Appendix B
EFDC Hydrodynamic and Water Quality Model

Draft
Lake Thunderbird TMDL Report

Prepared for
Oklahoma Department of Environmental Quality
Water Quality Division

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By

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PLEASE NOTE !

THIS IS A PRELIMINARY DRAFT DOCUMENT THAT HAS BEEN SUBMITTED TO EPA FOR TECHNICAL REVIEW ONLY. IT IS NOT THE DRAFT TMDL THAT WILL BE PROPOSED FOR ADOPTION. CHANGES WILL BE MADE AFTER THE EPA REVIEW. IN THE INTEREST OF FULL TRANSPARENCY, IT IS BEING RELEASED FOR INTERESTED PARTIES TO READ. DEQ IS NOT ACCEPTING COMMENTS ON THIS DOCUMENT AND WILL NOT RESPOND TO QUESTIONS REGARDING ITS CONTENTS. FOLLOWING EPA CONCURRENCE, DEQ WILL RELEASE A REVISED DRAFT TMDL FOR A FULL PUBLIC REVIEW AND COMMENT PROCESS.

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The objective of a TMDL study is to estimate allowable pollutant loads expected to achieve compliance with water quality criteria. The allowable load is then allocated among the known pollutant sources in the watershed so that appropriate control measures can be implemented to reduce pollutant loading. To determine the effect of watershed management measures on in-lake water quality, it is necessary to establish a cause-effect linkage between the external loading of sediments, nutrients and organic matter from the watershed and the waterbody response in terms of lake water quality conditions for sediments, nutrients, organic matter, dissolved oxygen and chlorophyll-*a*.

The technical foundation for the determination of the required TMDL load reductions is based on a public domain surface water model framework that includes (1) a watershed hydrology and runoff model, and (2) a lake hydrodynamic and water quality model. The Hydrologic Simulation Program FORTRAN (HSPF) model has been developed to provide stream flow, sediment and water quality loading from the upper Little River watershed. The Environmental Fluid Dynamics Code (EFDC) model has been developed to link watershed flow and pollutant loading from the HSPF model to describe the water quality response of Lake Thunderbird to watershed loading. An overview of the HSPF watershed model is presented in Section 3.3 of the main TMDL report and Appendix A of this TMDL report presents a description of the HSPF model, setup, data sources, model results and analysis of watershed loads. This appendix describes the water quality modeling analysis of the EFDC linkage between water quality conditions in Lake Thunderbird and HSPF watershed pollutant loading. This appendix presents a description of the EFDC model, setup, data sources, model results and analysis of the effect of load reductions on lake water quality.

B.1 EFDC Model Description

EFDC is an advanced surface water modeling package for simulating three-dimensional (3-D) circulation, salinity, water temperature, sediment transport and biogeochemical processes in surface waters including rivers, lakes, reservoirs, estuaries, and coastal systems. The EFDC model has been supported by EPA over the past decade as a public domain, peer reviewed model to support surface water quality investigations including numerous TMDL evaluations (Ji, 2008). EFDC directly couples the hydrodynamic model (Hamrick, 1992, 1996) with sediment transport (Tetra Tech, 2002), water quality (Hamrick, 2007) and sediment diagenesis models (Di Toro, 2000). EFDC state variables include suspended solids, dissolved oxygen, nutrients (N, P), organic carbon, algae and bacteria. The EFDC model is time variable with model results output at user-assigned time intervals (e.g., 1 hr). The EFDC model requires input data to characterize lake geometry (shoreline, depth, surface area, volume), time varying watershed inputs of flow and pollutant loads, time varying water supply withdrawals and release flows, and kinetic coefficients to describe water quality interactions such as nutrient uptake by algae. Observed water quality data collected at lake monitoring sites is used for calibration of the model results to observations. Model setup, data input, and post-processing of model results is facilitated with the EFDC_Explorer graphical user interface (Craig, 2012).

B.2 EFDC Model Setup, Data Sources, Boundary Conditions and Initial Conditions

B.2.1 Model Domain

The EFDC model allows for the physical representation of the lake with either coarse or fine resolution grid blocks. For this study, a fine resolution mesh of grid cells was developed to obtain a good representation of the effect of lake geometry, particularly the remnant river channels of the Little River and Hog Creek, and river inflow on circulation in the lake (Figure B-1). In order to accurately describe the physical properties of Lake Thunderbird, a curvilinear horizontal computational grid was developed using the Delft Hydraulics grid generation software Delf3D-RGFGRID (Delft Hydraulics, 2007).The computational grid developed to map the geometry of Lake Thunderbird consisted of 1,660 horizontal cells. Depth of the water column was represented with 6 layers to account for the effects of seasonal stratification. The shoreline of the lake is defined by the normal pool elevation of 1039.0 ft (datum, NGVD29). Bottom elevation of the lake model was interpolated to each grid cell using high resolution bathymetry data collected by OWRB (Figure B-1). The wetting and drying feature of the EFDC model was used to represent cells as dry when lake water surface elevation is less than the bottom elevation of a grid cell. Horizontal projection for the XY data used to define shoreline and grid coordinates is UTM Zone 14 as meters with a horizontal datum of NAD83. Lake elevation, shoreline and bathymetry data was converted from a vertical datum of NGVD29 as feet (MSL) to a datum of NAVD88 as meters (MSL) for model setup. The Twin Bridges causeway on East Alameda Drive across the southwestern area of the Little River arm of the lake was represented in the model grid as a barrier to flow by removing selected model grid cells to force flow to be transported around the roadway.

B.2.2 Data Sources

Data sources used for development of the model included routine lake and tributary monitoring by Oklahoma Water Resources Board (OWRB) and the Oklahoma Conservation Commission (OCC); lake level and storage volume monitoring by the USGS and the U.S. Army Corps of Engineers (COE); and meteorological data from rain gages co-located with tributary sampling sites and the Oklahoma MESONET network. Data was collected by OWRB in 2001 with an Acoustic Doppler Continuous Profiler (ADCP) to map bathymetry of Lake Thunderbird. The Central Oklahoma Conservancy District (COMCD), in cooperation with OWRB, has been monitoring chlorophyll-a, nutrients, sediment, water temperature, organic matter and dissolved oxygen in the lake since 2000. In support of this TMDL study of Lake Thunderbird, OWRB and OCC conducted a special monitoring program from April 2008 through April 2009 to collect samples in watershed tributaries and to supplement the monitoring program conducted as part of the routine COMCD-BUMP surveys of Lake Thunderbird. Sediment bed data was also collected by OWRB at five stations in the lake in 2008 to provide sediment bed data needed for the sediment diagenesis model. The data collected by OWRB and OCC was used for development and calibration of the EFDC hydrodynamic, sediment transport, water quality, and sediment diagenesis models. Tables of observed water quality data used for model calibration are presented in Appendix D of this TMDL report.

B.2.3 Boundary Conditions

The lake model requires the specification of external boundary data to describe: (1) flow and pollutant loading from the watershed; (2) withdrawals from water supply intakes and releases at the dam; (3) meteorological and wind forcing; and (4) atmospheric deposition of nutrients.

<u>Watershed Flow and Pollutant Loading</u>. As described in Section 3.3 of the main TMDL report, flow and pollutant loading from the watershed was provided by the HSPF model as hourly time series data for tributaries and distributed flow areas. Tributary inflows included the Little River, Elm Creek, Rock Creek, Hog Creek, Dave Blue Creek, Jim Blue Creek, Clear Creek, Willow Branch and a number of unnamed streams. Figure B-2 shows the locations of the 18 tributary (red circles) and 18 distributed flow (green triangles) boundary inputs to the lake model.

Although HSPF and EFDC both model sediments, nutrients, organic matter, algae and dissolved oxygen, the model results for some HSPF state variables require stoichiometric transformations for linkage to EFDC state variables as shown in Table B-1. Stoichiometric coefficients assigned for input to the HSPF model are used for the HSPF-EFDC linkage to ensure that the mass loading of organic matter from HSPF is accurately assigned for input to the EFDC model.

Table B-1 Linkage of HSPF and EFDC State Variables

HSPF	Stoichiometry	EFDC	Units
Streamflow		Flow	cms
Distributed Runoff			
Water Temperature		Water Temperature	Deg-C
Sediment (sand)		Non Cohesive Sediment (not used)	mg/L
Sediment (silt)		Cohesive Sediment, CohSS	mg/L
Sediment (clay)			
Algae Biomass	C/CHL Chl/P	Bluegreen & Green Algae	mg C/L
BOD	CVBO	TOC, POC, DOC	mg C/L
Organic-Carbon	C/DW		
Organic-Phosphorus	C/P	TOP, POP, DOP	mg P/L
Organic-Nitrogen	C/N	TON, PON, DON	mg N/L
Total OrthoPhosphate		Total OrthoPhosphate, TPO4	mg P/L
Ammonium		Ammonium, NH4	mg N/L
Nitrite+Nitrate		Nitrite+Nitrate, NO23	mg N/L
Dissolved Oxygen		Dissolved Oxygen, DO	mg/L
C/CHL carbon:chlorophyll-a Chl/P chlorophyll-a: phosphorus CVBO oxygen: dry weight biomass C/DW carbon: dry weight biomass C/P carbon: phosphorus C/N carbon:nitrogen			

Labile HSPF BOD and refractory HSPF organic carbon (ORC), organic phosphorus (ORP), and organic nitrogen (ORN) are added as shown in the HSPF-EFDC linkage in Table B-1 to derive non-living TOC, TOP and TON for input to the EFDC model. HSPF derived TOC, TOP and TON is then split for input to EFDC as refractory, labile and dissolved components of total organic matter using the fractions given in Table B-2.

HSPF-derived concentrations for TOC, TON and TOP are split for input to EFDC as refractory particulate organic matter, labile particulate organic matter and dissolved organic matter (Table

B-2). The DOC:TOC fraction of 0.9 is supported by two very different data sets. The first data set is a composite database of worldwide rivers compiled by Meybeck (1982) where the DOC:TOC ratio was shown to be related to TSS concentration. DOC:TOC ratios greater than ~0.8 were consistent with TSS levels of ~5-50 mg/L. The second site-specific data set is based on a compilation of watershed station data records for DOC and TOC that were compiled and analyzed to determine a mean estimate of the DOC:TOC ratio for watershed loading to Lake Thunderbird. For the Lake Thunderbird watershed, TOC concentrations ranged from 2.6 to 7.4 while DOC concentrations ranged from 2.4 to 6.8. The ratio of DOC:TOC varied from 0.92 to 1.08 with a mean of 0.96.

BOD is represented as ultimate BOD in the HSPF model. The stoichiometric ratio for oxygen;dry weight of biomass (CVBO) has a value of CVBO=1.4 mg O2/mg-DW and the ratio of carbon: dry weight (C/DW) is 0.49 mg C/mg-DW. The parameter values used to convert BOD to an equivalent organic carbon basis are taken from parameter values assigned for the HSPF model. The stoichiometric ratios for Phosphorus to Carbon (P/C) and Nitrogen to Carbon (N/C) are based on Redfield ratios where C/P = 41.1 mg C/mg-P and C/N = 5.7 mg C/mg-N (Di Toro 2001). The stoichiometric ratios for Chl/P (0.5 mg Chl/mg P) and C/Chl (82.1 mg C/mg Chl) for algae biomass are taken from parameter values assigned for the HSPF model.

Table B-2. Refractory, Labile and Dissolved Splits for Organic Matter

	Refractory RPOM	**Labile LPOM**	**Dissolved DOM**
TOC	0.08	0.02	0.90
TOP	0.72	0.18	0.10
TON	0.30	0.20	0.50

<u>Withdrawals from Water Supply Intakes and Releases at the Dam</u>. A flow boundary was assigned to represent water supply withdrawals at a common intake location from the reservoir for the municipalities of Norman, Midwest City and Del City. Water supply withdrawal data was provided by the Central Oklahoma Master Conservancy District (COMCD). A flow boundary was assigned to account for release flow at the dam (designated by the U.S. Army Corps of Engineers as Station NRM02) with flow data provided by the Army Corps of Engineers. The primary spillway release from the lake is an overflow drawing from the base of the flood pool elevation (1039 ft MSL) while the secondary spillway releases is through the dam with water removed at a base elevation of 997 ft MSL. Secondary spillway releases over and above the primary spillway releases are controlled by the Tulsa District U.S. Army Corps of Engineers. COMCD drinking water withdrawals are generally from the center intake gate with the base set at an elevation of 1023 ft MSL. The base of the upper gate is at 1043 ft MSL while the base of the lower gate is at an elevation of 1004 ft MSL. In the lake model setup, releases over the dam and water supply withdrawals are assigned equally as 1/6 of the flow rate to each of the 6 vertical layers for two grid cells selected by proximity to the dam release site and the water intake structure (Paul Koenig, OWRB, personal communication, May 16, 2012). Figure B-2 shows the locations of the water intakes and the flow release at the dam. The only sources of water inflow to the lake model are from the simulated HSPF flows and precipitation and the only withdrawals of water are assigned from water supply withdrawals, release flow at the dam and evaporation.

<u>Meteorological Forcing</u>. The EFDC model requires time series data to describe the effect of meteorological forcing and winds on lake circulation processes. Wind speed/direction and

meteorological data was obtained from the Oklahoma MESONET database at Station NRMN. Meteorological data needed for the model includes wind, air temperature, air pressure, relative humidity, precipitation, evaporation, cloud cover and solar radiation.

Atmospheric Deposition of Nutrients. The EFDC model requires specification of wet and dry atmospheric deposition of nutrients over the entire surface area of the lake. As described in Section 3.2.1, atmospheric deposition of nutrients is an uncontrollable source component of the budget for nutrient loading to Lake Thunderbird. Atmospheric deposition of nutrients is represented using the same constant loading rate for both model calibration to existing conditions of 2008-2009 and model evaluations of watershed load reduction scenarios. Since atmospheric deposition is uncontrollable on the local watershed scale, there is no load allocation for atmospheric deposition of nutrients for the TMDL. For Lake Thunderbird, wet and dry deposition data (Table B-3) was estimated as the average of annual data from 2008-2009 for ammonia and nitrate from the National Atmospheric Deposition Program (NADP) for Station OK17 (Kessler Farm Field Laboratory, Lat 34.98; Lon -97.5214) and the Clean Air Status and Trends Network (CASTNET) Station CHE185 (Cherokee Nation, Lat 35.7507, Lon -94.67). Data was not available from the CASTNET or NADP sites for phosphate. Dry deposition for phosphate was estimated using annual average ratios of N/P for atmospheric deposition of N and P reported for 6 sites located in Iowa (Anderson and Downing, 2006) and the ammonia and nitrate data obtained from the NADP and CASTNET data sources. Using annual rainfall for Lake Thunderbird for the simulation period from 2008-2009 (36.9 inches) and the estimate obtained for dry deposition of phosphate, the annual average wet phosphate concentration was estimated in proportion to the Dry/Wet ratio for phosphate deposition fluxes reported by Anderson and Downing (2006).

Table B-3 Dry and Wet Atmospheric Deposition for Nitrogen and Phosphorus for Lake Thunderbird

	Dry	**Dry, Annual**	**Data**
	g/m^2-day	**kg/ha-yr**	**Source**
TPO4	1.3275E-05	0.048	Anderson & Downing (2006) Table VII
NH4	1.0359E-04	0.378	CASTNET, CHE185
NO3	1.4663E-04	0.535	CASTNET, CHE185
DIN (NO3+NH4)	2.5022E-04	0.913	CASTNET, CHE185
	Wet	**Wet, Annual**	**Data**
	mg/L	**kg/ha-yr**	**Source**
TPO4	0.001	0.009	Anderson & Downing (2006) Table VII
NH4	0.370	3.377	NADP, OK17 (2008-2009)
NO3	0.945	8.624	NADP, OK17 (2008-2009)
DIN (NO3+NH4)	1.315	12.001	NADP, OK17 (2008-2009)

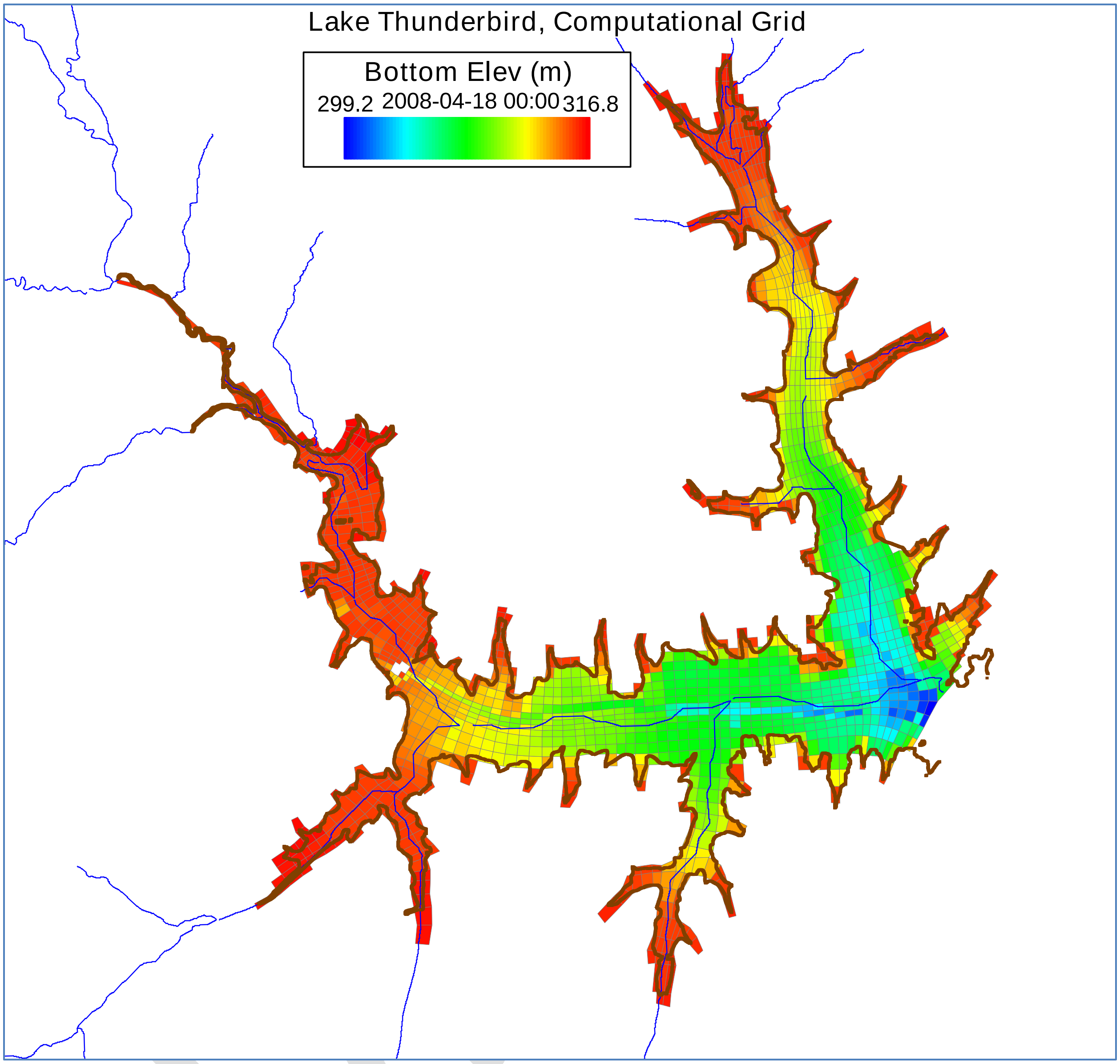

Figure B-1 Lake Thunderbird Computational Grid and Bottom Elevation

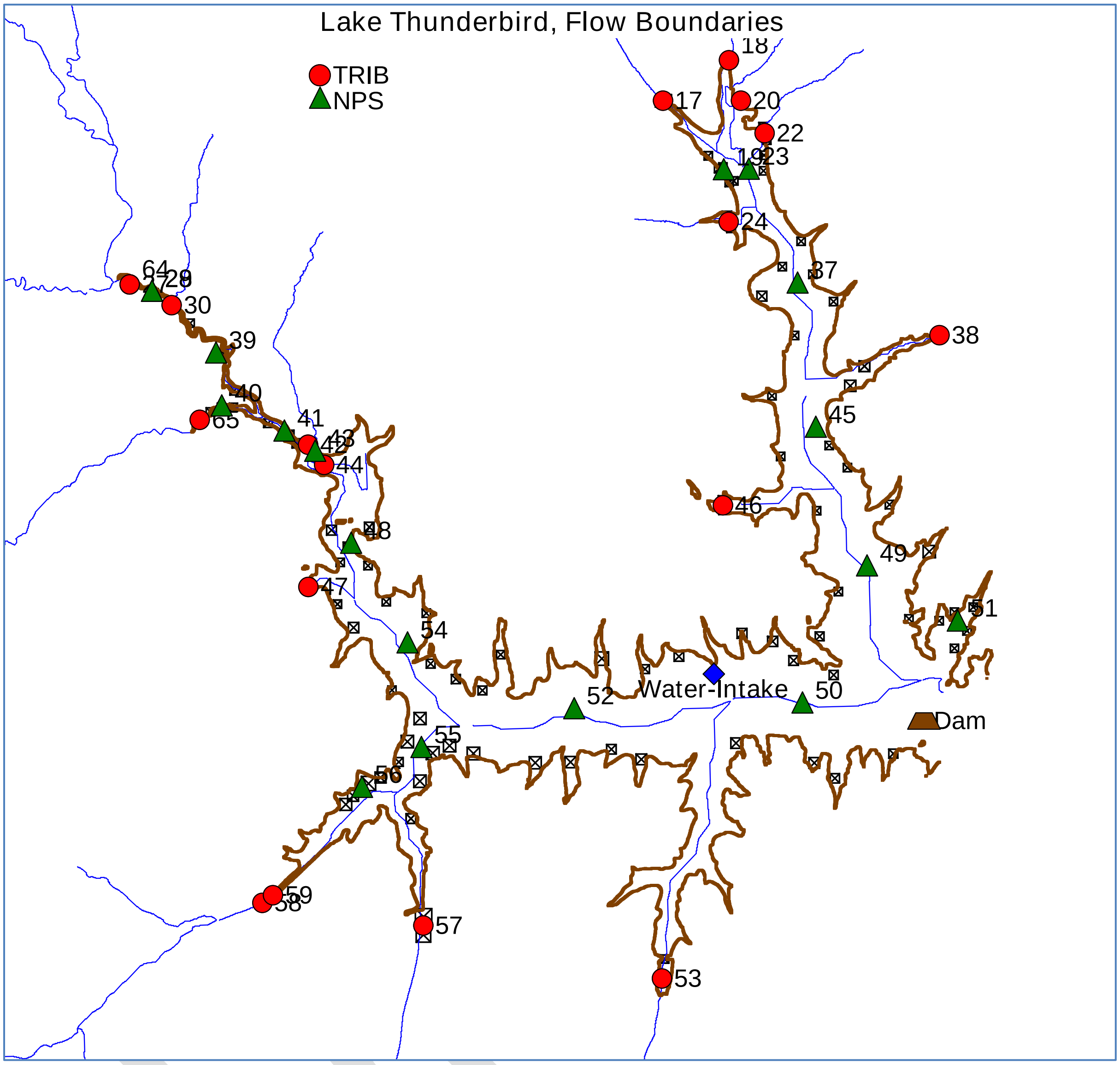

Figure B-2 Boundary Locations for HSPF tributary outlets and NPS distributed flow, Water Supply Intakes and Release at the Dam.

