during the calibration period of 2008 – 2010, beginning with total phosphorus. Surface layer predictions from the model are compared to composite samples collected over twice the Secchi depth.

Table 3-7. Selected Kinetic Parameters for High Rock Lake Eutrophication Model

Parameter	Value	Notes
k12c – Nitrification rate at 20°C, per day	0.2	EPA (1997) cites range of 0.05 – 0.20.
k12t – Arrhenius temperature coefficient for nitrification	1.08	EPA, 1997.
pcrb – Phosphorus to carbon ratio in phytoplankton	0.025	Default value.
ncrb – nitrogen to carbon ratio in phytoplankton	0.19	Optimized; default value is 0.25.
k71c – Mineralization rate of dissolved organic nitrogen (per day)	0.15	Optimized value; default cited by Wool et al. (2001) is 0.075.
k71t – Temperature coefficient for organic nitrogen mineralization	1.08	Default cited by Wool et al. (2001).
fon – Fraction of dead and respired phytoplankton nitrogen recycled to organic nitrogen	0.875	Example values cited by Wool et al. (2001) range from 0.5 to 1.0.
k83c – Mineralization rate of dissolved organic P (per day)	0.17	Optimized value; value cited by Wool et al. (2001) is 0.22.
k83t – Temperature coefficient for mineralization of dissolved organic P	1.08	Default recommended by Wool et al. (2001).
fop – Fraction of dead and respired phytoplankton phosphorus recycled to organic P	0.80	Optimized, should be generally similar to fon.

Table 3-8. Key parameters for the two phytoplankton groups

Parameter	Algal Group 1 (Warm-water)	Algal Group 2 (Cold-water)	Notes
Carbon to Chlorophyll Ratio	42	60	Wool et al. (2001) cites range of 20-50.
Growth Rate Constant @ 20°C	2.8	2.8	EPA (ppt) cites range of 0.5 -4.0.
Temperature Coefficient	1.068	N/A	Default value.
Optimal Temperature for Growth	N/A	10°C	Optimized value.
Shape Parameter for Below Optimal Temperature for Growth	N/A	0.02	Optimized value.
Shape Parameter for Above Optimal Temperature for Growth	N/A	0.02	Optimized value.
Death Rate Constant	0.08	0.01	Wool et al. (2001) cites value of 0.02.
Half Saturation Rate for N Uptake	0.01	0.005	EPA (1997) cites range of 0.005 – 0.025.
Half Saturation Rate for P Uptake	0.001	0.0005	EPA (1997) cites range of 0.001 – 0.005.
Optimal Light Saturation	300	150	Wool et al. (2001) cites range of 200 - 500.

3.3.2.1 Phosphorus Calibration and Validation

The phosphorus calibration focused on total phosphorus because inorganic phosphorus is often near detection limits in the lake and is recycled rapidly during periods of algal growth. Calibration for total phosphorus was achieved primarily by adjusting settling rates. The mineralization rate of organic phosphorus and the fraction of dead algae recycled to organic phosphorus (Table 3-7) were key factors in controlling inorganic phosphorus concentrations, but also affect the total phosphorus balance through differential settling. Benthic flux rates of orthophosphate were adjusted slightly from the measured values (Section 2.3.6). Total phosphorus calibration results are shown in Table 3-9. Time series plots for the calibration (Figure 3-13 and Figure 3-14) are shown together with plots for the validation period following discussion of the validation.

The total phosphorus simulations meet the RE target for "good" fit at all stations, indicating that the model represents annual and seasonal averages well. On the other hand, the CV and the correlation coefficient (*r*) statistics do not meet the "good" target, indicating that short-term temporal variability among individual observations is not well captured in this dynamic system.

Table 3-9. Calibration Statistics for Total Phosphorus (2008 – 2010)

Station	Count	Observed Mean (mg-P/L)	RE	RAE	CV	*r*	RMSE
HRL051 (Upper HRL above Swearing Cr)	45	0.17	-2.5%	59.5%	0.93	-0.17	0.15
YAD152A (Middle HRL at Town/Crane Cr)	45	0.14	-6.0%	60.8%	1.01	-0.16	0.14
YAD152C (Middle HRL below Town/Crane Cr)	45	0.12	-0.4%	61.2%	1.17	-0.14	0.14
YAD169B (Lower HRL below Abbotts Cr)	45	0.10	2.6%	67.1%	1.26	0.03	0.12
YAD169F (Lower HRL at forebay)	45	0.09	7.2%	69.5%	1.11	0.09	0.10
YAD152 (Town/Crane Cr Arm)	45	0.12	-20.4%	61.7%	1.08	-0.16	0.12
YAD1561A (Second Cr Arm)	45	0.09	-4.9%	59.8%	1.08	0.09	0.10
HRL052 (Upper Abbotts Cr Arm)	45	0.11	-19.1%	52.4%	0.96	-0.16	0.11
YAD169A (Lower Abbotts Cr Arm)	44	0.10	-13.4%	65.3%	1.19	-0.02	0.12
YAD169E (Flat Swamp Cr Arm)	45	0.09	6.6%	72.4%	1.17	0.10	0.10

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

Following calibration for nutrients, a model validation exercise was undertaken. Similar to the calibration results, the model validation statistics confirms that the model represents annual and seasonal averages well but not the short-term temporal variability among individual observations (Table 3-10).

Table 3-10. Validation Statistics for Total Phosphorus (2005 – 2006)

Station	Count	Observed Mean (mg-P/L)	RE	RAE	CV	*r*	RMSE
HRL051 (Upper HRL above Swearing Cr)	18	0.17	-3.0%	34.9%	0.45	0.20	0.08
YAD152A (Middle HRL at Town/Crane Cr)	17	0.13	14.0%	52.5%	0.76	0.19	0.10
YAD152C (Middle HRL below Town/Crane Cr)	18	0.16	-10.3%	59.8%	1.35	0.01	0.21
YAD169B (Lower HRL below Abbotts Cr)	18	0.09	19.5%	33.4%	0.53	0.60	0.05
YAD169F (Lower HRL at forebay)	18	0.07	19.2%	38.4%	0.66	0.28	0.05
YAD152 (Town/Crane Cr Arm)	7	0.12	-31.6%	52.3%	0.93	0.19	0.11
YAD1561A (Second Cr Arm)	7	0.06	22.3%	23.0%	0.27	0.80	0.02
HRL052 (Upper Abbotts Cr Arm)	17	0.08	32.0%	38.4%	0.51	0.43	0.04
YAD169A (Lower Abbotts Cr Arm)	18	0.07	45.1%	49.2%	0.68	0.51	0.04
YAD169E (Flat Swamp Cr Arm)	18	0.07	35.2%	41.3%	0.67	0.49	0.04

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

Time series plots are provided below for all monitoring stations in the main-stem of the lake as well as in the lake arms (Figure 3-13 and Figure 3-14).

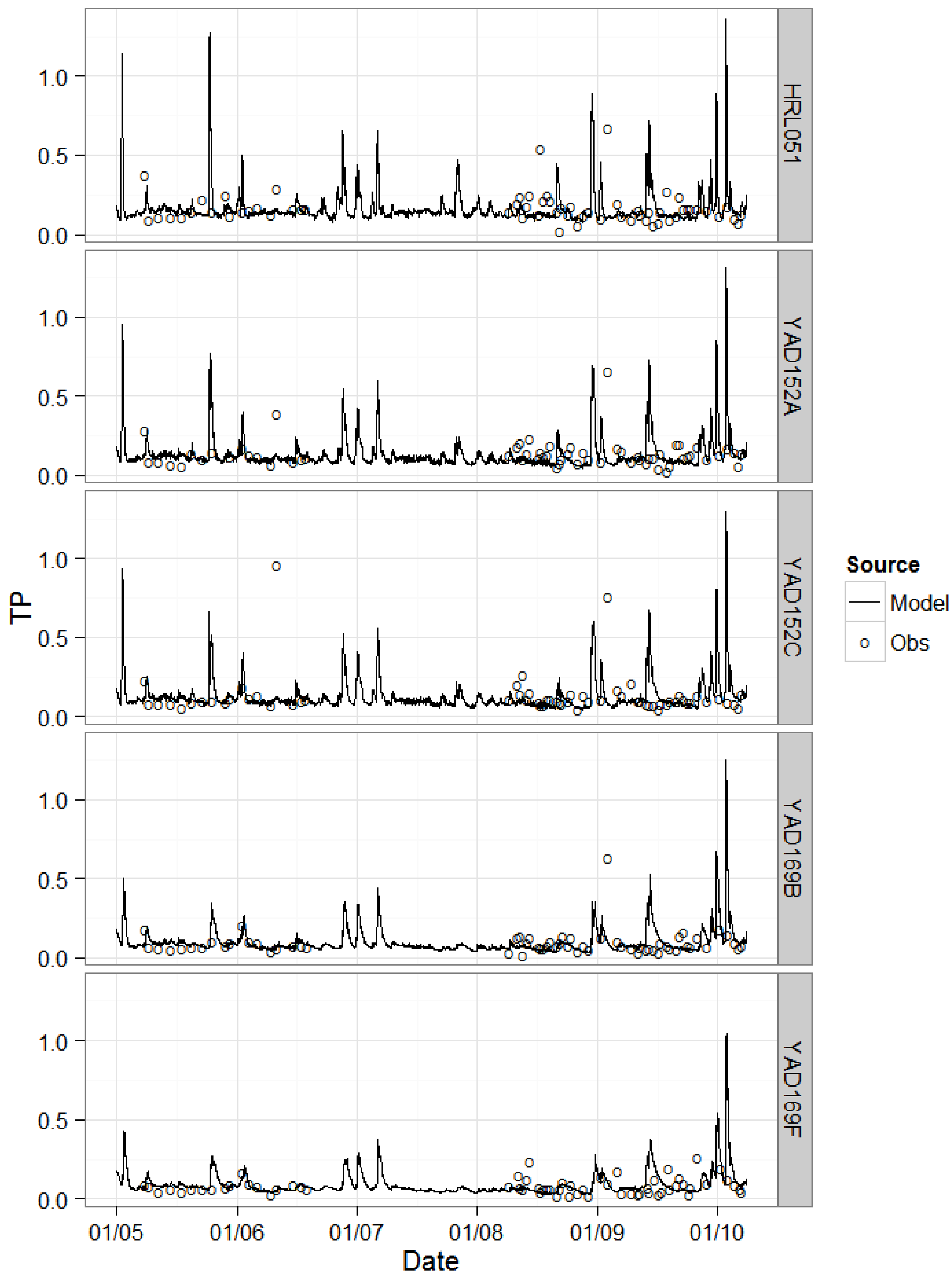

Figure 3-13. Total Phosphorus (TP, mg/l) calibration (2008-2010) and validation (2005-2006), main-stem stations in High Rock Lake

