Oklahoma Water Resources Board

Lake Thunderbird Water Quality

2017

for the

Central Oklahoma Master Conservancy District

June 15, 2018

FINAL REPORT

Oklahoma Water Resources Board
3800 North Classen Boulevard, Oklahoma City, OK 73118

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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)). Beneficial uses assigned for the lake include: public and private water supply (PPWS), primary body contact recreation (PBCR), fish and wildlife propagation (FWP) as well as the nutrient limited watershed (NLW) designation and can be found in Appendix A, Chapter 45 of the OWQS. Lake Thunderbird is listed as Category 4a in the State's 2016 Integrated Report (303(d) list) as impaired for excessive Chlorophyll-a (chl-a), low dissolved oxygen and turbidity (http://www.deq.state.ok.us/wqdnew/305b_303d/2016/2016%20Appendix%20C%20-%20303(d)%20List.pdf). Monitoring conducted during 2017 confirmed the impairment of PPWS and FWP uses assigned to Lake Thunderbird for the parameters of chlorophyll-a and turbidity respectively. Meeting these standards will improve the lake for recreational, aesthetic, fish and wildlife propagation and public and private water supply beneficial uses and can be accomplished by meeting Total Maximum Daily Load (TMDL) reduction targets. This monitoring season exhibited the second highest chl-a values in the period of record and excessive nutrient values, contradicting the oligotrophication trend observed from 2012 to 2014. Furthermore, 2017 data provide a clear connection between excessive algal growth and release of taste and odor causing compounds to consumer complaints of finished drinking water. In 2017, the application of predictive algal limitation tools (e.g. Carlson multivariate Trophic State Index plots, Total Nitrogen to Total Phosphorus Ratios, and multiple regression analysis) suggests light as the most likely nutrient to limit algal growth as nutrients are abundant and do not appear to stifle productivity.

An improved comprehensive plan emphasizing active in-lake and watershed management could help lead to Lake Thunderbird to meet OWQS for turbidity, chlorophyll-a and dissolved oxygen. A comprehensive plan should include coordination of in-lake and watershed-based suspended solids control for turbidity reduction and nutrient control for chlorophyll-a reduction. It is critical to correctly plan the stressor control, as turbidity reduction without prior or concomitant nutrient reduction could lead to increased light availability, subsequently increasing algal growth and chl-a. Current in-lake mitigation measures, such as the SDOX, should be continued, but have opportunities for improvement.

Increased eutrophication to an already nutrient-rich reservoir has decreased the effectiveness of the SDOX hypolimnetic oxidation system in 2017, resulting in a less measurable response than was seen in the first three years of operation. While delivering the largest oxygen load to date, the SDOX's positive effect is still overshadowed by increased nutrient accumulation and algal productivity. Estimating the hypolimnetic oxygen demand through laboratory analyses of lake samples will provide the empirical data needed to meet the performance measures outlined for hypolimnetic oxidation (**Appendix D**). Piloting a Speece Cone on Lake Thunderbird to oxidize the hypolimnion offers the potential for a more cost-effective means to satisfy the increased hypolimnetic oxygen demand (**Appendix E**). Additional in-lake planning efforts presented include updating the bathymetric survey (**Appendix F**). Implementation of these itemized actions allow for prioritized and cost effective decision-making to assist in the restoration of impaired beneficial uses.

Continued degradation of lake water quality underscores the need to continue installation of Best Land Management Practices (BMP) throughout the basin. Fostering cooperation and collaboration between all stakeholders within the Lake Thunderbird watershed will assist in reducing runoff from construction activities and urban land uses. Upon formation, the Central Oklahoma Master Conservancy District (COMCD) was designated as the responsible party to review construction activities throughout the watershed. In this role, the COMCD is uniquely positioned to encourage the implementation of watershed BMPs, facilitate work between the involved city governments, and serve as a general advocate for the health of Lake Thunderbird. Accessing the Clean Water State Revolving Fund (CWSRF) to offer prioritized financial incentives is also a positive avenue to exercise the COMCD's watershed wide scope.