TRIBUTARIES	TRIBUTARIES	DISTRIBUTED NPS	DISTRIBUTED NPS
17_[unknown]	44_[Little-River]	19_[Distributed]	45_[Distributed]
18_[Hog-Creek]	46_[Willow-Br]	23_[Distributed]	48_[Little-River]
20_[unknown]	47_[unknown]	28_[Little-River]	49_[Hog-Creek]
22_[unknown]	53_[Clear-Creek]	29_[Little-River]	50_[Little-River]
24_[unknown]	57_[Jim-Blue-Ck]	37_[Distributed]	51_[Distributed]
27_[Elm-Creek]	58_[unknown]	39_[Little-River]	52_[Little-River]
30_[unknown]	59_[Dave-Blue-Ck]	40_[Rock-Creek]	54_[Distributed]
38_[unknown]	64_[Little-River]	41_[Little-River]	55_[Distributed]
42_[unknown]	65_[Rock-Creek]	43_[Little-River]	56_[Dave-Blue-Ck]

B.2.4 Initial Conditions

As a time varying model, EFDC requires the specification of initial distributions of all the model state variables at the beginning of the model simulation period in mid-April 2008. The spatial distribution of initial conditions for the model is based on simulated conditions at the end of the 1-year model simulation period. Restart conditions, written for all state variables of the model at the end of a preliminary model run, were used to assign a simulated set of initial conditions that accounted for spatial variability of conditions in the water column and sediment bed. Bed concentrations of carbon, nitrogen and phosphorus are derived from the OWRB sediment bed survey data collected in 2008 (see Appendix D), solids density of 2.6 g/cm^3 and spatially dependent estimates of bed porosity for the riverine zone (0.5), transition zone (0.6) and lacustrine zone (0.7). The parameter values assigned for porosity are consistent with the dependency of porosity with median particle diameter shown by Di Toro (2001) where larger particle sizes are characterized by denser bed material and a lower porosity.

B.3 EFDC Model Calibration

B.3.1 Observed Data

The Central Oklahoma Conservancy District (COMCD), in cooperation with OWRB, has been monitoring chlorophyll-a, nutrients, sediment, water temperature, organic matter and dissolved oxygen in the lake since 2000. In support of this TMDL study of Lake Thunderbird, OWRB and OCC conducted a special monitoring program from April 2008 through April 2009 to supplement the monitoring program conducted as part of the routine COMCD-BUMP surveys of Lake Thunderbird. Figure B-3 and Table B-4 summarize the site designation names, station numbers and locations of the 8 water quality monitoring stations maintained by OWRB in Lake Thunderbird as a component of the Oklahoma Beneficial Use Monitoring Program (BUMP) network (OWRB, 2008). Detailed tables of observed data used for the lake model are presented in Appendix D of this report. Separate data tables are presented for Hydro Lab vertical profiles (water temperature, dissolved oxygen), water quality chemistry grab samples (TSS, turbidity, secchi depth, organic carbon, nutrients, chlorophyll-a) and sediment bed samples (nutrients, solids).

Table B-4 OWRB Water Quality Monitoring Stations for Lake Thunderbird

Site	Station Number	Latitude	Longitude	Represents
1	520810000020-1sX	35.223333	-97.220833	Dam Site; Lacustrine
	520810000020-1-4X			
	520810000020-1-8X			
	520810000020-1-12X			
	520810000020-1bX			
2	520810000020-2X	35.238889	-97.228889	Lacustrine
	520810000020-2bX			
3	520810000020-3X	35.262222	-97.238889	Transition
4	520810000020-4X	35.224444	-97.250833	Lacustrine
	520810000020-4bX			
5	520810000020-5X	35.220278	-97.290556	Transition
6	520810000020-6X	35.231667	-97.305556	Riverine
7	520810000020-7X	35.203056	-97.258056	Riverine
8	520810000020-8X	35.286409	-97.244887	Riverine
11	520810000020-11X	35.212292	-97.302545	Riverine

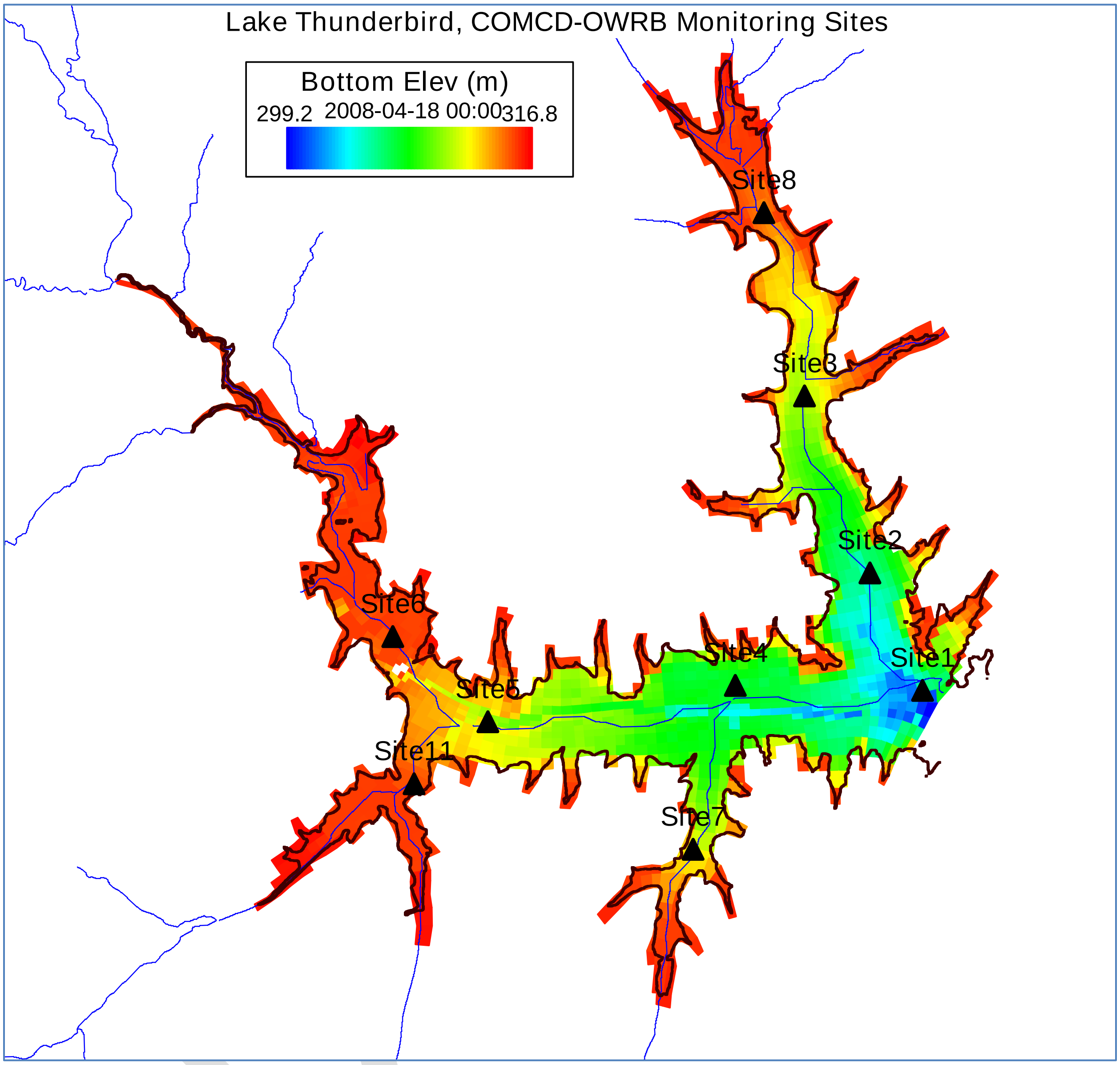

Figure B-3 OWRB Water Quality Monitoring Stations for Lake Thunderbird

B.3.2 **Model Calibration**

The EFDC lake model was run for a 375 day period from April 17, 2008 through April 26, 2009. Model results were calibrated to observed data sets collected at Site1 through Site 8 as shown in Figure B-3. Model results for Site 2 are presented in this section to show model-data comparison for parameters that directly relate to the water quality criteria targets for turbidity, chlorophyll-a and dissolved oxygen. Results are also presented to show the benthic flux rates of phosphate and sediment oxygen demand simulated with the sediment diagenesis model. Selected time series plots are presented in Section B.7 for the lacustrine zone (Site 2), transition zone (Site 3) and riverine zone (Site 6) to show the spatial variation of model results. A composite summary of model performance statistics for all sites is presented for each water quality variable.

Total Suspended Solids (TSS) and Turbidity. TSS results are presented in Figure B-4 for comparison to observed data for the surface layer (k=6) and bottom layer (k=1) for the lacustrine zone (Site 2). As can be seen in the model-data plot for Site 2, the model results for the surface and bottom layer are in reasonable agreement with measured TSS except for the time period that corresponded to the two large storm events in August 2008. Model results show a bottom layer peak in TSS of ~20-50 mg/L at Site 2. Simulated TSS during the winter-spring months of 2009 is seen to be lower than the observed TSS measurements.

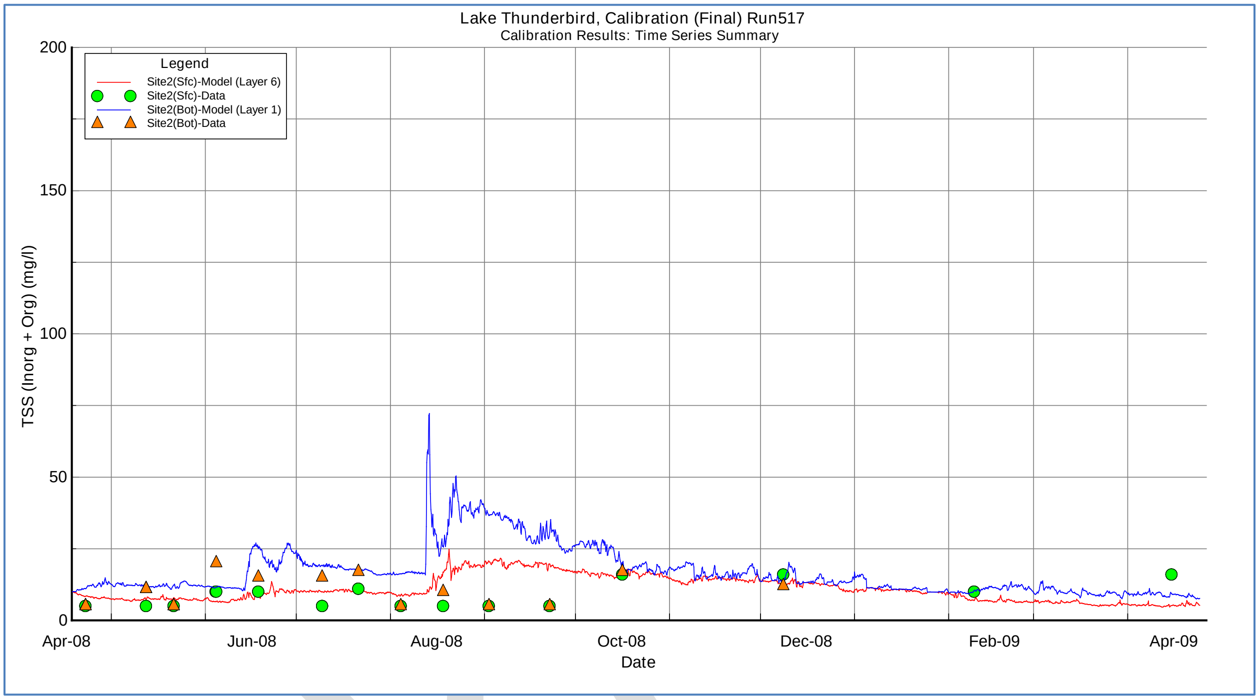

Figure B-4 Model-Data Comparison of TSS for Surface Layer (k=6) and Bottom Layer (k=1) for Site 2.

Water clarity is an issue for impairment in Lake Thunderbird and turbidity is the parameter used to determine if the lake fully supports designated uses. The Oklahoma water quality criteria states that no more than 10% of samples collected over the most recent 10 year period shall be greater than 25 NTU. Since the EFDC model does not simulate turbidity as a state variable, the comparison of EFDC results with the water quality criteria for turbidity requires the development of a regression-based relationship of TSS vs. turbidity based on site-specific paired TSS and turbidity data sets for Lake Thunderbird. EFDC state variables for cohesive sediment, detrital organic matter and algae are summed to compute a derived variable for total suspended solids (TSS) that compared to observed TSS data. The TSS vs. turbidity relationship developed for Lake Thunderbird, shown in

Figure B-5, was used to transform modeled TSS to modeled turbidity. Simulated turbidity is then used to evaluate model results in comparison to water quality criteria for turbidity (25 NTU). Model-data turbidity results are presented for the surface layer (k=6) for Site 2 (Figure B-6). As can be seen in the model-data plot, the model results for turbidity, mimicking the results obtained for TSS, are in reasonable agreement with measured turbidity except for the time period that corresponded to the two large storm events in August 2008.

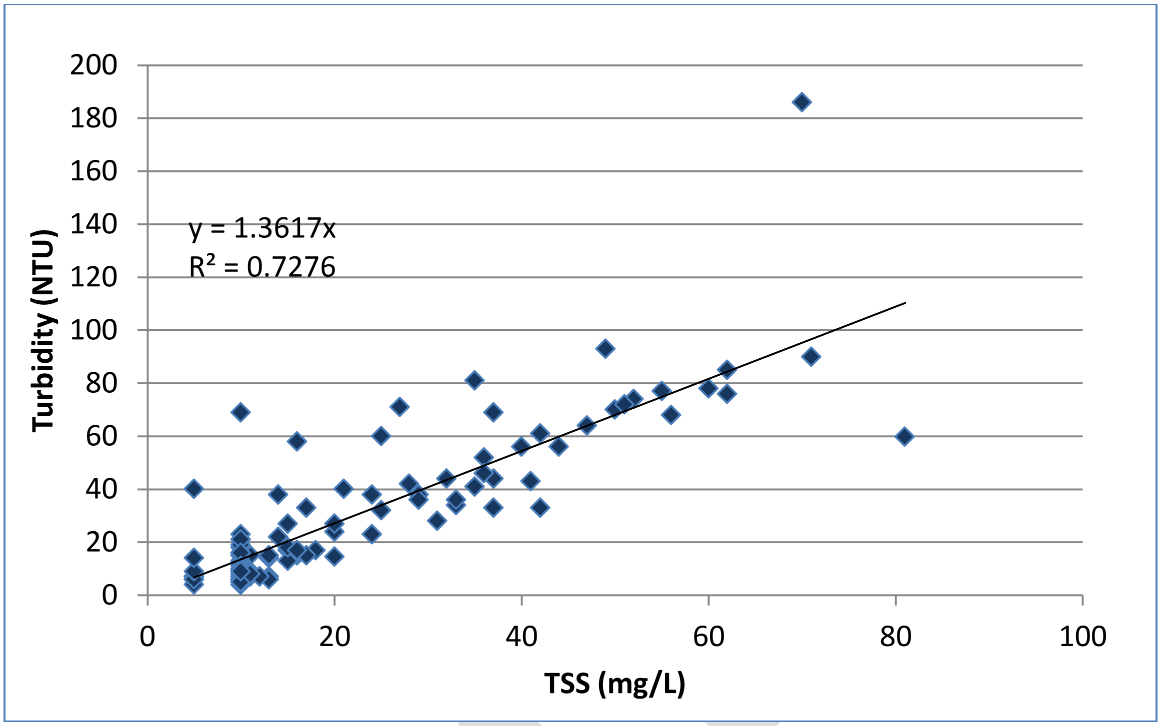

Figure B-5 TSS (mg/L) vs. Turbidity (NTU) Regression Relationship (R^2=0.7276) for Lake Thunderbird

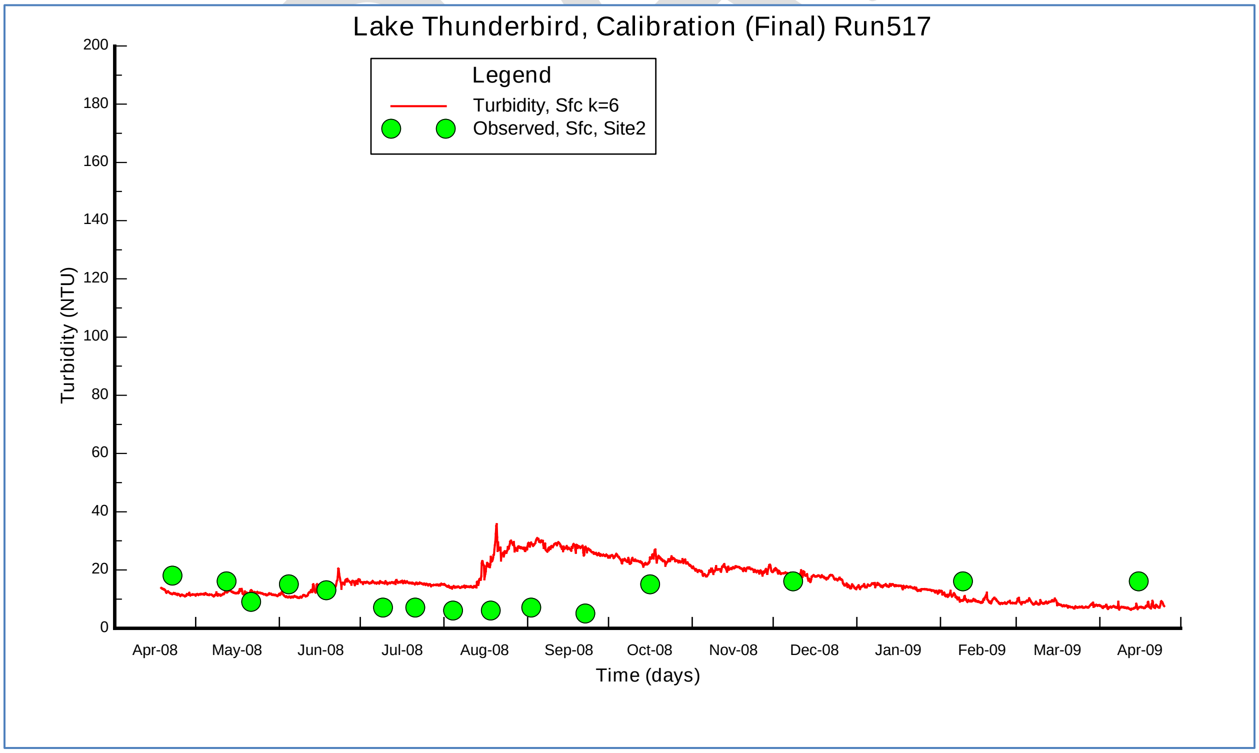

Figure B-6 Model-Data Comparison of Turbidity for Surface Layer (k=6) for Site 2.