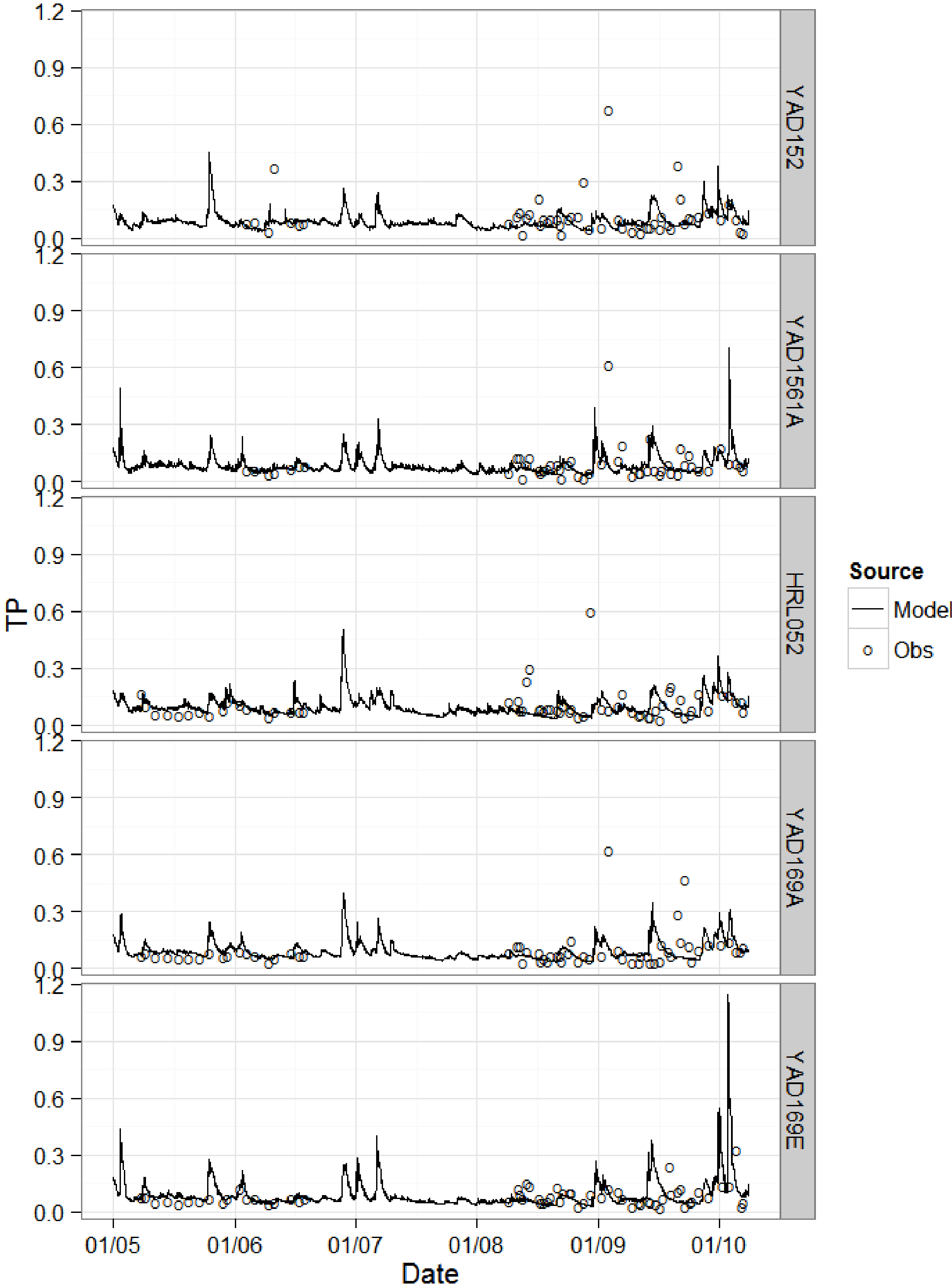

Figure 3-14. Total Phosphorus (TP, mg/l) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake

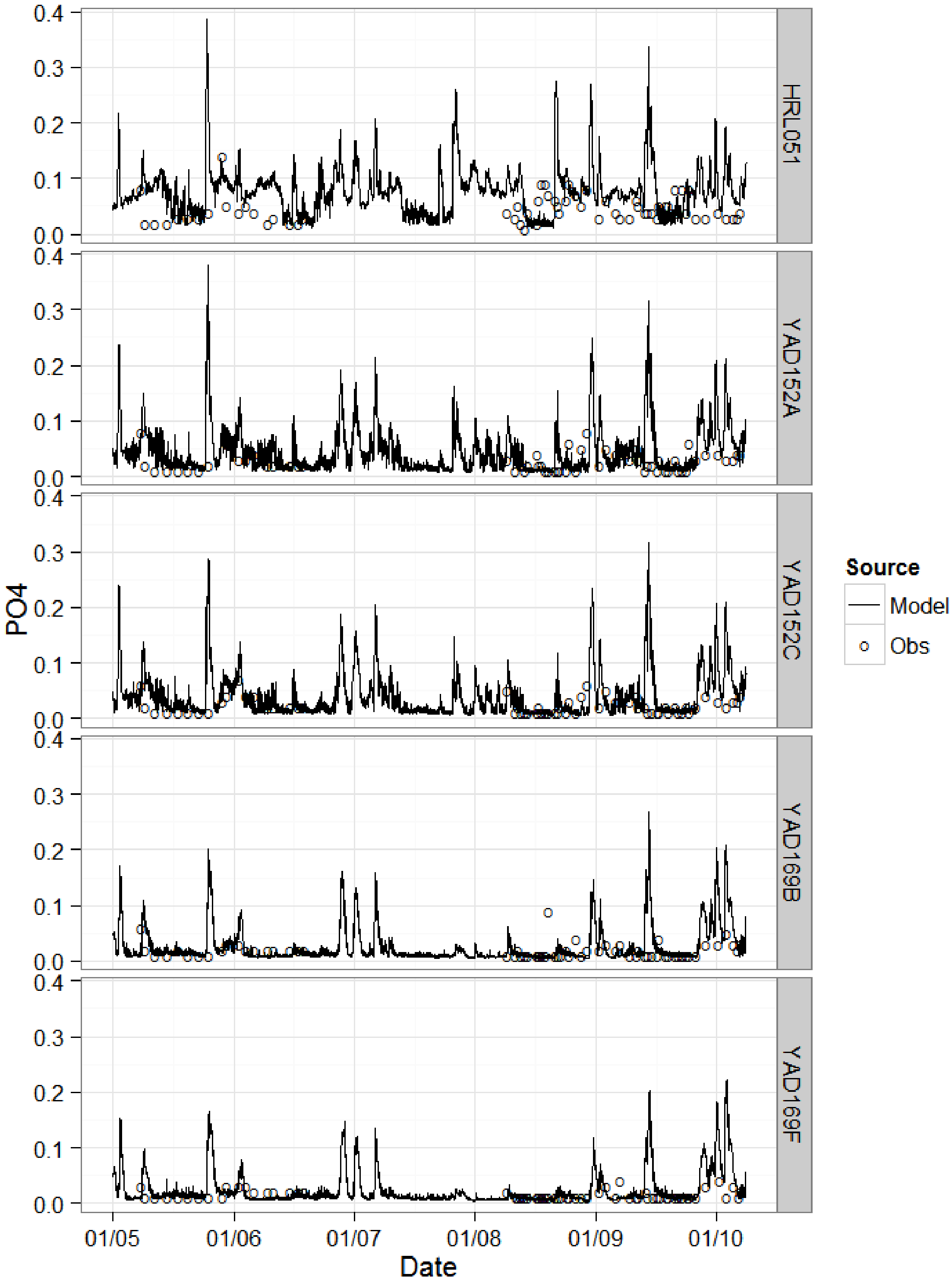

Figure 3-15. Phosphate (PO4, mg/l) calibration (2008-2010) and validation (2005-2006), main-stem stations in High Rock Lake

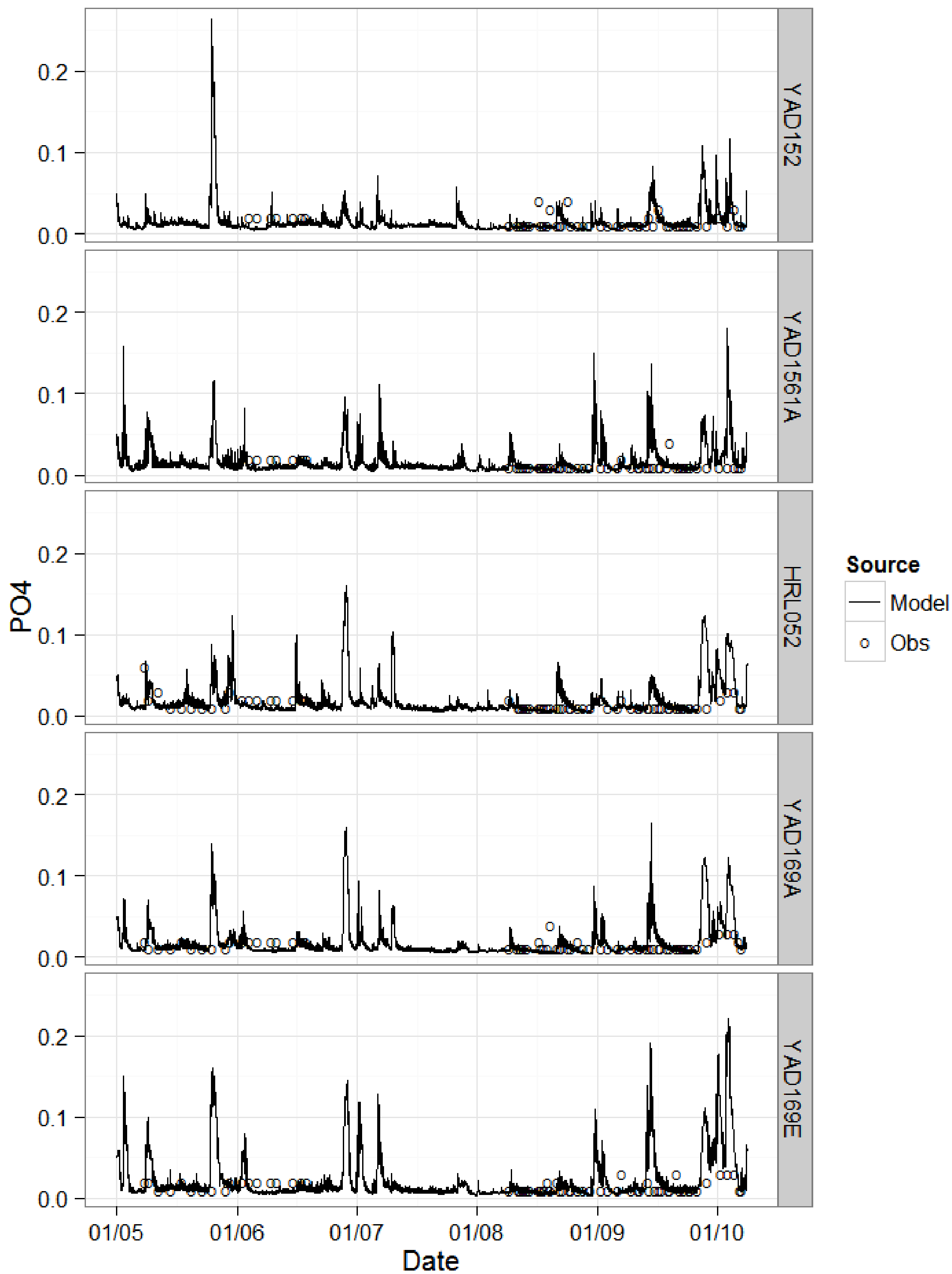

Figure 3-16. Phosphate (PO4, mg/l) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake

Phosphate time series plots are provided in Figure 3-15 and Figure 3-16 for both the model calibration and the validation periods. The model simulation results represent the observed average phosphate concentrations and the range of its variability well, however, model representation of individual events are often inaccurate in this dynamic system.

3.3.2.2 Nitrogen Calibration and Validation

The WASP model was calibrated for both total nitrogen and inorganic nitrogen species (nitrite+nitrate and ammonium). As with phosphorus, key parameters include dissolved fraction and settling rates and the mineralization rate of organic nitrogen.

The total nitrogen calibration meets all targets for RE and CV (as specified in Table 3-1), but not the correlation coefficient (*r*) target during the calibration period (Table 3-11) and validation period (Table 3-12). Predicted total nitrogen concentrations appear to be slightly low throughout the lake during the calibration period but such under-prediction is not present during the validation period.

Time series graphical comparisons for total nitrogen at all stations are shown in Figure 3-17 through Figure 3-18.