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. Routine monitoring and evaluating the performance of Lake Thunderbird's supersaturated dissolved oxygen injection system (SDOX) are the primary objectives in 2017.

Lake Thunderbird is listed as Category 4a in the State's 2016 Integrated Report (303d list) as waterbody ID OK520810000020_00 and impaired due to low dissolved oxygen, excessive turbidity, and excessive chlorophyll-a (chl-a).
(http://www.deq.state.ok.us/wqdnew/305b_303d/2016/2016%20Appendix%20C%20-%20303(d)%20List.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 report approved by the Environmental Protection Agency (EPA) on November 13, 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 to meet assigned beneficial uses. This 35% load reduction scenario equates to an allowable annual load of 76,399.6 kg of total nitrogen per year, 15,006.4 kg of total phosphorus per year, and 7,470,252.3 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)

Collaborative work with the City of Norman has illustrated that the water quality impairments, particularly the excessive algae growth, elevated total organic carbon (TOC) in raw drinking water, and increased taste and odor complaints in the finished drinking water are resulting in elevated treatment costs. Each summer, the City rents a Powered Activated Carbon (PAC) unit to reduce taste and odor complaints in the treatment process, although significant complaints regarding finished drinking water are still received. The City of Norman is now in the process of installing ozone and ultraviolet treatment into their drinking water treatment train in an effort to reduce taste and odor issues in the finished water. However, also meeting the TMDL reduction goals are imperative to accomplishing this effort.

In an attempt to mitigate the effects of cultural eutrophication documented in the reservoir, the COMCD gained funding through the American Recovery and Reinvestment Act, to install and operate an oxygenation system. The goal of this system is to oxygenate the deepest portion of the anoxic hypolimnion in the lake while maintaining thermal stratification, which limits the transfer of nutrients from the hypolimnion to the surface waters better than the less advanced oxygenation systems. 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 2017, represents the seventh season of SDOX operation.

Sampling Regime

In 2017, Lake Thunderbird water quality sampling occurred from April 18 through October 11, monitoring the parameters in **Table 1**~~**Table 1**~~ at the sites indicated in **Figure 1.** During each visit, all COMCD sites were sampled and were consistent with BUMP monitoring sites with the exception of BUMP site 7, which was not collected for this project. Sites 1, 2, and 4 represent the lacustrine or open water zones of the lake where consistent summer stratification and an underlying hypolimnion are common features. Sites 6, 8 and 11 represent riverine zones of their respective tributaries. Finally, sites 3 and 5 represent the transition zones between riverine and lacustrine portions of the lake. All zones of the lake are represented to allow for whole lake analysis and beneficial use assessment.

Water quality profiles for oxidation-reduction potential (ORP), DO percent saturation and concentration, temperature, specific conductance (SpC), total dissolved solids (TDS) and pH were collected at each site. The profiles were recorded in one-meter intervals from the lake surface to the just above the sediment-water interface at each site. Nutrient and chl-a samples were collected at the surface of sites 1, 6, 8, and 11. Additionally, at-depth samples were collected in 4-meter depth intervals at Site 1 to the bottom. Analyses performed on these samples included both a phosphorus (P) and a nitrogen (N) nutrient series indicated in **Table 1**. Field observations, Secchi disk depth, surface chl-a, and turbidity samples were collected at all eight sites. Additional profiles were recorded in November to confirm complete de-stratification and oxidation of the water column.

Table 1. 2017 Water quality sample dates and parameters.