Dissolved Oxygen and Anoxic Volume. Dissolved Oxygen results are presented in Figure B-7 for comparison to observed data for the surface layer (k=6) and bottom layer (k=1) for the Site 2 in the lacustrine zone**.** As can be seen in the model-data plot, the model results for Site 2 for both the surface and bottom layer are in very good agreement with measured oxygen. The exception is the period characterized by super saturated oxygen conditions that were observed in the surface layer during July in the lacustrine zone at Site 2. The contribution of algal photosynthetic oxygen production that is distributed over the surface layer thickness of ~ 2 m at this site is apparently "diluted" by the relatively coarse 6 layer vertical resolution of the surface layer. Similar super saturated oxygen conditions were also observed, and not matched by the model, at the other lacustrine stations (Site 1 and Site 4). What is most notable about the model results is that surface and bottom layer oxygen results at Site 2 clearly show the hydrodynamic impact of increased vertical mixing that resulted from the storm events in August 2008. Water column stratification was eroded and the water column became well mixed with only a very small gradient between bottom layer and surface layer oxygen. When the water column re-stratified in September bottom oxygen was once again reduced to anoxic levels less than 2 mg/L that persisted until seasonal stratification was finally eroded in October.

Oklahoma water quality standards for dissolved oxygen for Lake Thunderbird are specified in relation to (a) the surface layer/epilimnion and (b) the anoxic volume of the lake within the hypolimnion. Within the surface layer/epilimnion, dissolved oxygen shall be no less than 6 mg/L from April 1 to June 15 for protection of early life stages and no less than 5 mg/L from June 16 to March 31 for protection of other life stages of a warm water aquatic community. Within the hypolimnion, the anoxic volume of the lake, defined by a cutoff DO level of 2 mg/L, shall not exceed 50% of the lake volume during the period of seasonal stratification from mid-May through October 1.

Model results for dissolved oxygen at the deep lacustrine sites (1, 2 and 4) show good agreement with the observed seasonal trend of both surface layer oxygen levels and bottom layer oxygen depletion where the observed anoxic conditions are controlled by the onset and erosion of lake stratification. As shown in the surface layer observations and results for Site 2, dissolved oxygen levels within the epilimnion are in compliance with the water quality standards of 5 to 6 mg/L.

Model results for dissolved oxygen for each grid cell are post-processed to derive a composite time series to compute the percentage of the whole lake volume defined as anoxic by the cutoff target DO level of 2 mg/L. Model results are presented first as a map of anoxic volume of the lake on Aug-4-2008 08:00 to show a time snapshot of the spatial distribution of anoxic volume of the lake. Aug-4 is selected for the snapshot because the highest estimates of anoxic lake volume occur in early August and observed data is available from the OWRB survey on Aug-4.

Figure B-8 shows the spatial distribution of anoxic volume on Aug-4-2008 08:00. Model results for dissolved oxygen are presented in Figure B-9 as a composite whole lake time series for the percentage of the lake volume that is defined as anoxic with the cutoff target level of 2 mg/L. Figure B-10 shows a time series of the anoxic volume extracted for eight model grid cells that surround the location of Site 2. As shown in Figure B-10, the model anoxic volume computed at Site 2 is in good agreement with the estimate of 58% for the observed anoxic volume at Site 2 on August 4, 2008. August 4 was selected for comparison to the model because the highest estimates of anoxic lake volume occur in early August and observed oxygen profile data is available from the OWRB survey on August 4, 2008.

As shown in Figure B-8, the area defined by anoxic conditions is bounded by the deeper parts of the lake within the lacustrine zone at Site 1, 2 and 4. On a volume-weighted basis computed for all the grid cells of the model domain, the maximum percentage of the lake volume defined by the target oxygen level of 2 mg/L gradually increases from onset of stratification to a peak of ~25% in July with a maximum of ~30% in early August (Figure B-9). Stratification is eroded with the storm event in August, bottom oxygen increases and the anoxic volume percentage of the lake drops to zero. Stratification is re-established after the storm and the anoxic volume increases to a maximum of less than 10%. Since the maximum anoxic volume for the whole lake shown in Figure B-9 is ~30%, the water quality anoxic volume target of no more than 50% of the lake volume less than 2 mg/L dissolved oxygen content during seasonal stratification is attained for model calibration.

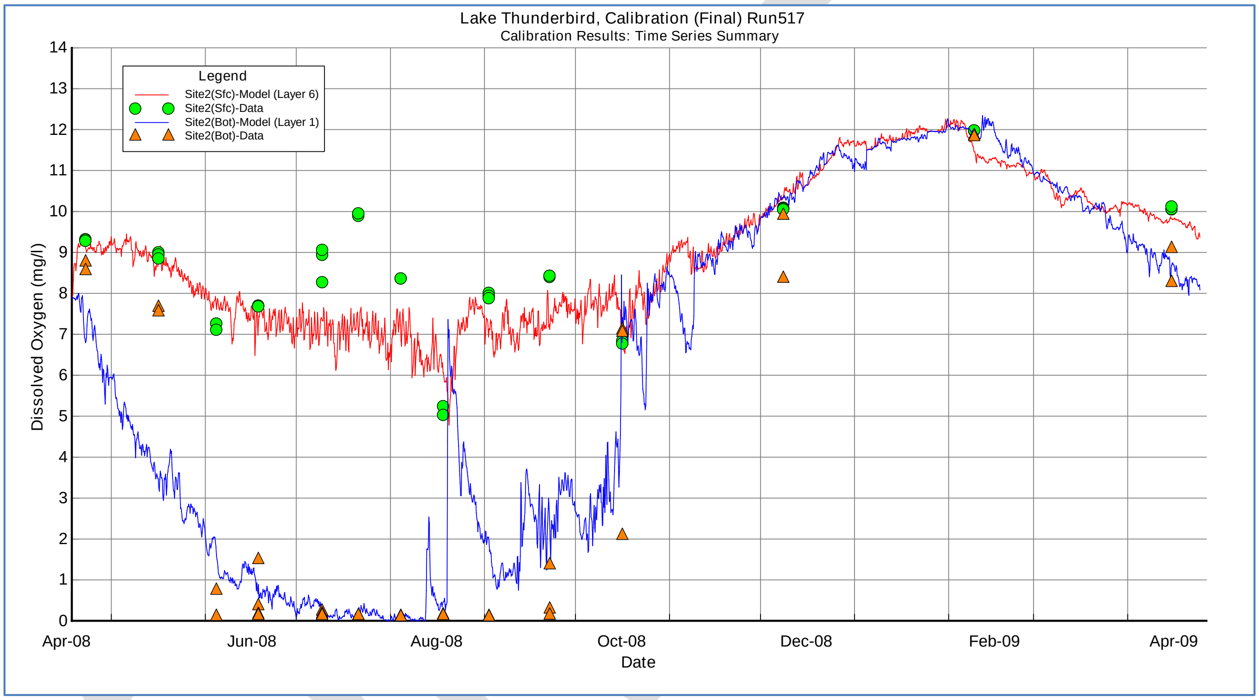

Figure B-7 Model-Data Comparison of Dissolved Oxygen for Surface Layer (k=6) and Bottom Layer (k=1) for Site 2.

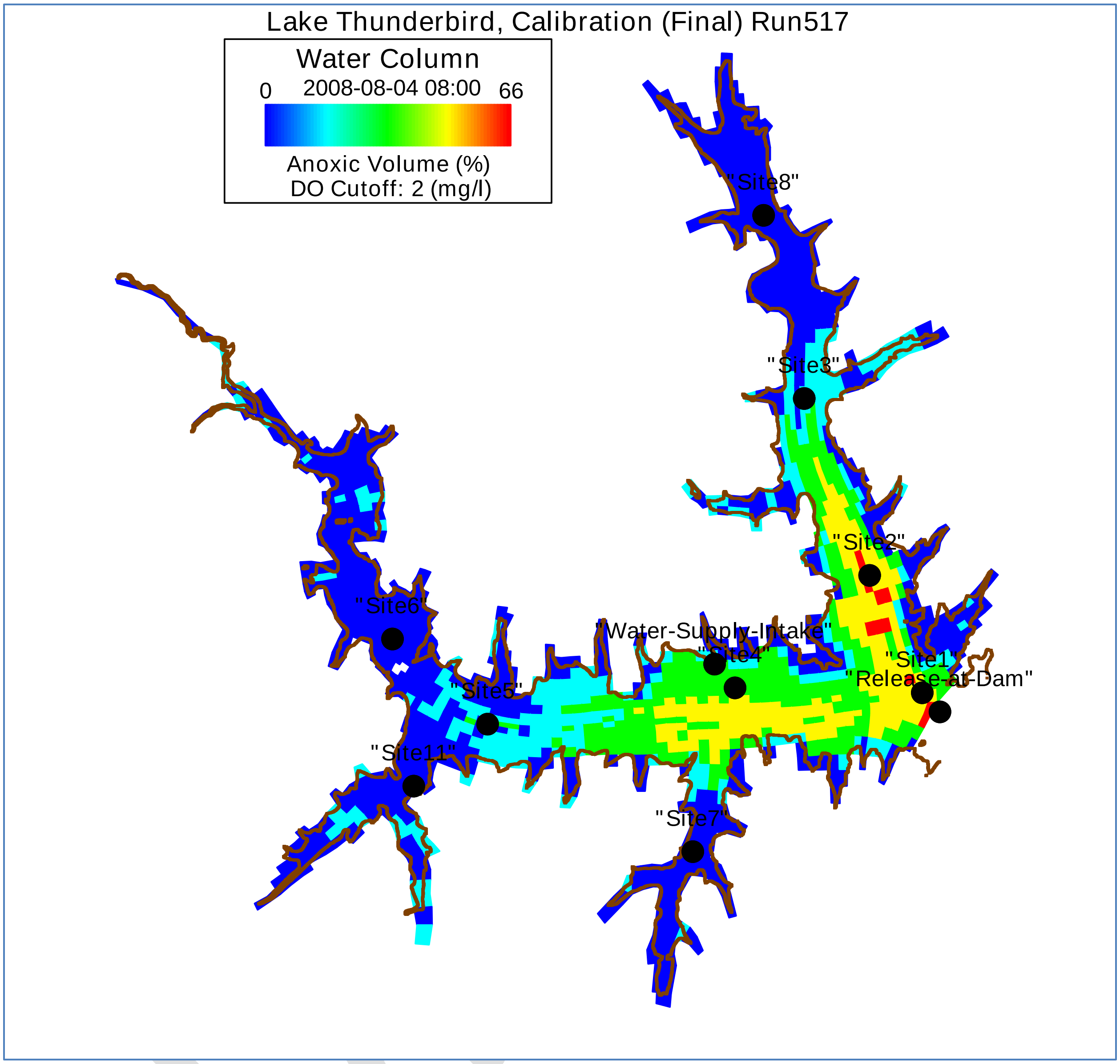

Figure B-8 Anoxic Volume of Lake Thunderbird on Aug-4-2008 08:00. Color gradient for 6-layer model as follows for anoxic volume percentage: dark blue=0%; light blue=16%; green=33%; yellow=50% and red =66%.

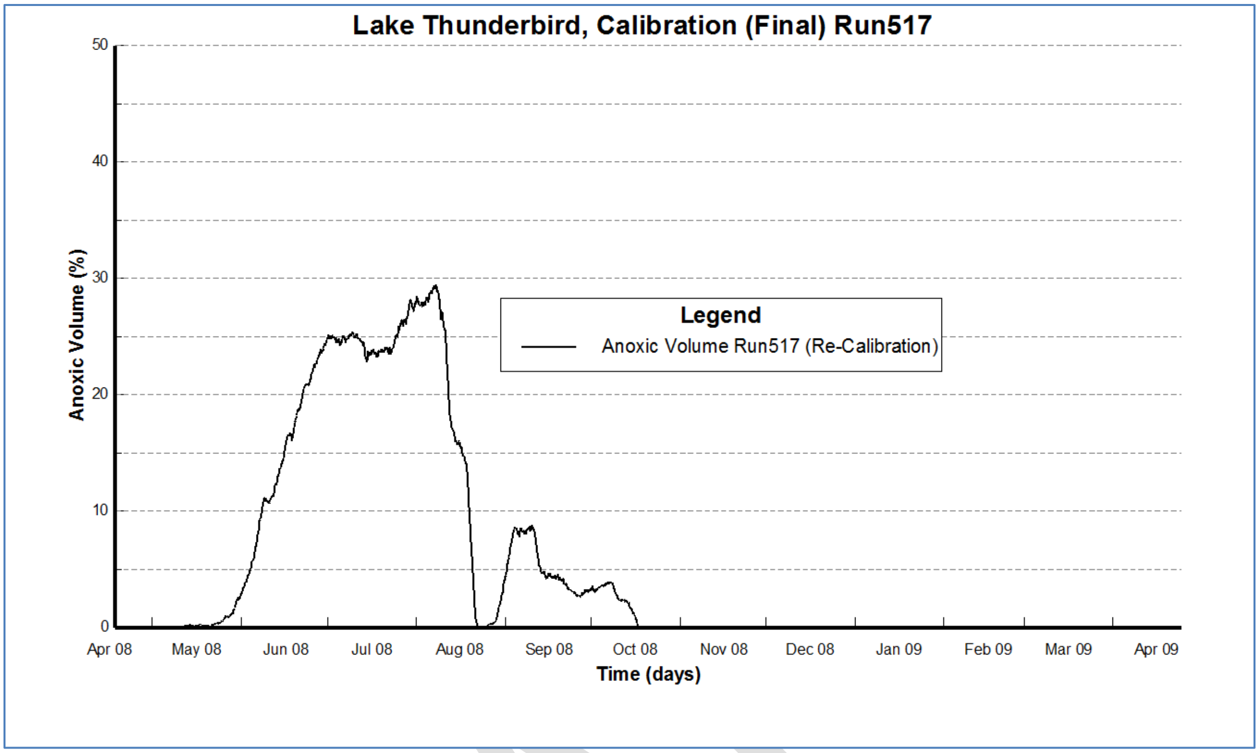

Figure B-9 Time series of anoxic volume of whole lake for model calibration. Percentage of anoxic volume is based on aggregation of all grid cells in the lake.

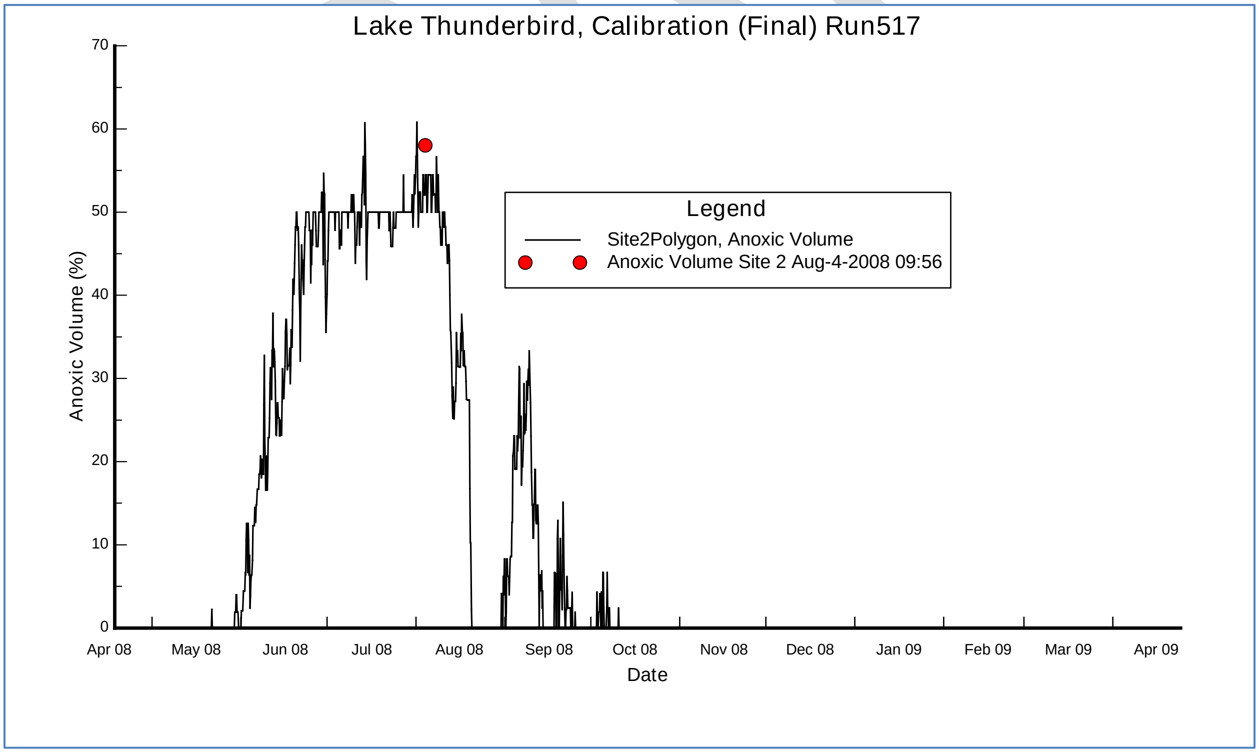

Figure B-10 Time series of anoxic volume of Site 2 for model calibration. Percentage of anoxic volume is based on eight grid cells that surround Site 2 in the lake. Red circle shows estimate of anoxic volume for Site 2 based on observed dissolved oxygen profile for Aug-04-2008 09:56.

Algae Chlorophyll-a. Algae biomass results (as chlorophyll-a) are presented for comparison to observed data for the surface layer (k=6) for Site 2 in the lacustrine zone (Figure B-11). As can be seen in the model-data plot, the model results are in good agreement with measured biomass for most of the calibration period. The exception to the good agreement with the observations is the late summer period in September where the model results (~35-45 µg/L) underestimate somewhat the observed chlorophyll-a biomass of ~50-60 µg/L at Site 2. The discrepancy between the observed and simulated Chlorophyll-a during this period appears to be related to the small peak of simulated TSS that is still larger than the observed TSS in the surface layer during the two storm events in August 2008. The peak simulated overestimate of TSS results in an increase in light limitation for the algae groups, suppression of the growth rate and a decline in algae biomass that did not match the somewhat higher observed levels of chlorophyll-a at Site 2.

Phosphorus. Total Phosphorus (TP), and total-phosphate (TPO4) results are presented for comparison to observed data for the surface layer (k=6) and bottom layer (k=1) for Site 2 in the lacustrine zone**.** As can be seen in the model-data plots shown for Site 2, the model results are in fair agreement with measured TP (Figure B-12) and TPO4 (Figure B-13) for the bottom layer from April 2008 through August 2008. The model results then overestimate surface and bottom layer TP and TPO4 beginning in September through winter-spring 2009. Observed data for bottom layer phosphate shows a sharp increase from relatively low concentrations (<0.05 mg/L) in April-June to much higher concentrations (~0.1-0.2 mg/L) in response to the onset and persistence of anoxia during July-August 2008. Bottom layer phosphate is overestimated early in the model simulation in May-June because thermal stratification is initiated in the model somewhat earlier than observed and bottom oxygen at Site 2 in the model then decreases more rapidly than was observed in May. Bottom phosphate then increases as a result of the increased benthic flux of dissolved phosphate triggered by anoxic conditions in the overlying hypolimnion. Following erosion of the thermocline, the model results for TP and phosphate are slightly higher than the lower levels of TP and phosphate observed during the winter-spring from October-November 2008 through April 2009.

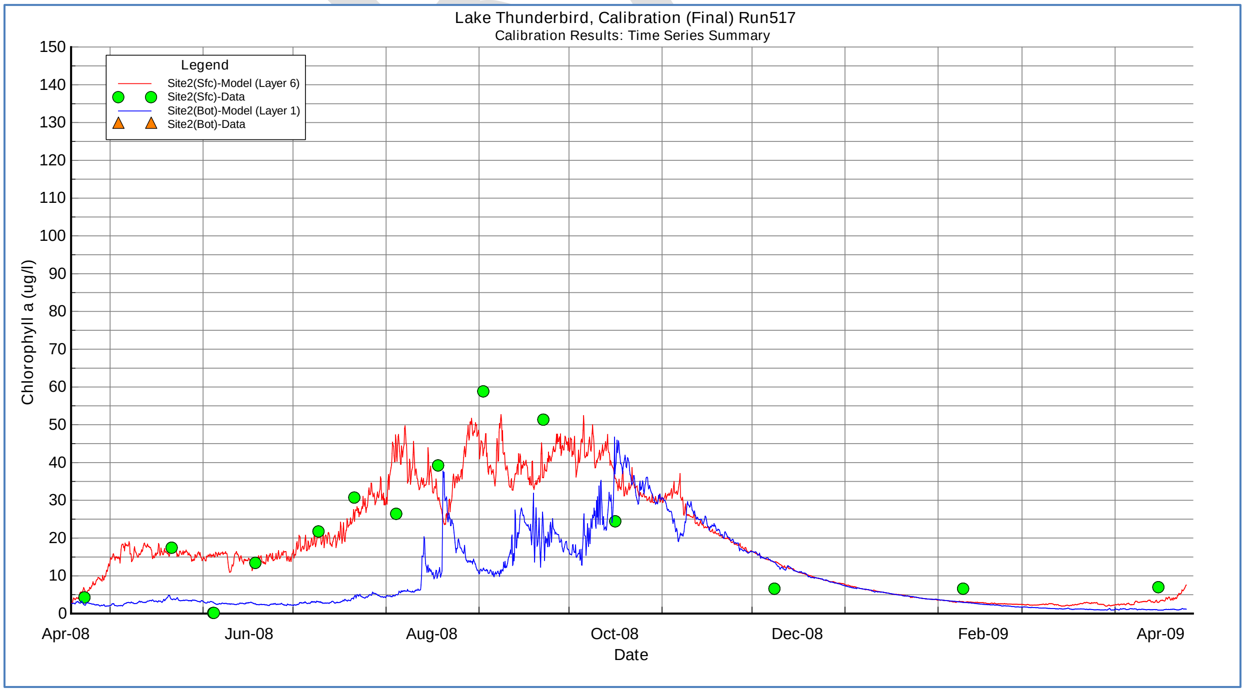

Figure B-11 Model-Data Comparison of Chlorophyll-a, Surface Layer (k=6) for Site 2.