Table 3-11. Calibration Statistics for Total Nitrogen (2008 – 2010)

Station	Count	Observed Mean (mg-N/L)	RE	RAE	CV	*r*	RMSE
HRL051 (Upper HRL above Swearing Cr)	45	1.61	-19.8%	36.4%	0.46	0.09	0.75
YAD152A (Middle HRL at Town/Crane Cr)	45	1.39	-19.5%	40.3%	0.52	-0.08	0.72
YAD152C (Middle HRL below Town/Crane Cr)	45	1.37	-21.4%	41.8%	0.69	0.01	0.95
YAD169B (Lower HRL below Abbotts Cr)	45	1.11	-17.4%	47.4%	0.71	0.02	0.79
YAD169F (Lower HRL at forebay)	45	1.08	-19.7%	48.0%	0.60	0.05	0.65
YAD152 (Town/Crane Cr Arm)	45	0.94	-13.9%	30.8%	0.38	0.06	0.35
YAD1561A (Second Cr Arm)	45	0.96	-10.8%	38.5%	0.52	-0.13	0.50
HRL052 (Upper Abbotts Cr Arm)	45	0.99	-14.6%	37.2%	0.46	0.16	0.45
YAD169A (Lower Abbotts Cr Arm)	44	1.00	-16.1%	39.0%	0.51	0.08	0.51
YAD169E (Flat Swamp Cr Arm)	45	0.99	-12.6%	47.4%	0.64	0.11	0.63

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

Table 3-12. Validation Statistics for Total Nitrogen (2005 – 2006)

Station	Count	Observed Mean (mg-N/L)	RE	RAE	CV	*r*	RMSE
HRL051 (Upper HRL above Swearing Cr)	18	1.25	1.5%	10.8%	0.21	0.47	0.26
YAD152A (Middle HRL at Town/Crane Cr)	17	1.08	15.1%	30.5%	0.43	0.49	0.47
YAD152C (Middle HRL below Town/Crane Cr)	18	1.06	11.3%	27.3%	0.39	0.43	0.41
YAD169B (Lower HRL below Abbotts Cr)	18	1.02	-5.0%	23.3%	0.30	0.63	0.30
YAD169F (Lower HRL at forebay)	18	0.95	-8.6%	23.3%	0.28	0.65	0.27
YAD152 (Town/Crane Cr Arm)	7	0.75	1.4%	23.4%	0.25	-0.31	0.18
YAD1561A (Second Cr Arm)	7	0.72	7.9%	21.0%	0.25	0.09	0.18
HRL052 (Upper Abbotts Cr Arm)	17	0.97	-3.0%	17.7%	0.22	0.63	0.21
YAD169A (Lower Abbotts Cr Arm)	18	0.91	-2.5%	17.4%	0.24	0.67	0.22
YAD169E (Flat Swamp Cr Arm)	18	0.87	-2.4%	17.6%	0.26	0.69	0.23

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

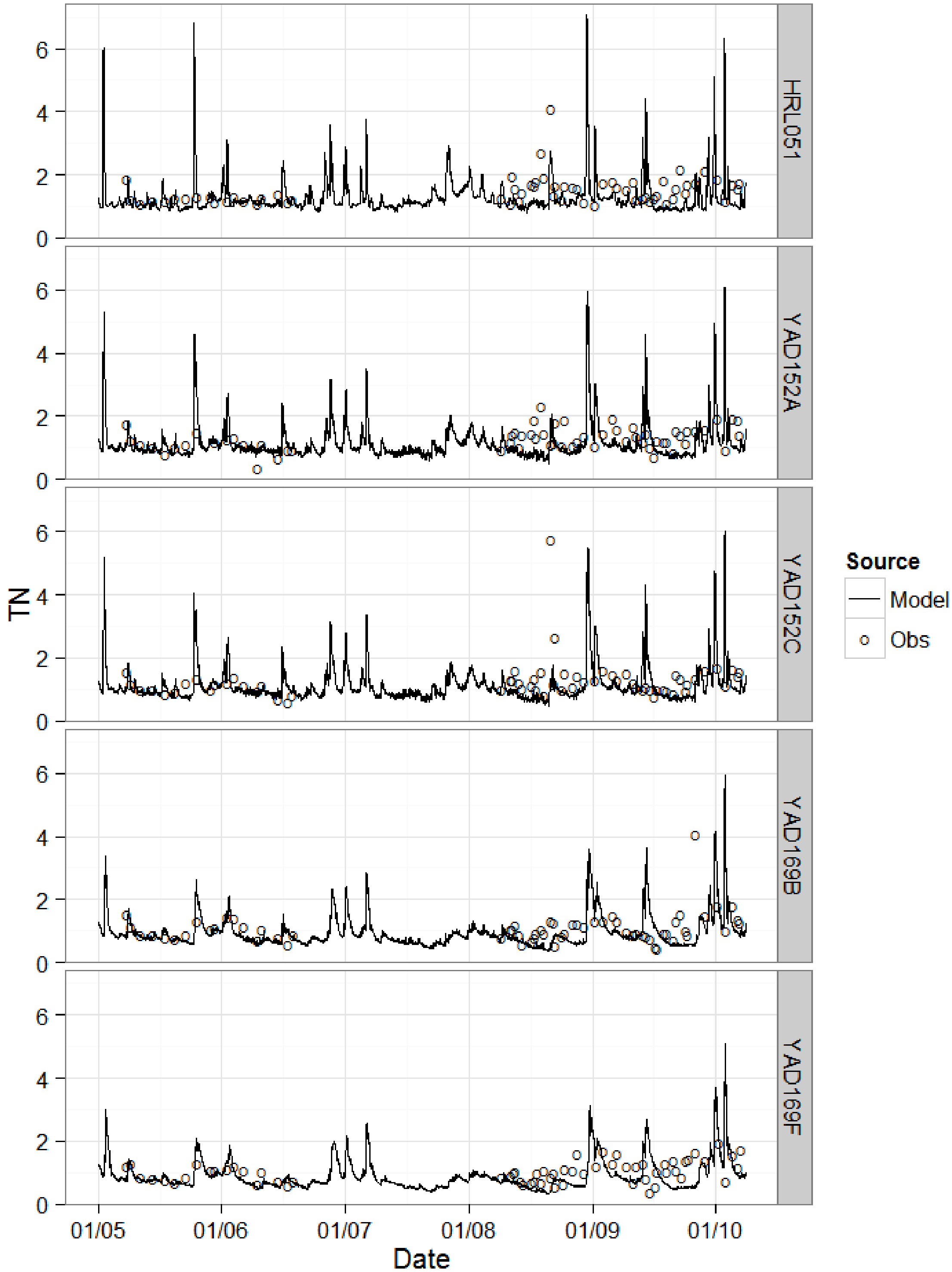

Figure 3-17. Total Nitrogen (mg/l) calibration (2008-2010) and validation (2005-2006), main-stem stations in High Rock Lake

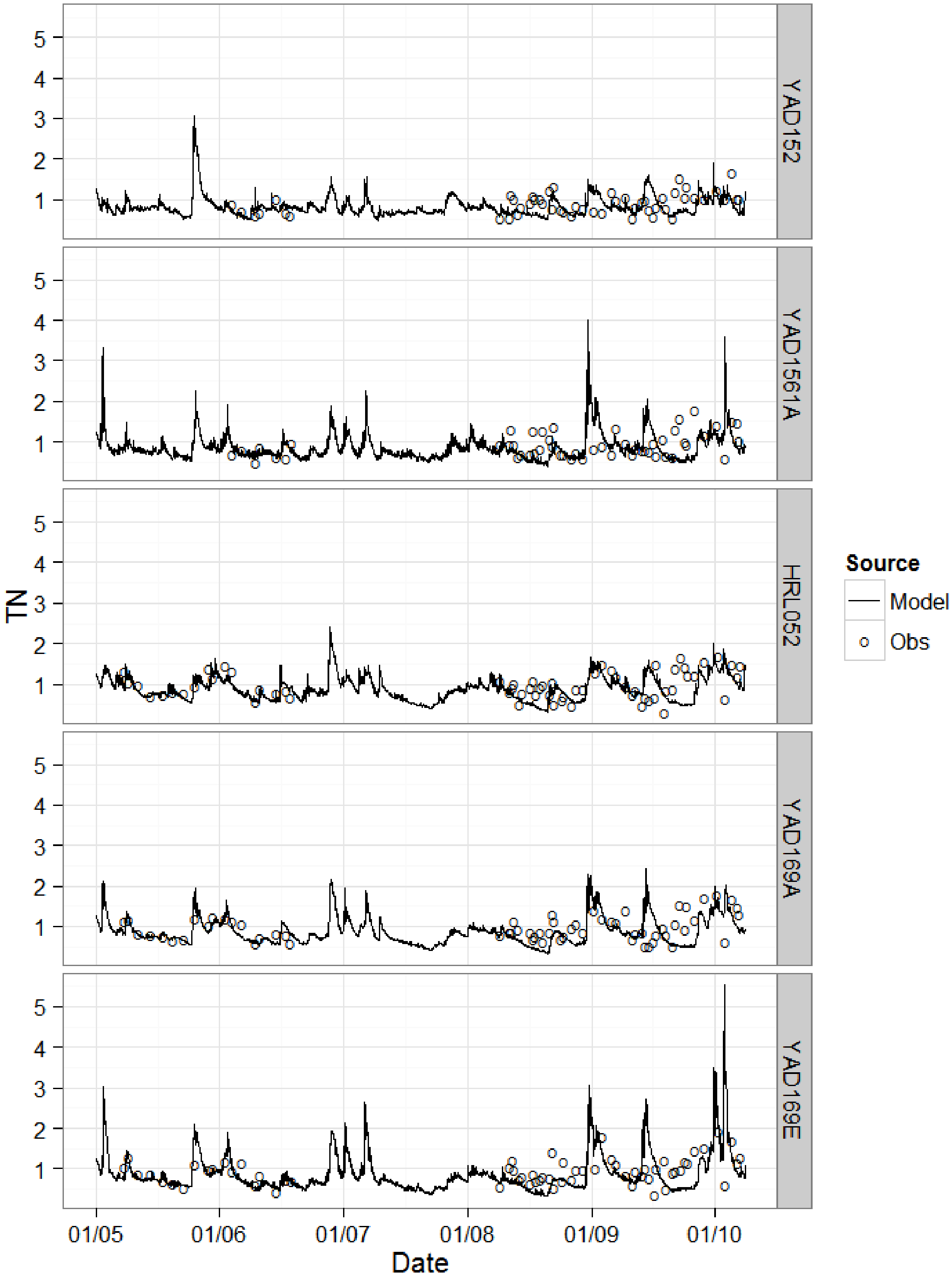

Figure 3-18. Total Nitrogen (mg/l) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake

Unlike phosphorus and total nitrogen, nitrite+nitrate nitrogen (NOx) has a more apparent seasonal pattern. This can be seen from both observed and model simulated NOx distributions throughout the lake (Figure 3-19 and Figure 3-20). Both RE and CV targets for a “good” quality simulation of NOx concentrations are met at the majority of stations during the model calibration and the validation periods (Table 3-13 and Table 3-14). Model simulated NOx concentrations also met the r target at some of the monitoring stations. However, the model under-predicted NOx concentrations at the majority of the stations during both the calibration and the validation periods. The discrepancies occur mainly in summer or early fall, likely due to under-estimated NOx loading or recycled sources in the Lake.

For ammonium nitrogen, observed concentrations are often at, near, or below the practical quantitation limit (with some exceptions), so the data are imprecise, and quantitative statistics are uninformative. As a result, only a qualitative visual fit is presented for ammonium nitrogen (Figure 3-21 through Figure 3-22). In general, the model is predicting the range of observed ammonium concentrations very well.

Table 3-13. Calibration Statistics for Nitrite+Nitrate Nitrogen (2008 – 2010)

Station	Count	Observed Mean (mg-N/L)	RE	RAE	CV	*r*	RMSE
HRL051 (Upper HRL above Swearing Cr)	45	0.81	-20.4%	48.3%	0.60	-0.17	0.49
YAD152A (Middle HRL at Town/Crane Cr)	45	0.61	-31.0%	52.3%	0.67	0.35	0.41
YAD152C (Middle HRL below Town/Crane Cr)	45	0.47	-18.1%	52.3%	0.72	0.48	0.34
YAD169B (Lower HRL below Abbotts Cr)	45	0.38	-28.8%	56.1%	0.81	0.50	0.31
YAD169F (Lower HRL at forebay)	45	0.34	-29.4%	54.9%	0.72	0.64	0.24
YAD152 (Town/Crane Cr Arm)	45	0.09	15.8%	89.3%	1.23	0.38	0.12
YAD1561A (Second Cr Arm)	45	0.22	-1.6%	56.9%	0.76	0.57	0.16
HRL052 (Upper Abbotts Cr Arm)	45	0.11	64.7%	79.7%	1.13	0.84	0.13
YAD169A (Lower Abbotts Cr Arm)	44	0.21	-12.6%	47.7%	0.67	0.69	0.14
YAD169E (Flat Swamp Cr Arm)	45	0.29	-21.6%	57.6%	0.78	0.56	0.23

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

Table 3-14. Validation Statistics for Nitrite+Nitrate Nitrogen (2005 – 2006)

Station	Count	Observed Mean (mg-N/L)	RE	RAE	CV	*r*	RMSE
HRL051 (Upper HRL above Swearing Cr)	18	0.75	-21.4%	35.0%	0.45	0.54	0.34
YAD152A (Middle HRL at Town/Crane Cr)	17	0.46	-7.2%	44.8%	0.55	0.74	0.25
YAD152C (Middle HRL below Town/Crane Cr)	18	0.50	-18.4%	37.7%	0.47	0.79	0.23
YAD169B (Lower HRL below Abbotts Cr)	18	0.42	-28.4%	42.8%	0.53	0.81	0.22
YAD169F (Lower HRL at forebay)	18	0.41	-33.7%	41.9%	0.55	0.83	0.22
YAD152 (Town/Crane Cr Arm)	7	0.05	115.6%	161.0%	2.13	0.22	0.11
YAD1561A (Second Cr Arm)	7	0.17	-14.1%	44.7%	0.61	0.73	0.10
HRL052 (Upper Abbotts Cr Arm)	17	0.23	-20.6%	58.6%	0.96	0.66	0.22
YAD169A (Lower Abbotts Cr Arm)	18	0.30	-36.3%	47.0%	0.63	0.81	0.19
YAD169E (Flat Swamp Cr Arm)	18	0.37	-30.9%	40.1%	0.51	0.84	0.19