SAMPLE VARIABLES		
General Water Quality –		
Chlorophyll-a (chl-a)	Nephelometric Turbidity	Secchi Disk Depth
Nutrients –		
Total Kjeldahl Nitrogen (TKN)	Ortho-Phosphorus (ortho-P)	Total Phosphorus (TP)
Nitrate, as Nitrogen (NO_{3-})	Nitrite, as Nitrogen (NO_{2-})	Ammonia, as Nitrogen (NH_3)
Total Organic Carbon (TOC)		
Profile Parameters –		
Dissolved Oxygen (DO)	Dissolved Oxygen % saturation	Temperature
Specific Conductance (SpC)	Total Dissolved Solids (TDS)	pH
Oxidation Reduction Potential (ORP)	Salinity	
Field Observations -		
Air Temp	Wind (Direction/Speed)	Cloud Cover
Precipitation	Wave Action	Barometric Pressure
Site Depth		

Figure 1. 2017 Lake Thunderbird 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) (OWRB, 2010). Laboratory quality control samples included duplicates, replicates, laboratory, and analytical blanks. Replicate samples were collected at the surface of the dam site and labeled Site 1(12) and Site 1(22) respectively. In addition, the Site 1 chl-a sample was split to produce duplicate samples (Site 1(12) and Site 1(21)) during chlorophyll-a post processing at the OWRB, then delivered to the laboratory for analysis. Analytical blank samples (Site 1(31)) collected from reagent grade water at OWRB were also submitted to the laboratory for analysis. **Appendix A** summarizes laboratory results of duplicate, replicate, and blank sample analysis. Accurate Labs, the project's contract laboratory, performed its own internal quality control analysis in accordance with environmental lab accreditation practices, which is then verified by OWRB. The laboratory provides these QC checks with each sample report and are available upon request.

Duplicate, Replicate, and Blank Samples

Duplicate samples yield an overall estimate of potential error either due to sampler or laboratory error. Along with the environmental sample, this paired data set yields a measured difference between two relatively identical samples. In the scope of this project, a duplicate sample was submitted for chl-a analysis. Replicate samples primarily control for the collection of a representative sample, but these results also include a measure of uncertainty from laboratory analysis. 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 to each reported parameter; results were tabulated and statistical summaries were generated as box and whisker plots using Minitab software (**Figure 2**). All parameters showed an acceptable median PAD right at or below 20 per cent. Note that while PAD is acceptable over the entire sampling season, instances of high PAD for ammonia, ortho-phosphorus, and Total Kjeldahl Nitrogen occurred and are reflected by a larger upper quartile. Ammonia QC results collected August 9 were questionable with a PAD of 163 per cent; the analytical laboratory confirmed the results therefore, the outlier value was excluded from analysis.

Analytical blank samples are submitted to the laboratory as reagent grade water to ensure that all parameters are below reporting limit; they are designated as 1(31) and are collected every sample event. Reagent grade water is utilized in the extraction of chlorophyll and should not contain any amounts of contamination above the analytical lab's reporting limit. Analytical blank samples showed a comparatively low-level TKN contamination on May 18, 2017 and slightly more significant contamination on July 26, 2017. Results for July 12, 2017 indicated contamination of ammonia and TKN samples from this event were re-analyzed by the analytical laboratory and found to be below reporting limit. In general, all analytical blank samples were within acceptable range. A summary of the quality control data is located at the end of this report as **Appendix A.**

