Oklahoma Water Resources Board

Lake Thunderbird
Water Quality

2016

for the

Central Oklahoma Master Conservancy District

June 1, 2017

FINAL REPORT

Oklahoma Water Resources Board

3800 North Classen Boulevard, Oklahoma City, OK 73118

Table of Contents

Table of Figures

List of Tables

Executive Summary

Lake Thunderbird is listed in Chapter 45, Part 5 of the Oklahoma Water Quality Standards (OWQS) as a Sensitive Water Supply (SWS) (OAC 785:45-5-25(C)(4)). In 2016, lake water quality monitoring by the Oklahoma Water Resources Board (OWRB) continued to focus on the effects of the hypolimnetic oxygenation system, which began operation in 2011. Monitoring in 2016 continued to confirm the impaired status assessed to Lake Thunderbird for the parameters of chlorophyll-a and turbidity. Lake Thunderbird is a nutrient (both phosphorus and nitrogen) rich ecosystem resisting the impact of the oligotrophication induced by active lake management. In order to meet TMDL targets set forth through the Department of Environmental Quality, significant changes in water quality need to occur.

July flooding negatively affected lake water quality and the measured impact of the SDOX. Inflowing floodwaters also brought non-point source pollutants adding an external dissolved oxygen (DO) load on top of a higher than normal internal load (driven by algae growth). The internal load was unusually high, evidenced by the documentation of multiple algal “bloom and bust” events. These events were documented at several sampling events when chlorophyll-a values were surpassed by pheophytin-a values. Pheophytin-a is the degradation product of chlorophyll-a and is an indicator of algal cell senescence. Two of the monitoring "bloom and bust" events are the most likely explanation for why August was the peak month for City of Norman Taste and Odor (T&O) complaints. The normal trigger for a T&O event in Lake Thunderbird is a release of hypolimnetically stored T&O compounds such as Geosmin and MIB during fall turnover. However, in 2016, these events were likely triggered by release of T&O compounds by dead and dying algal cells in pulses in the epilimnion rather than steady stream release from the hypolimnion.

A comprehensive plan emphasizing active lake and watershed management is required for Lake Thunderbird to meet OWQS for turbidity, chlorophyll-a and dissolved oxygen. Meeting these standards will improve the lake for recreational, aesthetic, fish and wildlife propagation and public and private water supply beneficial uses. Primary mitigation efforts should focus on nutrient reduction; if successful nutrient load reduction is achieved, a positive impact will be reflected in algae growth and dissolved oxygen. Decreasing the amount of phosphorus, nitrogen, and solids washing into the lake from the watershed is critical to improving Lake Thunderbird's water quality and beneficial use attainment. In-lake mitigation efforts focused on minimizing the suspension of solids from shallow areas and transfer of these suspended solids from the riverine zones to the main lake body would show the greatest positive impact to turbidity. Although the SDOX system does not completely satisfy the oxygen demand, hypolimnetic oxygenation provides relief to the lake’s DO levels, algal problems, and drinking water taste and odor complaints. Although it is unlikely that the SDOX will be able to target the lowest zone of the lake (increasing its effectiveness), its capabilities can be increased by assessing and amending its ability to deliver oxygen at a greater rate. Additional in-lake goals include identification of

sediment resuspension areas and mitigation methods within the lake, as well as updating the bathymetric survey. These steps allow for prioritized and cost effective decision making toward restoring impaired beneficial uses and meeting TMDL endpoints to Lake Thunderbird.

Introduction

Constructed by the Bureau of Reclamation, Lake Thunderbird began operation in 1966. Designated uses of the dam and the impounded water are flood control, municipal water supply, recreation, and fish and wildlife propagation. Under the authority of the Central Oklahoma Master Conservancy District (COMCD), Lake Thunderbird serves as a municipal water supply, furnishing raw water for Del City, Midwest City, and the City of Norman. The Oklahoma Water Resources Board (OWRB) has provided water quality based environmental services for COMCD since 2000. The objective in 2016, in addition to routine monitoring, was to evaluate the performance of Lake Thunderbird's supersaturated dissolved oxygen injection system (SDOX), which was implemented in 2011.

Lake Thunderbird is listed as Category 4a in the State's 2014 Integrated Report (303d list) as waterbody ID OK520810000020_00 and impaired due to low dissolved oxygen and excessive Chlorophyll-a (Chl-a) (http://www.deq.state.ok.us/wqdnew/305b_303d/2014/2014_appendix_c_303d-final.pdf). It was listed as Category 5a in the State's 2012 Integrated Report, impaired for excessive turbidity, low dissolved oxygen and excessive Chlorophyll-a. (http://www.deq.state.ok.us/wqdnew/305b_303d/2012_draft_integrated_report.pdf). As a result of of these impairments, Lake Thunderbird has undergone total maximum daily load (TMDL) analysis by the Oklahoma Department of Environmental Quality (ODEQ) with the resultant TMDL approved by the Environmental Protection Agency (EPA) on November 13th 2013. In short, the TMDL analysis requires a 35% long-term average load reduction of total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) from the 2008-2009 watershed load estimates in order for Lake Thunderbird to meet all current OWQS. This 35% load reduction scenario equates to an annual load reduction of 76,340 kg of total nitrogen per year, 15,006 kg of total phosphorus per year, and 7,470,252 kg of total suspended solids per year. For more information on the findings of the TMDL, refer to the final TMDL report (http://www.deq.state.ok.us/wqdnew/tmdl/thunderbird/LakeThunderbirdFinalTMDL_ReportNov2013.pdf).

In addition to the water quality impairment listings, collaborative work with the City of Norman illustrated that the water quality impairments have translated into elevated total organic carbon (TOC) in raw drinking water, increased taste and odor complaints in the finished drinking water, and thereby, elevated treatment costs. This last summer Norman rented powered activated carbon (PAC) unit to reduce taste and odor complaints in the treatment process. However, some taste and odor complaints still exist. They are now in the process of installing ozone and ultraviolet treatment into their drinking water treatment train.

In an attempt to mitigate the effects of cultural eutrophication witnessed in the reservoir, the COMCD gained funding through the American Recovery and Reinvestment Act, to install and operate an oxygenation system. By design, the system will oxygenate the deepest portion of the anoxic hypolimnion in the lake while leaving thermal stratification intact. The targeted impacts of providing an oxygenated hypolimnion include attainment of dissolved oxygen OWQS, elimination of reducing conditions in the hypolimnion, reducing overall internal phosphorus load, dissolution of metals, and peak Chl-a events. Data collected in 2016 represents the sixth season of SDOX operation.

Water Quality Evaluation

Sampling Regime

In 2016, Lake Thunderbird water quality sampling occurred from April 27 through November 9, monitoring the parameters in **Table 1** at the Sites indicated in **Figure 1.** All ites were sampled during each visit. Sites 1, 2, and 4 represent the lacustrine or open water zones of the lake. Consistent stratification and an underlying hypolimnion are common features of the lacustrine Sites. Sites 6, 11 and 8 represent riverine zones of their respective tributaries. Finally, Sites 5 and 3 represent the transition zones between riverine and lacustrine portions of the lake. Site 7, in the Clear Creek arm, is not sampled as part of the COMCD project but as part of the OWRB's Beneficial Use Monitoring Program (BUMP) protocols.

Water quality profiles for oxidation-reduction potential (ORP), DO percent saturation and concentration, temperature, specific conductance, total dissolved solids (TDS) and pH were conducted at each Site. The profiles were recorded at each site, in one-meter intervals from the lake surface to the sediment-water interface. In addition, nutrient samples were collected at the surface of Sites 1, 6, 8, and 11 and at 4-meter depth intervals at Site 1 to 0.5m above the lakebed. Analyses performed on these samples included phosphorus (P) and nitrogen (N) series. Total organic carbon samples were also collected at the surface of Site 1. Field observations, secchi disk depth, surface chl-a, and turbidity samples were collected at all nine Sites. In order to limit laboratory costs, no nutrient samples were collected on June 8th or October 5th; these chl-a samples and profiles were collected to delineate stratification and algal growth periods.

Table 1. 2016 Water Quality Sample Dates and Parameters.

Date	27-Apr	25-May	8-Jun	22-Jun	6-Jul	20-Jul	4-Aug	17-Aug	7-Sep	21-Sep	5-Oct	9-Nov
Profile	X	X	X	X	X	X	X	X	X	X	X	X
Chl-a	X	X	X	X	X	X	X	X	X	X		X
Secchi Depth	X	X	X	X	X	X	X	X	X	X		X
TOC	X	X		X	X	X	X	X	X	X		
Turbidity	X	X	X	X	X	X	X	X	X	X		X
Nutrients	X	X		X	X	X	X	X	X	X		X

Figure 1. Lake Thunderbird 2016 Sampling Sites

Quality Assurance and Quality Control (QA/QC)

Water quality sampling followed the QA/QC procedures described in the EPA-approved Quality Assurance Project Plan (QAPP) "Clean Water State Revolving Fund Loan and American Recovery and Reinvestment Act ORF-09-0027-CW: Lake Thunderbird Water Quality Monitoring 2010-2012 executed August, 2010. Laboratory quality control samples included duplicates and replicates. Replicate samples were collected at the surface of Site 1 and labeled "Site 1(12)" and "Site 1(22)" respectively, then delivered to the laboratory for analysis. In addition, the Site 1 chl-a sample was split to produce duplicate samples (1(12) and 1(21)) during chlorophyll-a post processing at the OWRB, then delivered to the laboratory for analysis. Finally, laboratory blank samples were submitted to the laboratory as Site 1(31). **Appendix A** summarizes laboratory results of duplicate and replicate sampling. Additional chlorophyll-a replicates, were submitted while transitioning between analytical laboratories to increase accuracy and precision of reported values as well as increasing statistical significance. The sample preservation method used by the analytical laboratory for ortho-phosphorus varied from previous methods (by acidifying the sample prior to filtration) likely resulting in overestimates of the laboratory reported value. Comparison of ortho-phosphorus to total phosphorus reports did not show any obvious errors, such as ortho-phosphorus values greater than total phosphorus values. Accurate Labs also performs additional quality control analysis in accordance with environmental lab accreditation practices.

Duplicate and Replicate Samples

Duplicate samples yield an overall estimate of error either due to sampler or laboratory error. This paired data set yields a measured difference between two relatively identical samples. Site 1(22) is used as the replicate sample identifier for Site 1 quality assurance surface samples. The percent absolute difference (PAD) statistic is calculated to describe the precision of each laboratory parameter based on the comparison of replicate samples; Sites 1(12) ($x_{S1(12)}$) and 1(22) ($x_{S1(22)}$).

Eq. 1 $$PAD = \left| x_{S1(12)} - x_{S1(22)} \right| / \ \bar{x} * 100$$

Equation 1 was applied for each replicate sample for each reported parameter. Results were tabulated and statistical summaries were generated using the box and whisker plot function (**Figure 2**). All parameters showed relatively good precision with median PAD below 20 per cent. Note that while PAD is good over the entire sampling season, instances of high PAD for Ammonia as N, Ortho-phosphorus as P and Total Kjeldahl Nitrogen occurred and are reflected by a large upper quartile. PAD summary statistics were generally within the acceptable range. Blank samples showed comparatively low-level ortho-phosphorus contamination on 7/6/2016, 7/20/2016, and 9/7/2016. Significant contamination was noted on 5/25/2016 due to ammonia as N, as well as 9/21/2016 and 11/9/2016 due to Total Kjeldahl Nitrogen. These Total Kjeldahl Nitrogen and Ammonia as N blank reports were approximately two times the detection limit of

0.05 mg/L and 0.015 mg/L respectively. The value reported for the Blank, Site 1(31), sample (0.114) was substituted for the environmentally reported, Site 1 (22), sample (BPQL) for same date, 11/9/2016. The discrepancy was noted as both ammonia and total Kjeldahl Nitrogen have similar detection limits, and such ammonia should not be detected when Kjeldahl is not detected. Therefore, as the Kjeldahl blank, Site 1(31), sample reported a value within the range of ambient, environmental levels it was confirmed these sample bottles where switched and the blank sample report substituted for the environmental sample for data interpretation.

A review of chlorophyll-a and pheophytin-a reports for potential sample degradation did not indicate any issues. However, during examination of algal pigment content elevated amounts of pheophytin-a were noted in many of the samples. Replicate pheophytin-a samples confirmed these elevated values. All quality control data are summarized and presented at the end of this report as Appendix A.

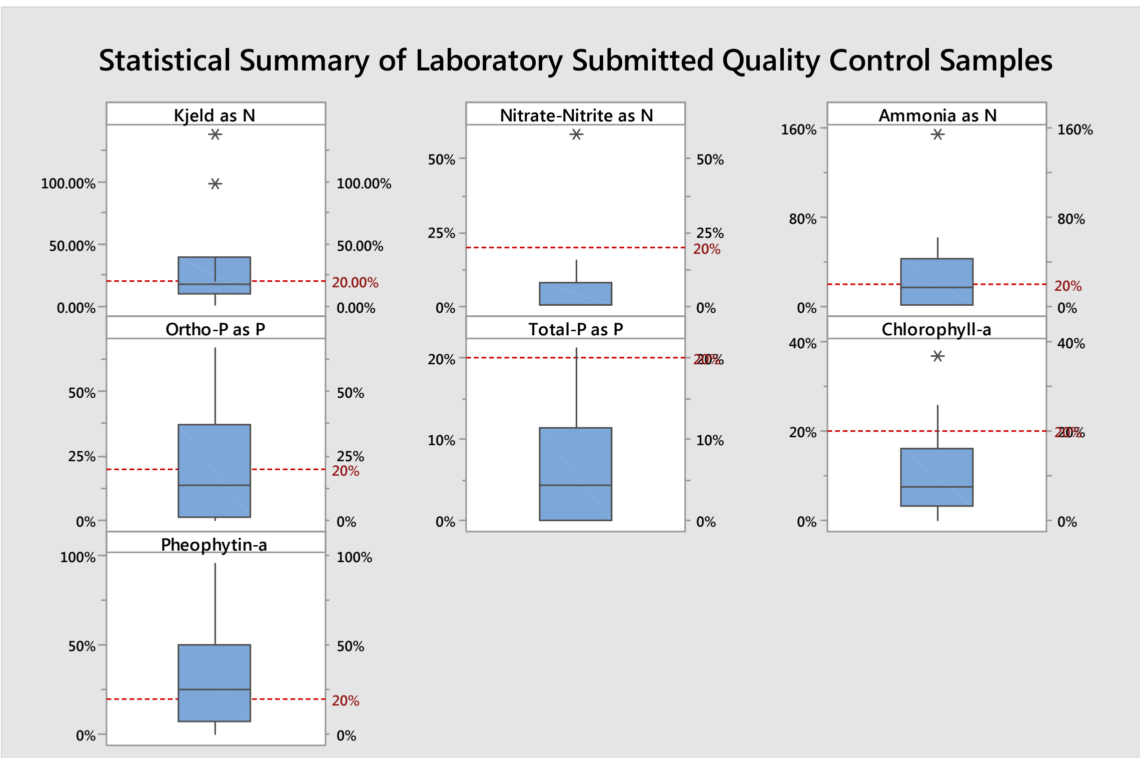


Figure 2. Summary Plots of Percent Absolute Difference for Replicate Laboratory Samples Lake Thunderbird April 27, 2016 - November 9, 2016. (Box Represents the Middle 50%; the Center Bar the Median Value, Top and Bottom Stems the Upper and Lower 25% Quartile and Asterisks as Outliers**)**

Climate

Knowledge of potential climatological influences is essential when assessing the water quality of a waterbody. The hydrology and physical processes of a given reservoir significantly influence internal chemical and biological processes. For example, storm water influences nutrient content and composition, sediment loading, sediment suspension and stratification patterns. In addition, changes in lake volume and nutrient concentrations affect the extent of anoxia in the hypolimnion and alter oxidation-reduction potentials. Anoxia, in turn directs the solubility of sediment borne phosphorus and metals.

Figure 3 provides a graphical representation of Lake Thunderbird’s rainfall, elevation, inflow, and sampling dates for calendar year 2016. Annual precipitation at Lake Thunderbird dam in 2016 totaled 28.76 inches, some 10 inches below the annual average of 38 inches. In general, pool elevation varied between 1039’ and 1040’ throughout the spring and summer seasons with a gradually dropping from 1039’ mid-August. The highest elevation was January 1 2016 at 1040.58‘; likewise, the lowest elevation was December 31, 2016 at 1036.95’. In addition to hydrology, air temperature influences lake characteristics such as stratification and primary productivity. **Figure 4** compares monthly mean temperatures from 2012 through 2016 to the long-term monthly mean. Deviations from the climatological norm in 2016 dampened the normal erosion of the hypolimnion and timing of complete mixis. This effect was produced by the combination of a cooler than normal April, warmer summer and cooler fall than normal. Interestingly, the last four years have consistently showed a warmer than normal spring and cooler than normal fall. The amount and timing of rainfall is the most likely contributor to this anomaly.

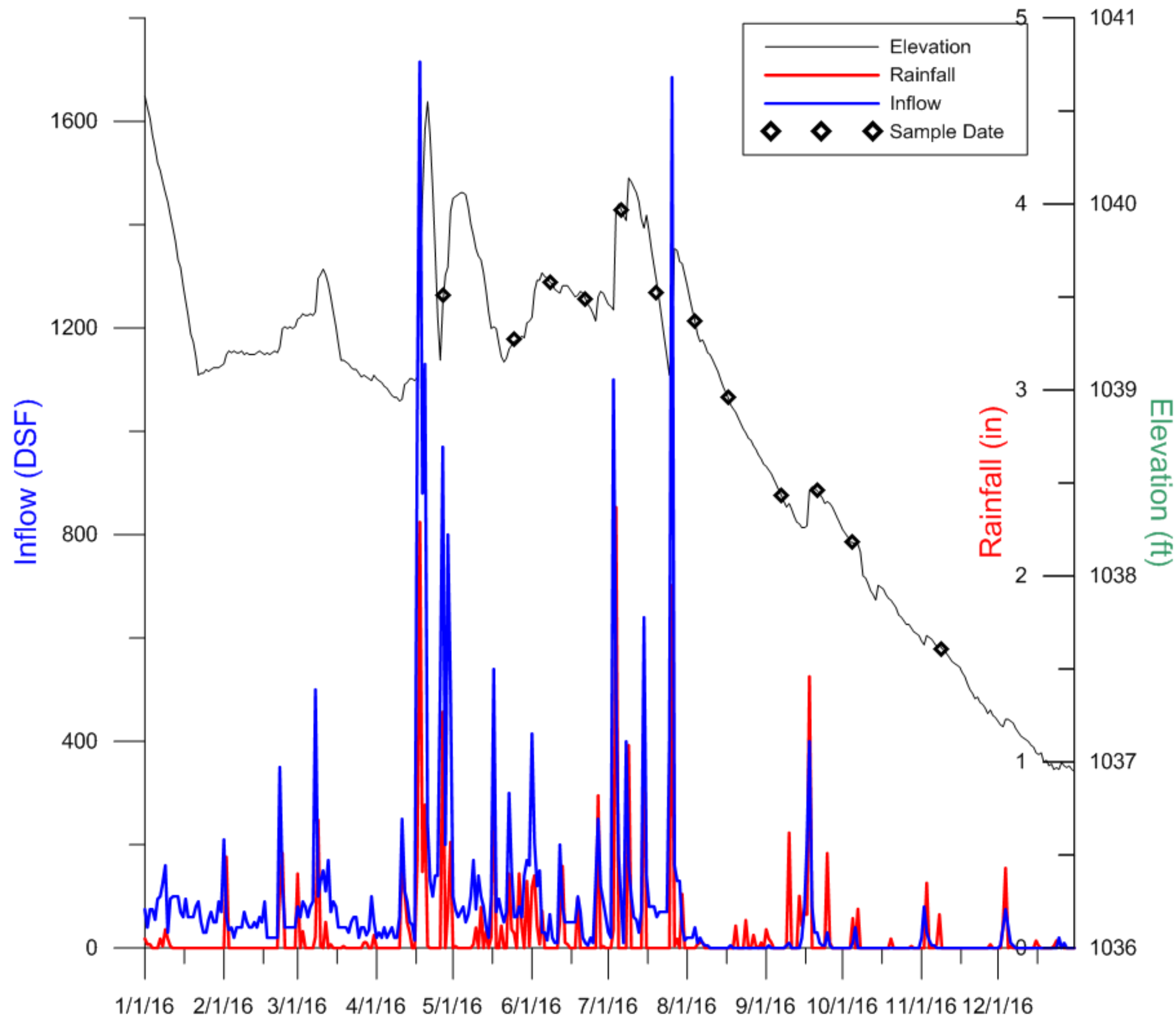


Figure 3. 2016 Inflow, Precipitation, and Elevation Data for Lake Thunderbird, with Sample Dates Indicated.