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

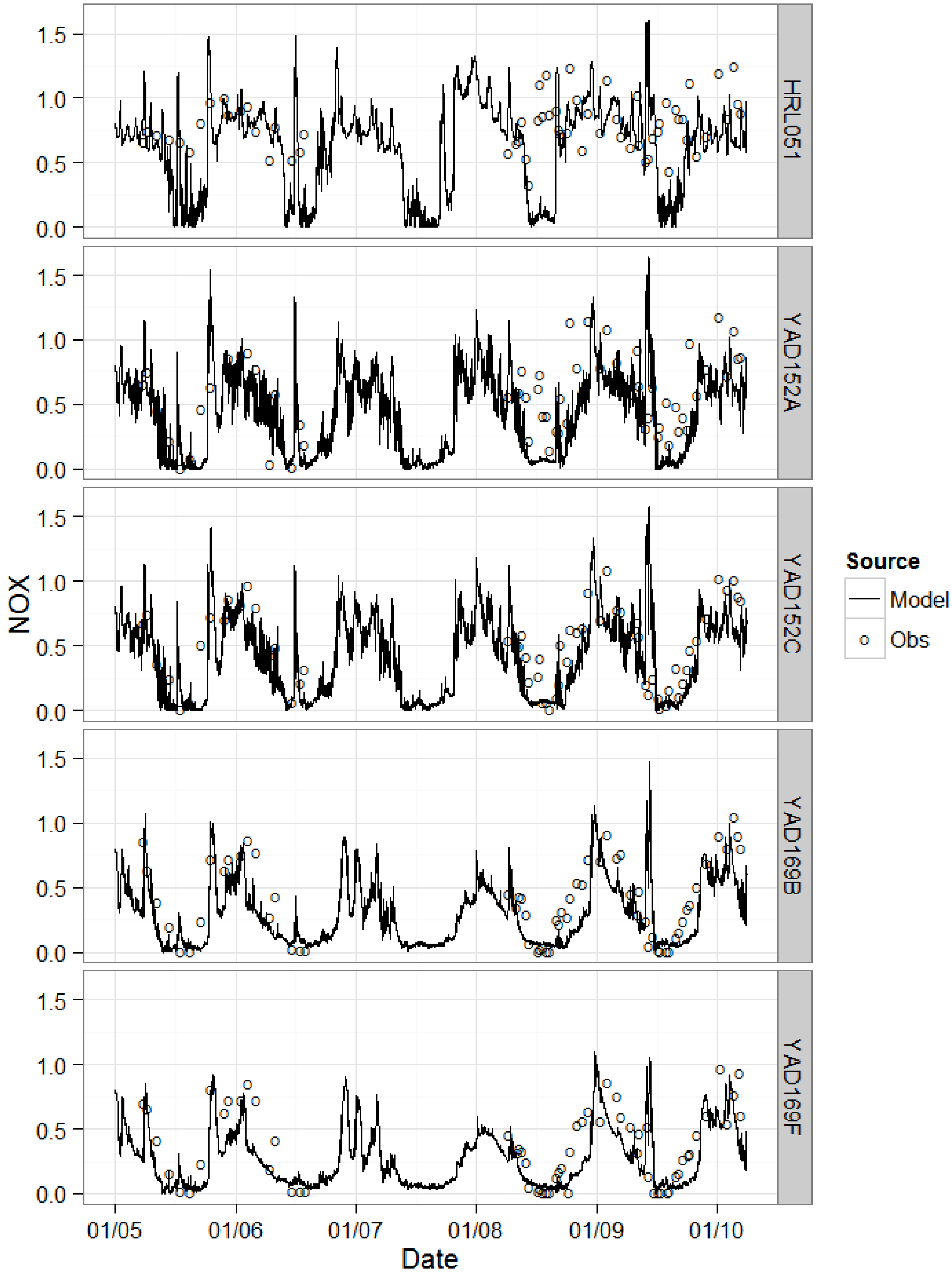

Figure 3-19. Nitrite+Nitrate Nitrogen (NOx, mg/l) calibration (2008-2010) and validation (2005-2006), main-stem stations in High Rock Lake

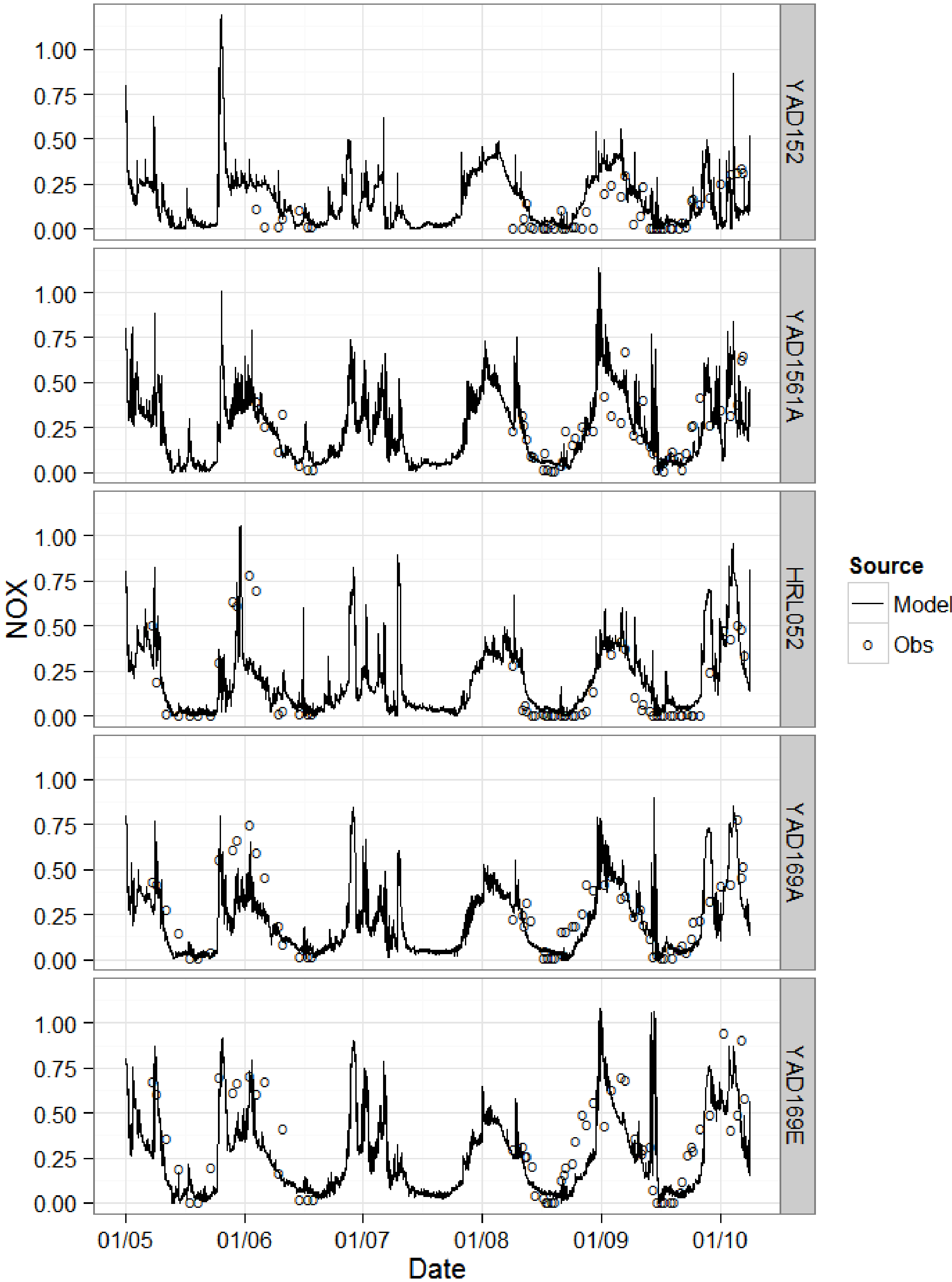

Figure 3-20. Nitrite+Nitrate Nitrogen (NOx, mg/l) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake

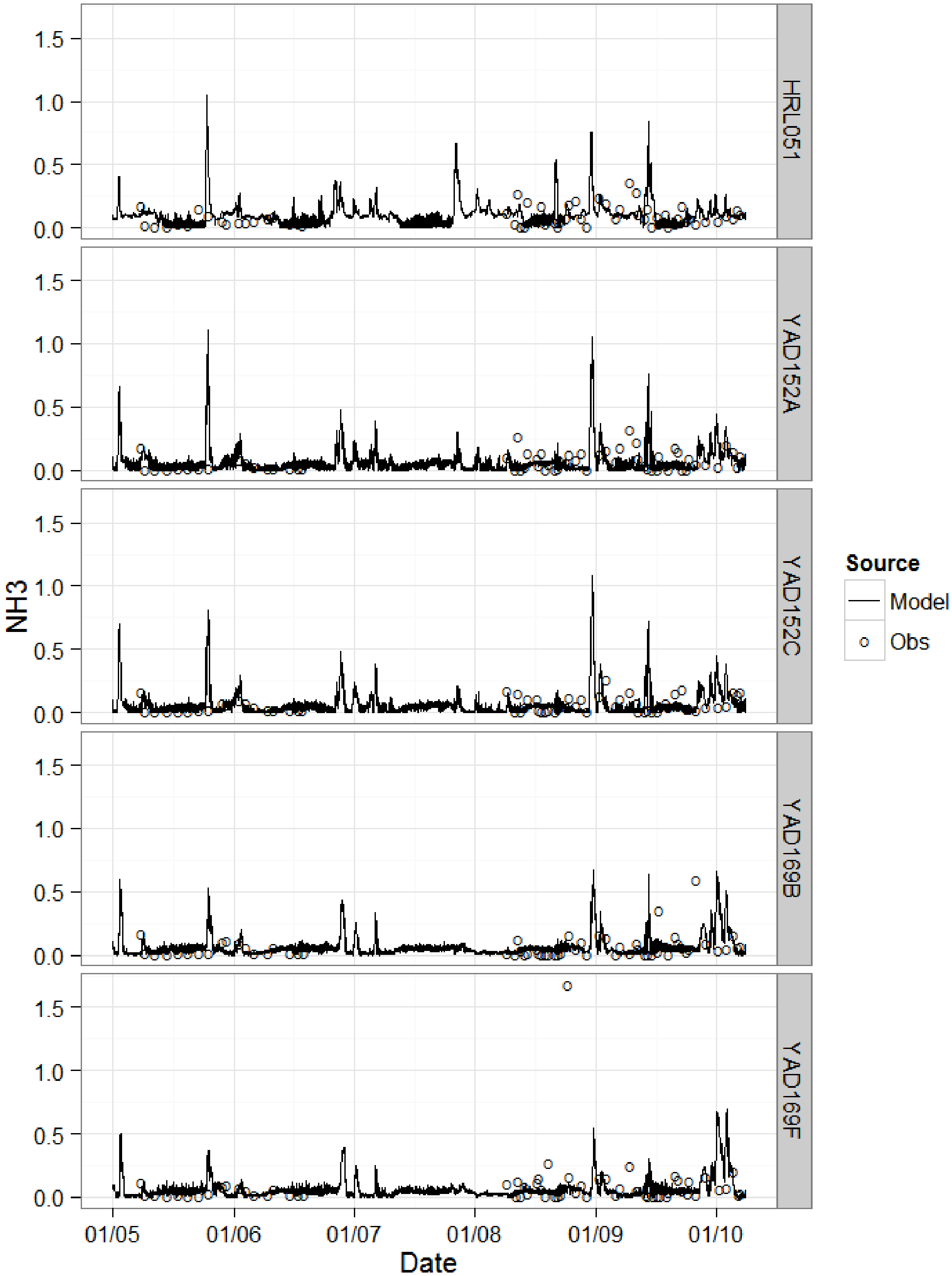

Figure 3-21. Ammonium Nitrogen (NH3, mg/l) calibration and validation, main-stem stations in High Rock Lake