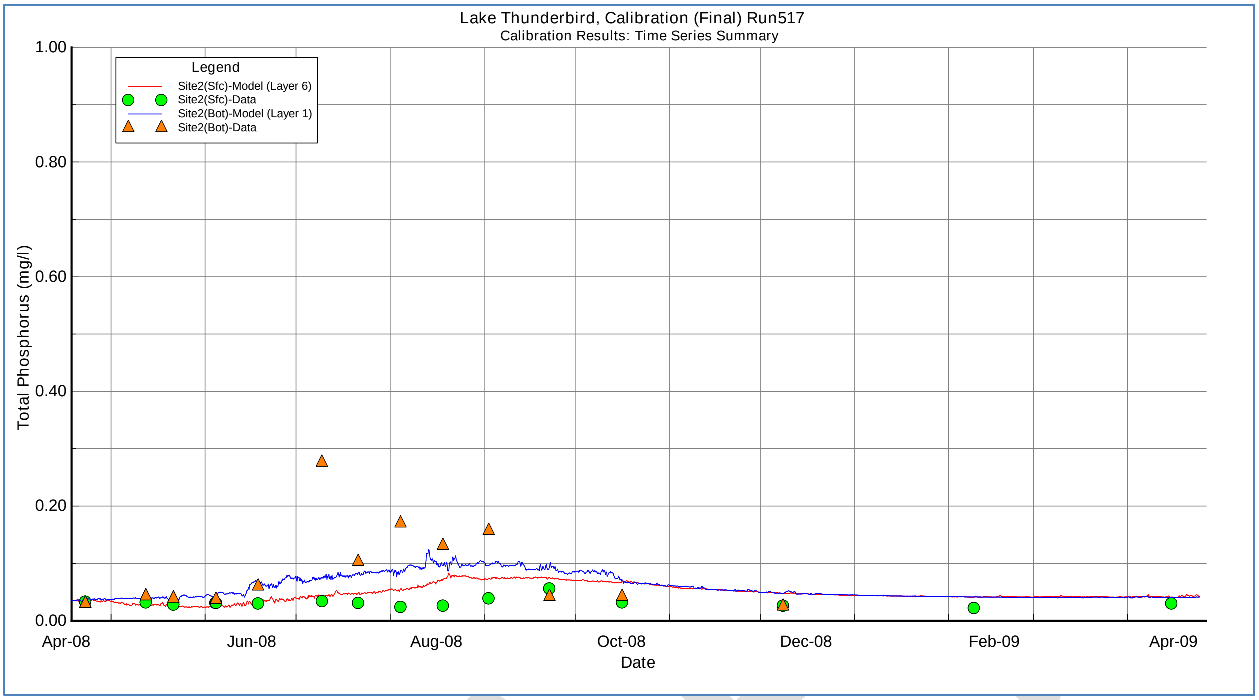

Figure B-12 Model-Data Comparison of Total-P (TP) for Surface Layer (k=6) and Bottom Layer (k=1) for Site 2.

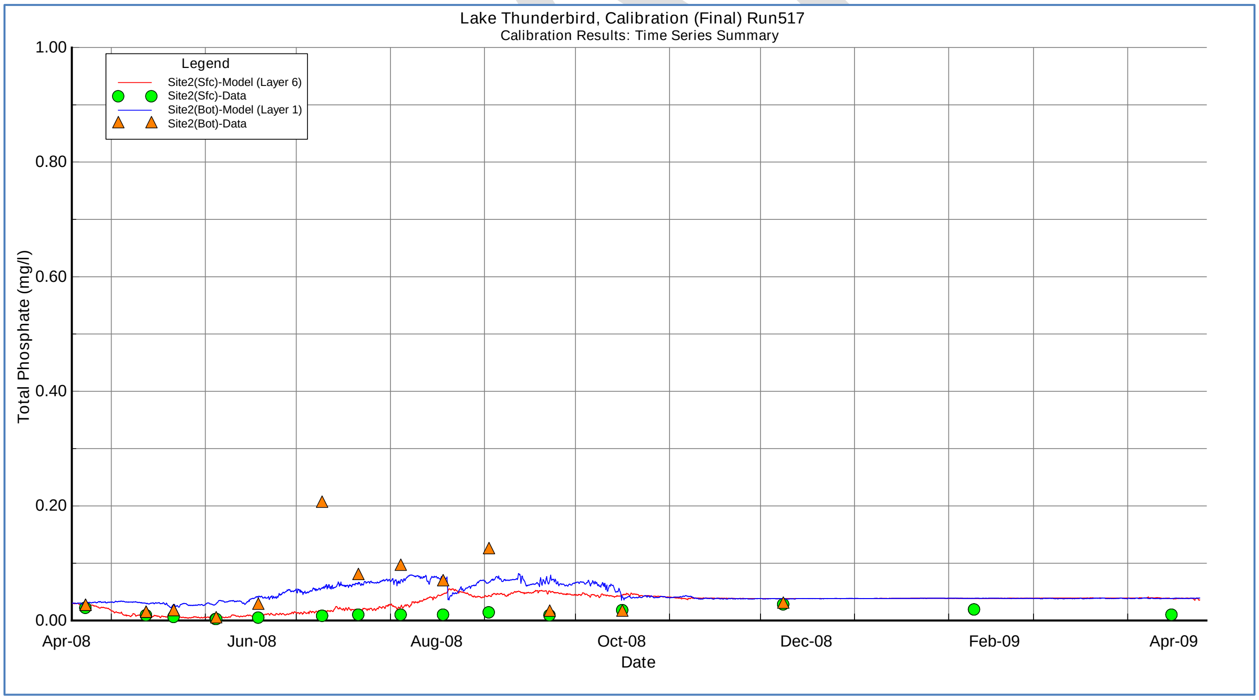

Figure B-13 Model-Data Comparison of Total-Phosphate-P (TPO4) for Surface Layer (k=6) and Bottom Layer (k=1) for Site 2.

The simulated benthic flux for phosphate is shown in Figure B-14 for the lacustrine zone stations (Site 1, 2 and 4). Using the data shown in Figure B-14, summary statistics for benthic phosphate fluxes for each site are computed for the summer stratified period from May 15 through October 1, 2008. The mean benthic flux for phosphate for the lacustrine sites, computed as 3.6, 2.7 and 5.2 mg P/m^2-day for Site 1, 2 and 4, respectively, are thus consistent with the range of anoxic phosphate fluxes of ~2-8 mg P/m^2-day measured by Dzialowski and Carter (2011) in mesotrophic reservoirs in the Central Plains (see
Figure B-15).

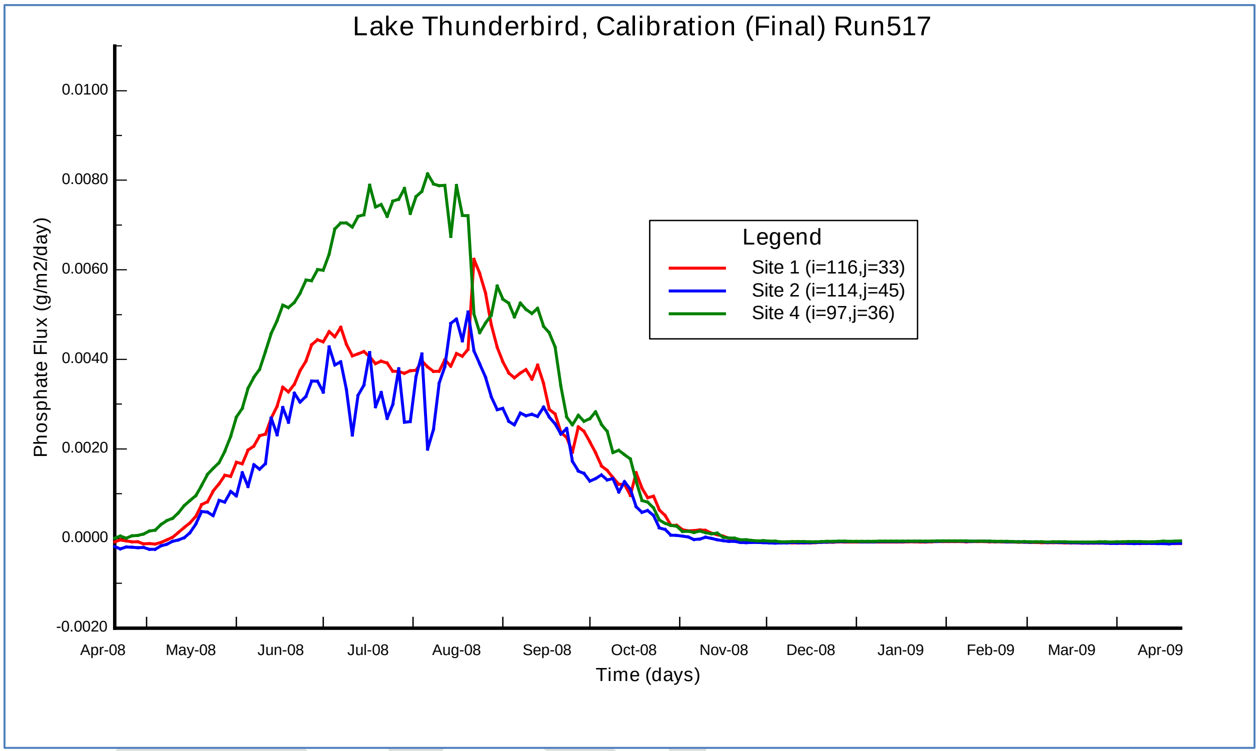

Figure B-14 Model Results for Benthic Flux of Dissolved Phosphate-P (PO4) (as g/m^2-day) for Sediment Diagenesis Model for Lacustrine Sites 1, 2 and 4.

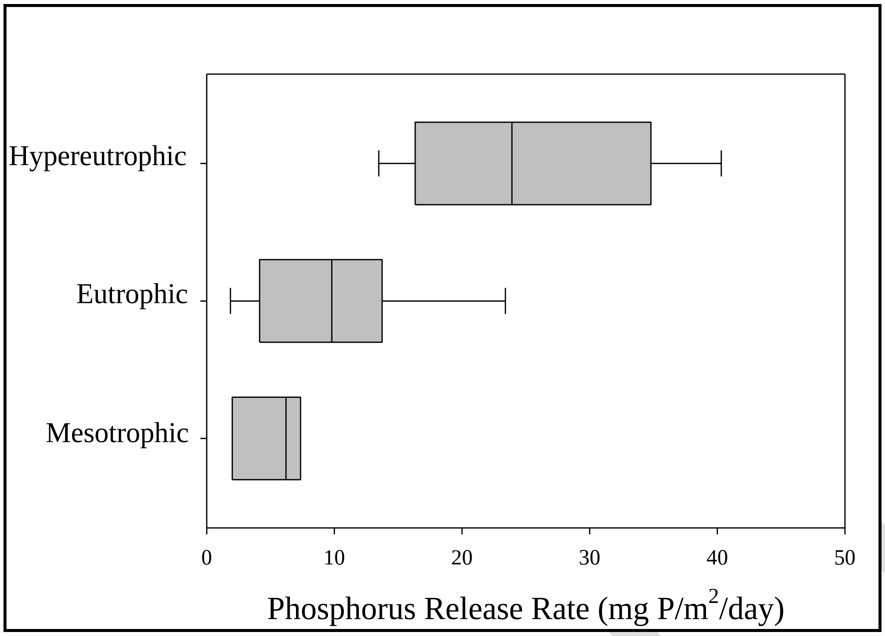

Figure B-15 Comparison of anoxic release rates of phosphorus (as mg P/m^2-day) from mesotrophic (n=3), eutrophic (n=9), and hypereutrophic (n=5) reservoirs in the Central Plains. Line within the box represents the median; edges of the box represent the 25th and 75th percentiles; error bars represent the 10th and 90th percentiles (Dzialowski and Carter, 2011).

B.3.3 Summary of Model Performance

Model performance is evaluated to determine the endpoint for model calibration using a “weight of evidence” approach that has been adopted for many modeling studies. The “weight of evidence” approach includes the following steps: (a) visual inspection of plots of model results compared to observed data sets (e.g., station time series); and (b) analysis of model-data performance statistics as the Root Mean Square (RMSE) Error and the Relative RMS Error as described below. The “weight of evidence” approach recognizes that, as an approximation of a waterbody, perfect agreement between observed data and model results is not expected and is not specified as a performance criterion for the success of model calibration. Model performance statistics are used, not as absolute criteria for acceptance of the model, but rather, as guidelines to supplement the visual evaluation of model-data time series plots to determine the endpoint for calibration of the model. The “weight of evidence” approach used for this study thus acknowledges the approximate nature of the model and the inherent uncertainty in both input data and observed data.

The model-data model performance statistics selected for calibration of the hydrodynamic and water quality model are the Root Mean Square Error (RMSE) and the Relative RMS Error. The RMSE, also known as the Standard Error of the Mean, has units defined by the units of each state variable of the model. The Relative RMS error, computed as the ratio of the RMSE to the observed range of each water quality constituent is as a percentage (Ji, 2008). Since the Relative RMS error is expressed as a percentage, this performance measure provides a straightforward statistic to evaluate agreement between model results and observations.

Observed station data has been processed to define time series for each station location for the surface layer and bottom layer of the water column. Observed data is assigned to a vertical layer based on surface water elevation, station bottom elevation and the total depth of the water column estimated for the sampling date/time. Station locations are overlaid on the model grid to define a set of discrete grid cells that correspond to each monitoring site for extraction of model results.

The equations for the RMSE and the Relative RMS Error are,

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\Sigma(O-P)^2}$$

$$\text{Relative RMS Error} = \frac{\mathrm{RMSE}}{(O_{range})} x100$$

Where

N is the number of paired records of observed data and EFDC model results,
O is the observed water quality data,
P is the predicted EFDC model result, and
O_{range} is the range of observed data computed from maximum and minimum values.

In evaluating the results obtained with the EFDC model, a Relative RMS Error performance measure of $\pm 20\%$ is adopted for evaluation of the comparison of the model predicted results and observed measurements of water surface elevation of the lake. For the hydrographic state variables simulated with the EFDC hydrodynamic model, a Relative RMS Error performance measure of $\pm 50\%$ is adopted for evaluation of the comparison of the predicted results and observed measurements for water temperature. For the water quality state variables simulated with the EFDC water quality model, a Relative RMS Error performance measure of $\pm 20\%$ is adopted for dissolved oxygen; $\pm 50\%$ for nutrients and suspended solids; and $\pm 100\%$ for algal biomass for the evaluation of the comparison of the predicted results and observed water quality measurements for model calibration. These targets for hydrodynamic, sediment transport and water quality model performance, defined for the overall composite statistic computed from the set of station-specific statistics, are consistent with the range of model performance targets recommended for surface water models (Donigian, 2000).

Given the lack of a general consensus for defining quantitative model performance criteria, the inherent errors in input and observed data, and the approximate nature of model formulations, *absolute* criteria for model acceptance or rejection are not appropriate for studies such as the development of the lake model for Lake Thunderbird. The Relative RMS Errors are used as targets for performance evaluation of the calibration of the model, but not as rigid absolute criteria for rejection or acceptance of model results. The “weight of evidence” approach used in this study recognizes that, as an approximation of a waterbody, perfect agreement between observed data and model results is not expected and is not specified as performance criteria for defining the success of model calibration.

As presented in Table B-5, the model performance results for water level, water temperature, chlorophyll-a, dissolved oxygen, nitrate and total organic phosphorus are either much better than, or close to, the target criteria. The model results for TSS, total phosphorus, total phosphate, and total nitrogen are also good with the model performance statistics shown to be only 5-6% over the target criteria of 50%. The exceptions to the overall good results achieved with the model are for Total Organic Carbon and Total Organic Nitrogen where the Relative RMS Errors exceed the target criteria of 50% by over 25%.

Table B-5 Composite Model Performance for Lake Thunderbird Hydrodynamic and Water Quality Model Based on Model-Data Comparison at All Station Locations

Composite Statistics, All 8 Station Locations (Apr 2008-Apr 2009)						**Target Relative RMS**
Parameter	**#Data Pairs**	**Avg Observed**	**Avg Model**	**RMS Error**	**Relative RMS**	
Water Surface Elevation (m)	8921	316.92	316.916	0.008	0.6%	20%
Temperature (Deg C)	465	20.726	20.817	1.834	8.4%	50%
TSS (Inorg + Org) (mg/L)	184	17.576	15.59	13.374	52.3%	50%
Chlorophyll a (µg/l)	217	23.332	25.419	11.038	20.8%	100%
Dissolved Oxygen (mg/L)	432	6.68	6.626	1.648	19.2%	20%
Total P (mg/L)	184	0.065	0.056	0.05	55.9%	50%
Total Org P (mg/L)	107	0.031	0.024	0.019	29.8%	50%
Total Phosphate (mg/L)	184	0.037	0.032	0.046	55.8%	50%
Total N (mg/L)	114	0.805	0.616	0.945	55.1%	50%
Nitrate Nitrogen (mg/L)	111	0.15	0.165	0.084	28.5%	50%
Total Org N (mg/L)	114	0.603	0.308	0.37	87.7%	50%
Total Organic Carbon (mg/L)	200	5.666	5.212	1.301	77.5%	50%
RMS Error Root Mean Square Error Relative RMS% Relative Root Mean Square Error%						

B.3.4 Pollutant Load Budget: Existing Model Calibration (2008-2009)

Using data developed for calibration of the watershed model and the lake model to 2008-2009 conditions, a mass balance budget for sediment, nutrients and BOD is compiled to identify the relative magnitude of the external and internal sources of pollutant loading to the lake. External sources include tributary inputs, wet and dry atmospheric deposition, and distributed runoff from the watershed. Internal sources include the benthic fluxes of inorganic nutrients across the sediment-water interface of the lake. Mass balance loading rates (as kg/day) are compiled for the 375 day simulation period from April 2008-April 2009.

Table B-6 presents a summary of the mass balance budget for the existing 2008-2009 calibration conditions for HSPF watershed loads. Table B-7 presents a summary, and comparison, of the external and internal benthic flux loading rates for the existing 2008-2009 calibration conditions. Table B-8 presents the percentage contributions of watershed, atmospheric deposition and benthic flux loading to the total inorganic nutrient load. As shown in Table B-8, internal benthic flux of phosphate accounts for 89% of the total phosphate loading to the lake on an annual basis. Atmospheric deposition of the sum of nitrate and ammonia (DIN) accounts for 46% of the inorganic nitrogen input while benthic flux of DIN accounts for 38% of the total DIN loading to the lake. Accounting for one-third or more of the total inorganic nitrogen loading, atmospheric deposition and benthic flux both represent significant contributions to the total load for inorganic nitrogen.

Table B-6 Annual Watershed Loading of Nutrients, BOD and Sediment for Existing Calibration Conditions (2008-2009)

Model Calibration	**Annual**
Source	**Watershed HSPF**
Existing 2008-2009	**kg/day**
Total Nitrogen (TN)	318.2
Total Phosphorus (TP)	59.7
BOD	636.9
Suspended_Solids	30,772.3

Table B-7 Comparison of Annual Watershed Loading, Atmospheric Deposition and Sediment Flux of Inorganic Nutrients for Existing Calibration Conditions (2008-2009)

Model Calibration	**Annual**	**Annual**	**Annual**	**Annual**
Source	**Watershed HSPF**	**AtmDep**	**SedFlux**	**Total**
Existing 2008-2009	**kg/day**	**kg/day**	**kg/day**	**kg/day**
Phosphate(PO4)	7.8	0.5	68.6	76.8
Nitrate (NO3)	30.5	79.5	61.0	171.0
Ammonia (NH4)	7.6	32.6	32.6	72.9
DIN (NO3+NH4)	38.1	112.1	93.6	243.8

Table B-8 Percentage Contribution of Annual Watershed Loading, Atmospheric Deposition and Sediment Flux of Inorganic Nutrients for Existing Calibration Conditions (2008-2009)

Model Calibration	**Annual**	**Annual**	**Annual**	**Annual**
Source	**Watershed HSPF**	**AtmDep**	**SedFlux**	**Total**
Existing 2008-2009	**%**	**%**	**%**	**%**
Phosphate(PO4)	10.1	0.7	89.2	100
Nitrate (NO3)	17.8	46.5	35.7	100
Ammonia (NH4)	10.5	44.7	44.8	100
DIN (NO3+NH4)	15.6	46.0	38.4	100

B.4 Modeled Load Reduction Scenarios

The calibrated lake model was used to evaluate the water quality response to reductions in watershed loading of sediment, nutrients and BOD. Load reduction scenario simulation runs were performed to determine if water quality targets for turbidity, chlorophyll-a and dissolved oxygen could be attained with watershed-based load reductions of 25%, 35%, 50%, and 75%. Based on an evaluation of the load reduction scenario results the 35% removal alternative was selected for a detailed “spin-up” analysis of the long-term water quality response of the lake to changes in watershed loads. The 35% removal load reduction scenario was used to simulate 8 years of sequential “spin-up” runs to evaluate the long-term response of water quality conditions in the lake to the 35% removal change in external loads from the watershed. For the set of spin-up runs, watershed flow and reduced pollutant loading from the HSPF model was repeated for each of the 8 spin-up years. The results derived from the 8 years of spin-up simulations did not, therefore, account for any projected, or future, conditions of hydrologic variability within the watershed.