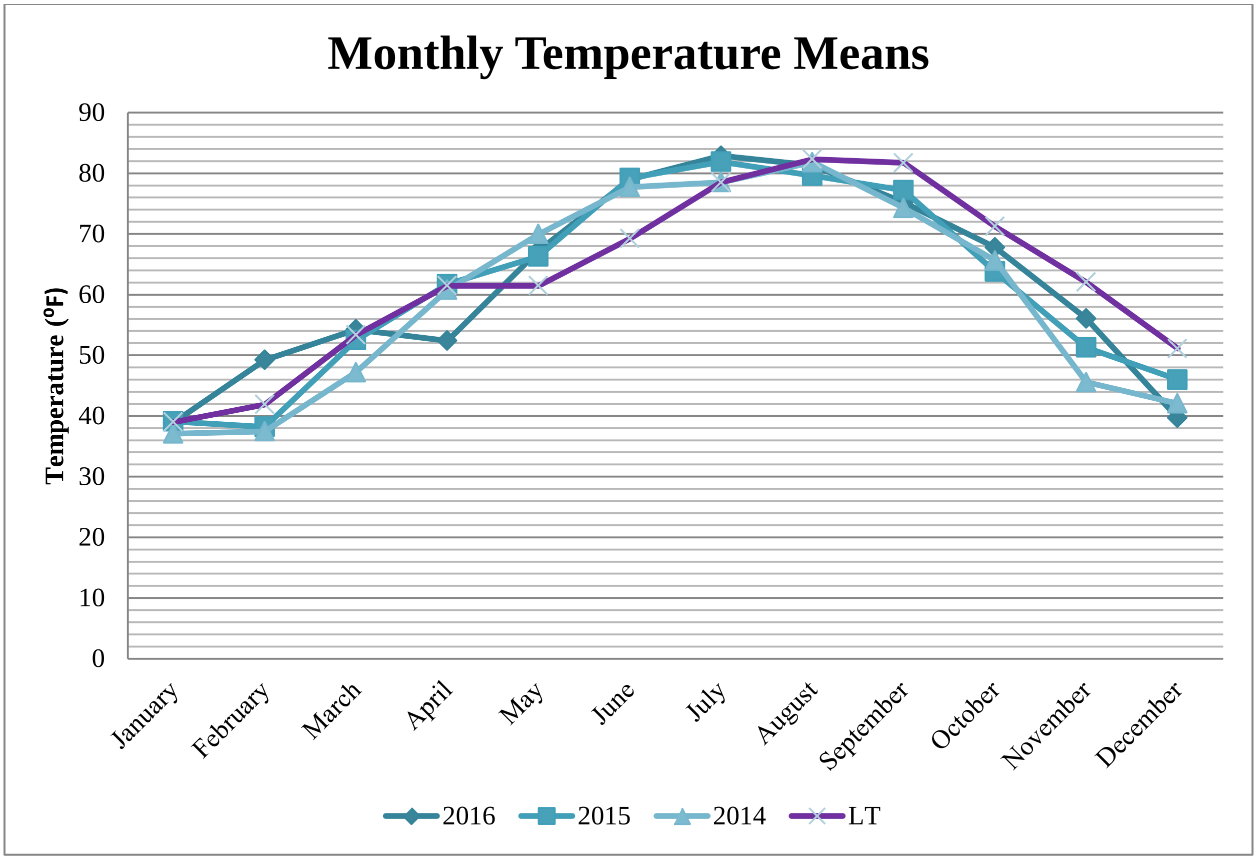


Figure 4. 2016 Average Monthly Temperature at the Norman Mesonet Station; Long Term (20 year) 2014 and 2015.

Hydrologic Budget

A hydrologic balance (or water balance) is of considerable importance in water quality analyses and management. A general and simple hydrologic budget equation for a given waterbody is defined by:

Eq. 2 $$\frac{dV}{dt} = Q_{in} - Q_{out} + PA_s - E_v A_s - W_s$$

Where V = lake volume [L^3],

A_s = lake surface area [L^2],

Q_{in} and Q_{out} [L^3/T] represents net flows into and out of the lake due to tributary inflows and gated releases,

P [L/T] is the precipitation directly on the lake,

E_v [L/T] is the lake evaporation,

W_s is the water exported for water supply use.

In other words, the rate of change in volume of water stored in or on the given area per unit time is equal to the rate of inflow from all sources, minus the rate of outflows. The input or inflows to a lake may include surface inflow, subsurface inflow, and water imported into the lake. The outputs may include surface and subsurface outputs and water exported (e.g. water supply) from the lake. For Lake Thunderbird, subsurface flow is likely insignificant, based on the relatively impermeable lake substrate.

The inputs to Lake Thunderbird include precipitation and inflow from the tributaries - encompassing all surface runoff in the basin. The outputs are evaporation, dam releases (spilled), and water supply intake. Precipitation was estimated from the direct rainfall measurements/data provided by the United States Army Corps of Engineers (USACE). The precipitation contribution to the total inflows is derived by multiplying the daily rainfall amounts by the surface area of the lake on each date, as shown by:

$$\boldsymbol{Q_p} = \mathbf{P} * \boldsymbol{A_s}$$

where **P** [L/T] is rainfall amount and $\boldsymbol{A_s}$ [L^2] is the surface area of the lake.

Daily evaporation rates were calculated and reported by the USACE. Empirical equations are applied to relate solar radiation, wind speed, relative humidity, and average daily air temperature to the rate of evaporation from the lake. These rates can then multiplied by the daily average surface area of the lake to give the amount of water evaporated per unit time.

$$\boldsymbol{Q_e} = \boldsymbol{E_v} * \boldsymbol{A_s}$$

where $\mathbf{E_v}$ [L/T] is the evaporation rate and $\boldsymbol{A_s}$ [L^2] is the surface area of the lake.

Water outputs from Lake Thunderbird generally include gated dam releases and water supply withdrawals. The USACE reports dam release and change in pool elevation at the end of every day, while COMCD reports water supply withdrawals. The lake volumes, corresponding to the elevations, were calculated and the difference summed over a month on a daily basis to account for the change in volume for each month. The volumes used were estimates from elevation-capacity curves generated from the OWRB's 2001 bathymetric survey of the lake. Due to the difference in capacity between the USACE (impoundment) and OWRB (2001) bathymetry, runoff volume was calculated as the monthly change in volume minus rain plus evaporation plus water supply releases.

Results

A summary of monthly water budget calculations for Lake Thunderbird is provided below in. In this table, Total Inputs is the sum of all the flows into the lake and Total Outputs is the sum of all the outflows from the lake. From **Equation 2**, the difference between the inputs and the outputs must be the same as the change in volume of the lake for an error free water budget. The difference between the inflow and outflow is in the I-O column. Total monthly error is calculated as the difference between the change in lake volume based on elevation and I-O. Examination of the estimated water budget for Lake Thunderbird showed that estimated inputs and outputs were close to the actual volume changes (as measured by change in pool elevation).

Table 2. Lake Thunderbird 2016 Water Budget Calculations Expressed in Acre-feet.

	INPUTS			OUTPUTS				NET
Month	Runoff	Rainfall	**Total Inputs**	Evaporation	Water Supply	Releases	**Total Outputs**	ΔV
Jan	6,169	141	6,309	1,198	1,010	11,562	13,770	(7,460)
Feb	1,184	494	1,677	2,296	1,028	-	3,324	(1,646)
Mar	3,965	705	4,670	2,619	1,082	3,798	7,500	(2,830)
Apr	11,954	3,090	15,045	2,912	1,340	9,558	13,810	1,235
May	6,624	1,478	8,102	2,834	1,270	7,033	11,138	(3,036)
Jun	5,395	1,233	6,628	3,601	1,586	-	5,187	1,441
Jul	12,187	4,145	16,331	4,367	1,773	7,773	13,913	2,418
Aug	2,603	145	2,748	3,122	1,854	1,168	6,144	(3,396)
Sep	1,017	1,231	2,249	2,527	1,471	-	3,998	(1,749)
Oct	1,092	180	1,273	1,998	1,230	-	3,228	(1,955)
Nov	817	221	1,037	1,386	989	-	2,375	(1,338)
Dec	605	196	801	1,010	1,110	-	2,120	(309)
Total	53,611	13,259	66,870	29,869	15,743	40,893	86,506	(18,625)

Once a hydrologic budget is constructed, additional features of reservoir dynamics can be estimated. The hydrologic retention time is the ratio of lake capacity at normal pool elevation to the exiting flow (usually on an annual basis). This represents the theoretical time it would take a given molecule of water to flow through the reservoir. The combination of lake releases and water supply withdrawals give Lake Thunderbird water a hydrologic residence time of 1.89 years for 2016, dropping the 2001 to present average hydrologic residence time to 3.85 years. (**Figure 5**). The lower than averaged 2016 tau is largely due to gated releases to drop the pool elevation.

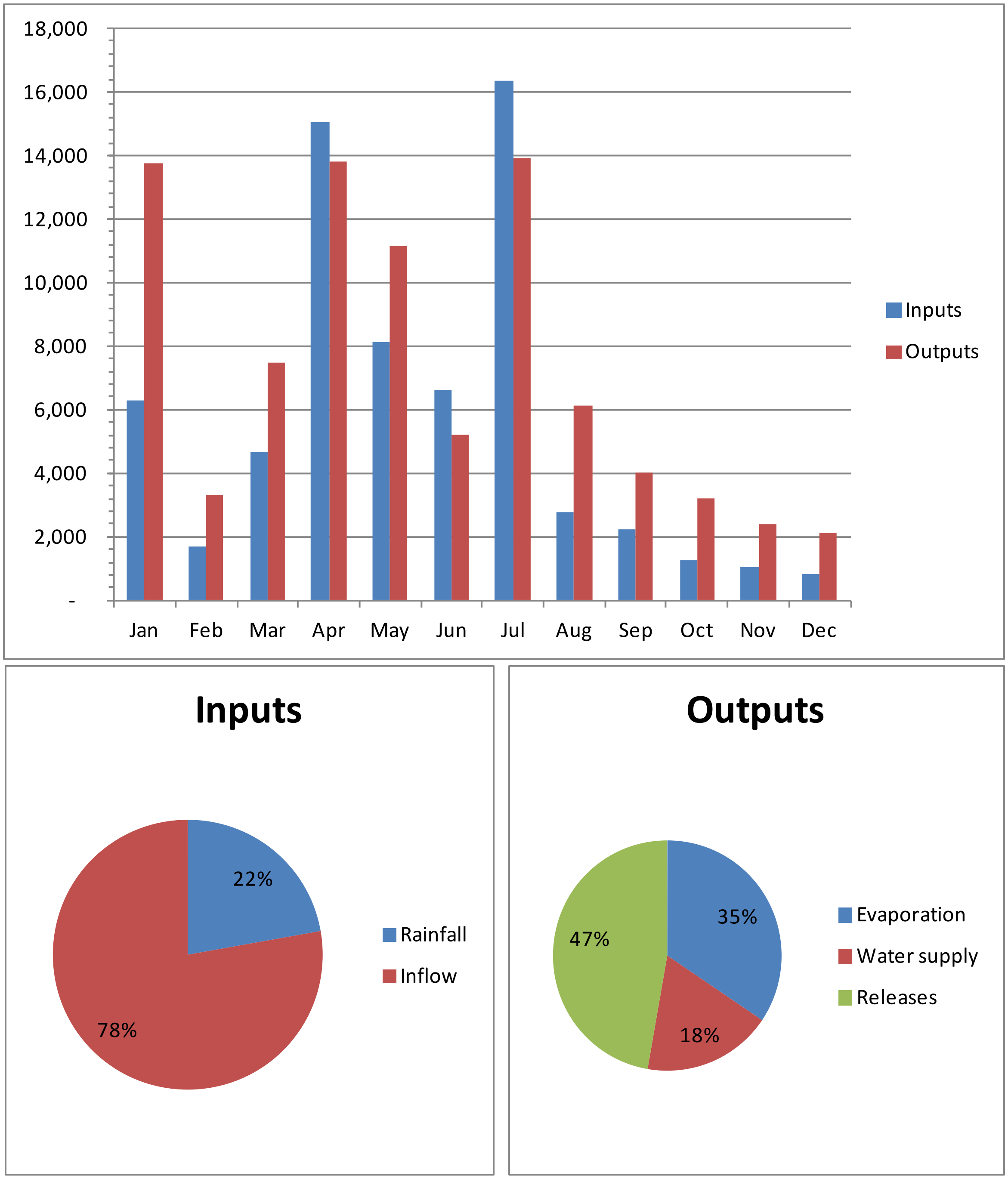


Figure 5. 2016 Lake Thunderbird Water Input and Output Sources by Month, Expressed as the Percent of Total.

Sources of Error

Although robust, the hydrologic budget does contain error. Inflow or runoff volume was calculated capturing error within this term. Errors in bathymetry and flood pool morphometry are the likeliest explanations for error, although a somewhat high error term for 2016 could be attributed to greater than average elevation fluctuations.

The USACE estimated inflow from the tributaries based on changes in lake volume using their original lake bathymetry. To account for this error, inflows are adjusted according to pool elevation using OWRB-determined bathymetry. Additional extrapolations were necessary due to the high pool elevations. Volume and areas estimated from the conservation pool into and above the flood pool were extrapolated using 2007 LiDAR data acquired from the City of Norman and appended to the OWRB's 2001 bathymetric survey (to the top of the conservation pool). The OWRB ArcGIS technician's assessment was that the LiDAR and OWRB lake boundary did not significantly deviate from each other.

According to the bathymetric survey completed by OWRB in 2001, a conservation pool sedimentation rate is estimated around 400 acre-feet per year. In 2009, limited additional bathymetric surveying was conducted around the dam area for the hypolimnetic oxygenation system. That survey indicated little sediment accumulation in the dead pool of the lake. Should the estimated sedimentation rate prove correct, newly depoSited sediment is predicted to be mostly in the upper portion of the conservation pool with a loss of approximately 6,800 acre-feet. Resurveying the reservoir with current data would allow for an accurate estimate of sedimentation using comparable survey methods and capacity curve for water budget construction. Current bathymetry also significantly reduces error for any future water quantity or quality modeling.

Groundwater loss and gain to the lake were assumed negligible. Verification of this is achievable with field measurements or through a review of the geology in the area.

While the hydrologic budget contains sources of error, it is still deemed robust enough to support lake nutrient budget development and water quality modeling.

Thermal Stratification, Temperature, and Dissolved Oxygen

Warming of the lake surface throughout spring marks the onset of stratification. Thermal stratification occurs when an upper, less dense layer of water (epilimnion) forms over a cooler, denser layer (hypolimnion). The metalimnion, or thermocline, is the region of greatest temperature and density change and occurs between the epilimnion and hypolimnion (**Figure 6**). Due to these differences, thermal resistance to mixing prevents the epilimnion and hypolimnion from coming in contact during stratification. Therefore, when dissolved oxygen is consumed and depleted by the decomposition processes in the hypolimnion, it is not replenished. The OWRB has documented this process at Lake Thunderbird each monitoring year since 2000, and is inevitable without the influence of outside forces.

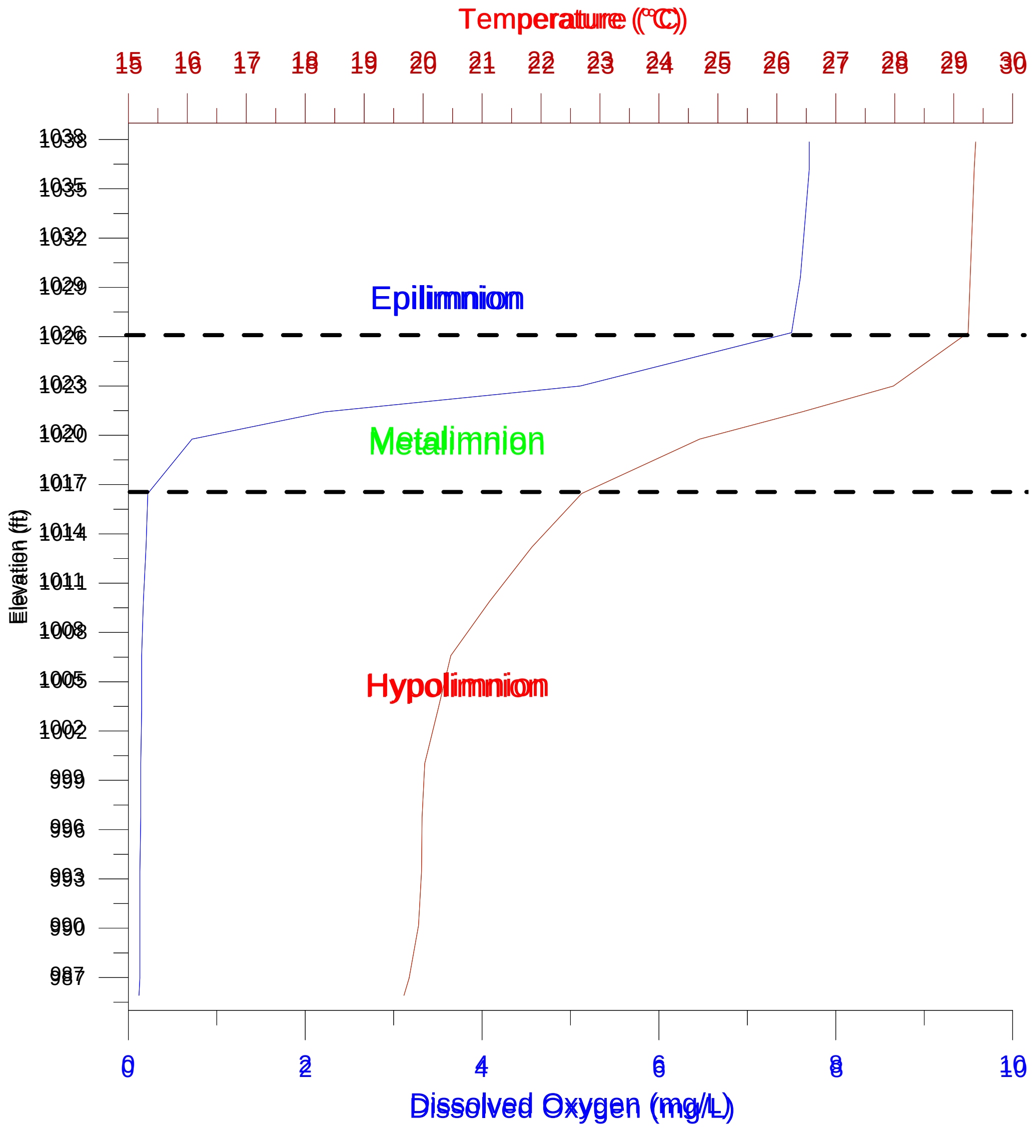


Figure 6. A Typical Temperature and Dissolved Oxygen Vertical Profile for Lake Thunderbird (June 22, 2016) Approximate Boundaries Between the Epilimnion, Metalimnion and Hypolimnion are Marked with Dashed Lines.

Prior to the onset of stratification, the lake had isothermal conditions throughout the water column. As stratification sets in and strengthens, the epilimnion stays relatively homogenous while the metalimnion (thermocline) changes radically with depth until reaching the hypolimnion. This physical structure maintains until surface temperatures start to decline, the epilimnion cools, eroding the thermocline as the epilimnion mixes with the lower layers. This process is referred to as mixis or turnover.

Lake stratification has a significant effect on water quality by isolating chemicals in areas of reduced chemical exchange – such as in the hypolimnion. An increased loading of nutrients can occur through settling of nutrients from the epilimnion and metalimnion primarily in the particulate form. Increased loading can also occur in the hypolimnion when the sediment bed is exposed to anaerobic conditions and releases inorganic phosphorus and ammonia into the water column. Starting in early fall/late summer these isolated (and largely dissolved) nutrients are brought back into epilimnetic waters in large volumes during mixing events, causing significant fluxes in surface water chemistry. A key feature of the influxes of hypolimnetic waters is a further stimulation of algae growth, which occurs as hypolimnetic nutrients mix into the epilimnion.

Lake stratification can also affect drinking water treatment quality and by escalating cost of treatment due to rising organic and dissolved metal content. Summer time increase in organic content is largely due to the stimulation in algae growth associated with turnover discussed later in this report. The quality of drinking water can also be affected as hypolimnetically stored algal cells are incompletely decomposed and contents of the algal cells are re-circulated into the water column with mixing events. The City of Norman has historically received taste and odor complaints about the finished drinking water at this time of year, and confirmed the presence of algal associated taste and odor compounds, Methyl-Isoborneol (MIB) and Geosmin.

Plots of temperature and dissolved oxygen with respect to depth at Site 1 for each monitoring event display the location of lake layers and how dissolved oxygen interacts within those layers. Intensity of stratification is quantified by calculating the relative thermal resistance to mixing (RTR). This is a unit-less measure of density differences based on temperature indicating how likely the layers will mix. Stratification was detected on the first sample date, April 27, 2016, with continued weak stratification noted at each May sample trip. The increased hypolimnetic temperature from the April to May monitoring event indicates that while monitoring showed stratification each time, some lake mixing had occurred. Stronger (and permanent) thermal stratification was not observed until June 22, 2016. As solar radiation and ambient temperatures increased, the upper portion of the water column began to heat up while the bottom of the lake stayed cooler, strengthening water column stratification. Since the first monitoring event both temperature and dissolved oxygen decreased with depth. By June 8, the hypolimnion was completely anoxic. By June 22, anoxia had moved into the metalimnion (**Figure 7**). Metalimnetic anoxia is indicative of a hypertrophic system and is driven by a high organic load; external (watershed based) and internal (algal growth) are contributors.