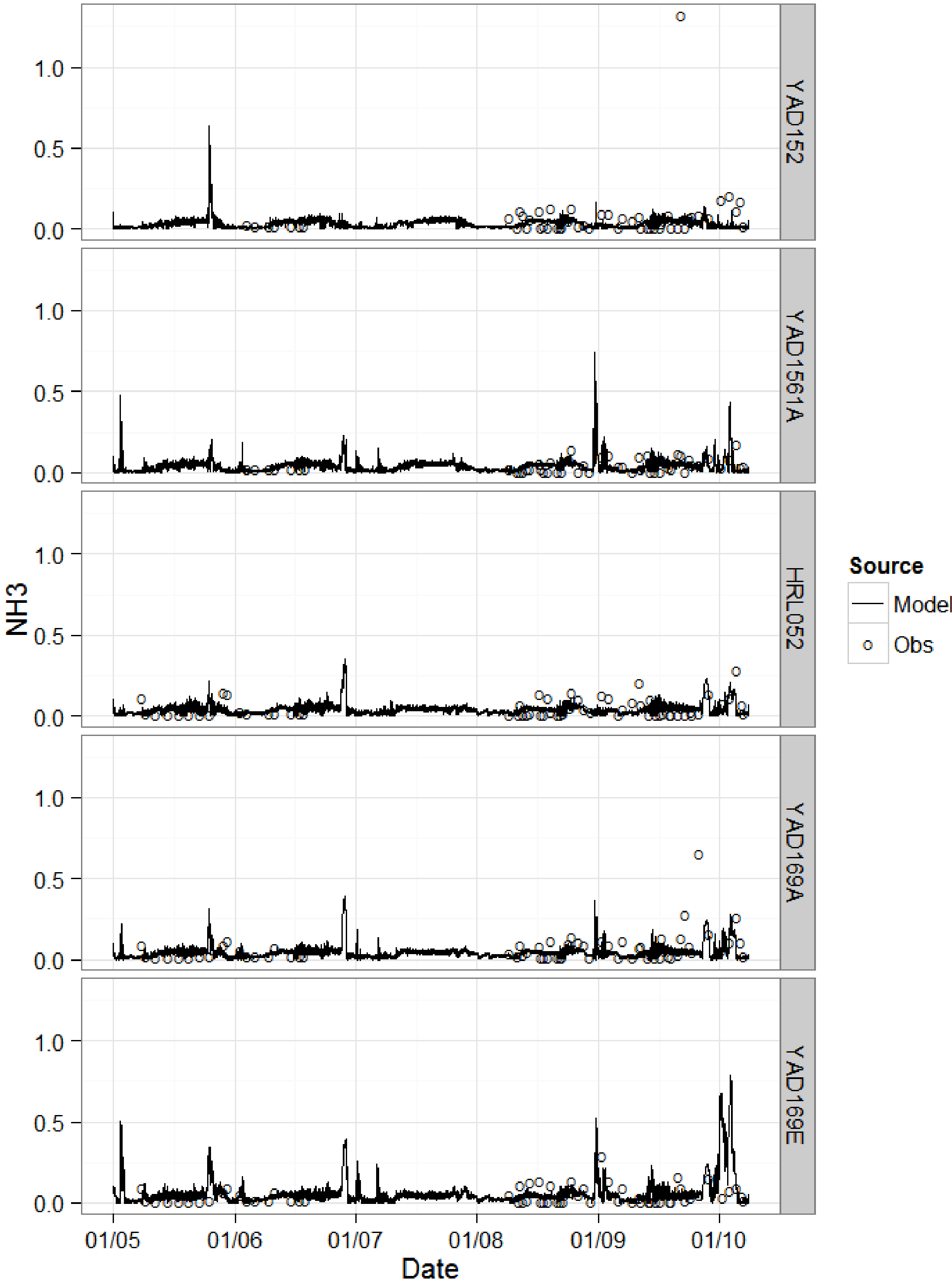

Figure 3-22. Ammonium Nitrogen (NH3, mg/l) calibration and validation, arm stations in High Rock Lake

3.3.3 ALGAE AND CHLOROPHYLL *A* CALIBRATION AND VALIDATION

WASP, as well as other comparable eutrophication models, predicts algal growth and density on the basis of biomass (expressed as organic carbon). Relevant monitoring, however, is conducted through measurements of chlorophyll *a* – the main photosynthetic pigment in algae. For comparisons of model simulation results to observed data it is assumed that biomass (as carbon) and chlorophyll *a* concentrations are related to one another in a fixed ratio. This is, however, known to be an imprecise approximation (Wool et al., 2001). First, chlorophyll *a* to organic carbon ratios are documented to vary systematically between different algal groups, with generally lower chlorophyll *a* to biomass ratios in blue-green algae. Second, within an individual algal species the chlorophyll *a* to biomass ratio is constantly changing over time to optimize the ability to use available light and nutrients. Also, obtaining a representative sample of chlorophyll *a* density in the water column is difficult due to the ability of some species to move vertically to optimize availability of light and nutrients while other species tend to float on the surface.

The algal community in High Rock Lake is dominated by different algal groups at different times of the year. Warm season populations are typically dominated by blue-green algae (cyanobacteria) and cold season populations tend to be dominated by diatoms (bacillariophytes) and green algae (chlorophytes), as described in Section 2.3.7. Two algal groups (the warm-water algae assembly and the cold-water algae assembly) are represented in the High Rock Lake model. The model calibration and validation process focus on the total algae, expressed as chlorophyll *a* concentrations.

Calibration statistics for the 2008-2010 intensive monitoring period (Table 3-15) show that observed chlorophyll *a* concentrations are fit fairly well. Model results at all stations meet the relative error target for a “good” quality of fit of 25 percent. In addition, nine of ten stations meet the CV target of less than or equal to 70%. The correlation coefficients between simulated and observed values do not meet the desired target except at the upper lake station of HRL051 and middle lake station of YAD152C, indicating that there is uncertainty in the prediction of individual observations especially in the lower lake and arms. This is evident from time series plots as well (Figure 3-23 and Figure 3-24). During the validation period of 2005 -2006, all stations meet the relative error target, nine stations meet the CV targets, and five stations meet the target for correlation coefficient for a “good” quality of fit (Table 3-16).

The model does a reasonable job of predicting the average and seasonal variation of chlorophyll *a* concentrations all year round, but not the timing and magnitude of individual algal bloom events – which is not surprising in a system where residence time is often less than a month. The model fit reflects the dynamic nature of the High Rock Lake system, in which lake conditions are strongly affected by the tributary boundary conditions. Collectively, Town/Crane Creek (YAD152), Second Creek (YAD1561A), and the middle of the lake (YAD152C and YAD152A) represent the most dynamically productive portion of the lake.

Table 3-15. Calibration Statistics for Chlorophyll *a* (2008 – 2010)

Station	Count	Observed Mean (µg/L)	RE	RAE	CV	r	RMSE
HRL051 (Upper HRL above Swearing Cr)	45	23.56	-6.3%	53.6%	0.71	0.77	16.80
YAD152A (Middle HRL at Town/Crane Cr)	45	37.04	-5.8%	41.1%	0.55	0.65	20.46
YAD152C (Middle HRL below Town/Crane Cr)	45	41.56	-18.3%	33.1%	0.45	0.71	18.74
YAD169B (Lower HRL below Abbotts Cr)	45	35.84	-12.0%	41.5%	0.53	0.44	19.06
YAD169F (Lower HRL at forebay)	45	30.06	0.6%	41.7%	0.54	0.52	16.12
YAD152 (Town/Crane Cr Arm)	45	46.22	-12.0%	46.3%	0.57	0.22	26.15
YAD1561A (Second Cr Arm)	45	47.09	-23.3%	38.0%	0.48	0.38	22.52
HRL052 (Upper Abbotts Cr Arm)	45	36.95	-3.0%	47.3%	0.59	0.10	21.62
YAD169A (Lower Abbotts Cr Arm)	44	33.58	5.7%	48.5%	0.64	0.12	21.64
YAD169E (Flat Swamp Cr Arm)	45	30.44	2.3%	42.6%	0.61	0.39	18.59

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

Table 3-16. Validation Statistics for Chlorophyll *a* (2005 – 2006)

Station	Count	Observed Mean (µg/L)	RE	RAE	CV	r	RMSE
HRL051 (Upper HRL above Swearing Cr)	14	18.36	11.7%	92.5%	1.28	0.81	23.57
YAD152A (Middle HRL at Town/Crane Cr)	13	33.00	5.1%	29.6%	0.39	0.89	12.99
YAD152C (Middle HRL below Town/Crane Cr)	14	33.36	2.5%	29.3%	0.37	0.86	12.39
YAD169B (Lower HRL below Abbotts Cr)	14	31.14	-2.6%	26.4%	0.34	0.76	10.58
YAD169F (Lower HRL at forebay)	14	25.57	7.2%	47.0%	0.54	0.25	13.78
YAD152 (Town/Crane Cr Arm)	7	44.29	-12.1%	28.7%	0.36	0.07	15.78
YAD1561A (Second Cr Arm)	7	42.00	-9.3%	21.4%	0.23	0.77	9.67
HRL052 (Upper Abbotts Cr Arm)	14	34.14	22.5%	42.5%	0.52	0.23	17.80
YAD169A (Lower Abbotts Cr Arm)	14	34.57	7.5%	44.3%	0.50	0.17	17.23
YAD169E (Flat Swamp Cr Arm)	14	27.50	-0.2%	38.2%	0.51	0.20	13.90

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

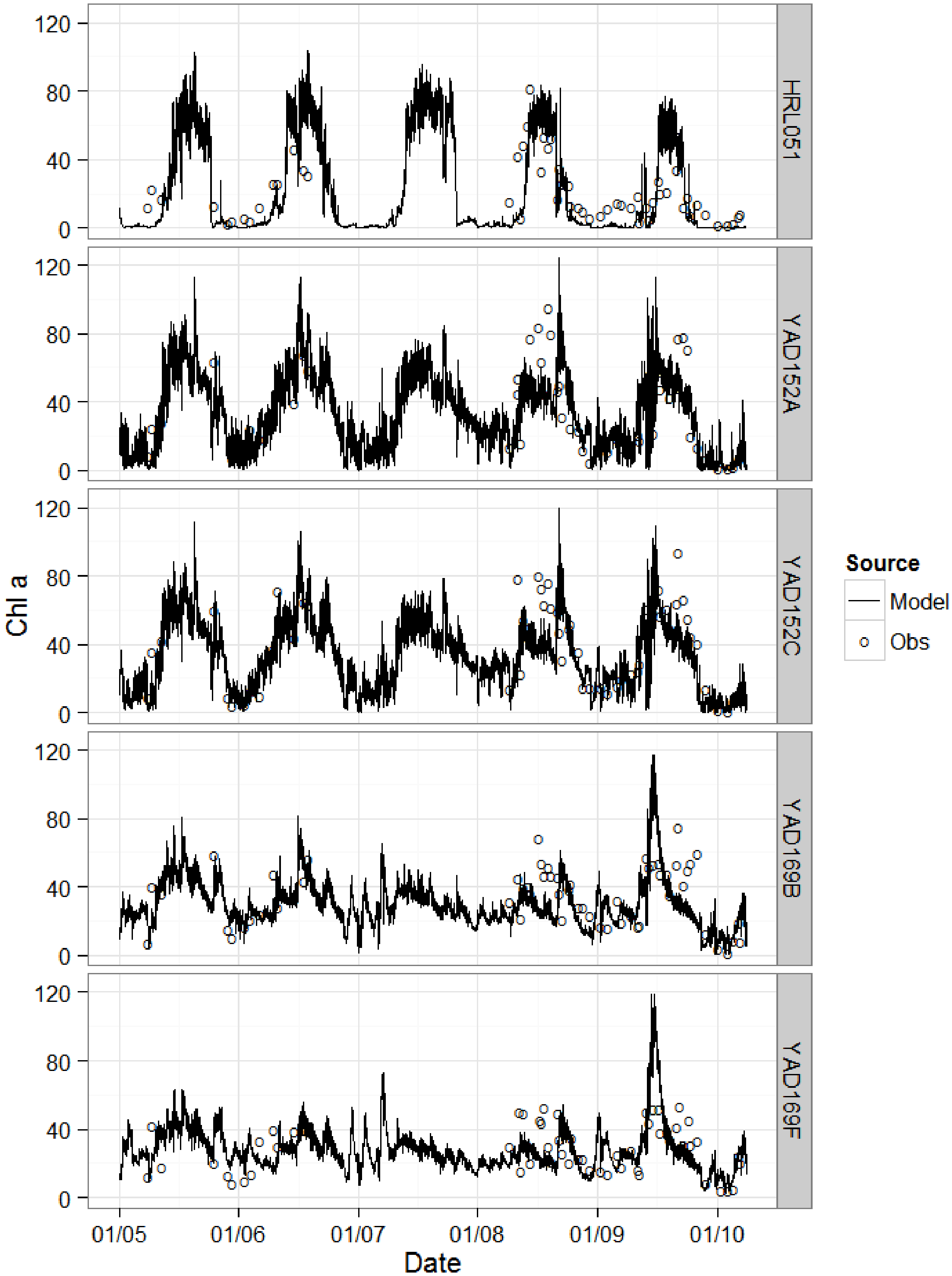

Figure 3-23. Chlorophyll *a* (Chl *a*, µg/l) calibration (2008-2010) and validation (2005-2006), main-stem stations in High Rock Lake