The 35% pollutant removal scenario identified for the TMDL for Lake Thunderbird is based on a simple uniform reduction of all sediment, BOD, TN and TP loads contributed by all tributaries, stormwater point sources and distributed runoff from the watershed to represent the reduction of pollutant loads to Lake Thunderbird. The methodology applied for developing the load reduction scenarios did not attempt to represent changes in external watershed loading based on implementation of specific BMPs or point source waste load allocations.

The lake model is applied as a “what-if?” tool to evaluate the long-term impact of the 35% removal scenario for external loads on changes in water quality conditions in Lake Thunderbird. Key management questions addressed with the lake model include:

- Will the 35% load reduction scenario succeed in attaining compliance with water quality standards for turbidity, chlorophyll-a and dissolved oxygen?

- Is the time frame for projected water quality conditions to attain compliance with water quality standards considered reasonable?

In evaluating the simulated impact of a 35% reduction in external loads of pollutants to the lake, the significant differences in the time scales needed for the response of the water column and the sediment bed to changes in external loading must be considered. Sediment bed conditions are known to respond to changes in external loads over a time scale that is measured on the order of several years (Di Toro, 2001). As shown with the mass balance budget of nutrient loading from the watershed and the sediment bed for model calibration, loading from the sediment bed dominates total loading of nutrients to the lake. Any changes that will occur in water quality conditions of the lake are controlled by changes in organic matter deposition from the water column to the bed, the reservoir of nutrients in the sediment bed and the resulting sediment flux loading of nutrients from the bed to the water column.

Based on the data used for the 35% removal of nutrients and sediment from the watershed, the change in external loading of pollutants from the watershed to the lake is specified. The initial conditions for water quality for the 35% removal scenario are assigned from the actual observed conditions from mid-April 2008 that are used to assign initial water quality conditions for model development and calibration to 2008-2009 data. The initial conditions that need to be assigned as input data to characterize the concentrations of organic matter and nutrients in the sediment bed for the projected 35% removal scenario are, however, unknown. It is only known that projected sediment bed conditions will be different than historical conditions measured by OWRB in 2008 and used for initial conditions of the bed for model calibration to the 2008-2009 data. A characterization of altered sediment bed conditions that might be expected under the 35% load reduction scenario can, however, be developed by repeatedly running the lake model for several years in a series of sequential restart runs. Each time the model is run, the sediment flux model provides new data about changes in sediment bed conditions and nutrient fluxes. Initial conditions for water quality in the water column and initial conditions for the sediment flux model are reset using model restart conditions simulated at the end of the 1-year period. The spatial distribution of model conditions at the end of the 1-year model run is saved and written to restart files that are then used as input to the water quality and sediment flux model for the next restart run.

Using the watershed loading data developed for the 35% removal scenario, the lake model is repeatedly run with a series of restart runs to track how water quality and sediment bed conditions within the lake change over time, or spin-up, in response to the changes in sediment bed conditions and sediment fluxes of nutrients from the bed to the water column. Lake water quality conditions are compared to the standards for turbidity, chlorophyll-a and dissolved oxygen and tracked over time for each restart run to evaluate how lake water quality conditions spin-up in response to the 35% removal of external loads and the changes in internal loads. The results of the 8 sequential restart runs are post-processed to track how sediment bed conditions and benthic nutrient flux rates change and how water quality conditions in the lake, in turn, change over time because of the reduced watershed load and changes in the sediment bed.

Model calibration is defined by the 1-year period from April 18, 2008 to April 29, 2009. The results of the initial 35% removal run are reported as Year 0 and the 8 sequential restart runs are reported as Year 1, 2, 3, 4, 5, 6, 7, and 8. Based on extraction of model results generated for the final restart run for Year 8, a mass-balance budget of TSS, nutrients and BOD is compiled and presented in Section B.4.2 to determine the magnitude of external controllable sources and internal uncontrollable sources of loading to the lake under projected conditions for the final Year 8 spin-up run for the 35% removal load allocation scenario.

B.4.1 Lake Water Quality Response with 35% Removal of Watershed Loads

Results of the spin-up model runs for the 35% removal load reduction scenario are presented to show long-term trends in turbidity, chlorophyll-a, dissolved oxygen, benthic phosphate flux, and sediment oxygen demand. The spin-up results are also used to evaluate long-term changes in the contribution of internal phosphate loading from the sediment bed to external phosphate loads from the watershed and atmospheric deposition.

Turbidity and Chlorophyll-a. As discussed in Section 2 of the main TMDL report, Oklahoma water quality standards for Lake Thunderbird turbidity and chlorophyll-a are as follows:

- Turbidity: 90th percentile value of surface turbidity no greater than 25 NTU based on compilation of records of most recent 10 years
- Chlorophyll-a: Average value of surface chlorophyll-a no greater than 10 µg/L based on compilation of records of most recent 10 years

Table B-9 summarizes the annual statistics for turbidity and chlorophyll-a for (a) the observed data collected in 2008-2009 used for model calibration, (b) the calibrated model results and the results generated with (c) eight years of spin-up runs for the 35% removal scenario, respectively. Summary statistics are computed from model results for all 8 sites for the annual simulation period from April 2008-April 2009. The chlorophyll-a statistic is computed as the average of the model results for all 8 sites. The turbidity statistic is computed as the 90th percentile of the model results for all 8 sites. The number of simulation records for the model statistics (N=17,856) is based on 2,232 records per site for 8 sites.

As can be seen in the data presented in Table B-9, the 90th percentile for observed turbidity (29.7 NTU) exceeds the target of 25 NTU. The calibrated model results for surface turbidity (27.6 NTU) also show non-compliance with the target of 25 NTU. Each of the spin-up runs for the 35% load reduction scenario show a gradual improvement in turbidity with respect to compliance with the target of 25 NTU. Figure B-16 presents the long-term trends for the turbidity data presented in Table B-9 for the 35% removal scenario.

As shown in Table B-9, the 2008-2009 average for observed surface chlorophyll-a (24.8 µg/L) exceeds the target criteria for SWS lakes of 10 µg/L. The calibrated model results for chlorophyll-a (21.5 µg/L) also show non-compliance with the SWS target criteria. Figure B-17 shows the spin-up trend for the chlorophyll-a data presented in Table B-9 for the 35% removal scenario. Algae biomass increases after the first year of the 35% removal scenario because turbidity is reduced, water clarity is improved and primary productivity increases with increased light availability for algae growth. After the first year, chlorophyll-a progressively declines each year until the SWS water quality criteria of 10 µg/L is attained by Year 5 under the 35% removal scenario. Chlorophyll-a gradually declines after the first spin-up year because the supply of phosphorus available to support primary production in the euphotic zone diminishes as internal phosphorus loading from benthic phosphate flux is reduced (see Figure B-18). The largest contribution of internal loading of phosphate to the lake, controlled by hypoxic bottom water oxygen conditions, occurs during the summer stratified period from mid-May to early October. As can be seen in Figure B-18 the whole lake seasonal benthic phosphate flux declines from 5.4 mg P/m^2-day for the initial year (Yr0) to 1.7 mg P/m^2-day (Yr8) after 8 years of model spin-up as the coupled interaction of the sediment-water system attains a new equilibrium condition.

Table B-9 Summary Statistics for Chlorophyll-a and Turbidity for observed data, model calibration and 8 years of spin-up runs of the 35% removal scenario. Observed data and model results are aggregated over the whole lake for the simulation period from April 2008-April 2009.

35%R	**8 SITES**	**8 SITES**
	CHL	**TURBIDITY**
	(µg/L)	**(NTU)**
ANNUAL	**AVERAGE**	**90%ile**
Target	10	25
Observed	24.8	29.7
Calibration	21.5	27.6
Yr0	23.0	19.3
Yr1	24.5	18.5
Yr2	20.5	18.4
Yr3	15.6	18.0
Yr4	11.8	17.7
Yr5	10.0	17.6
Yr6	9.3	17.4
Yr7	8.9	17.3
Yr8	8.9	17.3

8 SITES	**8 SITES**
CHL	**TURBIDITY**
(µg/L)	**(NTU)**
Pct_Chng	**Pct_Chng**
6.6%	-3.8%
-16.4%	-0.6%
-23.9%	-2.5%
-24.3%	-1.4%
-15.2%	-0.6%
-7.6%	-1.1%
-3.4%	-0.7%
-0.9%	0.0%

The spin-up simulation analysis of the coupled water column-sediment bed response to the 35% reduction in watershed loading of sediment and nutrients indicates that compliance with the SWS target for chlorophyll-a of 10 µg/L can be attained within a reasonable time frame. **It is important to emphasize that the model spin-up results are <u>not</u> an absolute prediction of the number of years required for lake recovery because of the idealized spin-up conditions of a precisely maintained watershed load reduction level and repeated climatic and hydrologic conditions of 2008-2009.** The model results, do, however, provide technically credible evidence that future conditions can be in compliance with SWS water quality criteria for chlorophyll-a within a reasonable time frame if watershed loads are reduced as recommended and the reduction is sustained. The model results, do, however, provide technically credible evidence that future conditions can be in compliance with SWS water quality criteria for chlorophyll-a within a reasonable time frame if watershed loads are reduced as recommended and the reduction is sustained over time.

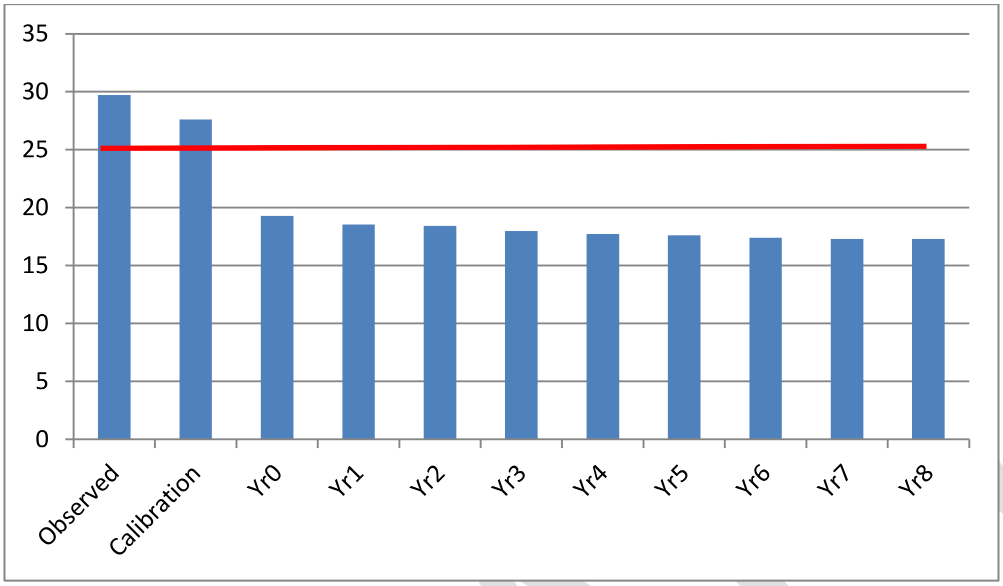

Figure B-16 Surface Turbidity (NTU): Spin-Up Model Results for 35% Removal, Annual 90th Percentile of all 8 Sites

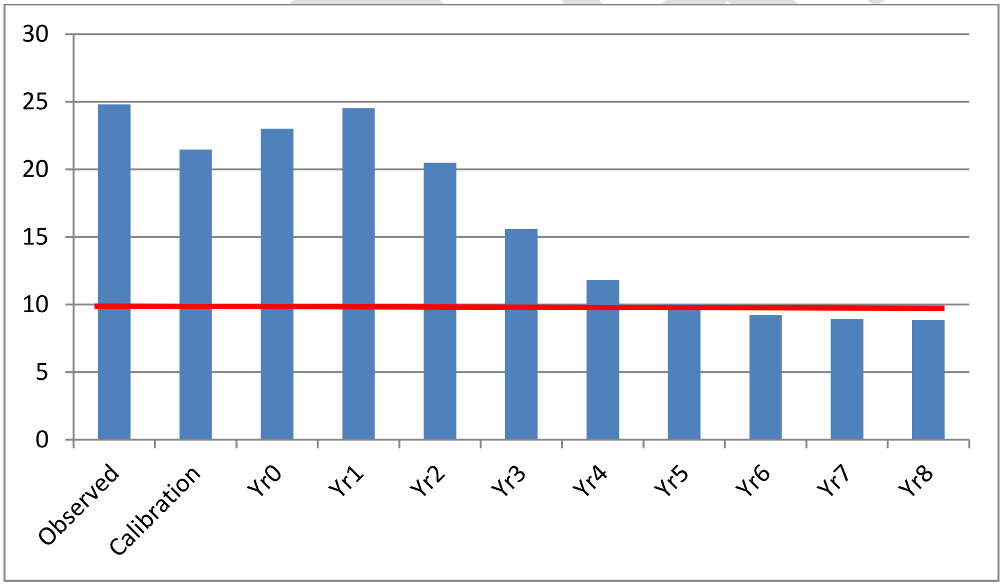

Figure B-17 Surface chlorophyll-a (µg/L): Spin-Up Model Results for 35% Removal, Annual Average of all 8 Sites

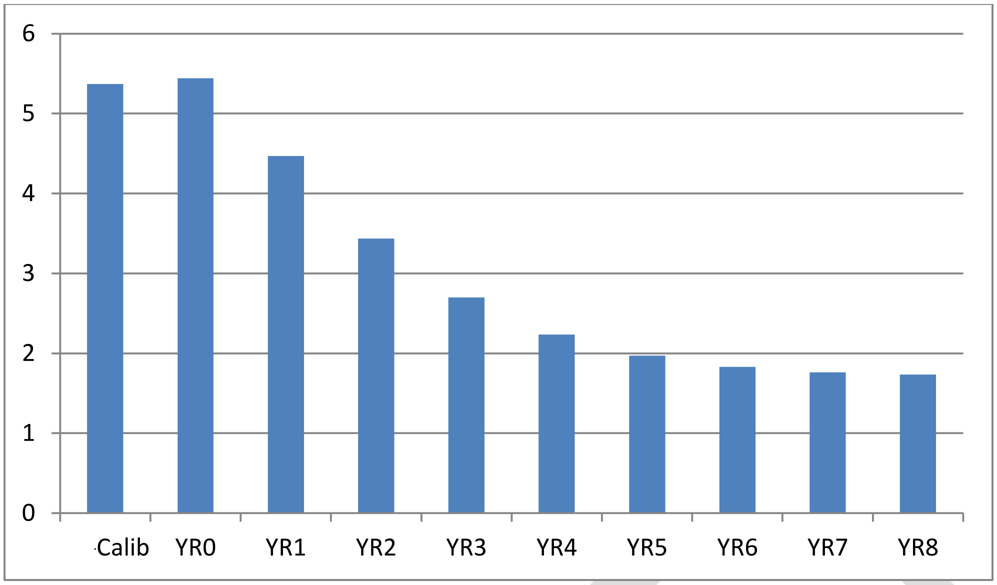

Figure B-18 Sediment Flux PO4 (mg P/m^2-day), whole lake average for seasonal stratified period from May 15-Oct 1, 2008 for the 35% removal scenario

Dissolved Oxygen and Sediment Oxygen Demand. Oklahoma water quality standards for dissolved oxygen for Lake Thunderbird are specified in relation to (a) the surface layer/epilimnion and (b) the anoxic volume of the lake within the hypolimnion. Within the surface layer/epilimnion, dissolved oxygen shall be no less than 6 mg/L from April 1 to June 15 for protection of early life stages and no less than 5 mg/L from June 16 to March 31 for protection of other life stages of a warm water aquatic community. Within the hypolimnion, the anoxic volume of the lake, defined by a cutoff DO level of 2 mg/L, shall not exceed 50% of the lake volume during the period of seasonal stratification from mid-May through October 1.

The results of the computations of anoxic volume, based on a target oxygen level of 2 mg/L, are presented as time series of anoxic volume in Figure B-9 for the whole lake and in Figure B-10 for Site 2 for the existing calibration conditions of 2008-2009. Figure B-19 presents the anoxic volume of the whole lake simulated for the 35% removal scenario with a comparison shown to the existing calibration conditions. As can be seen by comparison of the model calibration to the progression of spin-up years, the anoxic volume gradually decreases with each spin-up year from the 35% reduction of watershed loading.

The anoxic volume of the lake gradually decreases because the whole lake sediment oxygen demand (SOD) is reduced with each spin-up year of the 35% removal scenario (Figure B-20). SOD gradually declines from ~0.78 g O_2/m^2-day for the initial year (Yr0) to 0.2 g O_2/m^2-day after 4 years (Yr4) and ~0.12 g O_2/m^2-day after 8 years (Yr8) of spin-up for the 35% removal scenario. The gradual decline in SOD reflects the response of the coupled water column and sediment bed of the lake to new equilibrium conditions for particulate organic matter deposition to the sediment bed based on the effectiveness of the load reduction scenario for 35% removal of sediments and nutrients from watershed loading.

As a management alternative in response to the repeated occurrence of hypolimnetic anoxia during summer stratified conditions, an oxygen injection system has been installed in Lake Thunderbird (Cadenhead, 2012). COMCD received an American Recovery and Reinvestment Act of 2009 grant (ARRA) to install and operate a Supersaturated Dissolved Oxygen (SDOX) system and in 2010, the COMCD partnered with the OWRB, to design, install, and monitor the

SDOX pump at the lake's deepest area near the dam. This energy-efficient pump uses the latest technology to prevent the lakes hypolimnion from going anoxic throughout the summer months without disrupting the lake's natural thermocline. As discussed in Section B.3.2, seasonal anoxia exacerbates eutrophic conditions in the lake by triggering the benthic release of nutrients as an internal load to the water column. Eutrophic conditions favor bluegreen algae blooms that can contribute to taste and odor problems in drinking water. Operation of the SDOX device is targeted to improve oxygen levels in the lake to support the warm water fishery but also to reduce the treatment cost for drinking water. Since the SDOX system became operational after the study period of 2008-2009, the effects of the oxygen injection system are not represented in either calibration of the model to existing conditions or to the projection of the water quality impact of the 35% removal scenario.

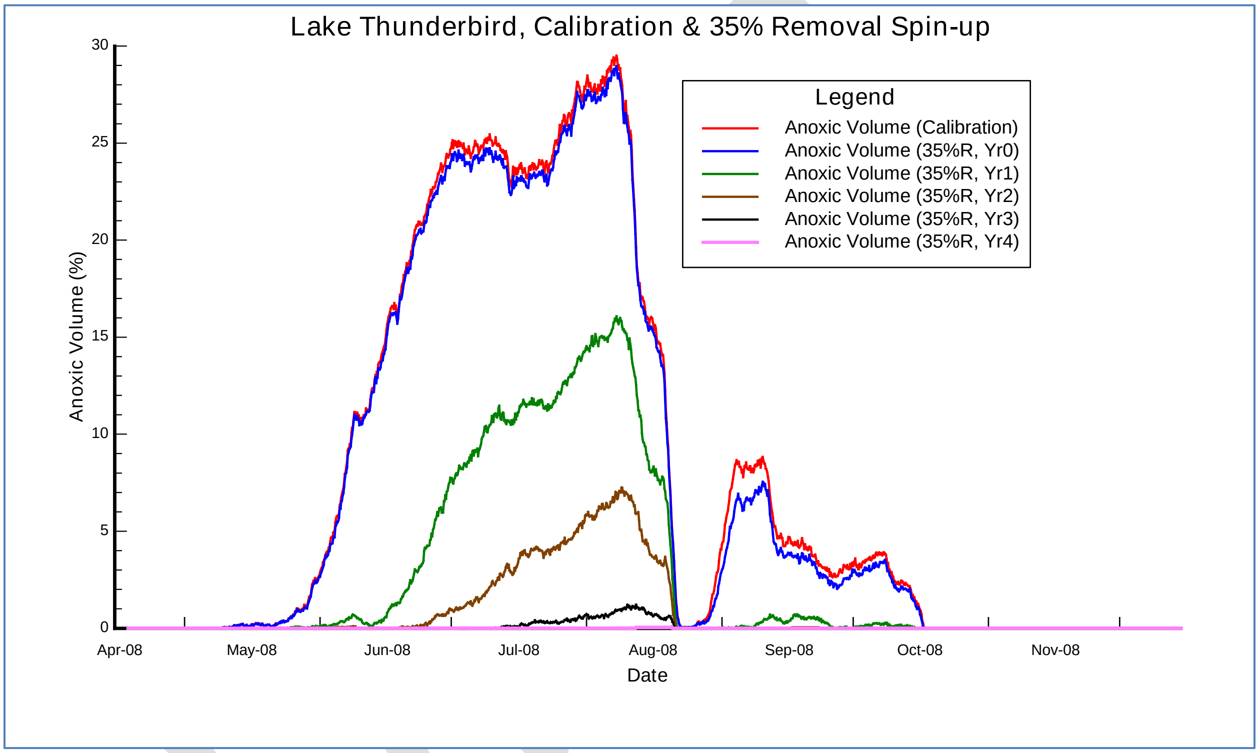

Figure B-19 Time series of anoxic volume of whole lake for 35% Removal Load reduction scenario. Model calibration results are shown as red line. Percentage of anoxic volume is based on aggregation of all grid cells in the lake.