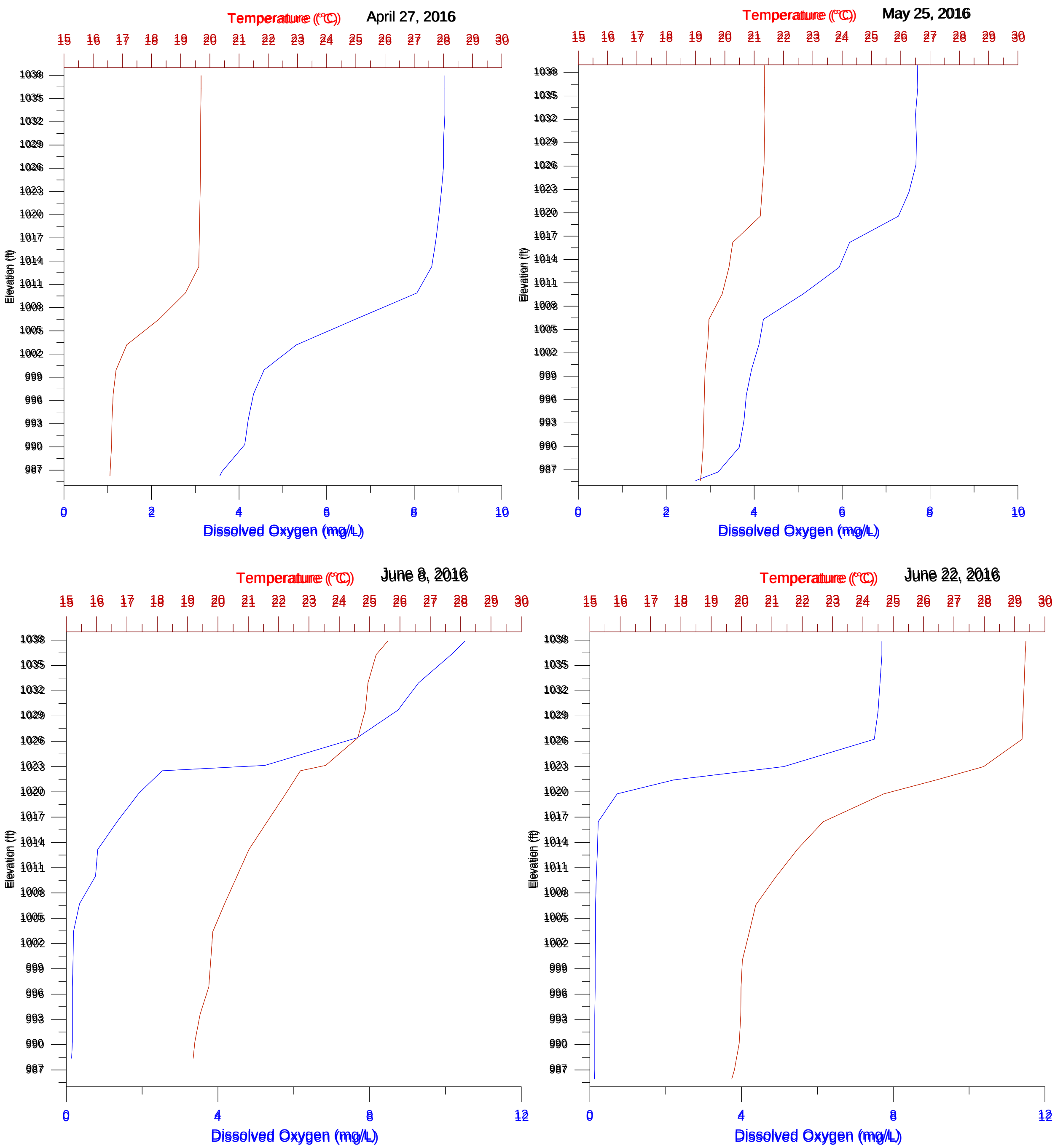


Figure 7. Temperature (red) Dissolved Oxygen (blue) Vertical Profiles. Site 1: April 27, 2016 – June 22, 2016.

As the season progressed from late spring through summer, heating at the surface continued from July to a peak temperature of 30.1°C at Site 1 on August 14, 2016. While anoxia still pushed into the metalimnion, the hypolimnion rapidly decreased heading into the August 17 monitoring event; likely due to a strong cold front (**Figure 8**).

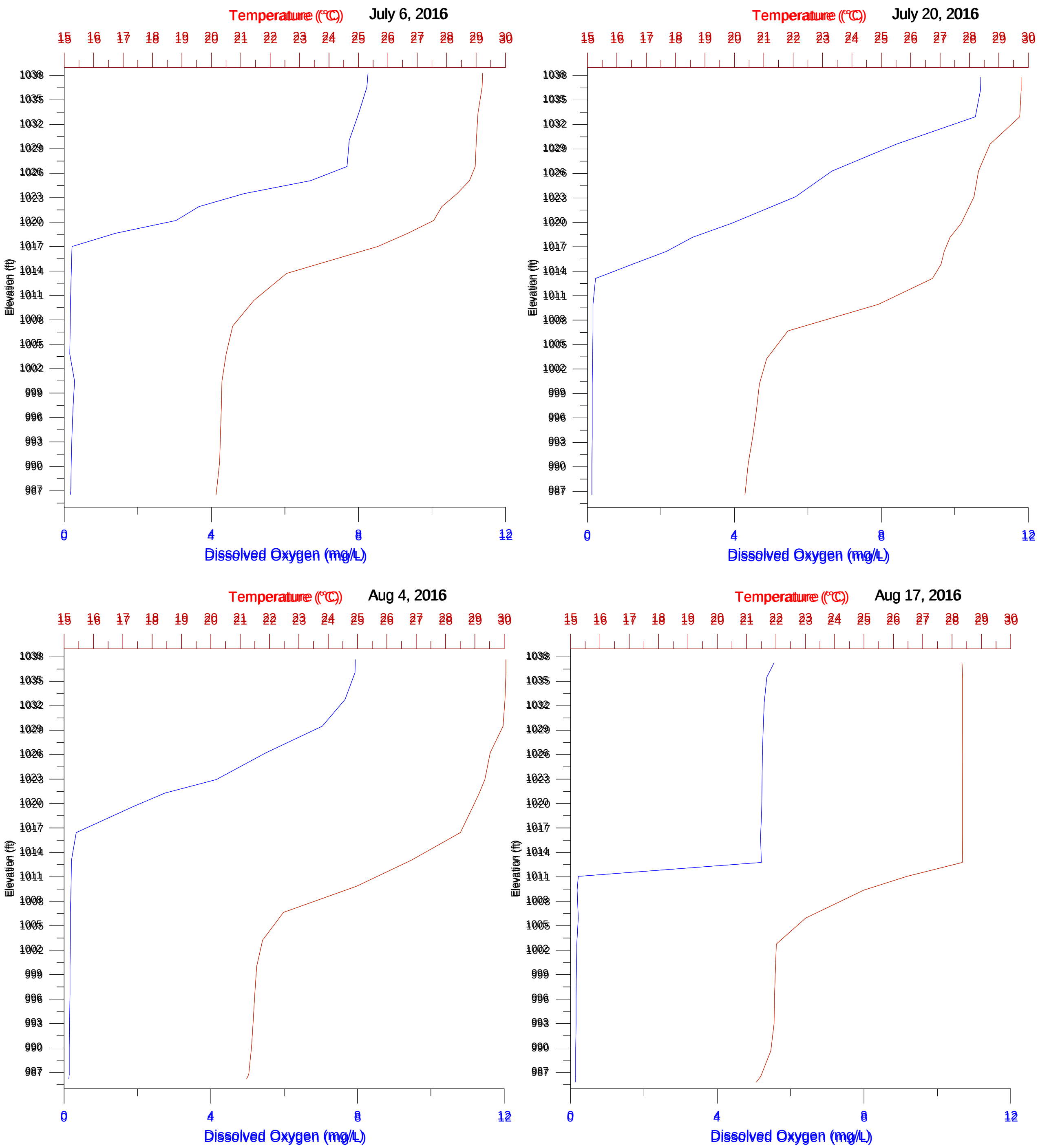


Figure 8. Temperature (red) Dissolved Oxygen (blue) Vertical Profiles Site 1: July 6, 2016 – August 17, 2015.

While no overt effect of the SDOX on hypolimnetic dissolved oxygen was noted there was an increase in the rate of temperature gain in the hypolimnion that could be attributed to the SDOX. Warming of the hypolimnion was observed starting June 22, 2016 (immediately following SDOX startup) into complete mixis. Even with compete de-stratification and lake mixing, anoxia was noted at the lake bottom during the October 5 monitoring event (**Figure 9**). Monitoring on

November 9, 2016 showed an oxidized water column with some drop of oxygen with depth and negligible change in temperature with depth.

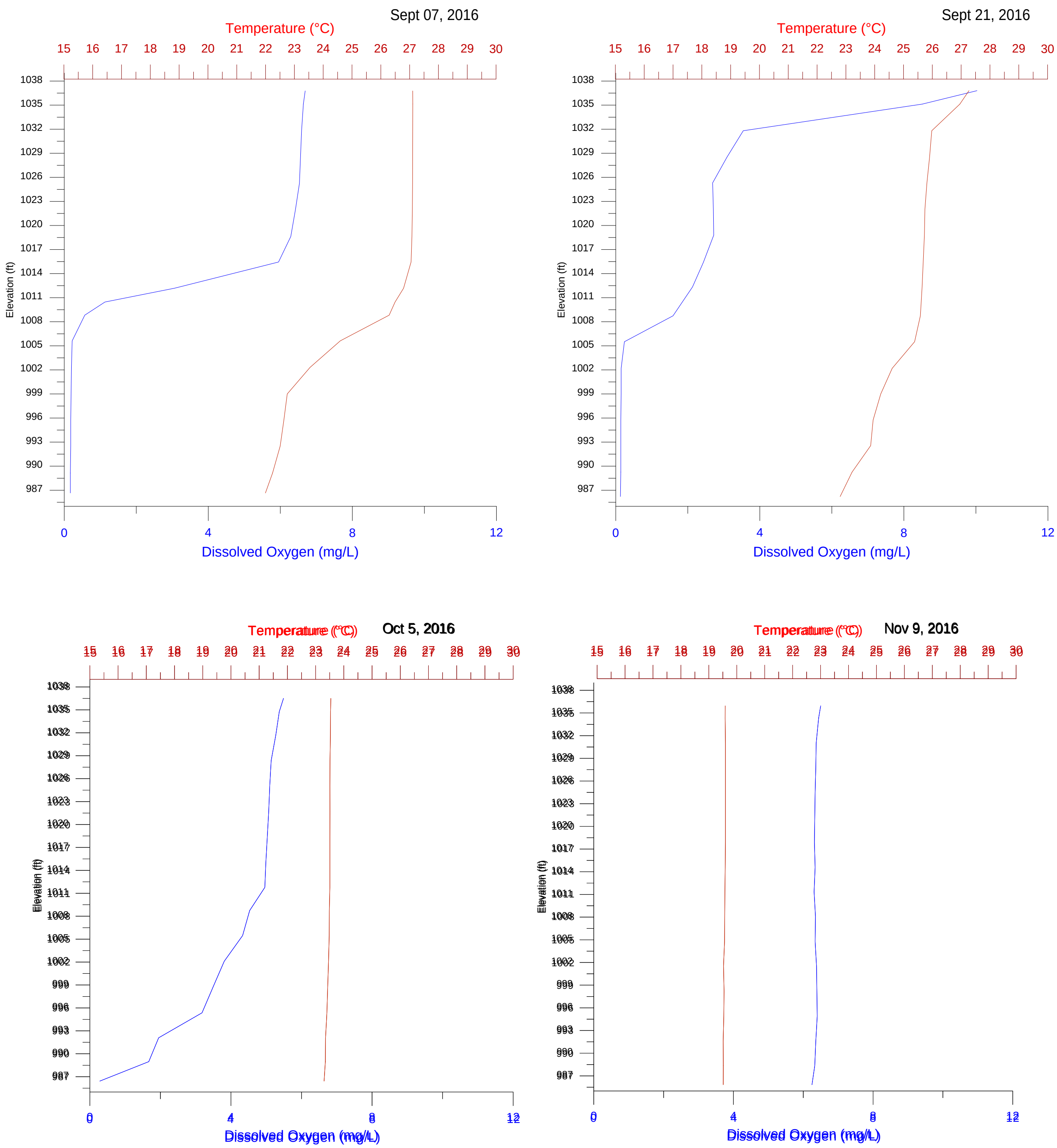


Figure 9. Temperature (red) Dissolved Oxygen (blue) Vertical Profile Site 1: September 07, 2016 – November 9, 2016.

An alternate method for illustrating physical lake data is by using isopleths. These three-dimensional plots interpolate hundreds of data points into one figure to show variation in physical parameters over depth and time. The following isopleths show the same temperature and DO data for Site 1 in a summarized form (**Figure 10**). Site 1 is largely representative of seasonal dynamics of the lacustrine zone of Lake Thunderbird. Each line on the isopleths represents a specific temperature or DO value. Vertical lines indicate a completely mixed water column. When lines run horizontally, some degree of stratification is present. On the temperature plot, warmest temperatures are colored red, graduating to blue as temperature gets cooler, while on the DO plot, lowest DO values are colored red, graduating to blue at the highest DO.

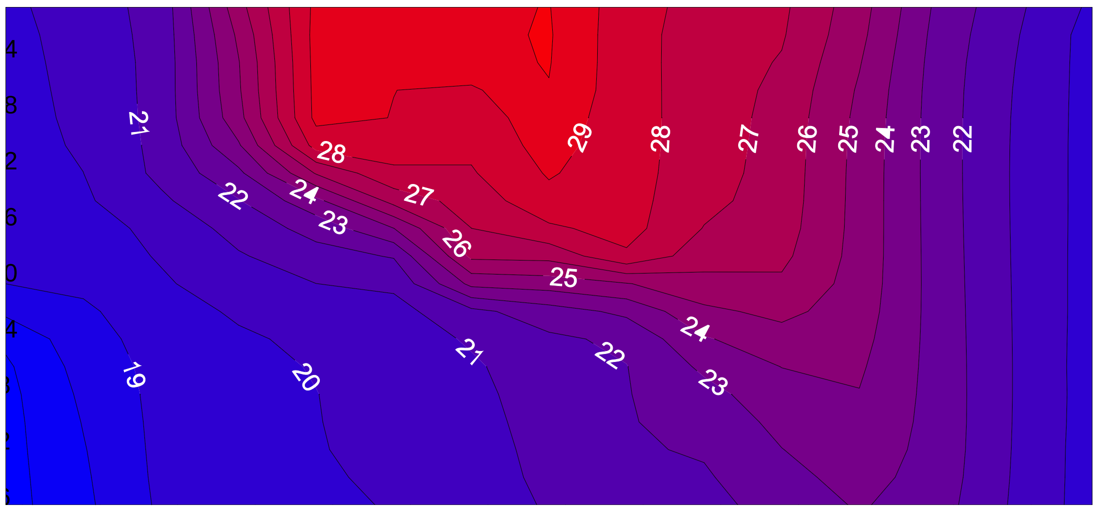


Figure 10. Isopleths of Temperature (°C) and Dissolved Oxygen (mg/L) by Depth (m) Lake Thunderbird 2016.

During 2016, thermal stratification followed a pattern typical in respect to onset and mixing. During late May and June, the upper portion of the water column began to heat up at a faster rate than the bottom, creating thermal stratification. Thermal stratification strengthened in mid-June and is indicated on the isopleths as the tightening of contour lines that run parallel with the x-axis into September (**Figure 10**). While thermal stratification strengthened in June, measurable dissolved oxygen rapidly dropped through May with significant anoxia in June. A slight, apparent recovery of DO was noted from July on as the hypolimnion shallowed until complete mixis by the end ogf September. Complete mixing had occurred by late October, bringing isothermal, but not fully oxygenated conditions throughout the entire water column.

When strong anaerobic conditions occur, elements other than oxygen act as terminal electron acceptors in the decomposition process. This results in nutrients and other constituents being released from the sediment interface into the isolated waters of the hypolimnion. When mixing events occur, these released nutrients trapped in the hypolimnion flux to the surface waters where they can further stimulate algal growth. The partial mixing events are evident when examining the oxygen isopleths as the blue area (higher oxygen content) pushes down toward the red area (lower oxygen content).

Dissolved oxygen concentration decreases in the epilimnion due to high plant and animal respiration rates, but is offset by high photosynthetic rates and physical mixing of atmospheric oxygen into the water. The areas of intense blue at the surface in **Figure 10** represent oxygen production by excess algae growth with epilimnetic (surface) dissolved oxygen percent of saturation well above 100%. Greatest supersaturation occurred in late July. Supersaturation as the epilimnetic water warms is evidence of high algal productivity; epilimnetic waters below the saturation point indicate respiration rates greater than photosynthetic oxygen production and diffusion of oxygen from the atmosphere.

Nutrients and Chlorophyll-a

High nitrogen and phosphorus loading, or nutrient pollution, has consistently ranked as one of the top causes of degradation in U.S. waters. In fact, lakes with excess nutrients are 2½ times more likely to have poor biological health (USEPA 2009). Excess nitrogen (N) and phosphorus (P) lead to significant water quality problems including reduced spawning grounds and nursery habitats for fish species, fish kills, hypoxic/anoxic conditions, harmful algal blooms, taste and odor problems in finished drinking water, public health concerns related to recreation and increased organic content of drinking water sources. Sources of these pollutants to Lake Thunderbird are largely non-point source in origin.

Several measures of N and P were made during monitoring visits, including dissolved and total forms. Dissolved nutrient concentrations consist of nutrients that are available for algal growth, such as ortho-P, ammonia, nitrate, and nitrite. High dissolved nutrient concentrations in the epilimnion generally indicate that nutrients are immediately available for (and not limiting to) algal growth, while hypolimnetic concentrations are nutrients that could be available for future algal growth. Nitrogen and phosphorus concentrations in the epilimnion can also indicate what may be limiting algal growth. Generally, when both N and P are readily available, neither is a limiting nutrient to algal growth, and excessive Chlorophyll-*a* values are expected. When high P concentrations are readily available in comparison to very low N concentrations, algal growth may be N-limited. High to excessive levels of algal growth, or primary production, can be expected under nitrogen-limited conditions. This can give a competitive advantage to undesirable Cyanobacteria (blue-green algae). In the absence of adequate dissolved N, certain blue-greens have the ability to convert atmospheric N into a usable form by way of specialized cells called heterocysts. These blue-green algae are generally implicated for producing harmful toxins and chemicals that cause taste and odor problems in public water supplies. There has been no documentation of blue-green algae blooms at Lake Thunderbird during our monitoring, but the frequency and severity of blue-green algae blooms have increased in Oklahoma, resulting in measurable amounts of cyanotoxins found in afflicted waterbodies. The detection of taste and odor compounds, geosmin and MIB, in recent years, confirms presence of nuisance blue-green populations in Lake Thunderbird.

With regard to nutrient limitation, P as the limiting nutrient is desired for most freshwater systems. Under P limiting conditions, more desirable, green algae will typically be predominant. Dzialowski *et al.* (2005) has broken the molecular ratio of total N to total P (TN:TP) into three ranges, wherein a TN:TP ratio of less than or equal to 18 indicates a nitrogen-limited waterbody, ratios of 20-46 indicate a co-limitation of N and P, and waters having ratios greater than 65 are regarded as phosphorus-limited. This interpretation scheme is applicable to Lake Thunderbird. In most eutrophic reservoirs, a co-limitation condition is more of a “no-limitation,” where both nutrients are readily available in significant amounts, although phosphorus limitation is, in general, the desired state. Lake Thunderbird has generally had TN:TP ratios in the 40’s to 60’s over the years, indicating the lake was phosphorus and co-limited. Similar to 2015, most Site 1 TN/TP ratios were below 40, with around 40% of monitoring dates in the lower nitrogen limited range (**Figure** 11). This recent trend of decreasing TN/TP ratio is disturbing; highlighting the need for external and in-lake nutrient control as neither nitrogen nor phosphorus truly limits algal growth.

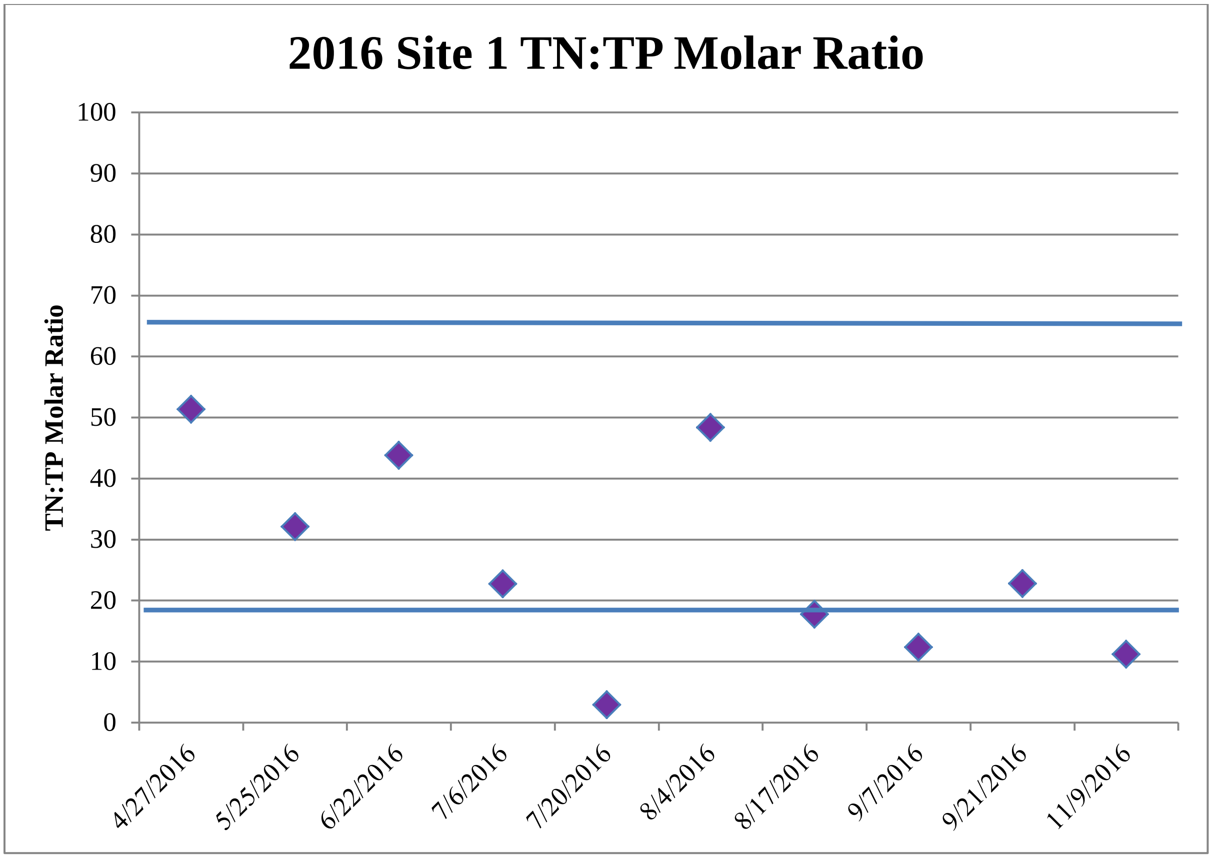


Figure 11. 2016 Site 1 Surface TN:TP Molecular Ratio

Phosphorus – P

Total phosphorus and ortho-P concentrations produced patterns typical of eutrophic to hypereutrophic lakes (**Figure 12**). The summer and fall spike of TP can be explained by early July recharge and complete lake mixing event by the end of September. Notable is the recharge events in May did not show a sharp increase in total phosphorus as witnessed for the July event.