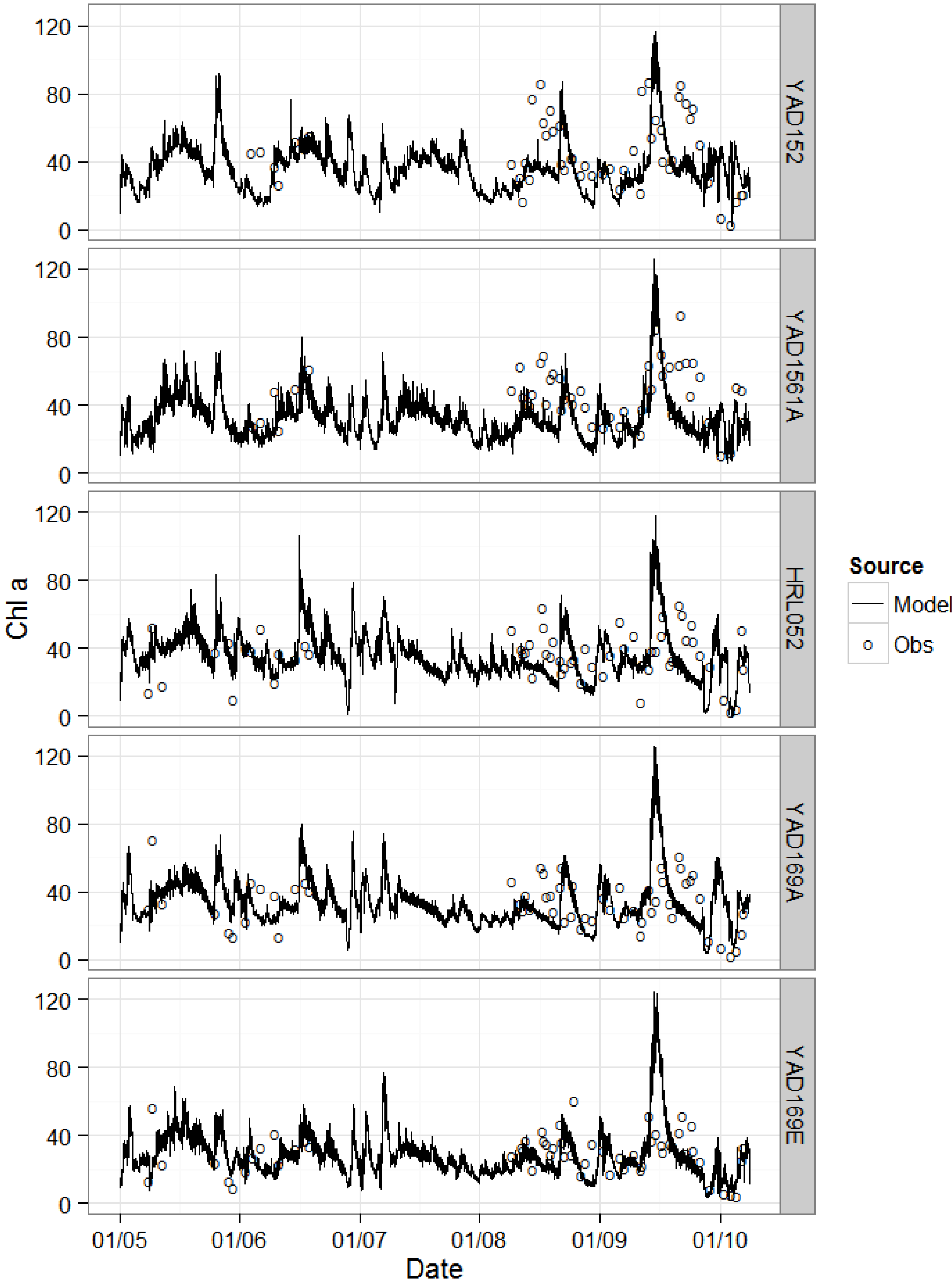

Figure 3-24. Chlorophyll *a* (Chl *a*, µg/l) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake

3.3.3.1 Chlorophyll *A* Exceedance Rate

Another way to evaluate the model's performance with regards to predicting chlorophyll *a* is to compare the model predicted chlorophyll *a* water quality standard exceedance rates to observed field data exceedance rates. Figure 3-25 shows comparisons of the percent exceedance rate between field data and model simulated results. The red shaded areas include predictions and observations over 10% exceedance of the existing 40 µg/l chlorophyll *a* water quality standard.

Sampling frequencies from field data (in general, more frequent samples were collected during warm seasons than during cold seasons from 2005 to 2009) are different from those by the model (output at four times per day throughout the year from 2005 to 2009). In addition, there was no data collected during 2007. Slightly lower curves (less exceedance rates for high chlorophyll *a* values) are therefore expected from model predictions than from the observations. This trend is shown in all stations in Figure 3-25 except at station HRL051 (upstream High Rock Lake) where the model seems under-predicted at low observed chlorophyll *a* levels and over-predicted when observed chlorophyll *a* concentrations were higher (than ~30 µg/l), and at station YAD1561A (Second Creek), where the model under-prediction of the exceedance rate appears to be beyond the difference that is caused by the different sampling frequency. The pattern discussed above suggests reasonable model representation of chlorophyll *a* exceedance rates in the middle toward downstream part of High Rock Lake and Abbotts Creek.

Figure 3-25 also suggests that the model uncertainty on predicting the timing and magnitude of individual bloom events likely will not affect lake management decisions suggested by model results, since any over-prediction falls in the 10% chlorophyll *a* standard exceedance rate.

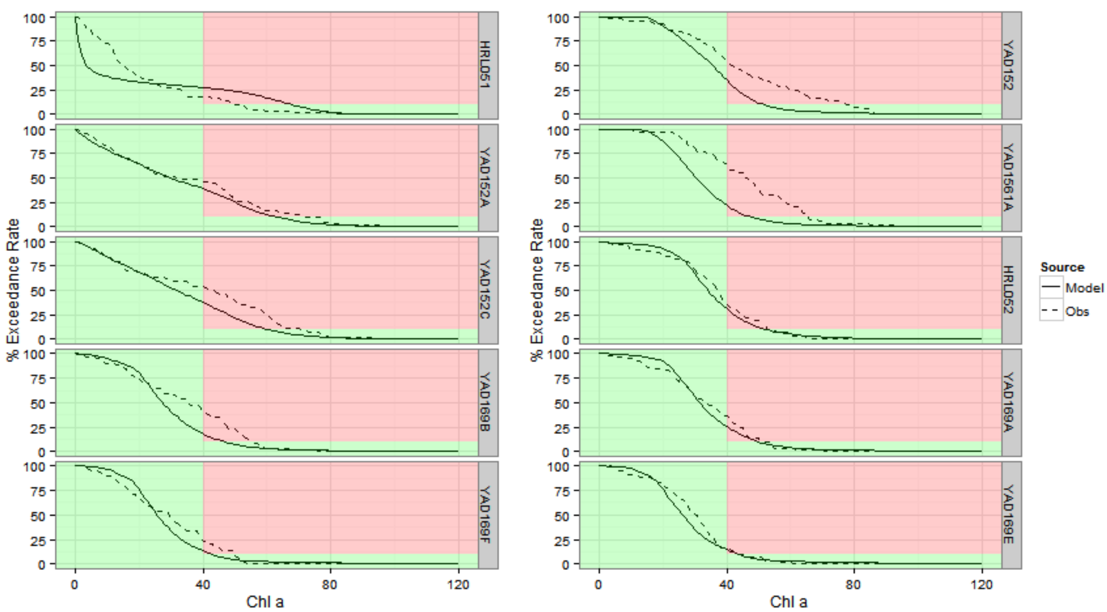

Figure 3-25. Chlorophyll *a* exceedance rate distributions in High Rock Lake

3.3.4 Dissolved Oxygen Calibration and Validation

Dissolved oxygen observations were collected at different depths of monitoring stations. Model predicted DO concentrations at the surface layer of the model cell are used to compare with the observations within one meter from water surface at each monitoring station.

During both the model calibration and validation periods, the model does a good job predicting the average and the seasonal trend of dissolved oxygen concentrations. Statistics (Table 3-17 and Table 3-18) show that the results at all stations meet the RE and the CV targets for a "good" quality of fit. In fact, the RE and CV statistics are far less than their targets of 25% and 70%, respectively, indicating good confidence in model performance in predicting average and range of DO concentrations. However, the correlation coefficient target is not met at the majority of the stations, suggesting lack of model fit for individual events. Time series plots also lead to similar conclusions (Figure 3-26 and Figure 3-27).

Table 3-17. Calibration Statistics for Dissolved Oxygen (2008 – 2010)

Station	Count	Observed Mean (µg/L)	RE	RAE	CV	r	RMSE
HRL051 (Upper HRL above Swearing Cr)	90	8.40	0.3%	10.3%	0.13	0.80	1.12
YAD152A (Middle HRL at Town/Crane Cr)	90	9.29	-0.9%	14.9%	0.18	0.47	1.72
YAD152C (Middle HRL below Town/Crane Cr)	90	9.76	-6.6%	15.7%	0.20	0.35	1.96
YAD169B (Lower HRL below Abbotts Cr)	90	9.55	-8.6%	16.8%	0.23	0.44	2.20
YAD169F (Lower HRL at forebay)	89	8.64	0.5%	14.6%	0.19	0.72	1.64
YAD152 (Town/Crane Cr Arm)	90	8.86	0.0%	17.9%	0.23	0.52	2.00
YAD1561A (Second Cr Arm)	89	9.10	-0.3%	17.5%	0.22	0.51	2.00
HRL052 (Upper Abbotts Cr Arm)	90	8.61	0.1%	14.4%	0.18	0.71	1.58
YAD169A (Lower Abbotts Cr Arm)	88	8.51	2.7%	16.7%	0.22	0.53	1.88
YAD169E (Flat Swamp Cr Arm)	90	8.86	-1.6%	13.9%	0.18	0.68	1.59

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

Table 3-18. Validation Statistics for Dissolved Oxygen (2005 – 2006)

Station	Count	Observed Mean (µg/L)	RE	RAE	CV	r	RMSE
HRL051 (Upper HRL above Swearing Cr)	36	8.44	5.7%	15.1%	0.20	0.48	1.73
YAD152A (Middle HRL at Town/Crane Cr)	37	11.06	-12.9%	16.5%	0.21	0.02	2.37
YAD152C (Middle HRL below Town/Crane Cr)	37	10.92	-10.6%	17.7%	0.22	-0.03	2.44
YAD169B (Lower HRL below Abbotts Cr)	38	10.65	-17.8%	23.5%	0.28	-0.31	2.95
YAD169F (Lower HRL at forebay)	35	10.23	-14.2%	22.5%	0.26	-0.13	2.65
YAD152 (Town/Crane Cr Arm)	14	10.44	-20.8%	21.6%	0.27	-0.14	2.80
YAD1561A (Second Cr Arm)	13	10.78	-20.9%	23.4%	0.31	-0.27	3.32
HRL052 (Upper Abbotts Cr Arm)	36	9.90	-12.2%	18.5%	0.22	0.41	2.16
YAD169A (Lower Abbotts Cr Arm)	36	9.81	-11.9%	21.8%	0.25	0.20	2.43
YAD169E (Flat Swamp Cr Arm)	35	10.36	-16.0%	21.5%	0.25	0.06	2.56

Note: RE = relative error, RAE = relative absolute error, CV = coefficient of variation, r = correlation coefficient, RMSE = root mean squared error.