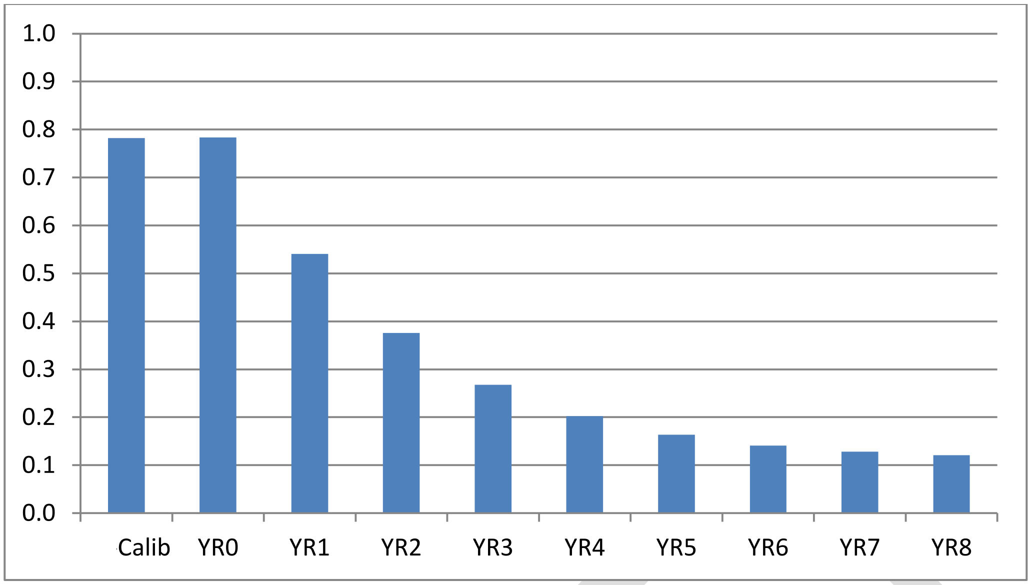

Figure B-20 Sediment Oxygen Demand (g O_2/m^2-day), whole lake average for seasonal stratified period from May 15-Oct 1, 2008 for the 35% removal scenario

B.4.2 Pollutant Load Budget: 35% Removal Scenario

Table B-10 presents a summary of the April 2008-April 2009 mass balance budget for the 35% removal scenario for HSPF watershed loads.

Table B-11 presents a summary, and comparison, of the external and internal benthic flux loading rates for the 35% removal scenario.

Table B-12 presents the percentage contributions of watershed, atmospheric deposition and benthic flux loading to the total inorganic nutrient load for the 35% removal scenario. As shown in

Table B-12, the contribution of the internal benthic flux of phosphate to the total phosphate load decreases from 89% for the existing calibration condition (see Table B-8) to 80% for the 35% removal case after a spin-up period of 8 years.

In contrast to the existing conditions for model calibration where the sediment bed is a significant source of inorganic nitrogen (DIN) to the lake (see Table B-7), the model spin-up results after 8 years suggest that the sediment bed may be a sink for DIN. The results of the spin-up after 8 years for the 35% removal scenario indicates that DIN may be lost from the water column to the sediment bed under the simulated conditions for the bed. As shown in Table B-9, a negative sediment flux load for ammonia and nitrate represents a loss of inorganic nitrogen from the water column to the sediment bed**.** With reduced external watershed loading and organic matter deposition from the water column, organic matter in the sediment bed is slowly decomposed and DIN concentrations in porewater decline. Benthic release rates gradually decrease over time until conditions exist where the DIN concentration in the sediment bed is lower than the DIN concentration in the overlying water column; and DIN is transported by diffusion from the water column to the sediment bed.

As shown in

Table B-11 for the 35% removal scenario, the external input of nitrate from the watershed (~20 kg/day) is approximately equivalent to the internal loss of nitrate from the water column to the bed (~21 kg/day). The internal loss of ammonia from the water column to the sediment bed (~14 kg/day) is almost three times the external input of ammonia from the watershed (5 kg/day). Overall, the total estimated benthic input of phosphate is decreased by 37% with the phosphate load declining from 76.8 kg/day for the existing calibration case (Table B-7) to 28.6 kg/day (

Table B-11) for the 35% removal scenario. Similarly, the total estimated input of inorganic nitrogen is decreased by 42% with the sum of the nitrate and ammonia (DIN) load declining from 243.9 kg/day for the existing calibration case (Table B-7) to 101.8 kg/day (

Table B-11) for the 35% removal scenario.

Table B-10 Annual Watershed Loading of Nutrients, BOD and Sediment for 35% Removal Scenario

Model 35% Removal	**Annual**
Source	**Watershed HSPF**
Spinup after 8 Years	**kg/day**
Total Nitrogen (TN)	206.8
Total Phosphorus (TP)	38.8
BOD	414.9
Suspended_Solids	20,002.0

Table B-11 Comparison of Annual Watershed Loading, Atmospheric Deposition and Sediment Flux of Inorganic Nutrients for 35% Removal Scenario

Model 35% Removal	**Annual**	**Annual**	**Annual**	**Annual**
Source	**Watershed HSPF**	**AtmDep**	**SedFlux**	**Total**
Spinup after 8 Years	**kg/day**	**kg/day**	**kg/day**	**kg/day**
Phosphate(PO4)	5.1	0.5	23.1	28.6
Nitrate (NO3)	19.8	79.5	-21.4	77.9
Ammonia (NH4)	5.0	32.6	-13.7	23.9
DIN(NO3+NH4)	24.8	112.1	-35.1	101.8

Table B-12 Percentage Contribution of Annual Watershed Loading, Atmospheric Deposition and Sediment Flux of Inorganic Nutrients for 35% Removal Scenario

Model 35% Removal	**Annual**	**Annual**	**Annual**	**Annual**
Source	**Watershed HSPF**	**AtmDep**	**SedFlux**	**Total**

Spinup after 8 Years	%	%	%	%
Phosphate(PO4)	17.7	1.7	80.6	100
Nitrate (NO3)	25.4	102.1	-27.5	100
Ammonia (NH4)	20.8	136.4	-57.2	100
DIN(NO3+NH4)	24.3	110.2	-34.5	100

B.5 Summary

The EFDC lake model incorporates external watershed loading and internal coupling of organic matter production and deposition from the water column to the sediment bed with decomposition processes in the sediment bed that, in turn, produce benthic fluxes of nutrients and sediment oxygen demand across the sediment-water interface. Lake Thunderbird, like many reservoirs, is characterized by seasonal thermal stratification and hypolimnetic anoxia. Summer anoxic conditions, in turn, are associated with internal nutrient loading from the benthic release of phosphate and ammonia into the water column that is triggered, in part, by low dissolved oxygen conditions. The mass balance based model, calibrated to 2008-2009 data, accounts for the cause-effect interactions of water clarity, nutrient cycling, algal production, organic matter deposition, sediment decay, and sediment-water fluxes of nutrients and oxygen.

The spin-up results for the 35% removal scenario suggest that chlorophyll-a may increase initially because of the availability of nutrients combined with the reduction of turbidity and the related improvement in water clarity, all favorable conditions for algal growth. Over time, however, the sediment bed reservoir of nutrients will diminish, benthic release of nutrients to the lake will be reduced and the pool of nutrients available in the water column to support algal production will be diminished. The model spin-up results demonstrate a gradual reduction in internal loading of nutrients from the sediment bed and an improvement in water quality conditions over the years based on the spin-up runs for the 35% removal scenario simulation.

The model indicates that water quality conditions are expected to be in compliance with the SWS water quality criteria for chlorophyll-a of 10 µg/L within a reasonable timeframe. It is important to note, however, that the spin-up results for the 35% removal scenario should not be taken as absolute projections of future water quality conditions in the lake with certainty as to some future calendar date because of the idealized spin-up conditions of a precisely maintained watershed load reduction level and repeated climatic conditions of a past year. The model, does however, provide a technically credible framework that clearly shows that water quality improvements can be achieved in Lake Thunderbird within a reasonable time frame to support the desired beneficial uses if watershed loading can be controlled and sustained to a level based on 35% reduction of the existing loading conditions. Attainment of water quality standards will occur, however, only over a period of time and only after full implementation of source controls and BMPs considered necessary to achieve an overall 35% removal of sediment and nutrients from the watershed.

Although the model demonstrates that internal loading of phosphate is a significant controlling factor for eutrophication in the lake, loading from the watershed is a direct factor in the deterioration of water quality conditions and ultimately the accumulation in the lake sediment of excessive nutrients and organic matter from the watershed over the past 5 decades is the source of the internal loading. Reductions in watershed loading are therefore required to achieve improvements in lake water quality. The model results suggest that compliance with water quality criteria for turbidity, dissolved oxygen and chlorophyll-a can be achieved with a 35% removal of sediments and nutrients from watershed loading to the lake within a reasonable time frame. The model results thus support the development of TMDLs for sediments, BOD, TN and TP to achieve compliance with water quality standards for turbidity, chlorophyll-a and dissolved oxygen. The calibrated HSPF watershed runoff model and the EFDC hydrodynamic and water quality model of Lake Thunderbird provides DEQ with a scientifically defensible surface water model framework to support development of TMDLs and water quality management plans for Lake Thunderbird.

B.6 Time Series Plots for EFDC Lake Model Results for Lacustrine, Transition and Riverine Zones of Lake Thunderbird

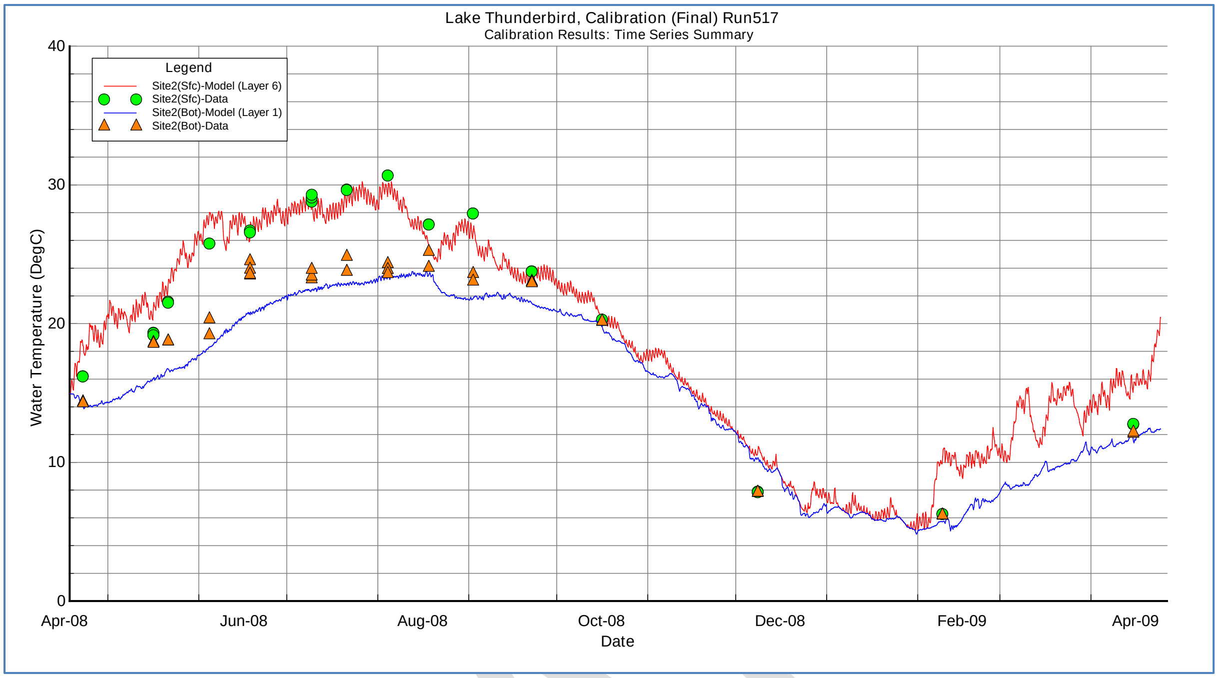

Figure 21 TS_Cal003_Temp_Site2 (Surface & Bottom)

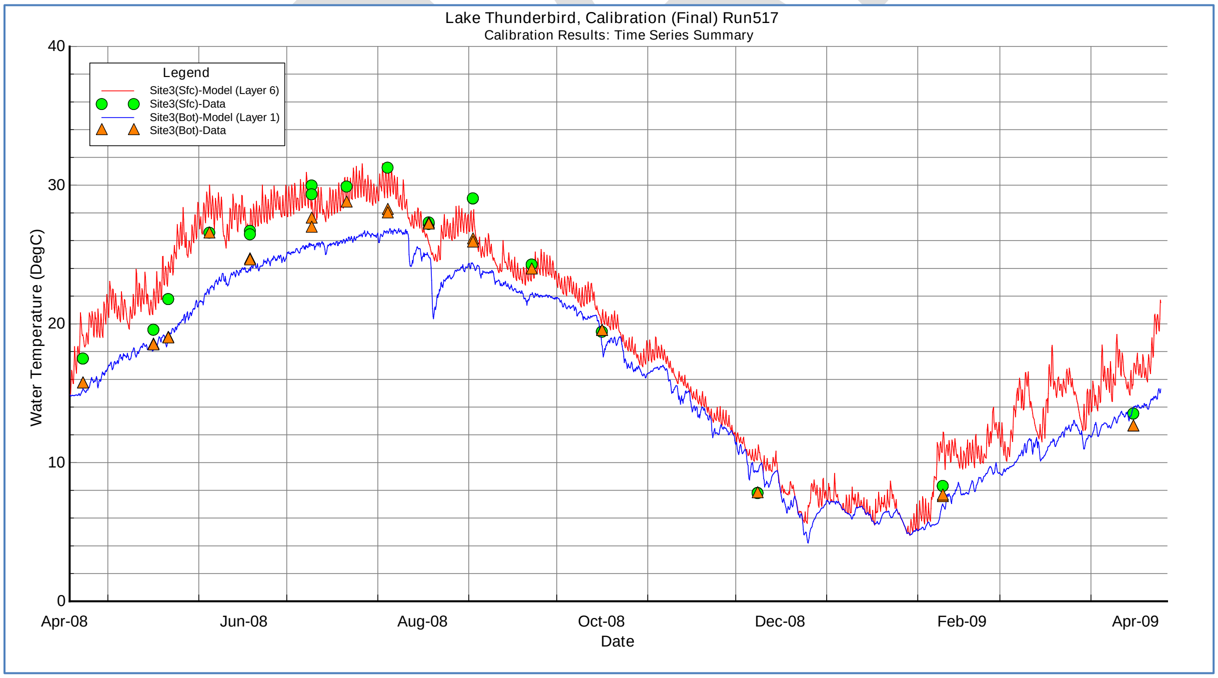

Figure 22 TS_Cal004_Temp_Site3 (Surface & Bottom)

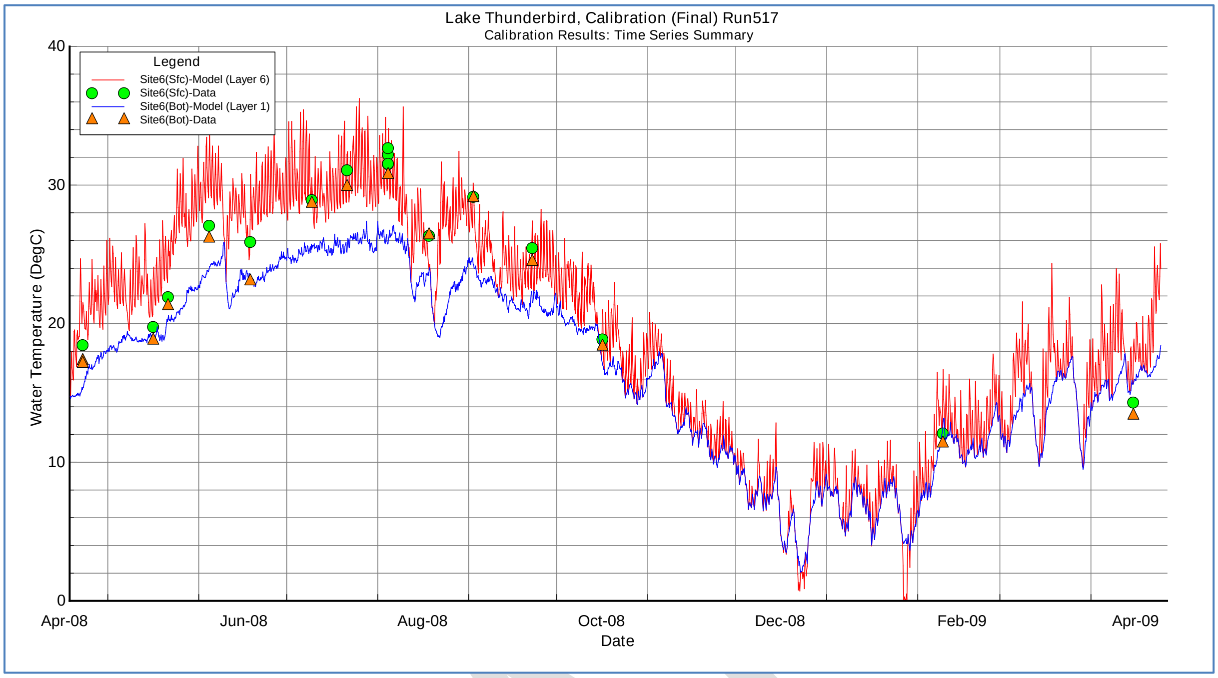

Figure 23 TS_Cal007_Temp_Site6 (Surface & Bottom)

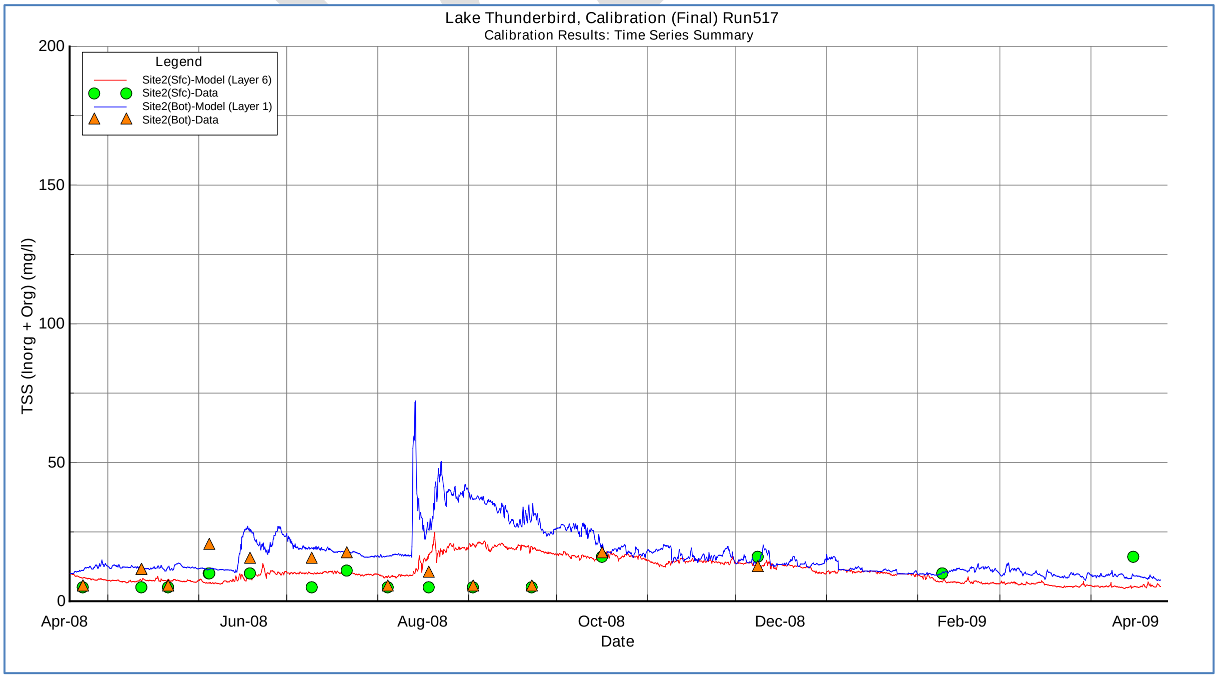

Figure 24 TS_Cal011_TSS(io)_Site2 (Surface & Bottom)