Bottom and hypolimnetic ortho-P increased throughout the stratification period before decreasing following lake destratification. The buildup of hypolimnetic ortho-P is evidence of the settling of material from the epi- and metalimnion, in addition to active release from the anoxic sediment (**Figure 12).** Rise in surface ortho-P in September coincided with the turnover timeframe, indicating that portions of the nutrient rich hypolimnion were mixing into the less nutrient rich surface waters. This mixing coincides with a depression of metalimnetic and surface DO, confirming the source of the nutrients.

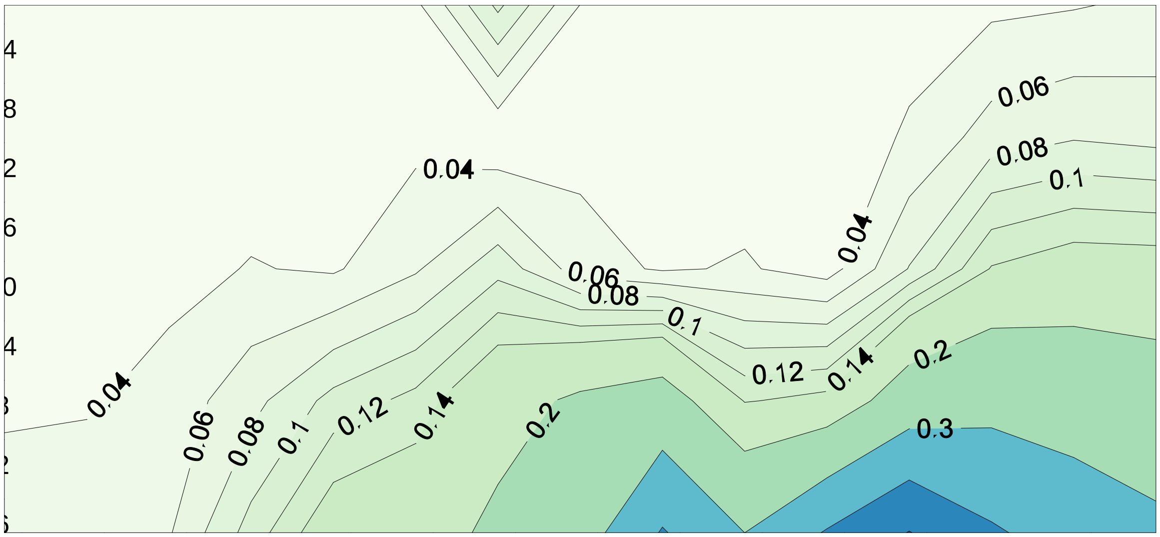


Figure 12. 2015 Lake Thunderbird Total Phosphorus. Contours With Depth, by Date, at Site 1.

Phosphorus sampled from the upper arms (riverine portion) of the lake was consistently higher than the open water, lacustrine Sites (**Figure 13**). The Little River Site 6, had the highest phosphorus and the Hog Creek Site 8, the lowest (**Figure 14**). Phosphorus in the upper arms of the lake represents the potential for hypereutrophic algal growth.

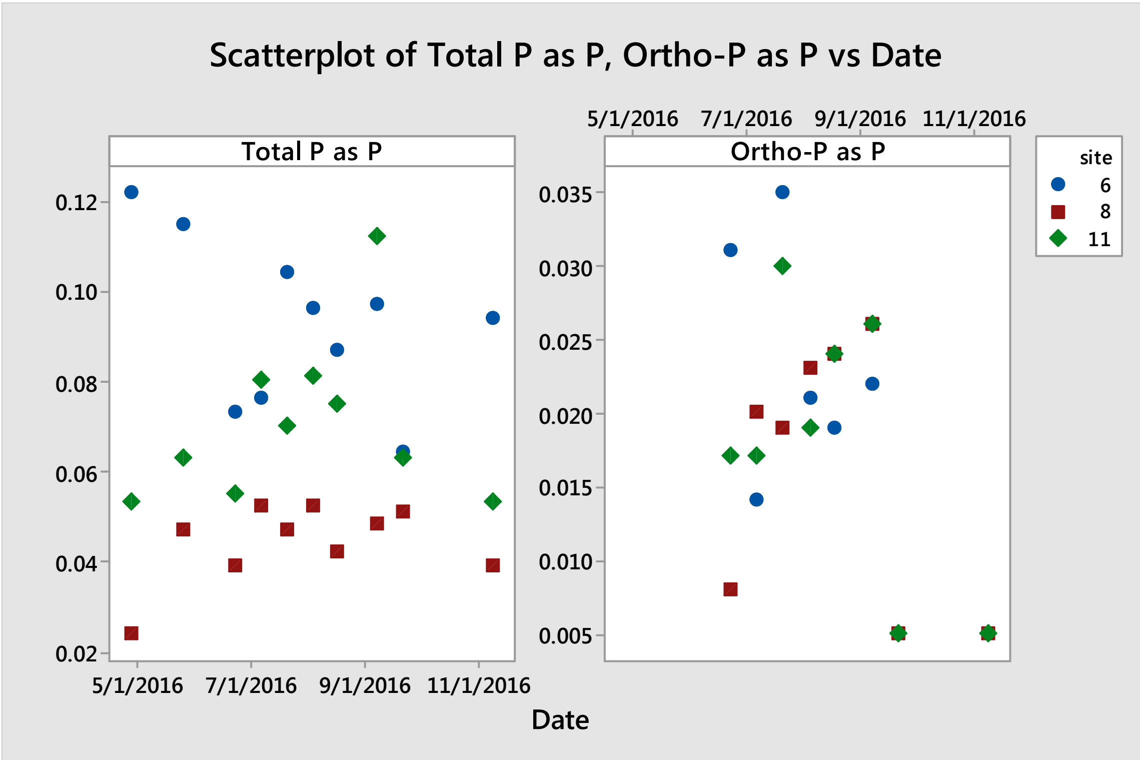


Figure 13. Surface Total and Ortho-P data from the Three Riverine Sites 2016.

For total phosphorus, Sites 6 and 11 were statistically similar and Sites 8 and 11 were statistically similar at a 95% confidence using both the non-parametric Tukey's and Fisher's comparisons. Site 6 showed the highest mean TP concentration of 0.092 mg/L with Site 8 the lowest, 0.044 mg/L. For ortho-phosphorus, only the Fisher comparison showed statistical differences at a 95% confidence with Site 6 and 11 similar and Sites 8 and 6 similar. Sites 8 and 11 indicate ortho-phosphorus were similar at 0.016 mg/L and 0.018 mg/L respectively and Site 6 the highest at 0.021 mg/L.

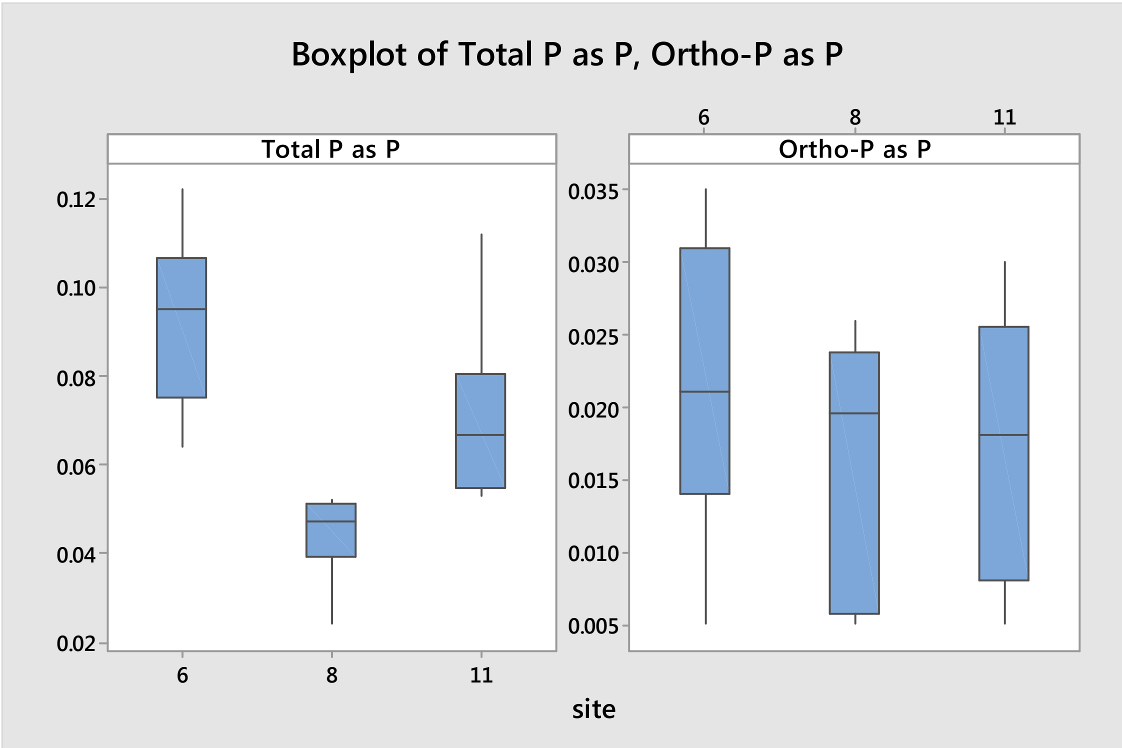


Figure 14. 2016 Phosphorus Series Box and Whisker Plots for the Riverine Sites 6, 8 and 11.

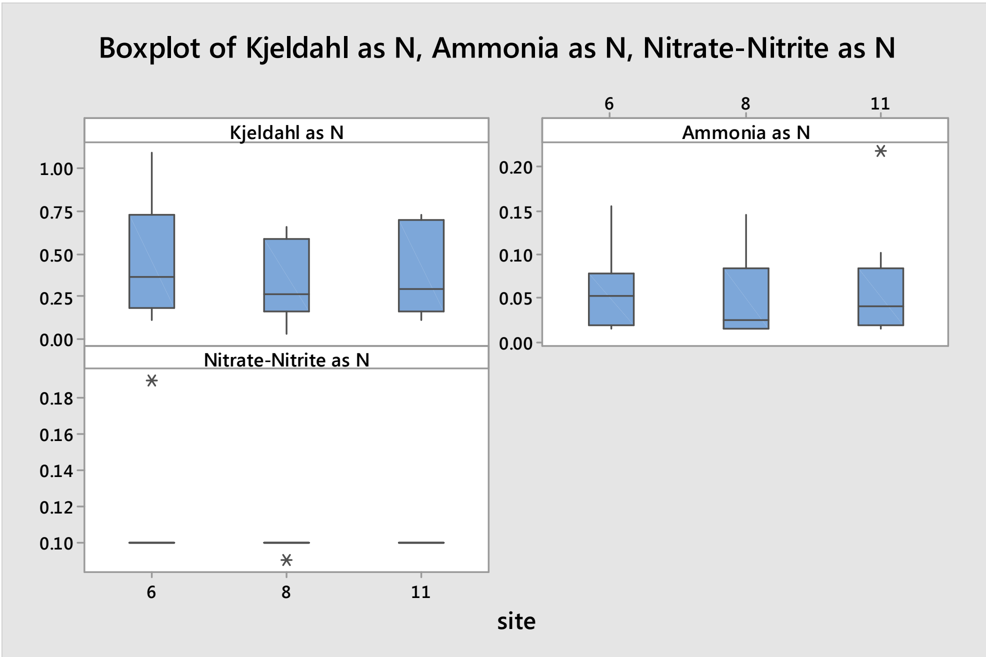
Nitrogen – N

Total and dissolved nitrogen produced patterns somewhat typical of seasonal ecological cycles in reservoirs (**Figure 15**). Surface Kjeldahl nitrogen was variable with an epilimnetic peak midsummer (likely associated with rainfall event) but generally decreased over time until stratification ended.

Examination of ammonia and nitrate distribution with depth and over time showed a general increase in ammonia in the hypolimnion. This is attributed to release from anoxic sediment and as a decomposition product of senescent algae cells and organic material (**Figure 15**). Ammonia gradually increased in the hypolimnion until the breakdown of thermal stratification mixed the ammonia rich hypolimnetic waters to the surface. In the epilimnion, nitrate serves as an important nutrient for algal growth. Data indicates it was exhausted by early June when it was below the detection limit. In the hypolimnion, nitrate serves as an electron acceptor in respiration; here nitrate did not fall below detection limit until late June. The low concentrations of nitrate in the hypolimnion suggest a change in the bacterial community to production of methane and sediment activity with release of phosphorus and ammonia. Nitrate returned to the entire water column following oxidation of the mixed hypolimnetic water.

Examination of the riverine Sites showed no statistical differences between Sites with respect to nitrogen (**Figure 16**). The abundance of ammonia, the most easily assimilated nitrogen nutrient, was similar to 2015 and in sharp contrast to 2014 data set where 32 of 35 riverine samples were reported as BDL. Oxic conditions in the riverine Sites along with the fact that all nutrient samples lake-wide showed a below detection limit on July 22 2017, monitoring event suggest a regular inflow of ammonia from the tributaries.

Figure 15. 2016 Lake Thunderbird Total Kjeldahl, NO2-NO3, and Ammonia as N with Depth Over Time at Site 1.



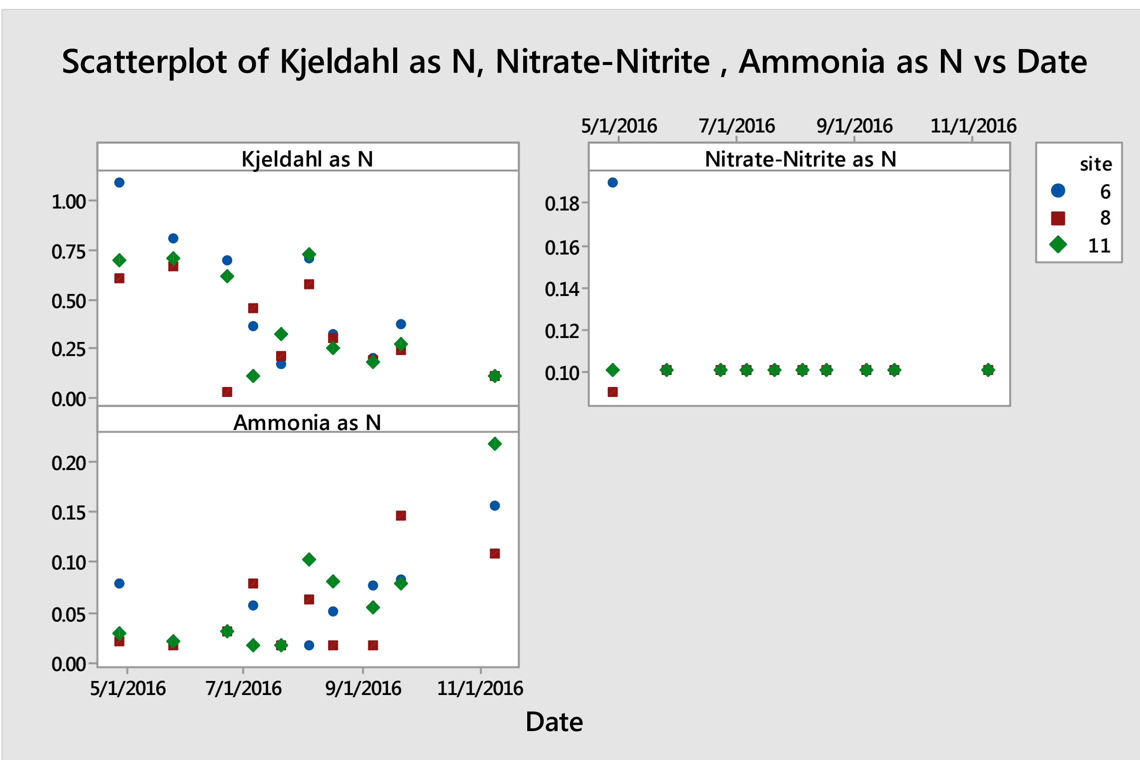


Figure 16. Nitrogen (Ammonia, Nitrite-nitrate and Kjeldalh Nitrogen as N mg/L) Parameters of the Riverine Sites (6, 8, and 11) in Lake Thunderbird 2015.

Nutrient Budget - Phosphorus

A phosphorus budget for Lake Thunderbird was prepared integrating the estimated outflows from the water budget with water quality data. Vertical profiles of physical parameters combined with reservoir bathymetry act to partition total phosphorus reports in one-meter intervals between epilimnetic, metalimnetic and hypolimnetic layers. The cumulative summation of these layers allows the massing of P for each sample date (**Table 3**). Once the lake mass was established, the distribution within the lake and losses were estimated using USACE and COMCD water quantity reports (**Table 2**). Missing from this lake nutrient budget are estimates of phosphorus inflow, dry deposition and sediment flux.

Table 3. 2016 Lake Thunderbird Site 1 Phosphorus Mass (kg) at Depth Intervals by Sample Date (Bold Red Numbers Represent Anoxic Layers While Blue Shaded Cells Represent the Epilimnion, Clear Cells Metalimnion and Red Shaded Cells Hypolimnion).

Average Elevation	4/27/20176	5/25/2016	6/22/2016	7/6/2016	7/20/2016	8/4/2016	8/17/2016	9/7/2016	9/21/2016	11/9/2016
1037.97	547	742	518	1389	2576	716	659			
1036.21	542	728	460		2323	643	537	1210	1319	906
1032.80	441	550	417	573	2078	553	489	501	534	805
1029.48	413	538	377	490	1723	504	423	462	459	681
1026.21	319	483	292	256	268	402	376	360	391	613
1022.92	324	374	137	906	369	416	326	369	334	537
1020.08	254	326	191		132	**329**	275			464
1018.64			271	273	256			242	320	397
1016.20	199	268	**227**	**335**	137	**261**	232	242	198	
1013.29	195	219	**238**	**295**	634	**260**	104	134	216	334
1010.12	156	195	**269**	**306**	429	**423**	623	312	**324**	275
1006.51	117	149	**253**	**385**	**391**	**457**	**460**	**214**	**345**	209
1003.19	81	105	**206**	**206**	**312**	**399**	**423**	**187**	**297**	142
999.95	52	68	**148**	**141**	**221**	**300**	**320**	**105**	**194**	89
996.67	27	34	**79**	**76**	**134**	**150**	**173**	**71**	**169**	50
993.43	13	15	**38**	**37**	**70**	**67**	**90**	**51**	**103**	23
990.11	5	6	**14**	**12**	**28**	**24**	**37**	**15**	**45**	10
986.93	1	1	**3**	**5**	**6**	**4**	**5**	**5**	**7**	3
TP mass	3685	4802	4139	5686	12087	5908	5551	4478	5257	5539
Anoxic TP mass	0	0	1476	1798	1163	2674	1507	647	1484	0
% anoxic vol.	0%	0%	36%	32%	10%	45%	27%	14%	28%	0%
Lake mean conc.	0.028	0.036	0.031	0.043	0.088	0.163	0.043	0.035	0.041	0.045

The constructed water and nutrient budget demonstrates pre-stratification lake P mass, in 2016, of approximately 3685 kg; is consistent with the historical (2009 – 2014) pre-stratification average of 3200 kg. As in previous years, a relatively steady increase in Lake P-mass occurs. This observation should be tempered with the epilimnetic jump observed on the July 20, monitoring event; the preceding rainfall and inflow noted in **Figure 3** are the reason for this increase. The next monitoring event indicates that this watershed-sourced phosphorus settled into the sediment. The largest impact of this inflow to the lake is the increase of anoxic volume from the 1006’ elevation at the top of the hypolimnion on July 20 into the base of the epilimnion at elevation 1002’. The significant increase of anoxic volume indicates a large load of organic material washing into the lake.

It is worthwhile to note that anoxia extended out of the hypolimnion and into the metalimnion first documented in late June extending through September with one break of only hypolimnetic anoxia in late August. The upward push of anoxia in 2016 indicates the factor to which sediment mediated phosphorus release from metalimnetic and even epilimnetic areas can exert. Using calculations based on Nürnberg (1994) and those specifically developed for Lake Thunderbird by OWRB, it was calculated that anaerobic mediated sediment P release had increased 39% from the average release from 2005 – 2009. Although this is lower than 2015, a historic flood year, 2016 continues the trend started in 2014 of above baseline Anoxic Factor (AF).

Chlorophyll-a

Chlorophyll-a (Chl-a*)* is a pigment common to all photosynthetic plants and is used as a proxy for measuring algal biomass in aquatic ecosystems. First appearances suggested algal growth was similar to that measured in 2014 and 2015. Quality control checks noted at the beginning of this report showed unusually high values for pheophytin-a, the primary degradation product of chlorophyll-a. Without accounting for the degradation product of chlorophyll-a algal growth in Lake Thunderbird would have been grossly underestimated.