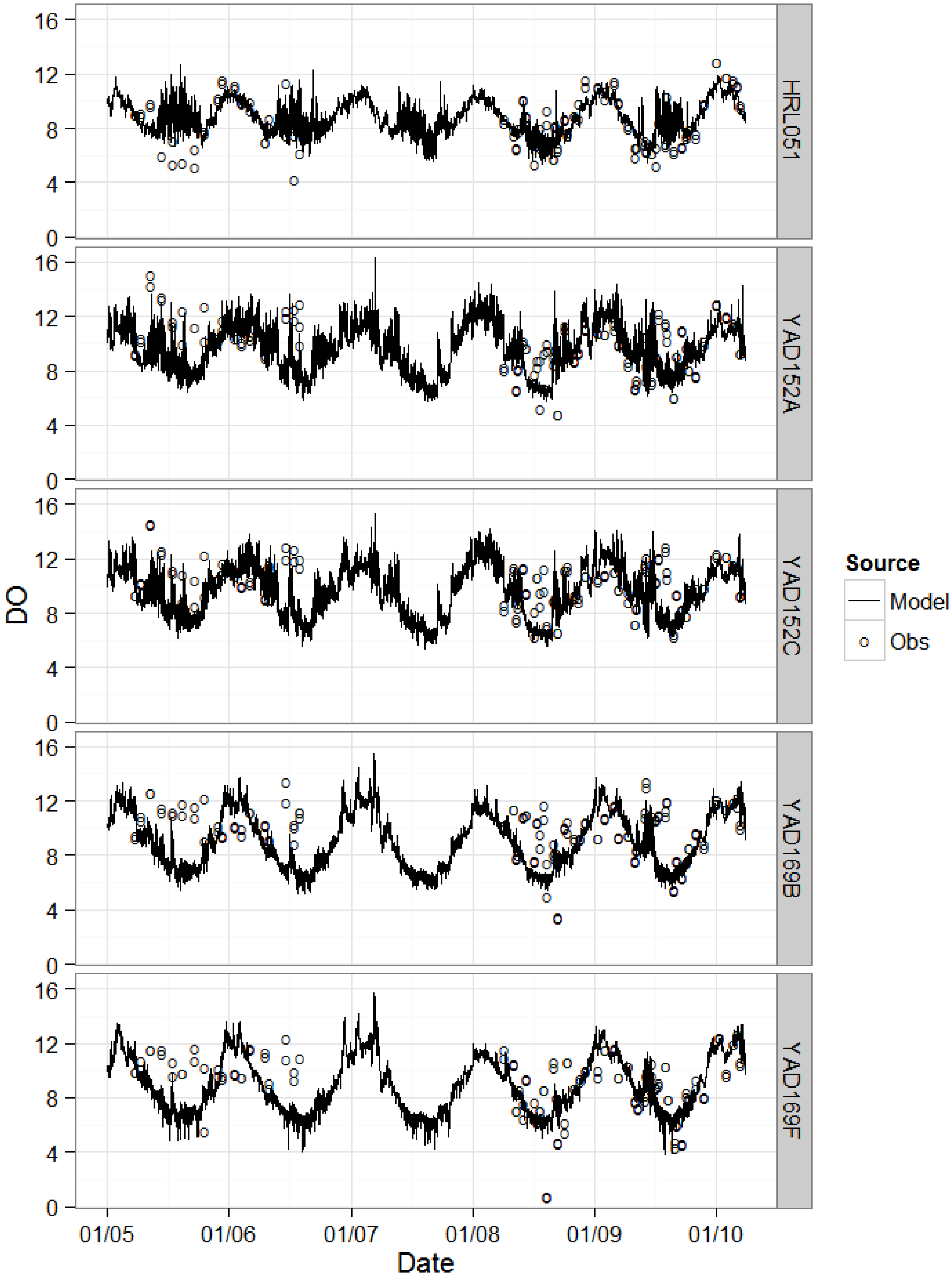

Figure 3-26. Dissolved Oxygen (DO, mg/l) calibration (2008-2010) and validation (2005-2006), main-stem stations in High Rock Lake

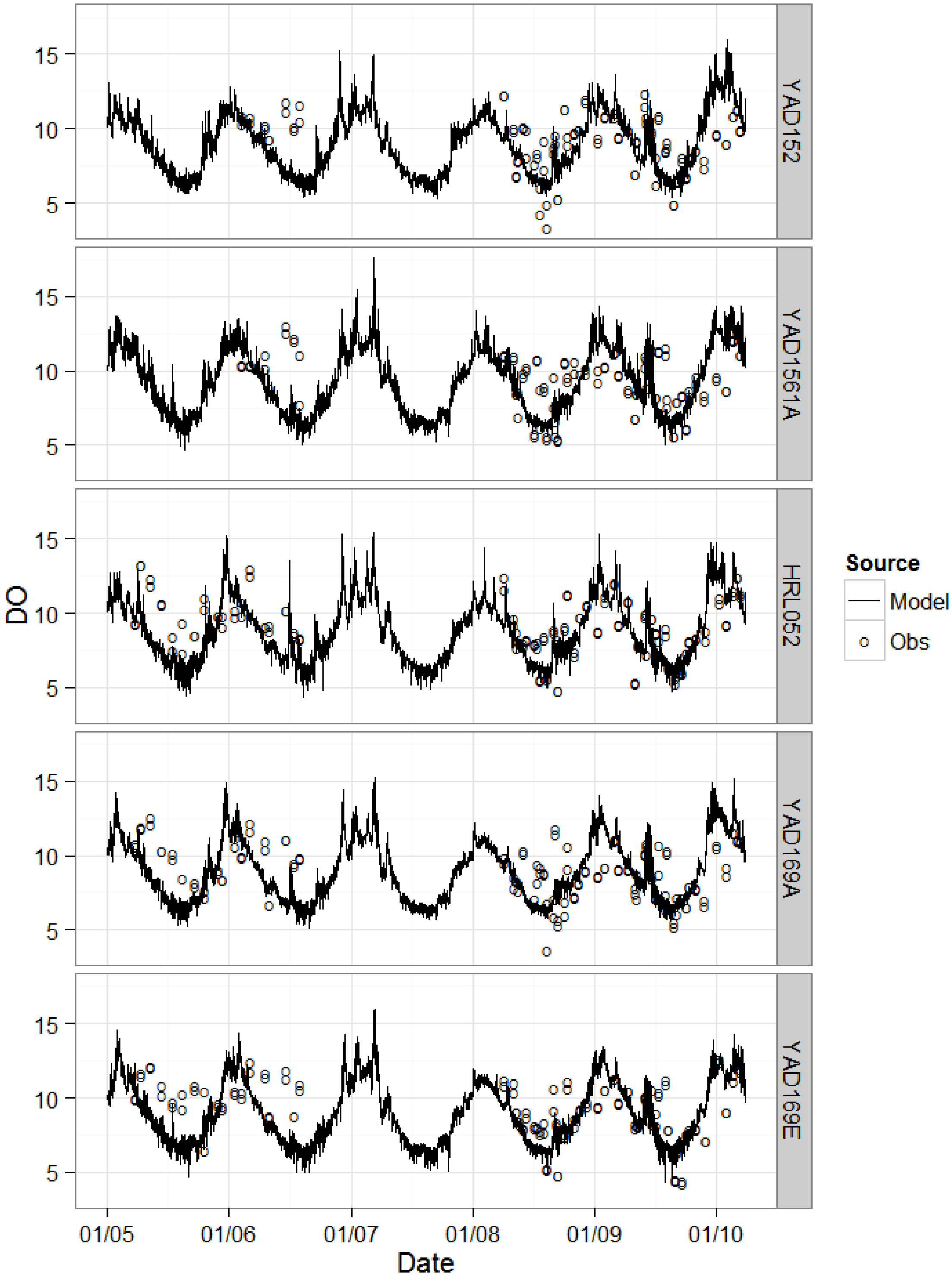

Figure 3-27. Dissolved Oxygen (DO, mg/l) calibration (2008-2010) and validation (2005-2006), arm stations in High Rock Lake

4 Model Application

4.1 Limiting Factors on Algal Growth

Inputs that determine chlorophyll *a* response in the lake are primarily flow, nutrient load (nitrogen and phosphorus), and light availability, which is strongly affected by fine sediment load. To provide the linkage necessary to evaluate potential options to control algal growth, it is important to understand the degree to which different factors control algal growth in the lake. The maximum potential growth rate of algae is limited by light, nutrients, and flushing of algae downstream. Specifically, the maximum potential growth rate at a given temperature is reduced by a multiplicative factor between zero and one that represents the degree to which light is less than the optimum and another factor that represents the lower of the limitations due to insufficient inorganic nutrients, while losses are caused by algal death, settling, predation, and losses to advection downstream. The light and nutrient limitation factors for algal group 1 predicted by the model are shown for the top layer at three stations spanning the centerline of the lake in Figure 4-1 through Figure 4-3. Light is limiting most of the time with seasonal and event-driven fluctuations. Light limitation is more severe at the upper lake station (HRL051), reflecting the relatively high turbid nature in the Yadkin River. Significant nutrient limitations occur occasionally in the upper lake with nitrogen more limiting than phosphorus in some of the years (e.g. summer 2007) and phosphorus more limiting in others (e.g. summer 2008). Moving downstream to station YAD152C (middle lake), limitation by phosphorus is more frequent during the growing season, except during some years (e.g. 2005), when co-limitation by both nitrogen and phosphorus was predicted. Finally, at the forebay (YAD169F), phosphorus is usually limiting on algal growth. This downstream progression is similar to the trends seen in the observed data. Temporally, phosphorus is predicted to provide strong limitation at the forebay and mid-lake in late summer of most years.

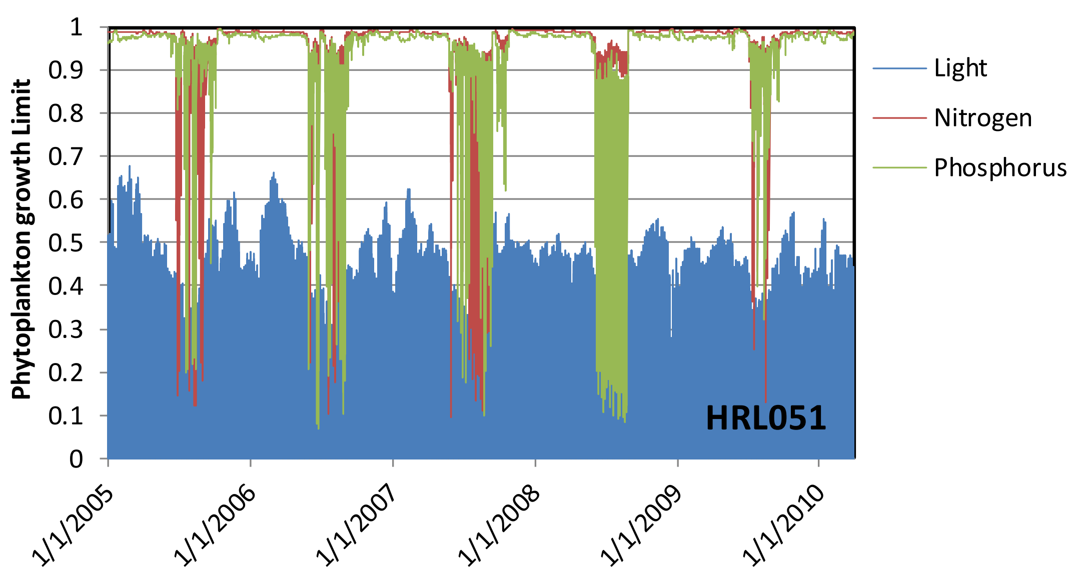

Figure 4-1. Factors Limiting Phytoplankton Growth in Upper High Rock Lake (HRL051)

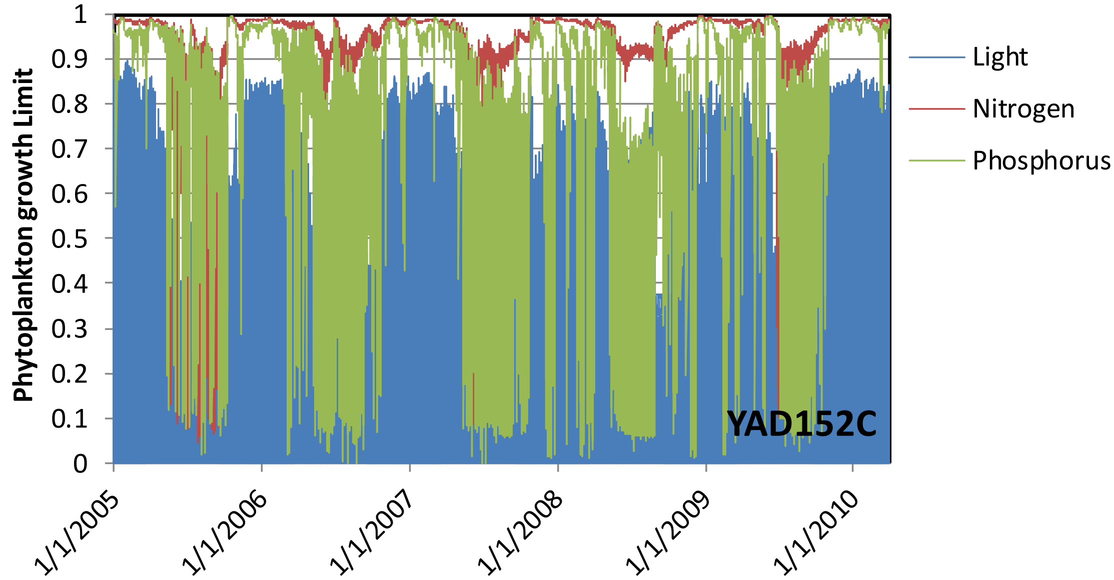

Figure 4-2. Factors Limiting Phytoplankton Growth in Middle High Rock Lake (YAD152C)