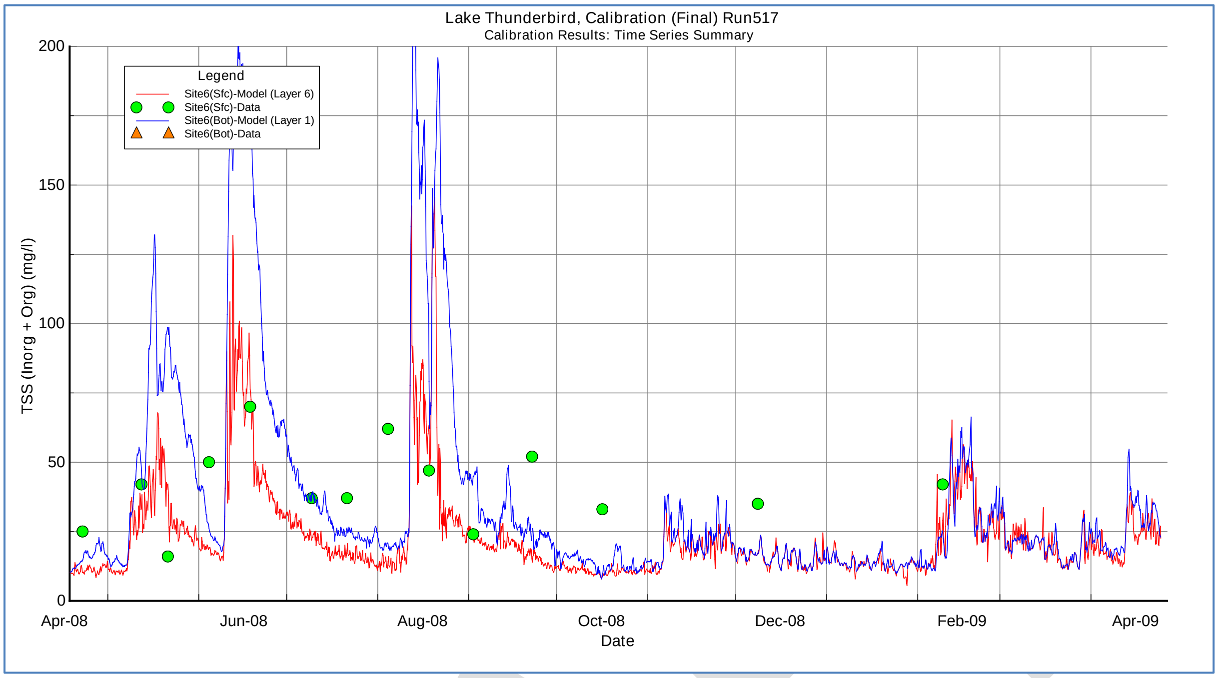

Figure 25 TS_Cal015_TSS(io)_Site6 (Surface)

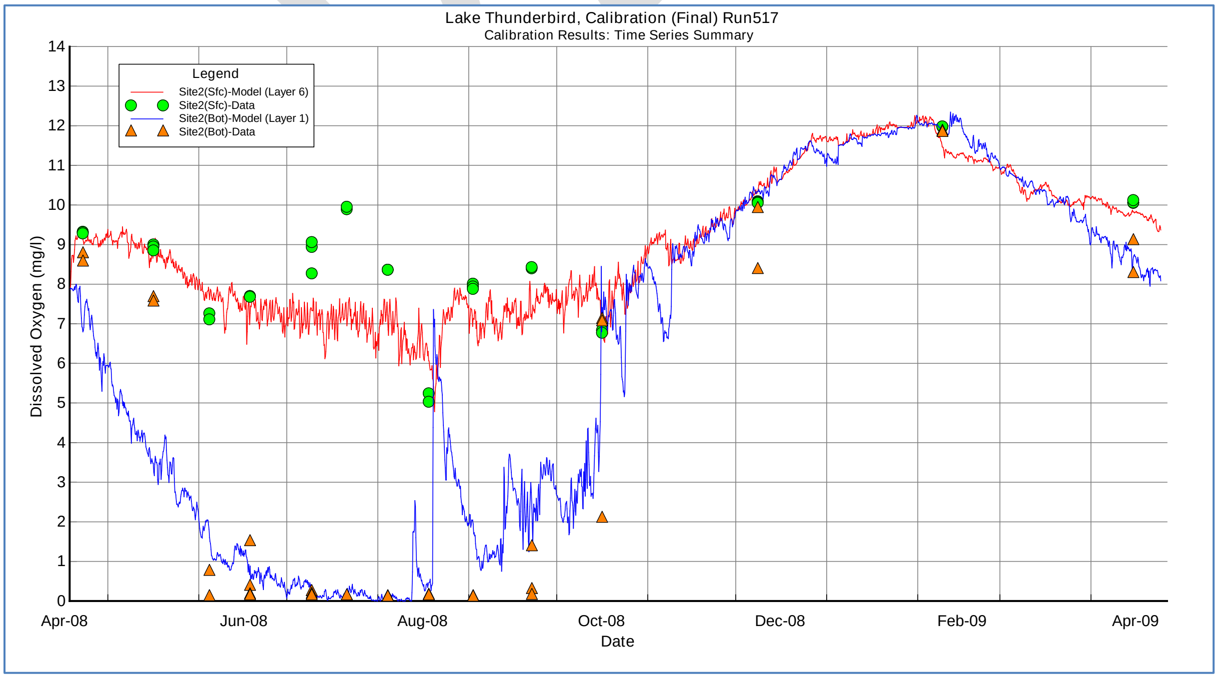

Figure 26 TS_Cal019_DO_Site2 (Surface & Bottom)

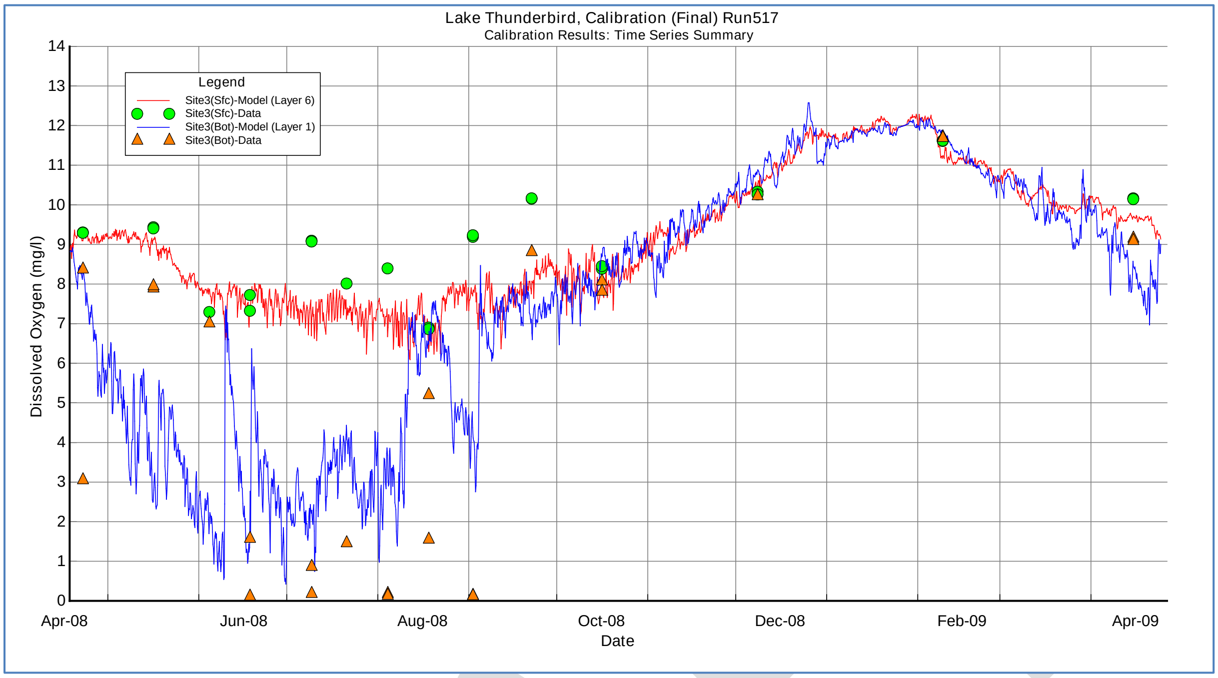

Figure 27 TS_Cal020_DO_Site3 (Surface & Bottom)

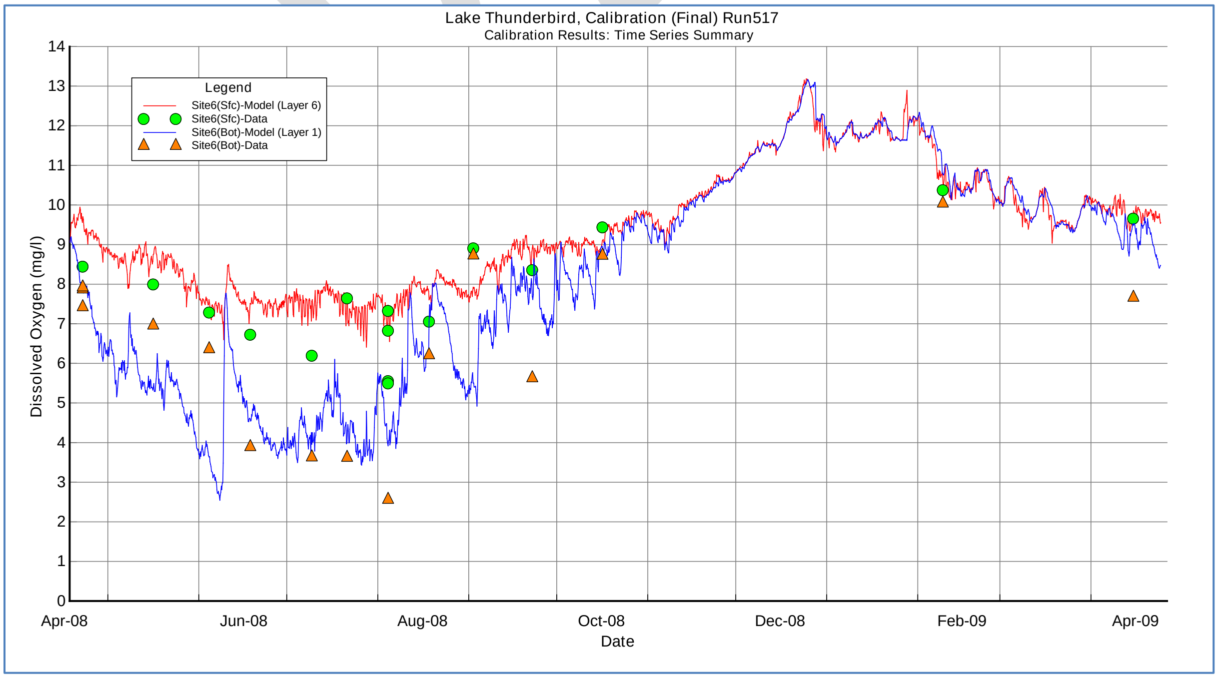

Figure 28 TS_Cal023_DO_Site6 (Surface & Bottom)

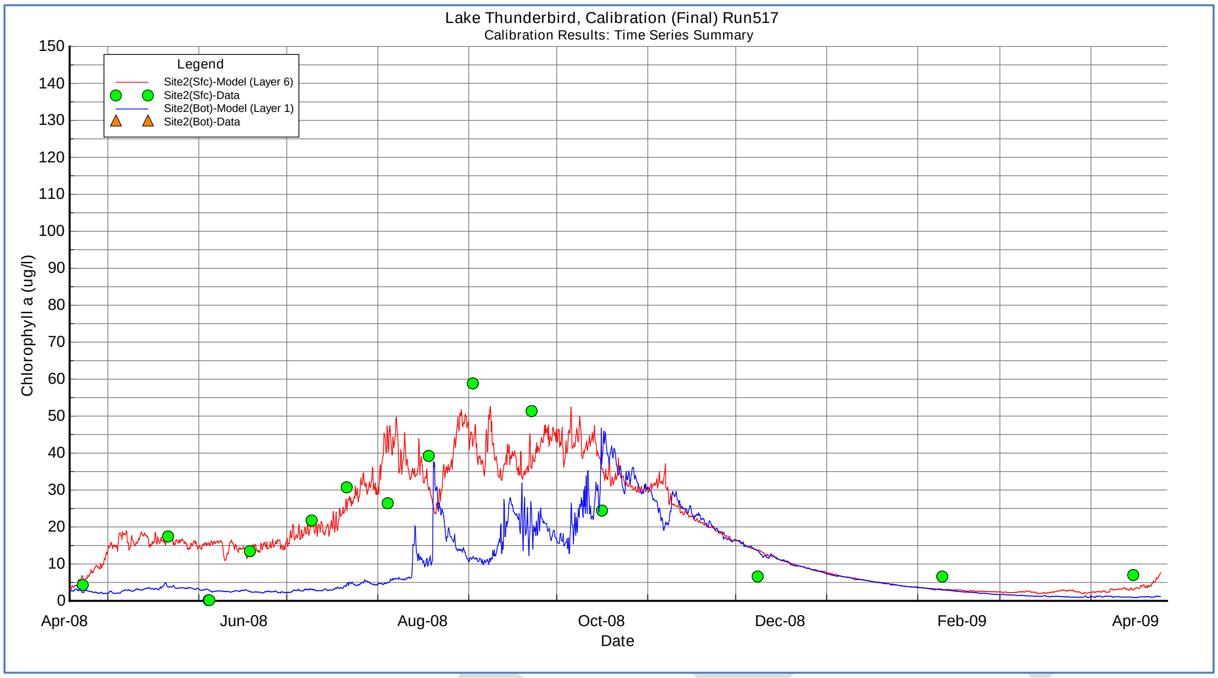

Figure 29 TS_Cal027_Chl a_Site2 (Surface)

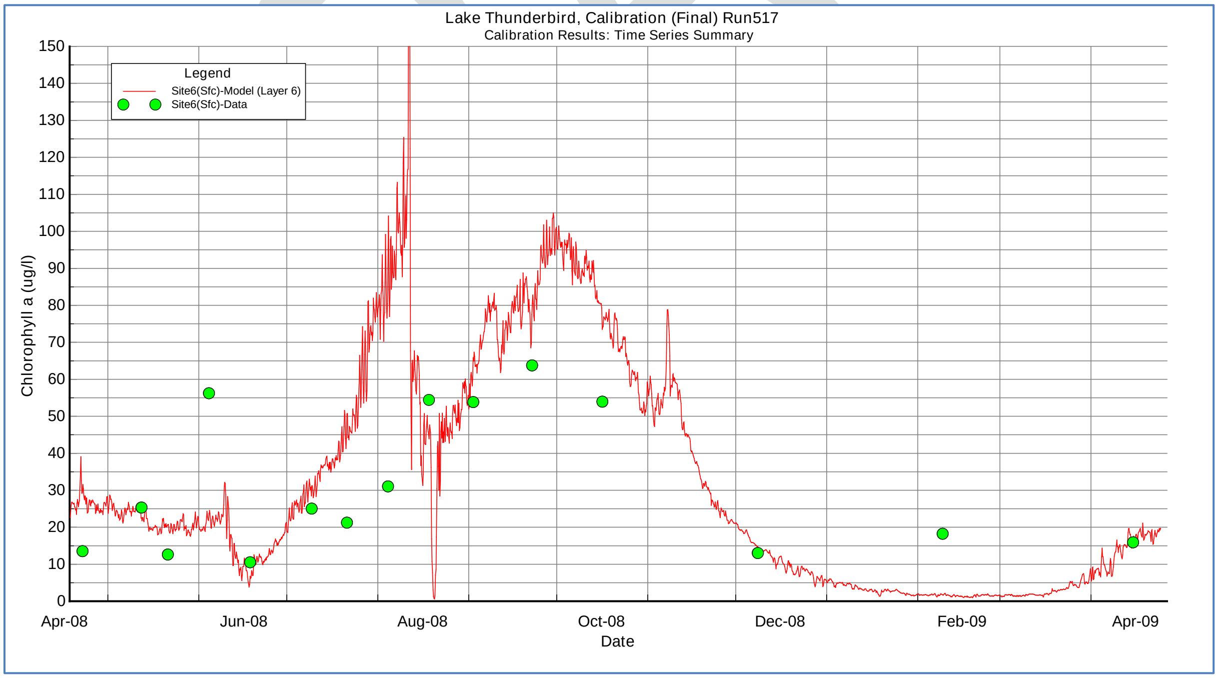

Figure 30 TS_Cal031_Chl a_Site6 (Surface)

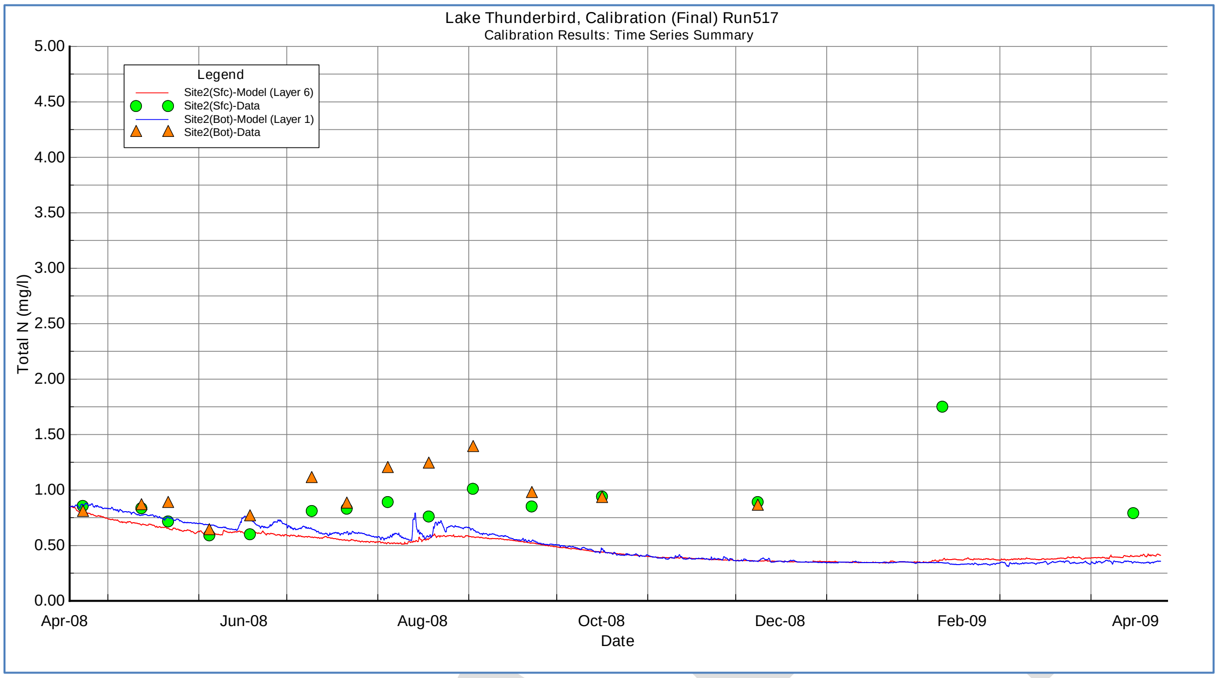

Figure 31 TS_Cal035_Tot N_Site2 (Surface & Bottom)

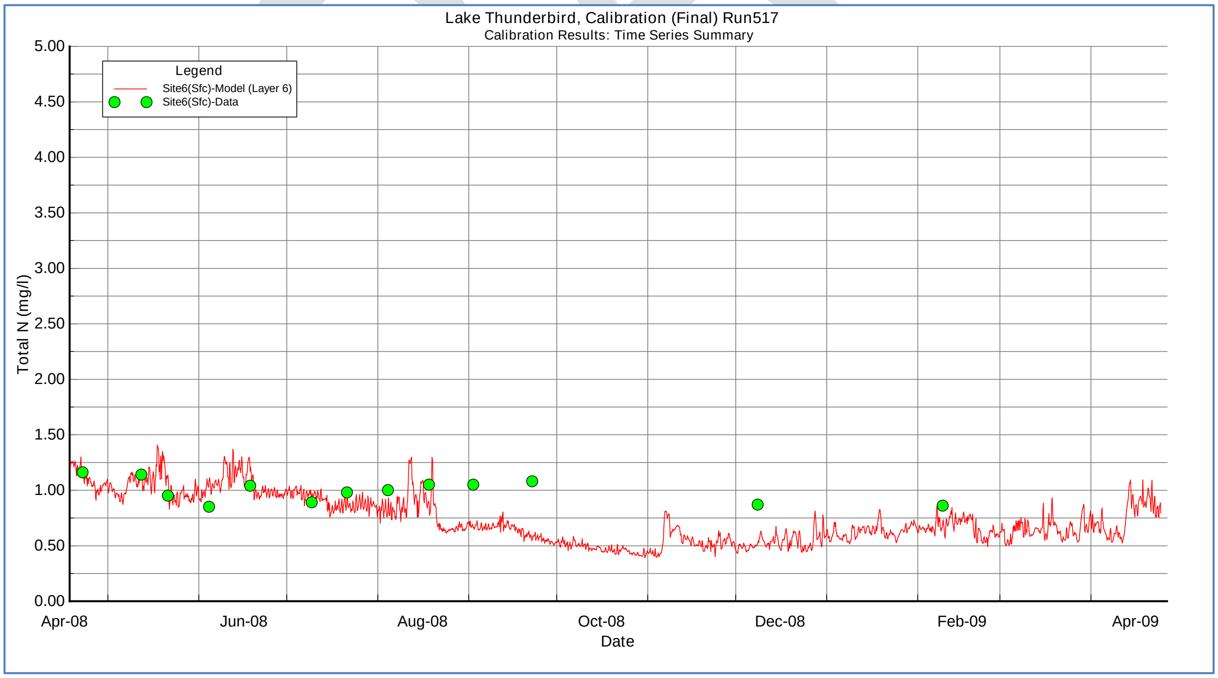

Figure 32 TS_Cal039_Tot N_Site6 (Surface)