By considering only chlorophyll-a, as required by Oklahoma Water Quality Standards, Site 1 average chlorophyll-a reflects a continued leveling of reductions since the installation of the SDOX device (**Figure 17**). For the 2016 sampling season, the lake wide average Chl-a at Lake Thunderbird was 22.8 µg/L, similar to the 2014 and 2015 averages and just below the pre-SDOX (2007-2010 historical) average of 25.9 µg/L; although following a possible upward trend since 2014 (**Figure 18**). Observed peak lacustrine chl-a was also reduced from the previous five years with Site 2 and 4 maximums of under 40 µg/L, lower than pre-SDOX but still a step up from the 2013 low (since 2007). Using only chlorophyll-a as an indicator of lake trophic level, 35% of lake samples were simply eutrophic while 53% of all samples were in the hypereutrophic or excessive algal growth, level. Unfortunately, these analyses do not shed full light on algal dynamics within the reservoir.

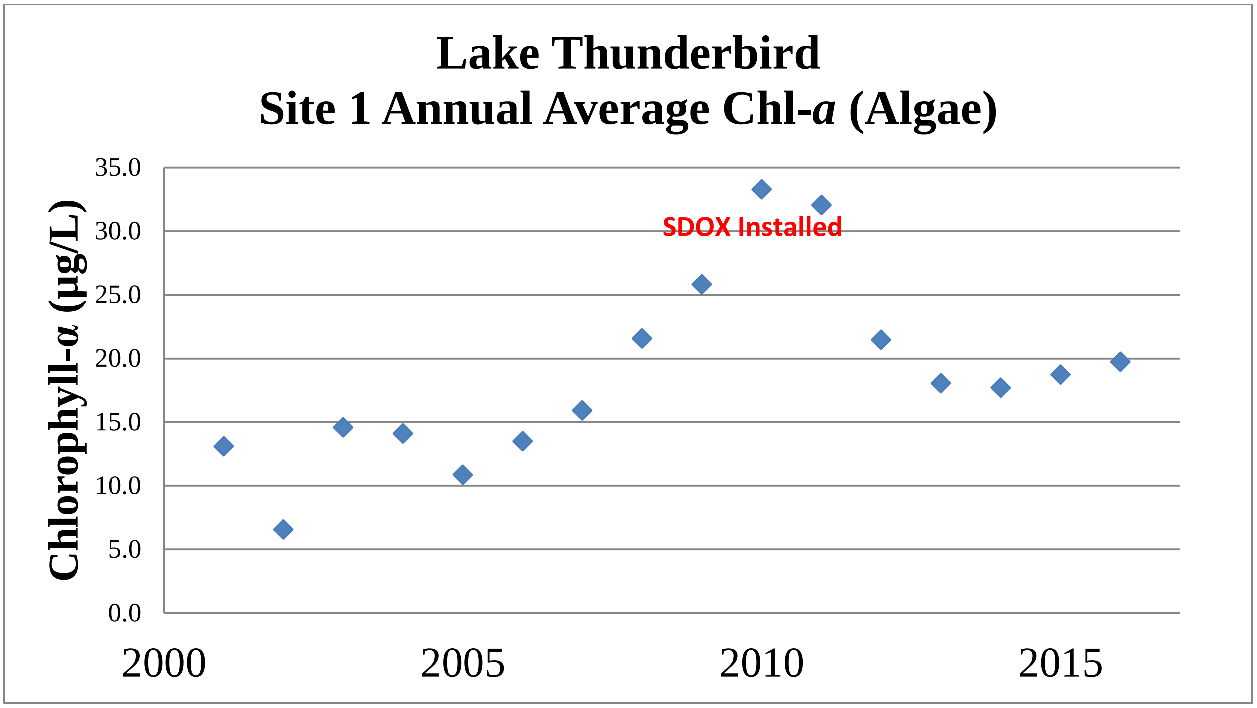


Figure 17. Lake Thunderbird Site 1 Average Seasonal Chlorophyll-a from 2005 through 2016.

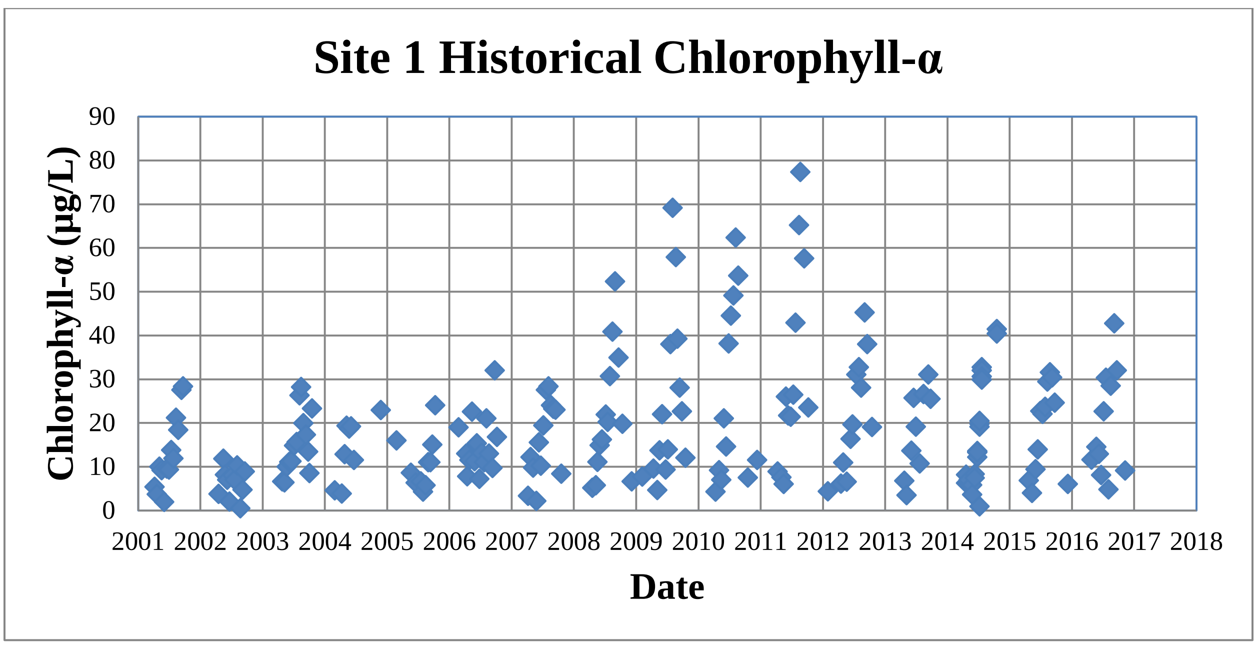
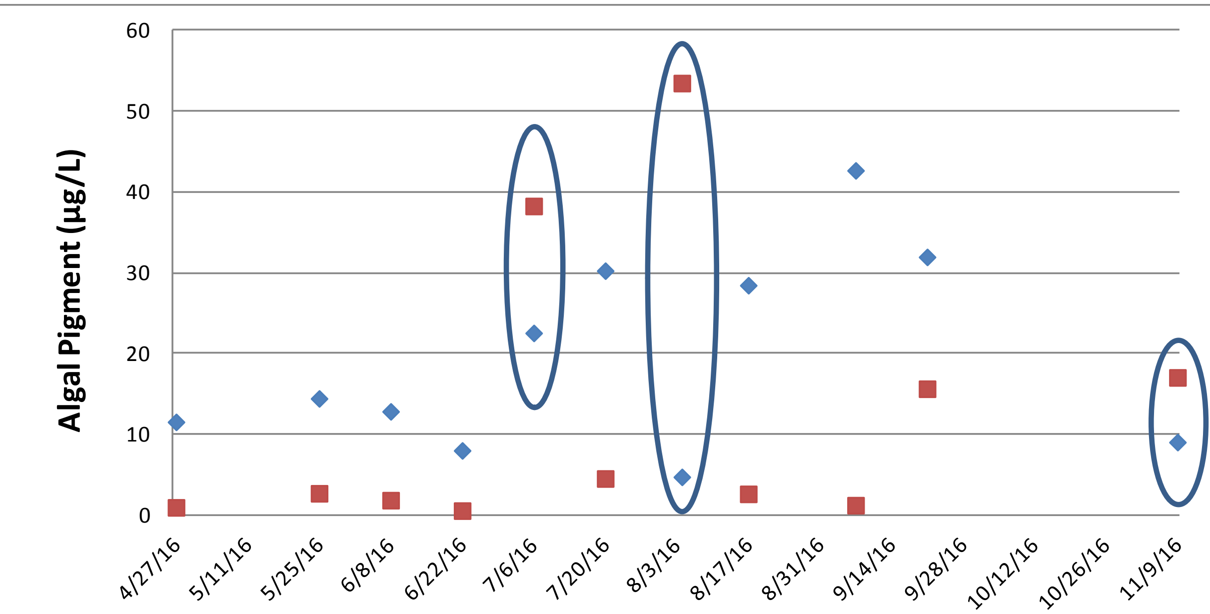


Figure 18. 2001-2016 Lake Thunderbird Surface Chl-a µg/L (or ppb) at Site 1

When the measures of pheophytin– a are incorporated into the dataset, the assessment of algal growth during 2016 must be revised to account for the increased algal growth. The circled values represent monitoring events when pheophytin-a, the degradation product of chlorophyll-a, was greater than 100% chlorophyll-a (**Figure 19**). These monitoring events have captured either an active algal die-off or complete die off following a bloom. For example, on July 6, chlorophyll-a was 22.6 ug/L, in the hypereutrophic range, yet the pheophytin-a value was 38.3 ug/L; indicating that an active bloom die off had begun. This is contrasted by August 4, where chlorophyll-a was below the eutrophic range (4.8µg/L) and pheophytin-a content was 55.2 µg/L, greater than any chlorophyll-a lacustrine sample taken this season. This represents the very end of an algal bloom die-off.

Incorporating these bloom and die-off events (as represented by pheophytin-a) complicates the use of chlorophyll-a as a diagnostic tool for algal growth. The plot for Site 1 chlorophyll-a suggests a continued dampening of peak chlorophyll-a yet pheophytin-a indicates chlorophyll-a was likely quite higher (Figure 19). Implications of these bloom and die off events are hard evidence of pulsed dissolved oxygen loads generated in-lake. From an ecological assessment perspective, these events underscore the need for analysis of both pigments and the need to place an asterisk to the chlorophyll-a 2016 summaries.



	4/27/16	5/25/16	6/8/16	6/22/16	7/6/16	7/20/16	8/4/16	8/17/16	9/7/16	9/21/16	11/9/16
Chlorophyll-a	11.6	14.5	12.9	8.07	22.6	30.3	4.8	28.5	42.7	32	9.1
Pheophytin-a	1.03	2.77	1.92	0.63	38.3	4.6	53.5	2.7	1.3	15.7	17.1

Figure 19. Lake Thunderbird Surface Algal Pigment, chlorophyll-a and Pheophytin-a (µg/L) at Site 1 2016. Monitoring Events when Pheophytin-a Measurements were Greater than Concurrent Chlorophyll-a are Marked with Oval Shapes.

General Water Quality

Total Organic Carbon - TOC

Total organic carbon (TOC) is an additional measure of organic content and productivity, and an important drinking water treatment parameter. Total organic carbon samples were collected at the surface of Site 1 during 2016. Similar to 2014 and 2015, TOC and Chl-a did not correlate evidenced by an R^2 of 2.2% and p-value of 0.68. However, a clear statistical relationship was noted between TOC and the sum between chlorophyll-a and pheophytin-a (**Figure 20**). This new relationship continues to underscore the fact that in-lake production of TOC via algal growth is significant.

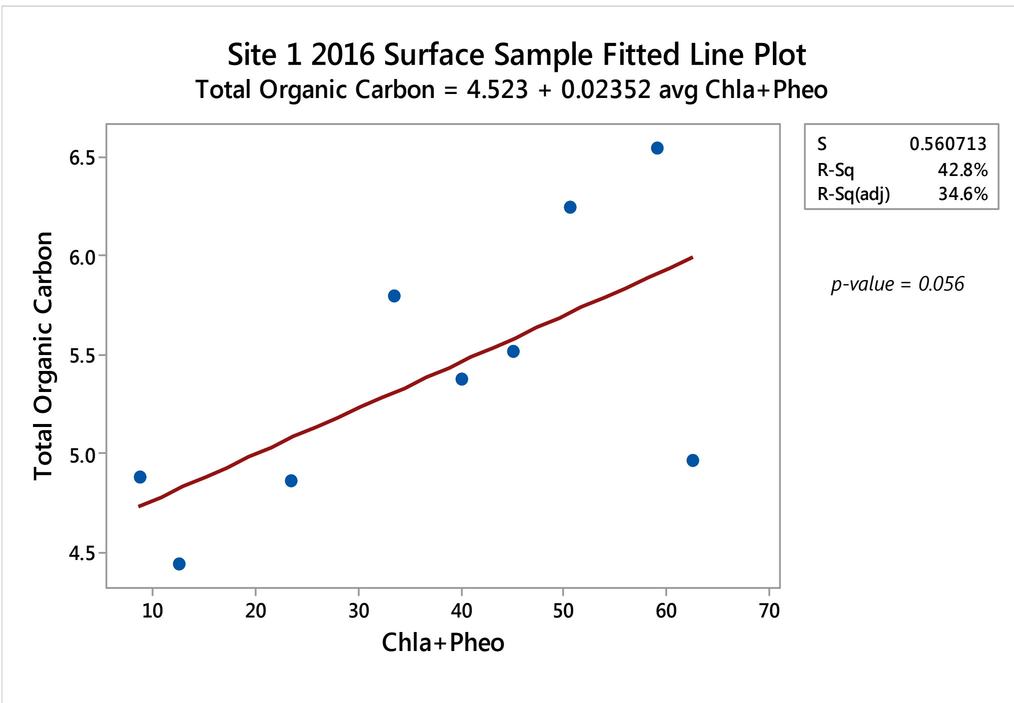


Figure 20. Site 1 surface TOC, Chl-a and Chl-a+Pheo-a at Lake Thunderbird 2016.

pH, Oxidation-Reduction (redox) Potentials, and Dissolved Metals

Increases in surface pH during the summer months indicate high rates of photosynthesis, while lower hypolimnetic pH is due to the buildup of bacterial respiration byproducts. Sinking organic matter in summer months (due to high algal production or influx of organic material from the watershed) stimulates decomposition processes in the hypolimnion by pushing pH and ORP down. In general, peaks of high and low pH correspond to peaks in algal productivity. High rates of photosynthesis will temporarily elevate pH as carbon dioxide is stripped from the water column (generally in the epilimnion), while catabolism of the settling algae depresses pH (generally in the hypolimnion).

Lake Thunderbird followed a typical eutrophic pattern of pH in 2016 in lacustrine Sites (1,2 and 4), where pH peaked in mid-summer at the surface during the time of highest algal productivity and was lowest at the lake sediment interface (pH of approximately 6.8) due to decomposition processes within hypolimnion (**Figure 21**). These lower pH values were only noted in the hypolimnion toward the end of stratification. Without any impinging biological processes such as photosynthesis and respiration, baseline pH for Lake Thunderbird would be 8.2, the common pH of bicarbonate buffered systems.

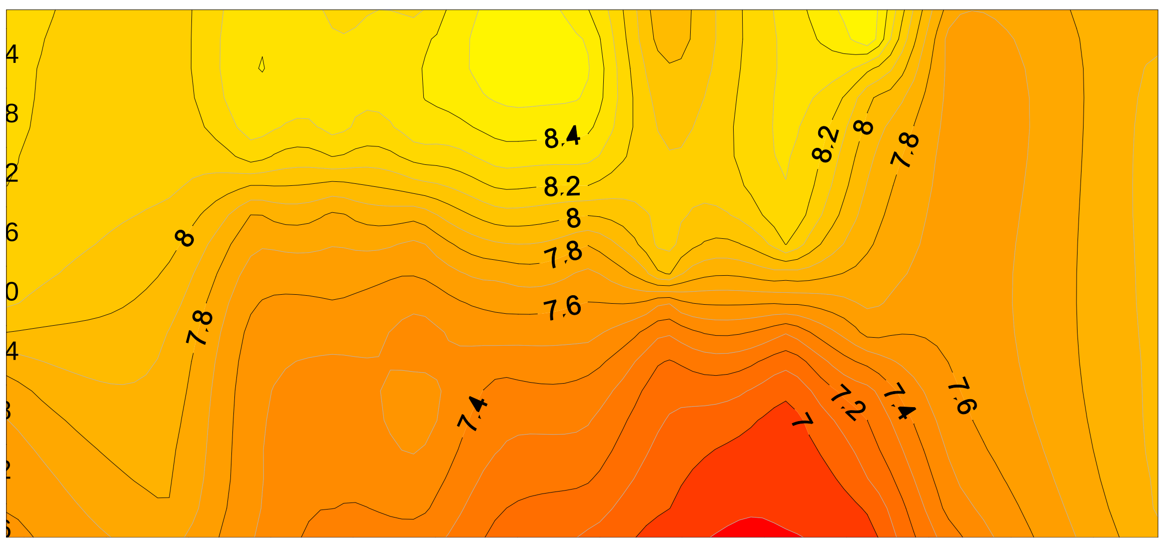


Figure 21. 2016 Lake Thunderbird Site 1 pH (S.U.) Versus Depth (m) Over Time

The biogeochemical cycling of inorganic nutrients is largely regulated by changes in oxidation-reduction potential (ORP) or redox states. Redox state plays a major role in the recycling of sediment bound phosphorus, iron, and manganese. Under oxygenated conditions, redox potentials remain highly positive (300-500 mV). Normally, as oxygen concentrations approach zero, redox potential drops in proportion to anaerobic metabolism. Generally, as the ORP drops towards 100mV or lower, solids such as phosphorus and metals dissolve into the water column.

Complete anoxia of the hypolimnion was noted at the beginning of June, yet low ORP was not seen until mid-June (**Figure 22**). This two-week period is when nitrate was used as the final electron acceptor for bacterial respiration maintaining a higher ORP. Interestingly throughout the entire summer, the isobar for low ORP (around 150 mV) was consistently lower than the anoxic isobar (2 mg/L dissolved oxygen) as noted in **Figure 10**. The differential is likely due to the settling of dead and dying alga cells collecting in the metalimnion: depleting oxygen but not causing a deep lowering of oxidation-reduction potential. It is important to note that along with sediment bound phosphorus and common metals, such as iron and manganese, production of sulfide and methane is common as electron acceptors for anaerobic metabolism become scarce. Therefore, the duration and extent of strong reducing conditions have a direct impact on the de-sorption of these compounds as well. Finally, low redox conditions slows the oxidation (breakdown) of organic materials such as the contents of dead and dying algal cells allowing these chemicals to build up in the hypolimnion.

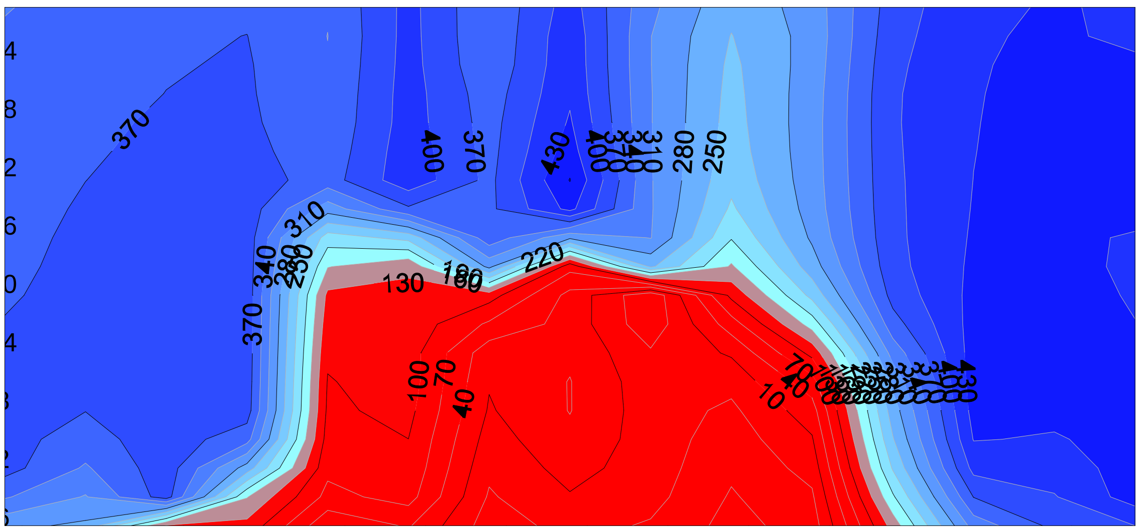


Figure 22. 2016 Site 1 Lake Thunderbird Oxidation-reduction Potential (ORP) as Millivolts (mV) Versus Depth (m).

Taste and Odor Complaints

The City of Norman has provided data on the number of taste and odor complaints from their water customers for our period of record (2000 – 2016). Lake Thunderbird is the major source of raw water for the city; changes in water quality parameters in the lake correlate with complaints in the final finished water. Consumers at the tap can detect taste and odor causing compounds in extremely low concentrations (~ 5 mg/L) (Graham et al 2008). The majority of these compounds are by-products of high algal productivity. The most commonly known drinking water taste and odor compounds, Geosmin and 2-methylisoborneol (MIB), are produced primarily by Cyanobacteria.