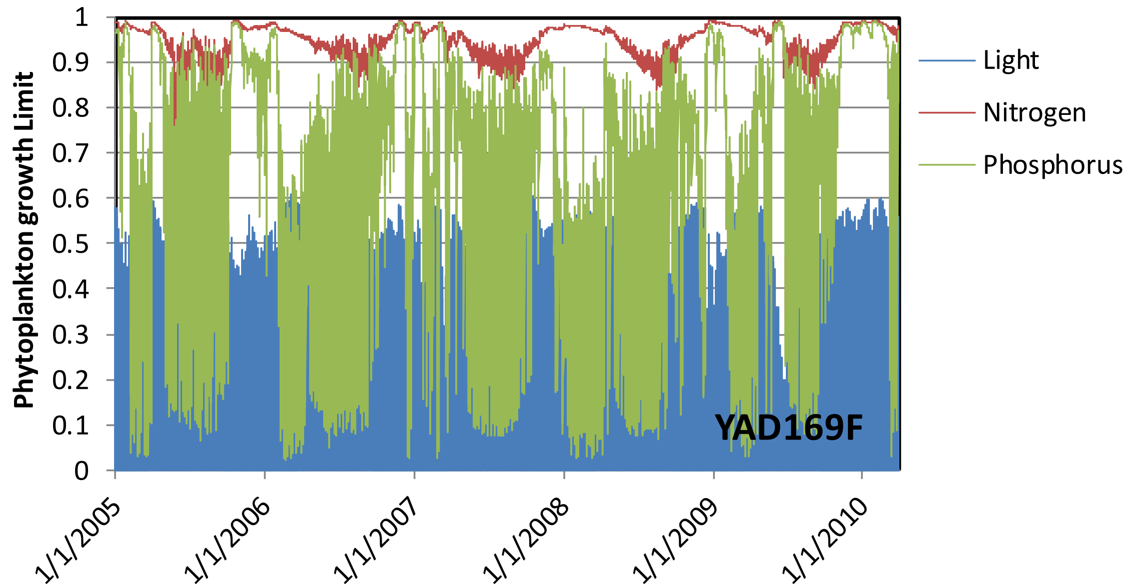

Figure 4-3. Factors Limiting Phytoplankton Growth in Lower High Rock Lake (YAD169F)

5 Summary

This report documents the development and calibration of the High Rock Lake nutrient response model. It does not address any scenario applications of the model for calculating reduction targets or investigating impacts of different potential management strategies.

As described in the preceding sections, a linked set of hydrodynamic and water quality response models has been developed and calibrated for High Rock Lake. The hydrodynamic model appears to perform well, and simulations of water temperature are satisfactory.

For nutrients and algae, the model has a low amount of bias and meets most targets for a "good" quality simulation in terms of relative error and coefficient of variation. Correlation coefficients between observed and daily simulated concentrations of nutrients and chlorophyll *a* are, however, generally low – suggesting a limited ability to predict individual algal blooms in this dynamic water body. Short residence times in the lake (5 – 40 days) imply a system in which response to nutrient loads is very sensitive to variations in boundary conditions and difficult to predict on a day-to-day basis.

As currently developed, the High Rock Lake eutrophication model provides valuable insights into the dynamics of nutrient and algal response in High Rock Lake and can provide a reasonable estimation of chlorophyll *a* responses to different nutrient loads in High Rock Lake.

6 References

APGI. 2002. Yadkin Hydroelectric Project FERC No. 2197, NC Project Relicensing, Initial Consultation Document. September 2002. Alcoa Power Generating, Inc., Yadkin Division, Badin, NC.

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

APGI. 2006b. Yadkin Hydroelectric Project FERC No. 2197, Application for License, Volume IV, Appendix E-2: Water Use and Water Quality. Alcoa Power Generating Inc., Yadkin Project.

Bennett, A.F. 1976: Open boundary conditions for dispersive waves. *J. Atmos. Sci.*, 32: 176-182.

Bennett, A.F., and P.C. McIntosh, 1982: Open ocean modeling as an inverse problem: tidal theory. *J. Phys. Ocean.*, 12: 1004-1018.

Bennett, J.R. and A.H. Clites, 1987: Accuracy of trajectory calculation in a finite-difference circulation model. *J. Comp. Phys.*, 68: 272-282.

Blumberg, A.F., and L.H. Kantha, 1985: Open boundary condition for circulation models. *J. Hydr. Engr*., 111: 237-255.

Blumberg, A.F., and G.L. Mellor, 1987: A description of a three-dimensional coastal ocean circulation model. In: *Three-Dimensional Coastal Ocean Models, Coastal and Estuarine Science,* Vol. 4. (Heaps, N. S., ed.) American Geophysical Union, pp. 1-19.

Cleveland, W.S., and S.J. Devlin. 1988. Locally-weighted regression: An approach to regression analysis by local fitting. *Journal of the American Statistical Association,* 83 (403): 596–610

Cole, T.M., and E.M. Buchak. 1995. CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 2.0 User Manual. U.S. Army Corps of Engineers. Instruction Report EL-95-1, June, 1995. Washington, DC.

Connolly, J.P., and R. Winfield. 1984. A User's Guide for WASTOX, a Framework for Modeling the Fate of Toxic Chemicals in Aquatic Environments. Part 1: Exposure Concentration. EPA-600/3-84-077. U.S. Environmental Protection Agency, Gulf Breeze, FL.

Copeland, R.R. 2007. Numerical Sedimentation Investigation, Yadkin River, North Carolina. Prepared for Salisbury-Rowan Utilities by Mobile Boundary Hydraulics, Clinton, MS.

Di Toro, D.M., J.J. Fitzpatrick, and R.V. Thomann. 1981, rev. 1983. Water Quality Analysis Simulation Program (WASP) and Model Verification Program (MVP) - Documentation. Hydroscience, Inc., Westwood, NY, for U.S. EPA, Duluth, MN, Contract No. 68-01-3872.

Di Toro, D.M., D.J. O'Connor, and R.V. Thomann. 1971. A Dynamic Model of the Phytoplankton Population in the Sacramento San Joaquin Delta. *Adv. Chem. Ser*. 106, Am. Chem. Soc., Washington, DC., pp. 131-180.

DWR. 2016. High Rock Lake Technical Advisory Committee Draft Lake Response Models Review Comments and Responses, October 27, 2016. https://ncdenr.s3.amazonaws.com/s3fs-public/Water%20Quality/Planning/TMDL/Internal%20files/High%20Rock%20Lake%20Model%20Review_10272016.2.pdf

EPA. 1990. Technical Guidance Manual for Performing Waste Load Allocations, Book III: Estuaries, Part 2: Application of Estuarine Waste Load Allocation Models. Office of Water, U.S. Environmental Protection Agency, Washington, DC.

EPA. 1997. Technical Guidance Manual for Developing Total Maximum Daily Loads, Book II: Streams and Rivers, Part I: Biochemical Oxygen Demand/Dissolved Oxygen and Nutrients/Eutrophication. Office of Science and Technology, U.S. Environmental Protection Agency, Washington, DC.

Galperin, B., L.H. Kantha, S. Hassid, and A. Rosati, 1988: A quasi-equilibrium turbulent energy model for geophysical flows. *J. Atmos. Sci.,* 45: 55-62.

Hamrick, J.M., 1992. A Three-Dimensional Environmental Fluid Dynamics Computer Code: Theoretical and Computational Aspects. Special Report No. 317 in Applied Marine Science and Ocean Engineering. Virginia Institute of Marine Science, The College of William and Mary, Gloucester Point, VA.

Hamrick, J.M. 1996. User's Manual for the Environmental Fluid Dynamics Code. Special Report No. 331 in Applied Marine Science and Ocean Engineering. Virginia Institute of Marine Science, The College of William and Mary, Gloucester Point, VA.

Johnson, B.H., K.W. Kim, R.E. Heath, B.B. Hsieh, and H.L. Butler, 1993: Validation of three-dimensional hydrodynamic model of Chesapeake Bay. *J. Hyd. Engrg*., 119: 2-20.

Kirk, J.T.O. 1994. *Light and Photosynthesis in Aquatic Systems*. Cambridge University Press, Cambridge.

LimnoTech. 2010. Data Collection in Support of Upper Yadkin River Watershed-High Rock Lake Chlorophyll-*a* and Turbidity TMDL Modeling, Final Report. Prepared for North Carolina Department of Environment and Natural Resources.
http://portal.ncdenr.org/c/document_library/get_file?uuid=901501d5-6df3-4815-8747-a24401782703&groupId=38364

Mellor, G. L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys.*, 20: 851-875.

Mellor, G.L., T. Ezer, and L.-Y. Oey. 1994. The pressure gradient conundrum of sigma coordinate ocean models. *Journal of Atmospheric and Oceanic Technology*, 11: 1126–1134.

Mellor, G.L., L.-Y. Oey, and T. Ezer, 1998. Sigma coordinate pressure gradient errors and the seamount problem. *Journal of Atmospheric and Oceanic Technology*, 15: 1122 – 1131.

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

NCDENR. 2014. NC 2014 Integrated Report. North Carolina Department of Environment & Natural Resources, Division of Water Quality. Raleigh, NC.

Normandeau. 2004. Sediment Fate and Transport Report. Alcoa Power Generating Inc., Yadkin Division, Yadkin Project Relicensing (FERC No. 2197). Prepared by Normandeau Associates, Inc. and PB Power.

Schwede, D., R. Dennis, and M. Bitz. 2009. The Watershed Deposition Tool: A tool for incorporating atmospheric deposition in water-quality analyses. *Journal of the American Water Resources Association*, 45(4): 973-985.

Smith 1980 . The theoretical basis for estimating phytoplankton production and specific growth rate from chlorophyll, light and temperature data. *Ecological Modeling*,10:243-264.

Smolarkiewicz, P.K. and L.G. Margolin, 1993: On forward-in-time differencing for fluids: extension to a curvilinear framework. *Mon. Weather Rev.*, 121: 1847-1859.

Steele, J.H. 1962. Environmental control of photosynthesis in the sea. *Limnol. Oceanogr*., 7:137 150.

Tetra Tech. 2006. EFDC Technical Memorandum; Theoretical and Computational Aspects of the Generalized Vertical Coordinate Option in the EFDC Model. Prepared for USEPA Region 4. Tetra Tech, Inc., Fairfax, VA.

Tetra Tech. 2012. High Rock Lake Watershed Model. Prepared for U.S. Environmental Protection Agency, Region 4 and NC Division of Water Quality by Tetra Tech, Inc., Research Triangle Park, NC. http://deq.nc.gov/about/divisions/water-resources/planning/modeling-assessment/special-studies#HRL

Tetra Tech. 2013. High Rock Lake Technical Advisory Committee Draft Lake Response Models Review Comments and Responses. Prepared for U.S. Environmental Protection Agency, Region 4 and NC Division of Water Quality by Tetra Tech, Inc., Research Triangle Park, NC. https://ncdenr.s3.amazonaws.com/s3fs-public/Water%20Quality/Planning/TMDL/Special%20Studies/High%20Rock%20Lake/Response%20to%20TAC%20Lake%20Model%20Review%20Comments_March2015.pdf

Watermark Numerical Computing. 2002. PEST, Model-Independent Parameter Estimation. (http://www.pesthomepage.org/Home.php)

Wetzel, R.G. 2001. *Limnology: Lake and River Ecosystems*, 3rd Edition. Academic Press, San Diego.

Wool, T., R.B. Ambrose, J.L. Martin, and E.A. Comer. 2001. Water Quality Analysis Simulation Program (WASP) Version 6.0, DRAFT: User's Manual. U.S. Environmental Protection Agency, Region 4, Atlanta, GA.

Zou, R. and W.S. Lung. 2004. Robust water quality modeling using alternating fitness genetic algorithm. *Journal of Water Resource Planning and Management, ASCE*, 130(6): 471-479.

Appendix A. Model Calibration and Validation Stations

Monitoring Stations	EFDC Cell Number (I – J –K)	WASP Cell Number (surface layer)
HRL051	56 -46 -5	472
YAD152A	65 -38 -5	343
YAD152C	66 -34 -5	308
YAD169B	65 -18 -5	118
YAD169F	66 -9 -5	7
YAD152	79 -47 -5	501
YAD1561A	54 -29 -5	247
HRL052	78 -24 -5	196
YAD169A	73 -21 -5	155
YAD169E	68 -10 -5	20