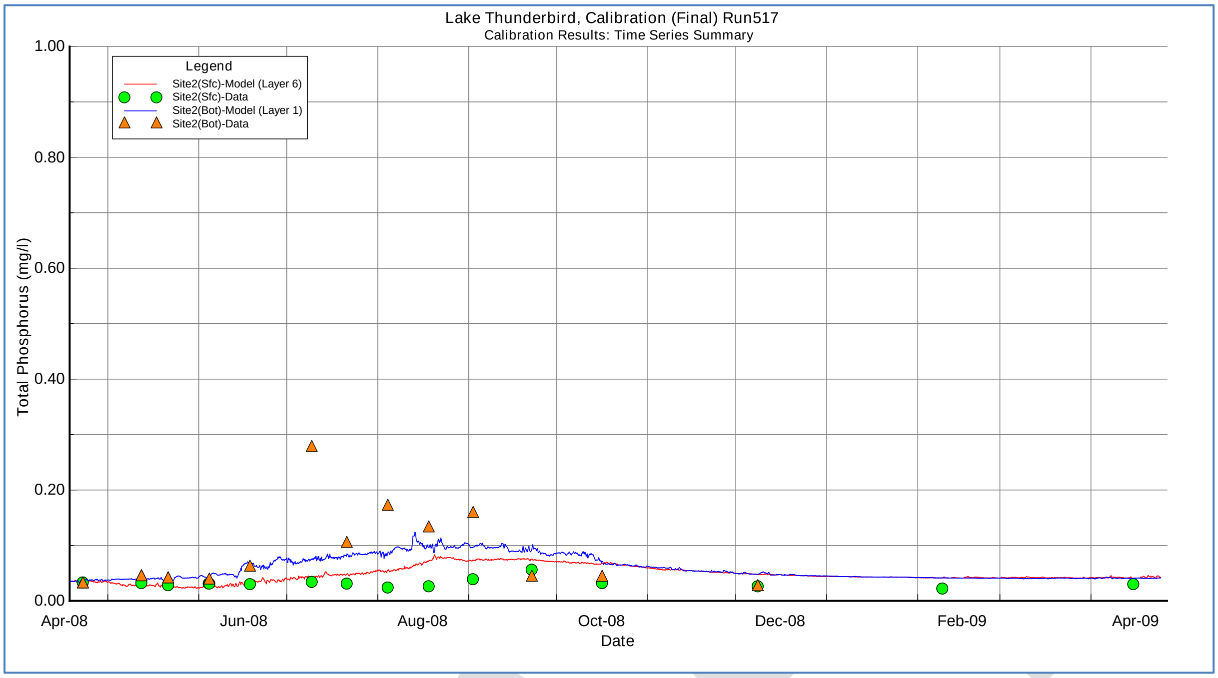

Figure 33 TS_Cal043_Tot P_Site2 (Surface & Bottom)

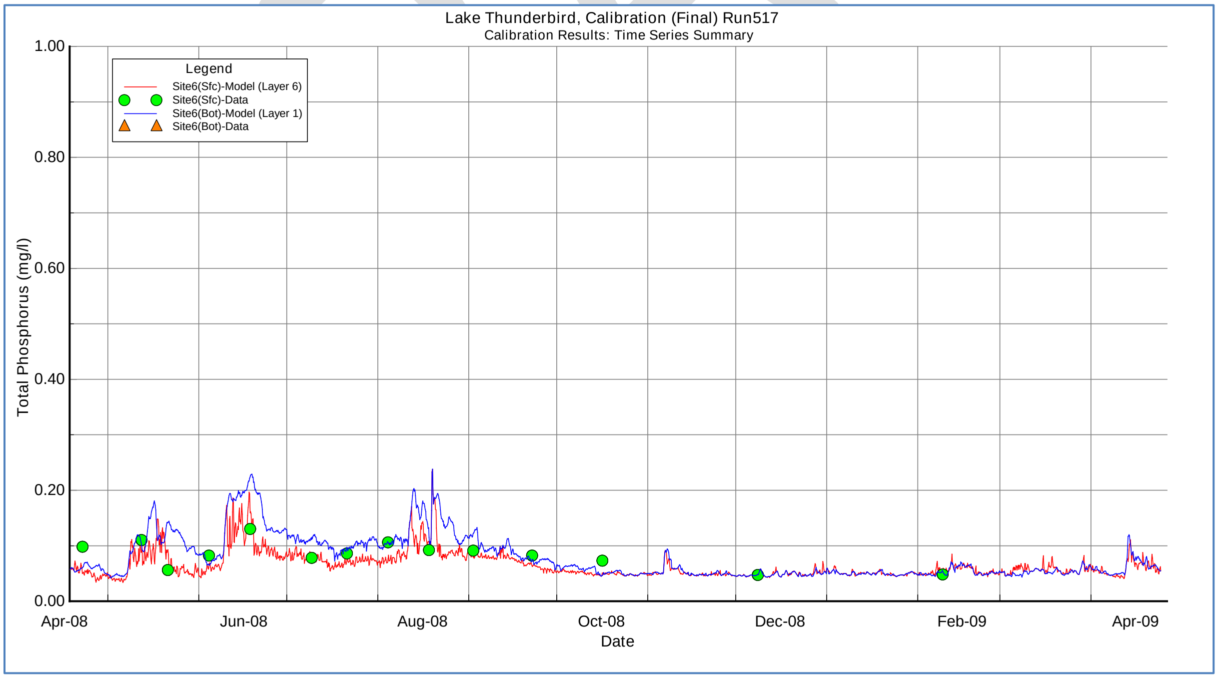

Figure 34 TS_Cal047_Tot P_Site6 (Surface)

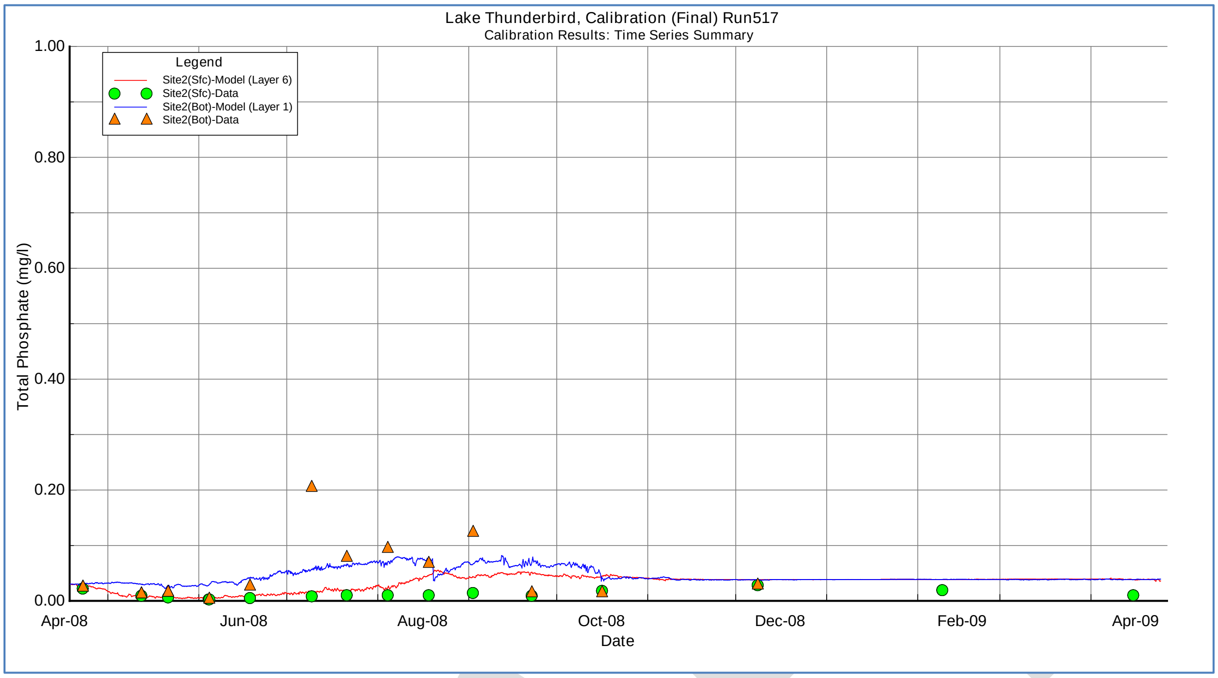

Figure 35 TS_Cal051_TPO4-P_Site2 (Surface & Bottom)

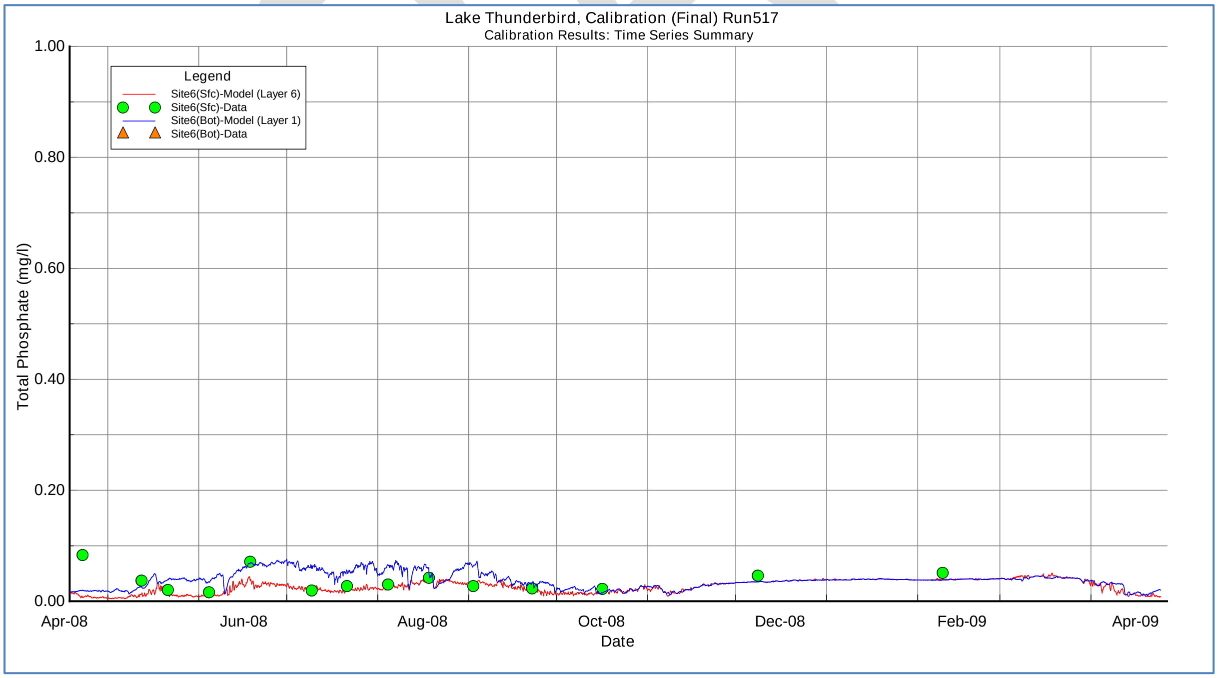

Figure 36 TS_Cal055_TPO4-P_Site6 (Surface)

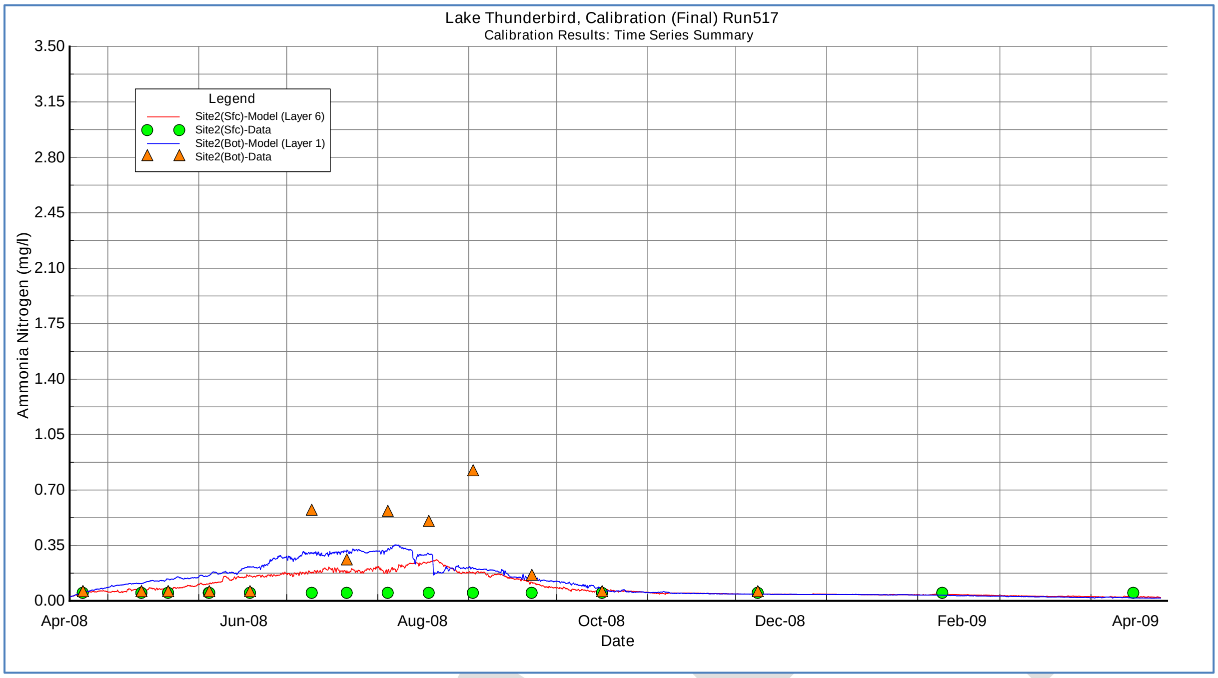

Figure 37 TS_Cal059_NH4-N_Site2 (Surface & Bottom)

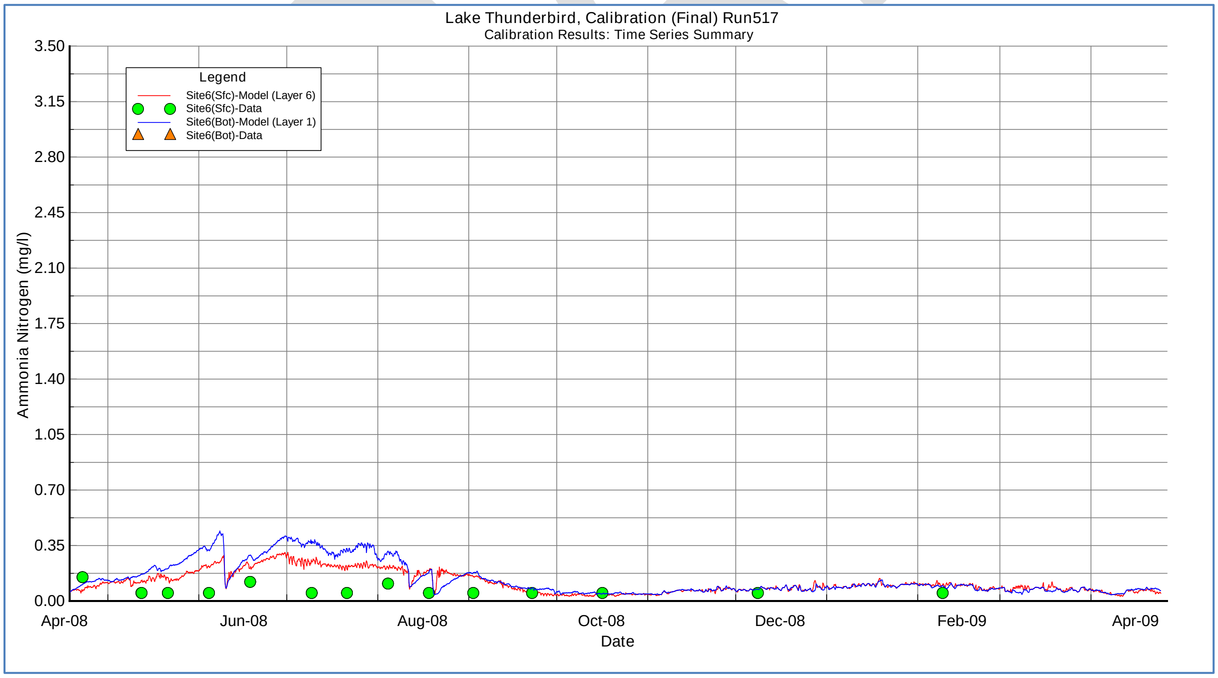

Figure 38 TS_Cal063_NH4-N_Site6 (Surface)

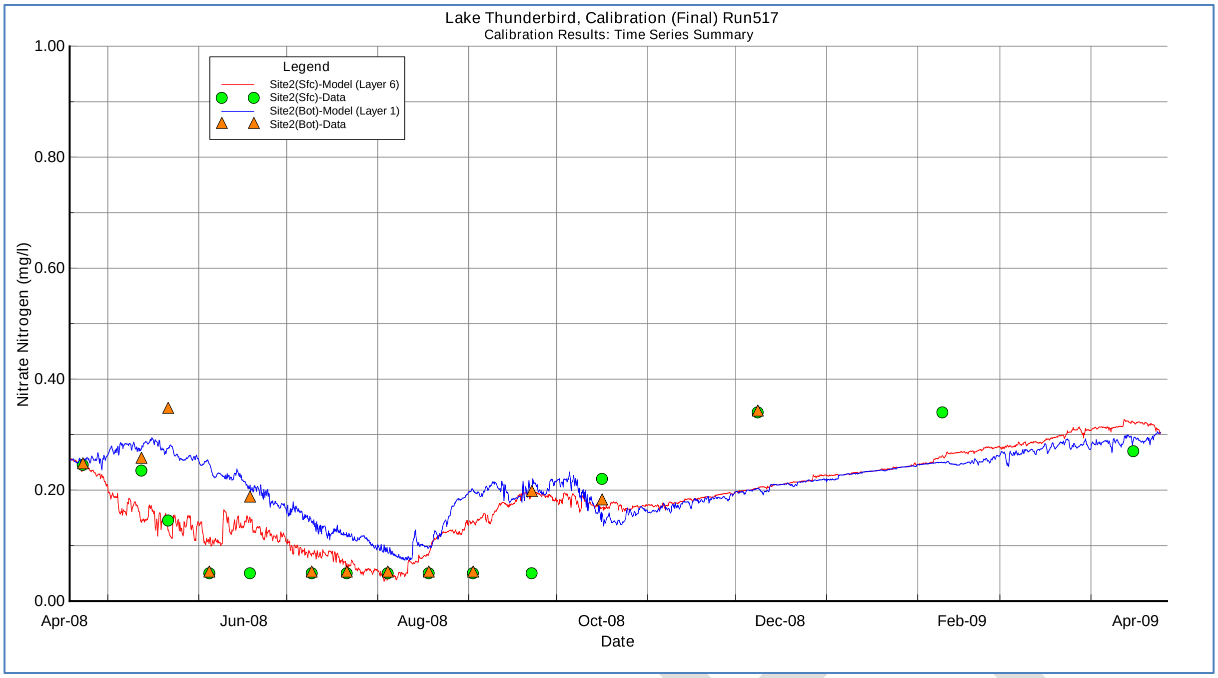

Figure 39 TS_Cal067_NO3-N_Site2 (Surface & Bottom)

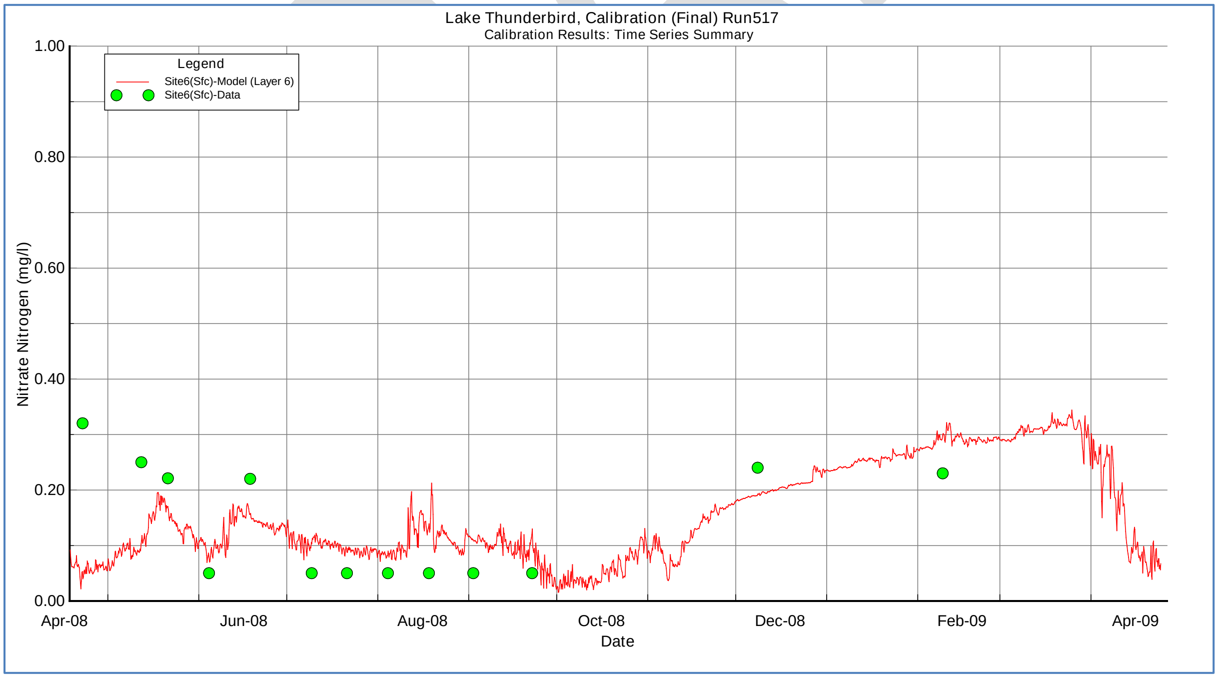

Figure 40 TS_Cal071_NO3-N_Site6 (Surface)

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