Fall taste and odor (T&O) complaints in 2016 generally exhibited the typical pattern of previous years' complaints, (**Figure 23**) with peaks occurring in September-November. However, an unusual peak of complaints in August, *prior* to significant fall mixing events, (**Figure 24**) occurred. Measured chlorophyll-a and pheophytin-a values showed a significant algal bloom die-off in August coinciding with the detection of significant amounts of Geosmin, a taste and odor chemical, in Norman's raw water. In 2016, episodic, epilimnetic T&O chemical release from the "bloom and bust" events received more complaints than the usual hypolimnetic release of T&O chemicals seen in previous years during fall turnover. The usual pattern of fall turnover complaints persisted, but were in fewer number than complaints in August (**Figure 24**).

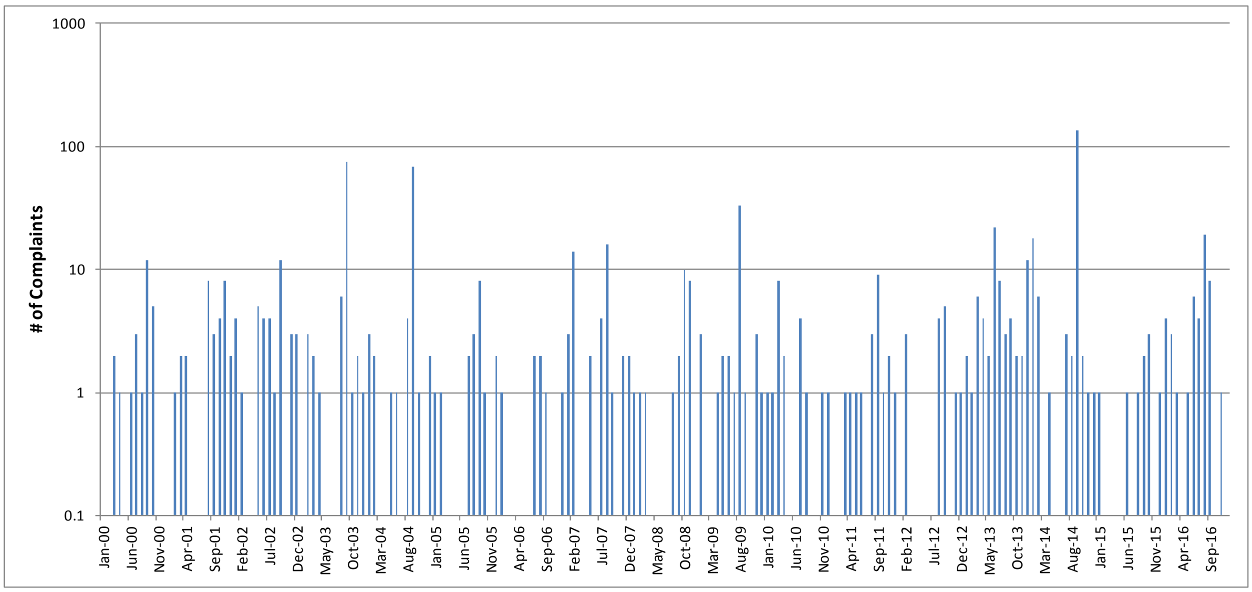


Figure 23. Taste and Odor Complaints to the City of Norman from 2000 through 2016.

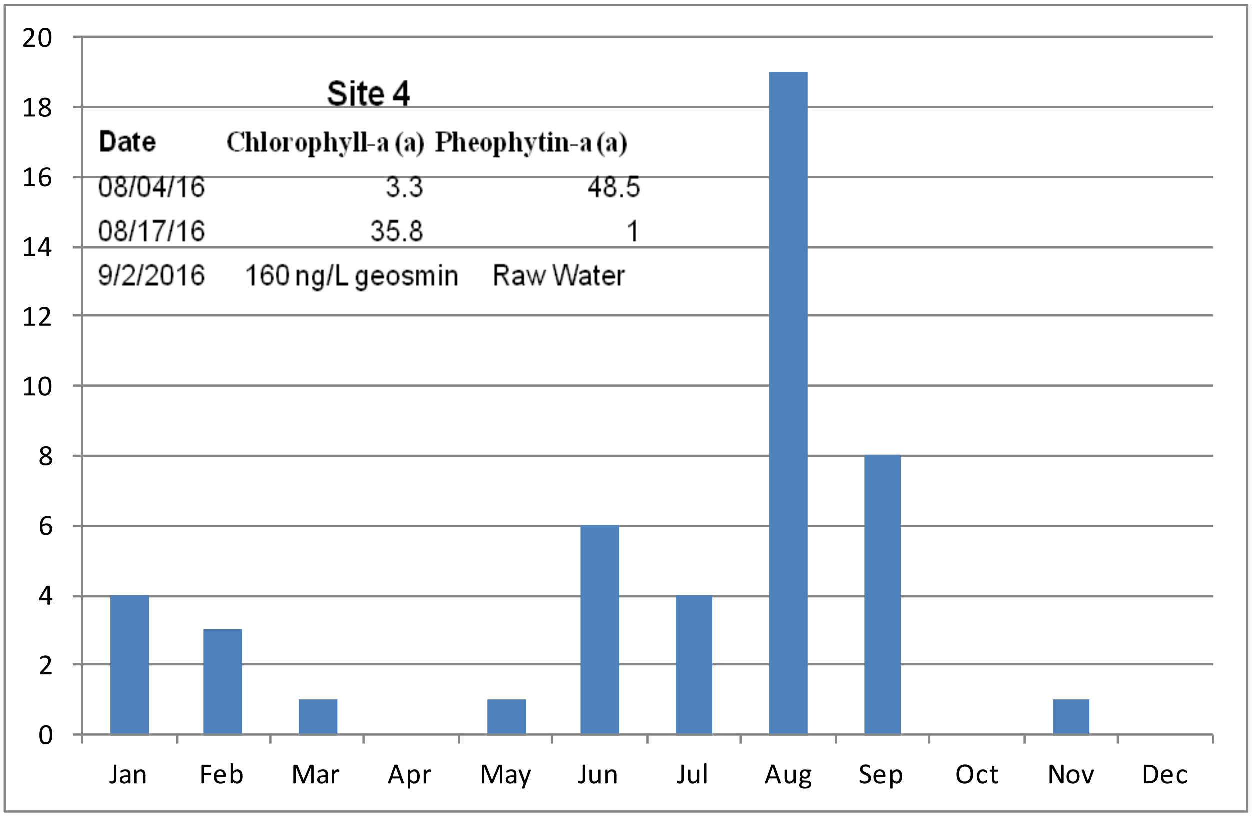


Figure 24. 2016 Taste and Odor complaints to the City of Norman. Chlorophyll-a and Pheophytin-a Reports as Well as Norman's Raw Water Taste and Odor Chemical Analysis are Presented as Explanatory for the August Complaint Peak.

Water Quality Standards

All Oklahoma surface waters are subject to Oklahoma's Water Quality Standards (OAC 785:45) and Implementation Rules (OAC 785:46), designed to maintain and protect the quality of the waters of the state. Oklahoma Water Quality Standards (OWQS) are a set of rules adopted by Oklahoma in accordance with the federal Clean Water Act, applicable federal regulations, and state pollution control and administrative procedure statutes. Water Quality Standards serve a dual role: they establish water quality benchmarks and provide a basis for the development of water-quality based pollution control programs, including discharge permits, which dictate specific treatment levels required of municipal and industrial wastewater dischargers.

Identification and protection of beneficial uses are vital to water quality standards implementation. Currently recognized beneficial uses listed in the OWQS Appendix A for Lake Thunderbird (listed as waterbody ID OK520810000020_00) include Public and Private Water Supply, Fish and Wildlife Propagation, and Primary Body Contact Recreation. The OWQS additionally designates Lake Thunderbird as a Sensitive Water Supply (SWS), due to its designated beneficial use as a Public and Private Water Supply and its relatively small watershed. Physical, chemical, and biological data on Lake Thunderbird were used to ascertain the condition of lake waters and determine if lake water quality supports the beneficial uses and SWS criterion.

The Oklahoma Water Quality Standards Implementation Rules contain Use Support Assessment Protocols (USAP) for Oklahoma waterbodies. Developed in coordination with all Oklahoma environmental agencies, the USAP establish a consistent and scientific decision methodology for determining support of beneficial uses. Presentation of Lake Thunderbird's water quality parameters in the following sections are in light of their accordance within the OWQS. Sites 1 through 6 are historical Sites originally monitored by Oklahoma's Beneficial Use Monitoring Program. Sites 8 and 11, are additional monitoring Sites added to gain perspective on the two other main tributaries of the lake, but are not used for USAP purposes.

Dissolved Oxygen – DO

Dissolved oxygen criteria are designed to protect the diverse aquatic communities of Oklahoma. For warm water aquatic communities, such as Lake Thunderbird, two assessment methodologies apply to protect fish and wildlife propagation: surface and water-column/volumetric (OAC 785:46-15-5). Surface water criteria is a seasonal threshold with a minimum DO while the volumetric criteria examines one-time events with a threshold of volume (50%) as anoxic (< 2 ppm DO).

No surface water violations occurred in 2016, with minimum surface DO registered at 5.49 mg/L on October 5, 2016 at Site 1, one month after the previous year's minimum surface DO. This 5.49 mg/L was above the summer minimum surface criteria of 4.0 mg/L but signified a recent hypolimnetic mixing event. Lake Thunderbird did not violate the volumetric criteria by exhibiting a maximum 32.8% of anoxic volume on June 22, 2016. (**Table 4**).

Table 4. Tabular Summary of Percent Anoxic Volume by Sample Date for the 2016 Sample Season.

Date	Pool Elevation	% Anoxic Volume
4/27/2016	1039.5	0.0%
5/25/2016	1039.3	0.6%
6/8/2016	1039.6	28.3%
6/22/2016	1039.5	32.8%
7/6/2016	1040.0	27.4%
7/20/2016	1039.5	21.4%
8/4/2016	1039.4	28.6%
8/17/2016	1039.0	14.2%
9/7/2016	1038.4	13.6%
9/21/2016	1038.5	13.9%
10/5/2016	1038.2	0.3%
11/9/2016	1037.6	0.0%

Chlorophyll-a – Chl-a

Lake Thunderbird has been shown to be vulnerable to eutrophication with high biological productivity driven by excess nutrients. This underscores its status as a sensitive water supply reservoir and need for protection Communities can experience substantial hardship and high costs to treat water adversely affected by excess algae. Specifically, blue-green algae (Cyanobacteria) blooms are considered a principal source of compounds that cause taste and odor problems. Blue-green algae also produce several toxic and carcinogenic compounds such as microcystins – a known hepatotoxin. For this reason, OWQS has identified a class of public water supplies known as Sensitive Water Supplies (SWS), giving additional protection from new point sources and protecting against additional loading from existing point sources. Lake Thunderbird has the SWS designation within OWQS and as such, is required not to exceed the long-term ten-year average Chl-a concentration criterion of 10 µg/L at a depth of 0.5 meters. For the 2016 sampling season, the lake wide Chl-a average in Lake Thunderbird was 22.8 µg/L, greatly exceeding the SWS Chl-a criterion **(Figure 25**). This value is slightly lower than the lake wide average of 24.9 µg/L in 2015 and much less than the 36 µg/L average in 2011, but slightly lower than the ten-year historical average of 24.4 µg/L. Eighty one percent of the chlorophyll-a samples were over the 10µg/L limit in 2016 concluding the lake is impaired for chlorophyll-a.

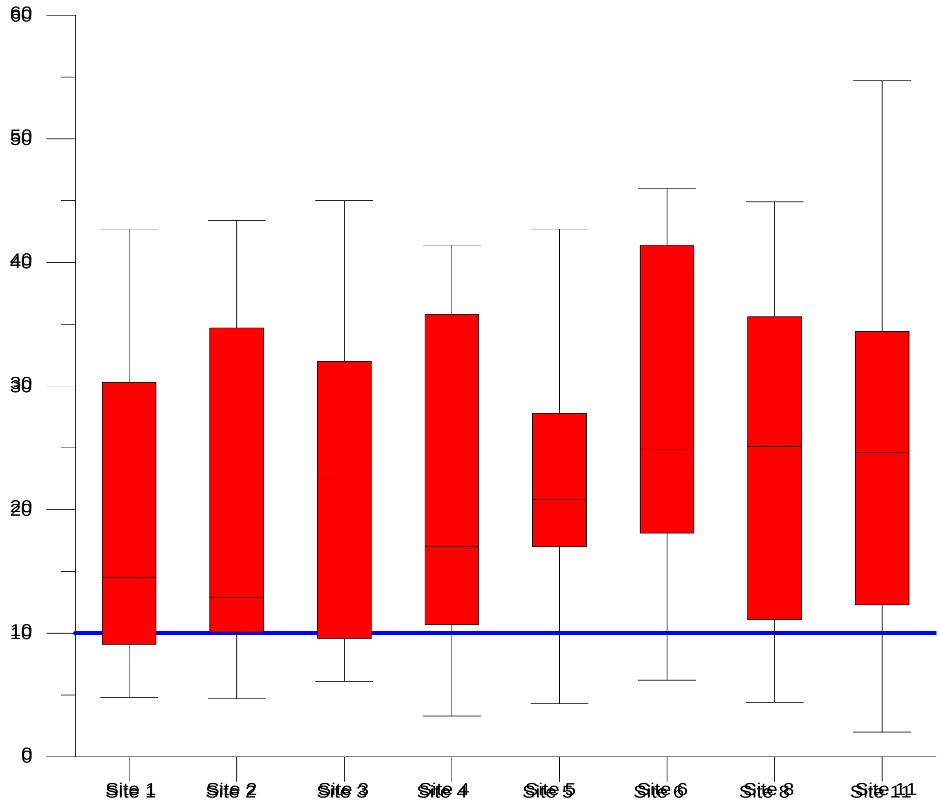


Figure 25. Chlorophyll-a Comparison to the Water Quality Standard for Sites 1 - 11 2016 (Where Boxes Represent 25% of the Data Distribution Above and Below the Median (Horizontal Black Line), and Lines (or Whiskers) Represent the Other 50% of the Data Distribution.

Water Clarity

Turbidity and secchi disk depth are ways of measuring the water clarity and amount of suspended particles in a lake. While natural to pristine lakes often have secchi disk depths of several meters, Oklahoma reservoirs typically have secchi depths measuring less than one meter. In Lake Thunderbird, secchi disk depths ranged from a 2016 mean of 17.6 centimeters at Site 6 to a mean of 74.1 centimeters at Site 1. Whole lake average of secchi depth was 46.9 centimeters. The lacustrine Sites (1, 2, and 4) had the deepest secchi depths, while the riverine or transition zone Sites (6, 8, and 11) had the shallowest as is typical of riverine portions of Oklahoma reservoirs (**Figure 26**). Lake Thunderbird secchi disk depth and turbidity show a strong inverse relationship and could be used as an indirect measure of turbidity.

The turbidity criterion for the protection of the beneficial use of Fish and Wildlife Propagation is 25 NTU (OAC 785:45-5-12 (f)(7)). If at least 10% of collected samples exceed this screening level in the most recent 10-year dataset, the lake is deemed not supporting its beneficial use, and is thus impaired for turbidity. In 2016, 28% of Lake Thunderbird samples exceeded the 25 NTU criteria (**Figure 27**). At the end of 2016, 26% of samples in the 10-year dataset exceeded the

WQS so Lake Thunderbird is considered impaired for turbidity. Again, the inverse relationship between turbidity and secchi disk depth is highlighted by the riverine Sites (6,8 and 11) with the highest turbidity readings and the lowest secchi disk depth readings.

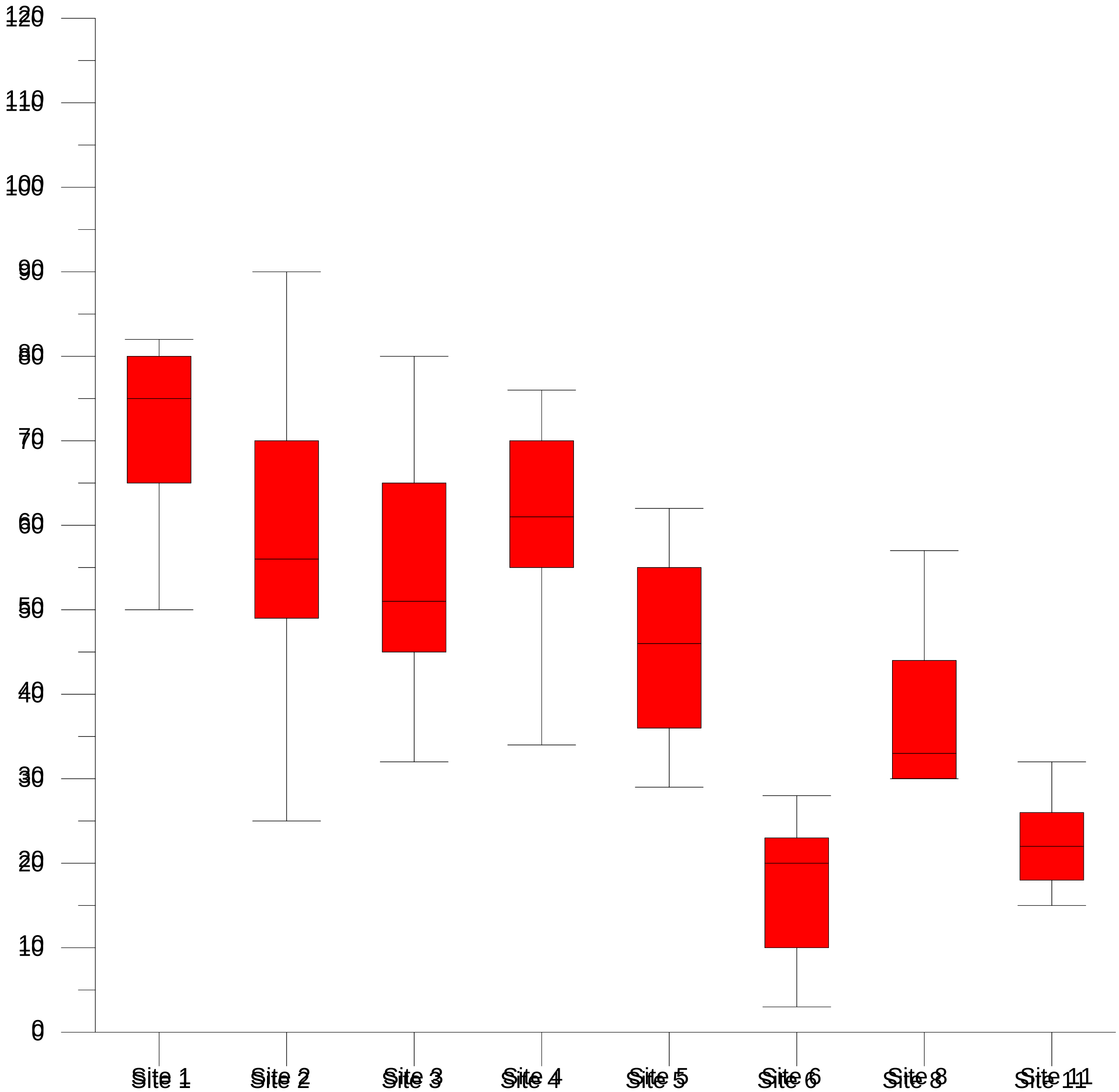


Figure 26. 2016 Lake Thunderbird Secchi Disk Depth (in Centimeters) by Site (Where Boxes Represent 25% of the Data Distribution Above and Below the Median (Horizontal Black Line), and Lines (or Whiskers) Represent the Other 50% of the Data Distribution.

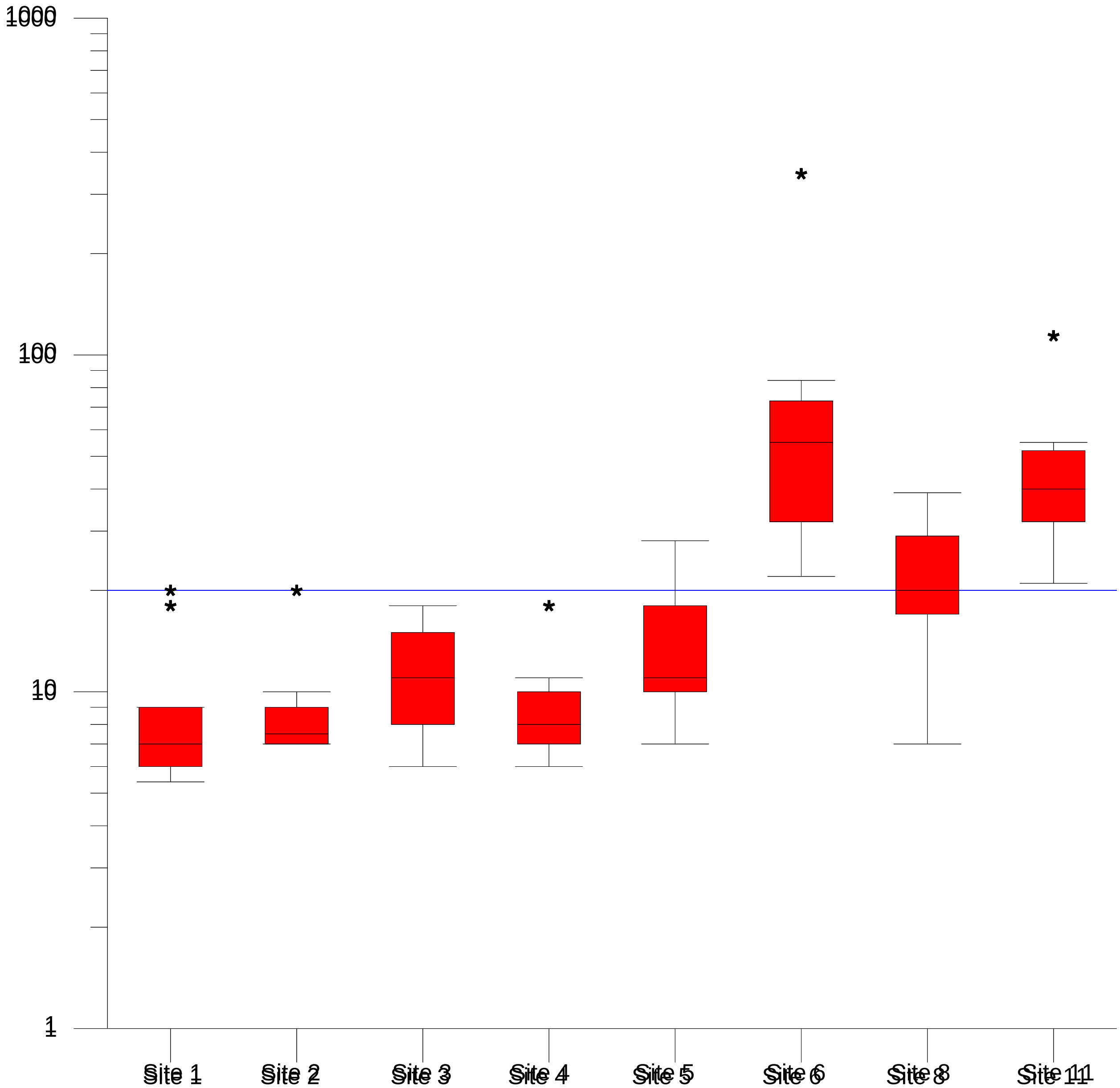


Figure 27. 2016 Lake Thunderbird Turbidity (NTU), by Site, where Boxes Represent 25% of the Data Distribution Above and Below the Median (Horizontal Black Line), and Vertical Lines (or Whiskers) Represent the Other 50% of the Data Distribution. Solid Blue Line Indicates the 25 NTU Water Quality Standard.

Supersaturated Dissolved Oxygen Injection System (SDOX)

Sample year 2016 was the sixth season of operation for the supersaturated dissolved oxygen injection system (SDOX) installed in Lake Thunderbird. It is designed to operate through the entire stratification period, oxygenating the lower five meters of the lake without disrupting thermal stratification (**Figure 28** and **Figure 29**). The system works by withdrawing water from the deepest area of the hypolimnion at approximately 986.5 elevation (16 meters within the conservation pool), supersaturating this water under pressurized conditions, and then re-injecting it at a separate location at approximately 993 elevation (13 meters within the conservation pool). At full capacity, this system is stated to treat 1,536 gallons per minute while delivering 5,202 lb DO/day, providing oxidant to the bottom 1,000 acre-feet of lake, encompassing 240 acres of nutrient rich sediment.

This monitoring season marked the fourth year of operation at optimal design, as large modifications occurred in both the system's components and operation early on. Data from the first two years of operation suggested that the system was inducing significant vertical mixing within the water column (OWRB, 2012). After reviewing all options with the system owner/operator, COMCD, and the system manufacturer, BlueInGreen, a decision was made to change the discharge nozzle to help diffuse the force from one opening to many openings (**Figure 30**). Installation and operation of the SDOX unit can be broken up into three time periods: pre-implementation, post-implementation or pre-modification and finally post-modification. In addition to the change in the nozzle, the system was modified to run at full capacity out of the south line, and all operation out of the north line ceased. The SDOX system has run with these modifications since 2013. The SDOX delivered at a rate of 4,200 pounds of oxygen per day to the hypolimnion in 2016, 1.25 times more than in 2015 and 2.3 times more than in 2014. In summary, the SDOX performed better in 2016 than in the previous 2 years.

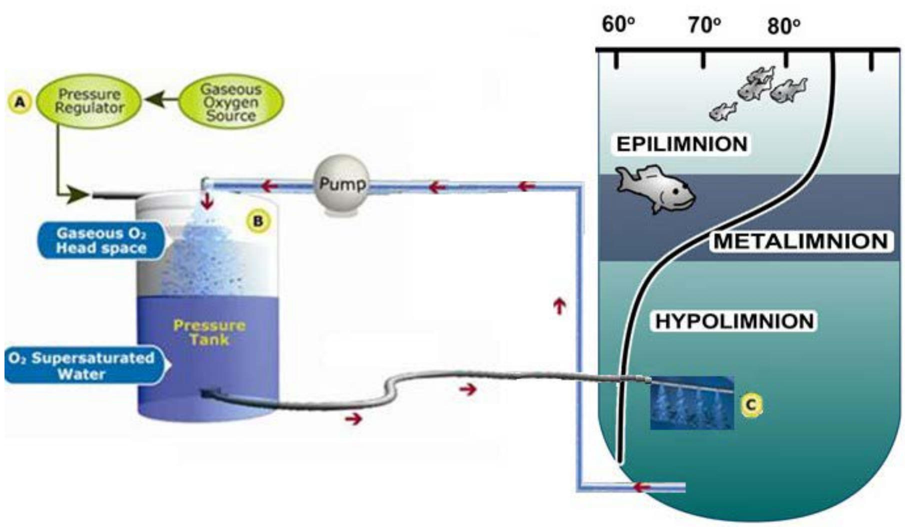


Figure 28. Conceptual Illustration of the SDOX System at Lake Thunderbird

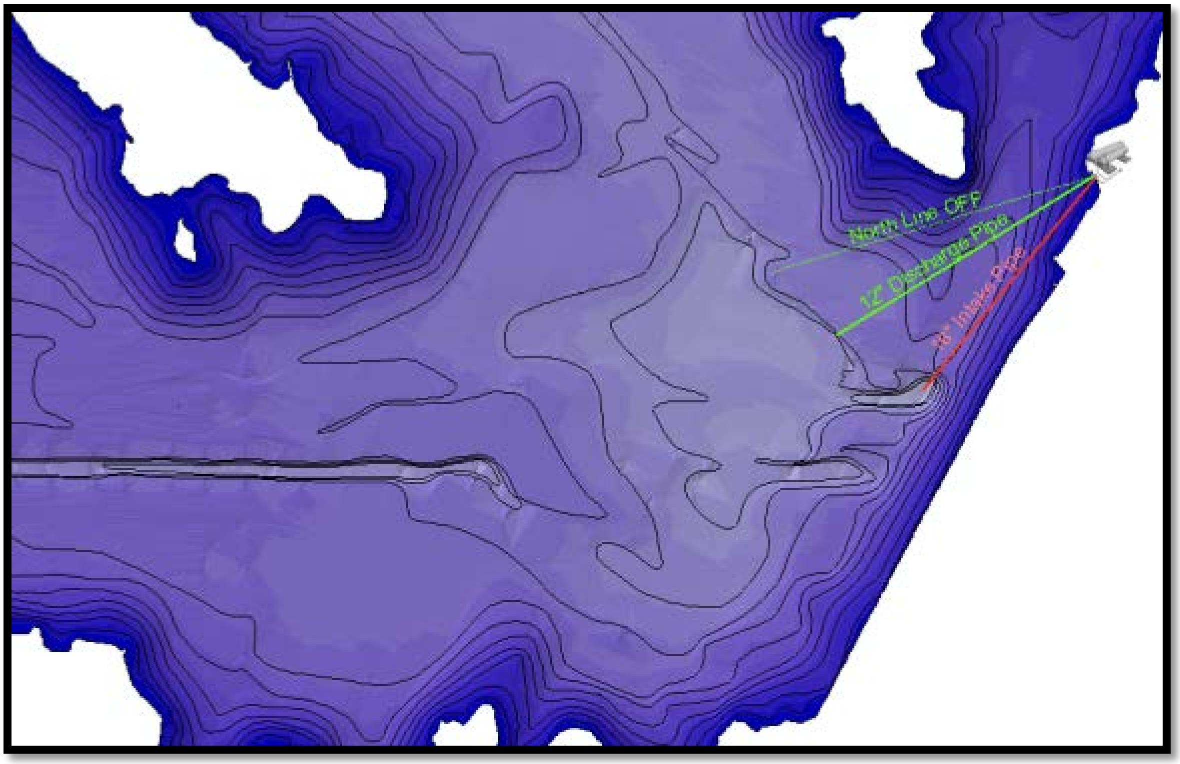


Figure 29. Map of SDOX Location and Current Configuration.

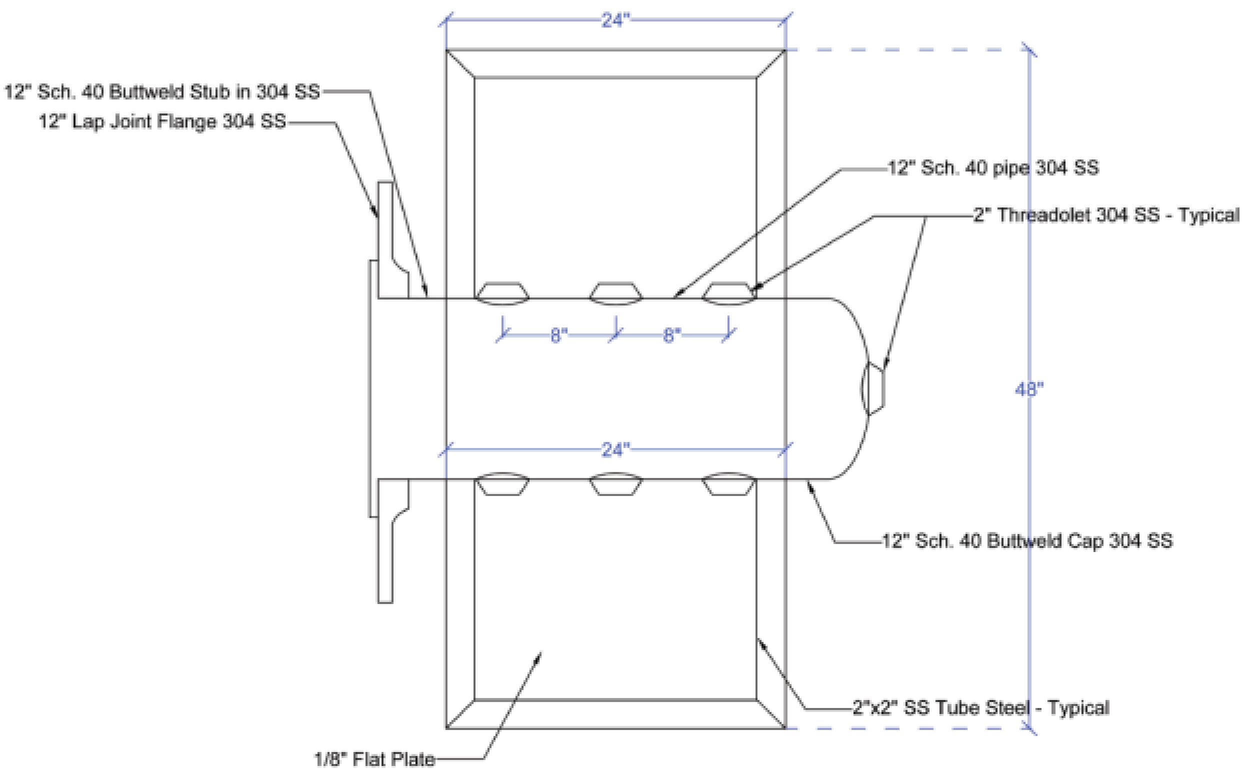


Figure 30. Schematic of the Modified Nozzle

When oxygen is present, it is used as the terminal electron acceptor in respiration, allowing the oxidation-reduction potential in the hypolimnion to be spared from the drop that is witnessed as other compounds are reduced through anaerobic respiration. Reducing conditions reflected by low redox potential increases the solubility of a wide range of nutrients and metals, causing a large sediment flux during the late summer months. If the SDOX system is able to provide an oxidized hypolimnion, potential benefits include reduction of the internal nutrient load by minimizing the recycling of nutrients from the sediment. Consequently, mitigation of peak Chl-a values would be observed. The introduction of oxygen in the hypolimnion should also lower dissolved metals, such as iron and manganese, in the water column and degrade organic chemicals.

Thermal Stratification

One of the advertised advantages of SDOX over traditional aeration techniques is the ability to oxidize without disruption of thermal stratification. In the first year of operation, thermal gradation was greatly reduced from the historical dataset, creating a water column that had much more uniform temperatures from top to bottom. It was also noted that the bottom temperature continually increased throughout the entire summer of 2011 until isothermal conditions were reached precipitating the turnover event. Increased hypolimnetic bottom temperature is not an expectation for stratified reservoirs. In 2012, a somewhat similar situation was observed where bottom water conditions were much warmer than normal and heated at a higher rate than what is observed in the historical dataset. After the system modifications occurred in early July of 2012 (post-modification), the rate of temperature increase at the bottom slowed noticeably at 0.034 C°/day from July through August) compared to the pre-modification rates of 0.085 C°/day from July through August. The rate of hypolimnetic warming has been tracked in subsequent years. **Table 5** summarizes the compiled data showing 2016 to be somewhat normal and 2015 somewhat high following SDOX modification. The higher post-modification rate in 2015 is likely due to the high inflow and ensuing outflow flood volumes from within the water column.

Table 5. Hypolimnetic temperature change during stratification

Pre or Post modification	Year	Rate (°C/day)
pre	2012	0.085
post	2012	0.034
post	2013	0.033
post	2014	0.037
post	2015	0.058
post	2016	0.035

Examination of Resistance to Thermal Mixing (RTM) plots (**Appendix B**) showed a strengthening of thermal stratification and homogenization of the hypolimnion following SDOX start up. As the season progressed into August and through September the most homogenous region of hypolimnion is roughly centered on the 996 elevation or 13 meter depth in the conservation pool. Mixing reached regularly into the 12 meter depth (1000’ elevation) and down to the 14 meter depth (993’ ft elevation). This is likely due to the mixing effect of the SDOX pressured discharge and related to the measured hypolimnetic temperature increase. The expected mixing pattern was to be from the 13 meter mark (996’ elevation) to the 16 meter mark (993 elevation).

Dissolved Oxygen (DO) and Oxidation-Reduction Potential (ORP)

The main goal of the SDOX system was to provide an oxygenated hypolimnion from 12 meters in depth and below through much of the summer. While it was not designed to prevent anoxia (<2mg/L DO) in the entire hypolimnion under maximum stratification, it was expected to raise DO levels in the deepest 1000 acre-feet of the lake. Low ORP (<100mV) followed onset of anoxia by about two weeks after observed nitrate depletion; it was largely contained in the hypolimnion (**Figure 31)**.

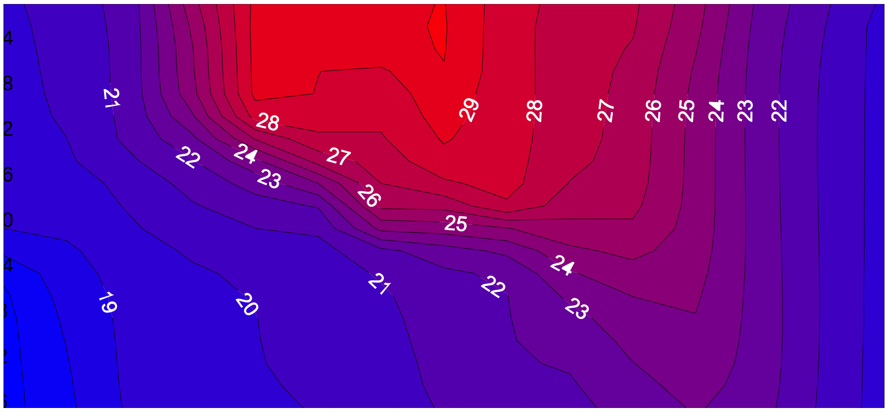


Figure 31. Temperature, Dissolved Oxygen and Oxidation-Reduction Potential (ORP) by Elevation for 2016 Site 1 Lake Thunderbird; Highlighting the Temporal Disparity Between Onset of Stratification (Temperature), Anoxia (Dissolved Oxygen), and Reducing Conditions (ORP).

The duration of low ORP, three months in 2016, was similar to pre-SDOX years. However, the volume encompassed, to 1013 elevation, is significantly less than the Pre-SDOX implementation volume. In short, the SDOX did ameliorate the magnitude of impact of highly reducing hypolimnion.

Location of the SDOX impact zone has consequences as to its measured effectiveness. The higher the impact zone is in the water column the significantly greater volume of water to oxidize. As installed, the target zone from the 993 elevation to the bottom encompasses approximately 1000 acre-feet volume and 240 acres surface area. The target zone assumes oxygenated water sinks at the 996-discharge elevation. Effect of an evaluated impact zone is highlighted by the oxygen plume that was noted on August 21, 2013, centered around the 1001 foot elevation mark. While the oxygen load in 2016, is higher than in 2013, it is evident that the larger than planned volume of water and area of sediment has reduced the possibility for more measurable water quality results.

Another metric of SDOX performance is the anoxic factor (AF). This metric estimates sediment mediated phosphorus release (Nürnberg, 1994). The AF gives a measure of the lake's oxygen state by integrating the number of days that sediment (equal to the surface area of the lake) is overlain by anoxic water. This metric is well suited to assess SDOX annual performance.

Eq. 3 $AF = \sum_{i=1}^{n}(t_i * a_i)/A_o$

Where n = number of time intervals
t = time interval
a = area of anoxic sediment within time interval
A_o = area of lake

The area of anoxic sediment within a given sample event was determined using the dissolved oxygen profiles for Site one. The depth when anoxia was first encountered is noted and the corresponding area is ascertained from the 2001 area-depth table. Application of this equation to the historical dataset provided an insight to SDOX performance (**Table 6**). We used the average of 2005 – 2009 to represent pre-SDOX conditions as a comparison against AF calculated for the following years. A marked reduction (lower AF and higher RPD) was noted for the first three full seasons of operation (2011 – 2013). However, a marked reduction of SDOX impact occurred during the past three seasons (2014 - 2016). Significant and extended breaks of SDOX operation in 2014 and 2015 help account for the reversal in AF values toward greater extent and duration of anoxia as well as the large influx of non-point source pollutants from the flood of 2015. While the 2016 AF is closer to 2011 - 2013 values than previous years, it is still considerably more than the pre-SDOX average. Additionally, 2016 marked the most oxygen delivered at the highest measured rate. Metalimnetic anoxia throughout the stratification period, one time anoxia in the epilimnion, nutrient spike associated with July inflow, and finally, documented lake-wide algal blooms and die offs all support this supposition.

Table 6. Summary of Anoxic Factor and Internal Phosphorus Load by Year (2011 – 2016) Including Relative Percent Difference (RPD). Reductions compare 2011 through 2016 to the average of 2005 - 2009.

Year	AF (day^{-1})	RPD	P-load (kg)	RPD
05 — 09 Average	***33.03***	**0%**	**3,548**	**0%**
2011	21.47	35%	2,307	35%
2012	25.5	23%	2,739	23%
2013	13.07	60%	1,404	60%
2014	38.26	-16%	2,257	36%
2015	56.28	-70%	5,884	-66%
2016	46.06	-39%	4,552	-28%

Nutrients, and Chlorophyll-a

The SDOX system induces physical changes (increased dissolved oxygen and oxidation-reduction potential) in the hypolimnion to trigger biological changes that would ultimately reduce phosphorus sediment loading. This sediment-derived nutrient release has been documented in previous years to fuel the rise in chl-a during the late-summer/fall turnover timeframe, in-turn causing a rise in TOC, drinking water treatment costs, potential for carcinogenic disinfectant by-products in finished drinking water, and taste and odor complaints. High July inflow showed a large spike in epilimnetic nutrients, which would mask sediment release of phosphorus as it sank toward the lakebed.

Examination of the 2016 chlorophyll-a alone suggests that while algal biomass had increased from the gains seen in 2013, it has not returned to pre-SDOX years. These data should be tempered by the large quantities of pheophytin-a documented throughout the monitoring season. This indicator of lake-wide algal blooms and busts were more frequent than previous years suggesting greater algal growth than indicated by normal, chlorophyll-a, measurements.

Sediment Phosphorus Analysis

Traditional use of sediment phosphorus concentration has been used as an input for estimating phosphorus release. While this is useful for estimating nutrient release under variable water quality conditions, no metric has been developed to gauge an important aspect of phosphorus dynamics, the ability of sediment to retain phosphorus. With the operation of the SDOX system actively inhibiting the release of phosphorus and enhancing the sorption of phosphorus to the sediment, a measure of the sediment's phosphorus binding ability would be useful. Two metrics commonly used for soil fertility is the Phosphorus Saturation Ratio (PSR) and Soil Phosphorus Storage Capacity (SPSC) (Vimala 2010). The underlying foundation of both measures is that iron and aluminum represent the primary binding factors responsible for release or uptake of phosphorus (Zhang 2005). Chemically and mathematically, via the oxalate extraction, aluminum and iron account for 100% of the sediment phosphorus binding ability under the PSR. Many biogeochemical factors other than aluminum and iron content influence phosphorus binding in lake sediments suggesting a tenuous use of a terrestrial index to track aqueous sediment dynamics. However, as iron is a primary factor binding phosphorus and aluminum plays a role in aqueous phosphorus dynamics, examination of the PSR poses merit for tracking sediment binding ability. Furthermore, the associated soil tests are standardized and relatively inexpensive. These make the PSR attractive as an option to track potential effects the SDOX equipment and the continual rain of organic matter to the phosphorus dynamics of the lake bottom.

Samples collection occurred at four Sites in Lake Thunderbird on May 27 and December 10 of 2016. Sediment taken at Site 1 is designated as the index Site as it is the area of lake bottom most affected by the SDOX system. Sediment taken at Sites 6, 8, and 11 provides a contrast of riverine sediment to lacustrine (Site 1) sediment. Cores were taken at each Site with two sets of analysis done for each core: the top 2 centimeters and the 5 to 10 centimeter zone. These two depth samples represent the surficial sediment layer (0 - 2 cm) and the deeper buried sediment (5 – 10 cm). The surficial values are used to calculate sediment phosphorus load in combination with anoxic factor. Wide-mouth polyethylene bottles that held the samples were kept at 40°F until delivered to the laboratory for analysis. Sample analysis was performed by Oklahoma State University's Soil Water Forage Analysis Laboratory (SWFAL) in Stillwater where acidified ammonium oxalate is used as an extractant to the sediment and the elutriate analyzed for phosphorus, aluminum and iron. Test results were used to calculate the Phosphorus Saturation Ratio (PSR) as a molar ratio using the equation:

Eq. 4 $PSR_{Ox} = (\text{Oxalate-P}) / [(\text{Oxalate-Fe}) + (\text{Oxalate-Al})]$

The underlying assumption is that the oxalate extraction represents a reasonable measure of aluminum and iron where as these elements represent 100% of the phosphorus binding capability. Terrestrial application of the PSR suggests values greater than 0.25 are samples saturated with phosphorus.

All sediment PSR was well below 0.25 with a low of 0.035 at Site 8 and maximum of 0.133 at Site 6(**Figure 32**). PSR ranking by Site followed overlying phosphorus water quality with Site 6 the highest and 8 the lowest (**Figure 14**). Differences between riverine Sites were statistically significant with Site 8 separate from the other Sites and Sites 1 and 6 the most similar, no statistical difference. The lower PSR corresponds with lower overlying phosphorus Sites, seen in Site 8 values. This highlights the sensitivity of sediment PSR to overlying phosphorus content and usefulness for indexing the ability of Lake Thunderbird sediments to sequester and retain phosphorus.

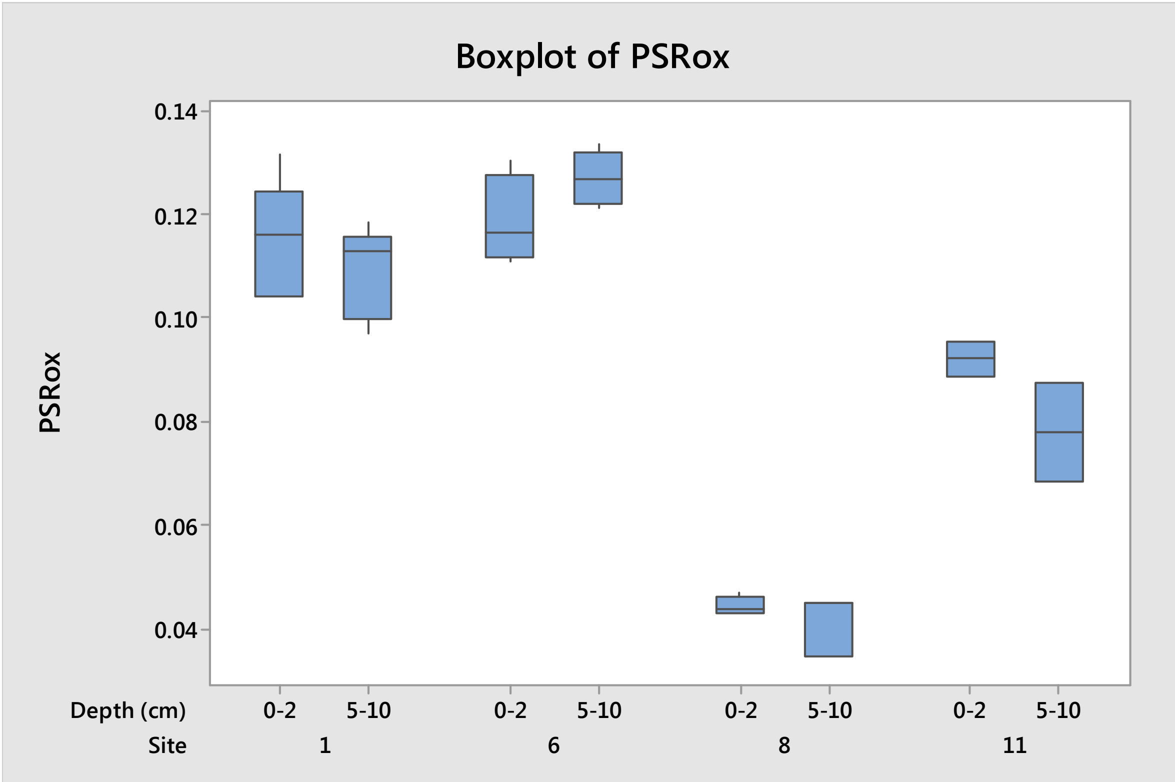


Figure 32. Box and Whisker Plot of Phosphorus Saturation Ratio by Site and Depth Zone.

Discussion

For the past 16 years, OWRB has monitored the water quality at Lake Thunderbird; observing the consequences of cultural eutrophication and degraded water quality. Over time, these consequences have become more severe, including increasingly high chlorophyll-a, elevated total organic carbon, elevated pH, and supersaturation of dissolved oxygen. Sample year 2013 represented the first year where the downward trend of water quality was resolutely reversed; then in 2014, the evidence was not as resolute, but still showed positive oligotrophication (reduced algal content). Flooding in 2015 and in 2016 has hampered the oligotrophication process in part due to high organic content floodwaters spiking the dissolved oxygen load to the water column past the SDOX's ability. Inflowing nutrients contribute to already high algal growth creating an internal positive feedback mechanism. The organic load of algae feeds bacterial respiration, further dropping oxidation-reduction potential while the reducing conditions triggers sediment nutrient release, which in turn stimulates further algae growth. The SDOX treats a zone higher in the water column than intended, further hampering the oligotrophication process, but still maintained the highest amount of oxygen delivery to date.

Harmful algal blooms, or HABs, are another consequence of cultural eutrophication that can lead to many environmental problems. Cyanobacteria, or blue-green algae, are the most common phylum of harmful algae in freshwaters. Several species of Cyanobacteria occur in and dominate phytoplankton communities in Oklahoma waters, including Lake Thunderbird. Taste and odor causing compounds such as Geosmin and 2-methylisoborneol (MIB) are released from blue-green algal cells following lysis, or senescence, and decomposition. This causes problems in public drinking water supply lakes, due to the difficulty of removing these chemicals beyond detection limits in the treatment process. The City of Norman has historically received taste and odor complaints, directly attributable to the presence of these compounds, in finished drinking water in September; following significant lake mixing events. Sample year 2016, was an exception to the typical pattern; the spike of taste and odor complaints preceded significant lake mixing events. Algal indicators of chlorophyll-a and pheophytin-a can explain the T&O complaints as epilimnetic release of chemicals from senescent algal cells rather than the mixing of hypolimnetically stored chemicals into the water column. In addition, blue-green algae have the capability to produce multiple toxins that can cause skin irritations, harm or lethality to humans, livestock, and pets that drink from untreated contaminated water sources. The lowering of peak and average chlorophyll-a in 2016 indicates that, while slipping, the lake is still in better condition than prior to SDOX implementation. However, even with the SDOX in constant use, cultural eutrophication continues to stress this reservoir ecosystem.

Lake Thunderbird is listed on Oklahoma's 2014 303(d) list of the Water Quality Integrated Report as impaired due to low dissolved oxygen and chlorophyll-a, with the *official* driver of these impairments remaining unspecified until more study is completed. OWRB has more thoroughly analyzed these impairments and conclusions are presented in this report. It is clear that excessive nutrients are the root cause of the low dissolved oxygen and excessive algae growth in Lake Thunderbird. Monitoring data, collected in 2016, were added to the data set and analyzed for beneficial use impairments in accordance with the USAP (OAC 785:46-15) of the OWQS and Lake Thunderbird was found to be not supporting its Fish and Wildlife Propagation beneficial use due to turbidity. Additionally, Lake Thunderbird did not meet the 10 μg/L chl-a criteria for Sensitive Water Supply (SWS) designation and is thereby not supporting for its Public and Private Water Supply beneficial use. Nutrient and solids reductions are necessary for the lake to meet these water quality standards. The last two monitoring years have reinforced the need to increase the capacity of oxygen delivery into the lake bottom as well as target the correct elevation. It is important to consider that the entire amount (470,891 lb) of oxygen delivered in 2016 was utilized by enabling the breakdown of organic detritus. It may be that the amount of taste and odor chemicals stored in the hypolimnion has been reduced due to the SDOX. Due to flood events, ongoing cultural eutrophication, and the SDOX's large-volume impact zone, the lake management strategy should be more aggressive in order to facilitate more effective, measurable mitigation in the future.

The past three years have significantly differed, in a positive way, from the first several years of SDOX operation, highlighting the value of the hypolimnetic oxidation to not only provide aerobic lake habitat but also improve the quality of raw drinking water for the municipalities and reduce recreational health risks due to the growth of harmful algae. SDOX operation alone will not provide the continued relief Lake Thunderbird needs to recover its attainment of beneficial uses, without concomitant improvements in the watershed. One of the strengths of the SDOX, its ability to deliver supersaturated water to hypolimnion and enabling bacterial breakdown of organic detritus, would be better suited as a tool aiding lake recovery in conjunction with watershed improvements.

Recommendations

Recent data show that the SDOX system has run near its capacity, but affects a larger than intended volume of water and area of sediment. Assessment of SDOX system capacity to deliver oxygen is a next logical step toward optimizing SDOX efficiency, as it is not likely for the current SDOX system, as installed, to focus solely on the original target zone. Alternative options or improvements for oxygen delivery to the intended target zone should be explored. To this end, a proposal has been received by COMCD to pilot a Speece Cone installation using the existing infrastructure. Speece cones have shown to produce a relatively laminar flow with high oxygen transfer efficiency, optimizing efficiency and cost effectiveness. Additional actions to develop in-lake best management practices (BMPs) include the development of a plan to reduce sediment suspension and transport. A sediment study and subsequent plan of action would identify areas of high sediment suspension and measures to minimize sediment transport. Similarly, areas of high shoreline erosion would be identified and the means to mitigate.

However, as long as watershed events deliver non-point source (NPS) pollutants above the Total Maximum Daily Load, the impact of in-lake measures will be greatly reduced. Finally, an updated bathymetric survey minimizes error when estimating DO load during SDOX assessment, it allows for field verification of lake dispositional areas identified from a sediment suspension and transport model and increases the accuracy of any future water quality (nutrient enrichment/eutrophication) response model.

Aggressive watershed BMP implementation is needed to reduce nutrient and solids movement into waterways. General ways to accomplish this include:

- Incorporating wetlands into the landscape to ameliorate NPS pollutant runoff
- Planning new vegetated swales and infiltration basins and retrofitting existing vegetated swales and infiltration basins
- Target the retention of precipitation and runoff to reduce the impact of impervious surfaces in the watershed
- Adopt Low Impact Development (LID) into COMCD's practices for maintenance and construction (Low Impact Development Center, 2014).
- Encourage municipalities within the watershed to incorporate Low Impact Development (LID) into any new construction within the watershed (Low Impact Development Center, 1999).

Fostering cooperation and collaboration between all stakeholders within the Lake Thunderbird watershed will assist in reducing runoff from construction activities and urban land uses.

References

Carlson, R.E. 1977. A trophic state index for lakes. Limnology and Oceanography. 22:361-369.

Carlson, R.E. 1991. *Expanding the Trophic State Concept to Identify Non-Nutrient Limited Lakes and Reservoirs*. Enhancing the States' Lake Management Programs, p. 59-71.

Expanding the trophic state concept to identify non-nutrient limited lakes and reservoirs
RE Carlson - Enhancing the states' lake management programs, 1991

COMCD, 2006. Rock Creek Watershed Analysis and Water Quality Evaluation. Prepared for the Central Oklahoma Master Conservancy District. August 2006.

Dzialowski, A.R., S.-H. Wang, N.-C. Lim, W. W. Spotts, and D.G. Huggins. 2005. Nutrient limitation of phytoplankton growth in central plains reservoirs, USA. *Journal of Plankton Research* 27(6): 587-595.

Gantzer, Paul. 2008. *Controlling Oxygen, Iron and Manganese in Water-Supply Reservoirs Using Hypolimnetic Oxygenation*. Dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University.

Graham, J.L., K.A. Loftin, A.C. Ziegler, and M.T. Meyer. 2008. Guidelines for design and sampling for cyanobacterial toxin and taste-and-odor studies in lakes and reservoirs: U.S. Geological Survey Scientific Investigations Report 2008-5038. Reston, Virginia.

Lerman, Abraham, and P. Baccini. *Lakes--chemistry, geology, physics*. Springer, 1978. 98-99. Print.

U.S. Environmental Protection Agency (USEPA). 2009. *National Lakes Assessment: A Collaborative Survey of the Nation's Lakes*. EPA 841-R-09-001. U.S. Environmental Protection Agency, Office of Water and Office of Research and Development, Washington, D.C

"Low Impact Development (LID) Urban Design Tools." *Low Impact Development (Center, Inc*. US EPA Office of Water, 1999. Web. 02 Mar. 2016. http://lid-stormwater.net/index.html

"Low Impact Development Center" *Low Impact Development Center, Inc.* US EPA Office of Water, 2014. Web. 02 Mar. 2016. *http://www.lowimpactdevelopment.org/index.htm*

Nurnberg, Gertrud. "Phosphorous Release from Anoxic Sediments: What We Know and How We Can Deal With It." *Limnetica*. 10.1 (1994): 1-4. Print.

OAC, Oklahoma Administrative Code. 2008. Title 785, Oklahoma Water Resources Board: Chapter 45, Oklahoma's Water Quality Standards, and Chapter 46, Implementation of Oklahoma's Water Quality Standards.

http://www.oar.state.ok.us/oar/codedoc02.nsf/frmMain?OpenFrameSet&Frame=Main&Src=_75tnm2shfcdnm8pb4dthj0chedppmcbq8dtmmak31ctijujrgcln50ob7ckj42tbkdt374obdcli00_

OCS, Oklahoma Climatological Survey. 2015. Rainfall Summary Statistics, 2015. http://climate.mesonet.org/rainfall_update.html

Oklahoma Department of Environmental Quality. 2010. The State of Oklahoma 2010 Water Quality Assessment Integrated Report.

http://www.deq.state.ok.us/wqdnew/305b_303d/2010/2010%20Oklahoma%20Integrated%20Report.pdf

OWRB, Oklahoma Water Resources Board. 2011. Technical Reports. Developing In-Lake BMPs to Enhance Raw Water Quality of Oklahoma's Sensitive Water Supply http://www.owrb.ok.gov/studies/reports/reports.php

Vimala, D. Nair, Willie G. Harris, and Debolina Chakraborty[2] 2010. An Indicator for Risk of Phosphorus Loss from Sandy Soils[1]. Publication #SL333. University of Florida, Institute of Food and Agricultural Sciences (IFAS)

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

Zhang H., J. L. Schroder, J. K. Fuhrman, N. T. Basta, D. E. Storm, and M. E. Payton. Path and Multiple Regression Analyses of Phosphorus Sorption Capacity. Soil Sci. Soc. Am. J. 69:96–106 (2005).

Appendix A: Quality Control Data

Tabular Summary of 2016 Chlorophyll-a Quality Control Samples: Site 1 duplicate samples labeled as 1 (12) & 1 (22) with summary statistics.

Date	Site 1 (12)	Site1 (22)	Average	sd
4/27/2016	11.6	7.8	9.7	2.7
5/25/2016	14.5	14	14.25	0.4
6/8/2016	12.9	12.7	12.8	0.1
6/22/2016	8.07	NA	8.07	NA
7/6/2016	22.6	24.3	23.45	1.2
7/20/2016	30.3	43.9	37.1	9.6
8/4/2016	4.8	2.7	3.75	1.5
8/17/2016	28.5	34.4	31.45	4.2
9/7/2016	42.7	45.7	44.2	2.1
9/21/2016	32	32	32	0.0
11/9/2016	9.1	NA	9.1	NA

sd – standard deviation

Tabular Summary of 2016 Blank Quality Control Sample Reports, labeled as Site 1 (31).

Date	Kjeldahl mg/l	Nitrite+Nitrate mg/l	Ammonia mg/l	Ortho-P mg/l	Total P mg/l
4/27/2016	<0.11	<0.02	<0.015		<0.005
5/25/2016	<0.11	<0.05	0.032		<0.005
6/22/2016	<0.11	<0.1	<0.015	<0.005	<0.005
7/6/2016	BPQL	BPQL	BPQL	0.008	BPQL
7/20/2016	BPQL	BPQL	BPQL	0.006	BPQL
8/4/2016	BPQL	BPQL	BPQL	BPQL	BPQL
8/17/2016	BPQL	BPQL	BPQL	BPQL	BPQL
9/7/2016	BPQL	BPQL	BPQL	0.007	BPQL
9/21/2016	0.091	BPQL	BPQL	<0.005	BPQL
11/9/2016	0.114	BPQL	BPQL	BPQL	BPQL

BPQL – Below Practicable Quantification Limit

Date	Site	Kjeldahl mg/l	Nitrite+ Nitrate (mg/l)	Ammonia mg/l	Ortho-P mg/l	Total P mg/l
4/27/2016	1(12)	0.49	0.16	0.038		0.029
5/25/2016	1(12)	0.43	0.07	<0.015		0.037
6/22/2016	1(12)	0.53	<0.1	0.025	<0.005	0.025
7/6/2016	1(12)	0.334	BPQL	0.071	0.012	0.034
7/20/2016	1(12)	0.272	BPQL	<0.05	0.013	0.11

8/4/2016	1(12)	0.718	BPQL	<0.05	0.017	0.034
8/17/2016	1(12)	0.273	BPQL	0.122	0.022	0.031
9/7/2016	1(12)	0.19	BPQL	0.089	0.014	0.033
9/21/2016	1(12)	0.322	BPQL	0.102	<0.005	0.035
11/9/2016	1(12)	BPQL*	0.163	0.132	0.015	0.048

4/27/2016	1(22)	0.49	0.16	0.035		0.027
5/25/2016	1(22)	0.5	0.06	<0.015		0.036
6/22/2016	1(22)	0.44	<0.1	0.025	<0.005	0.024
7/6/2016	1(22)	0.364	BPQL	0.065	0.013	0.034
7/20/2016	1(22)	<0.05	BPQL	BPQL	0.02	0.136
8/4/2016	1(22)	0.79	BPQL	0.062	0.014	0.035
8/17/2016	1(22)	0.225	BPQL	0.065	0.021	0.031
9/7/2016	1(22)	0.156	BPQL	0.069	0.028	0.029
9/21/2016	1(22)	0.378	BPQL	0.082	<0.005	0.033
11/9/2016	1(22)	0.146	0.297	0.092	0.012	0.043

Appendix B: Thermal Stratification (RTR) Plots

Appendix C: Concept Proposal for Sediment Erosion Control

Mitigating Suspended Sediment within Lake Thunderbird:

A Proposal by the Oklahoma Water Resources Board
to the Central Oklahoma Master Conservancy District

The Oklahoma Water Resources Board (OWRB) proposes to model suspended solids behavior within the Lake Thunderbird bathymetry to identity areas of sediment suspension and active shoreline erosion. In a collaborative effort, the United States Geological Survey (USGS) and United States Army Core of Engineers (USACE) have upgraded ArcGIS based geospatial models developed to quantify wind fetch length and calculate physical wave characteristics and sediment resuspension. The OWRB will also use the existing Environmental Fluid Dynamics Code (EFDC) model from the TMDL (ODEQ 2013) to simulate the effect of breakwater placement and fetch-reducing barriers to reductions of in-lake turbidity. The use of two separate models adds strength to the effort of identifying areas of erosion and suspension and credibility to predictive efforts of turbidity reduction. Characterization of shallow sediment quality allows for estimates of resuspension event contribution to lake nutrient content to be made. Estimates of erosion at flood and drought pool elevations are additional products available.

Methods: Meteorological data sourced from the Mesonet system will be combined with the existing OWRB bathymetry of Lake Thunderbird within an ArcGIS model to determine wind-induced sediment resuspension. Outputs of this model will be GIS layers showing wind-fetch, wave height, and sediment resuspension. Wind- and wave-breaks can be added to the model to determine best- and most cost-effective placement.

Materials: ArcGIS, EFDC Explorer software, existing EFDC lake model of Lake Thunderbird

Budget:

Tbird Suspended Solids Model & Mitigation Design

Personnel	Person Yrs.		Expenditure
Total Person Years =	0.27	Sub-total =	$ 39,203
			$ 17,907
Supplies			
Project Supplies and Materials			$ 252
Data Processing Materials			$ 3,000
Lab Equipment			$ -
Equipment Maintenance			$ -
		Supplies Sub-total =	$ 3,252
		TOTAL PROJECT COST =	$ 42,455

References

Rohweder, J., Rogala, J. T., Johnson, B. L., Anderson, D., Clark, S., Chamberlin, F., Potter, D., and Runyon, K., 2012, Application of Wind Fetch and Wave Models for Habitat Rehabilitation and Enhancement Projects – 2012 Update. Contract report prepared for U.S. Army Corps of Engineers' Upper Mississippi River Restoration – Environmental Management Program. 52 p. http://www.umesc.usgs.gov/management/dss/wind_fetch_wave_models_2012update.html

Oklahoma Department of Environmental Quality (ODEQ) 2013. Lake Thunderbird Report for Nutrient, Turbidity, and Dissolved Oxygen TMDLs.
http://www.deq.state.ok.us/wqdnew/tmdl/thunderbird/LakeThunderbirdFinalTMDL_ReportNov2013.pdf