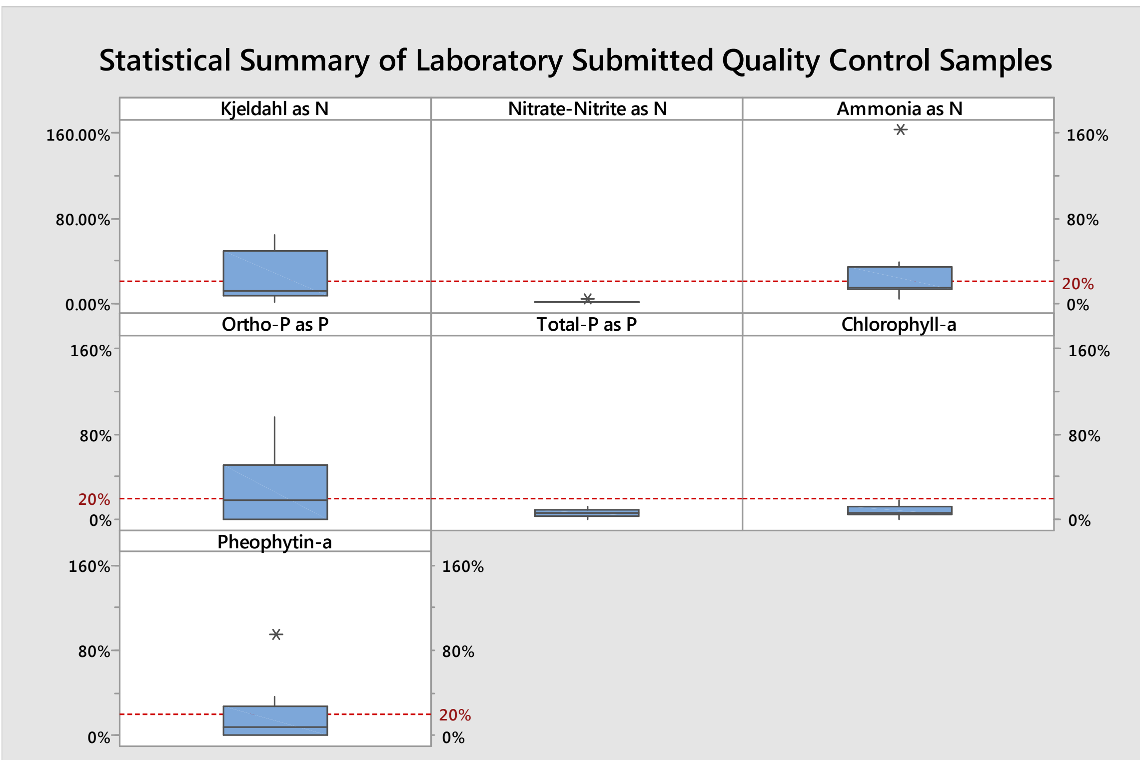


Figure 2. 2017 summary plots of Percent Absolute Difference for replicate laboratory samples Lake Thunderbird (Box represents the middle 50%; the center bar the median value, top and bottom stems the upper and lower 25% quartile and asterisks as outliers. Red dashed line indicates acceptable variance level.)

One final note of quality control pertains to the observation that several samples from April 18, 2017 and May 18, 2017 where ammonia was reported significantly greater than TKN. As TKN values are a summation of organic nitrogen and ammonia, this should not be possible. When organic nitrogen was calculated by subtracting TKN from ammonia, negative values were returned for all samples from April 18, 2017. It is plausible that all of nitrogen is as ammonia and the lower Kjeldahl value is within the precision limitations of the laboratory method. Examination of the laboratory quality control results were not explanatory; neither were the external quality control samples submitted by OWRB. Nitrogen data from the April 18, 2017 sample event were not included in any analysis within this report.

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 due to climactic events like rain or drought affect the extent of anoxia in the hypolimnion and alter oxidation-reduction potentials. Anoxia, in turn, influences 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 2017. Annual precipitation at Lake Thunderbird dam in 2017 totaled 32.4 inches, below the annual average of 38 inches, with peak rainfall events corresponding to increases in elevation. In general, pool elevation started at its lowest in mid-January 2017 at 1036.85', peaked on April 30, 2017 at 1040.08' and then slowly decreased throughout the rest of the year with recharge events in late August and early October. In addition to hydrology, air temperature influences lake characteristics such as stratification and primary productivity. **Figure 4** compares monthly mean temperatures in 2017 to the long-term monthly mean. Monthly average temperatures were similar to long term averages, except for a warmer winter and a wetter, cooler August. In 2017, the lake experienced peak water temperature in late July while August has shown to be more typical in previous years. An abnormally high rainfall throughout August was responsible for the lower air temperatures and likely kept water temperature from peaking past July. Even with slight climatological variance from the norm, the general pattern and duration of thermal stratification was typical for Lake Thunderbird in 2017.

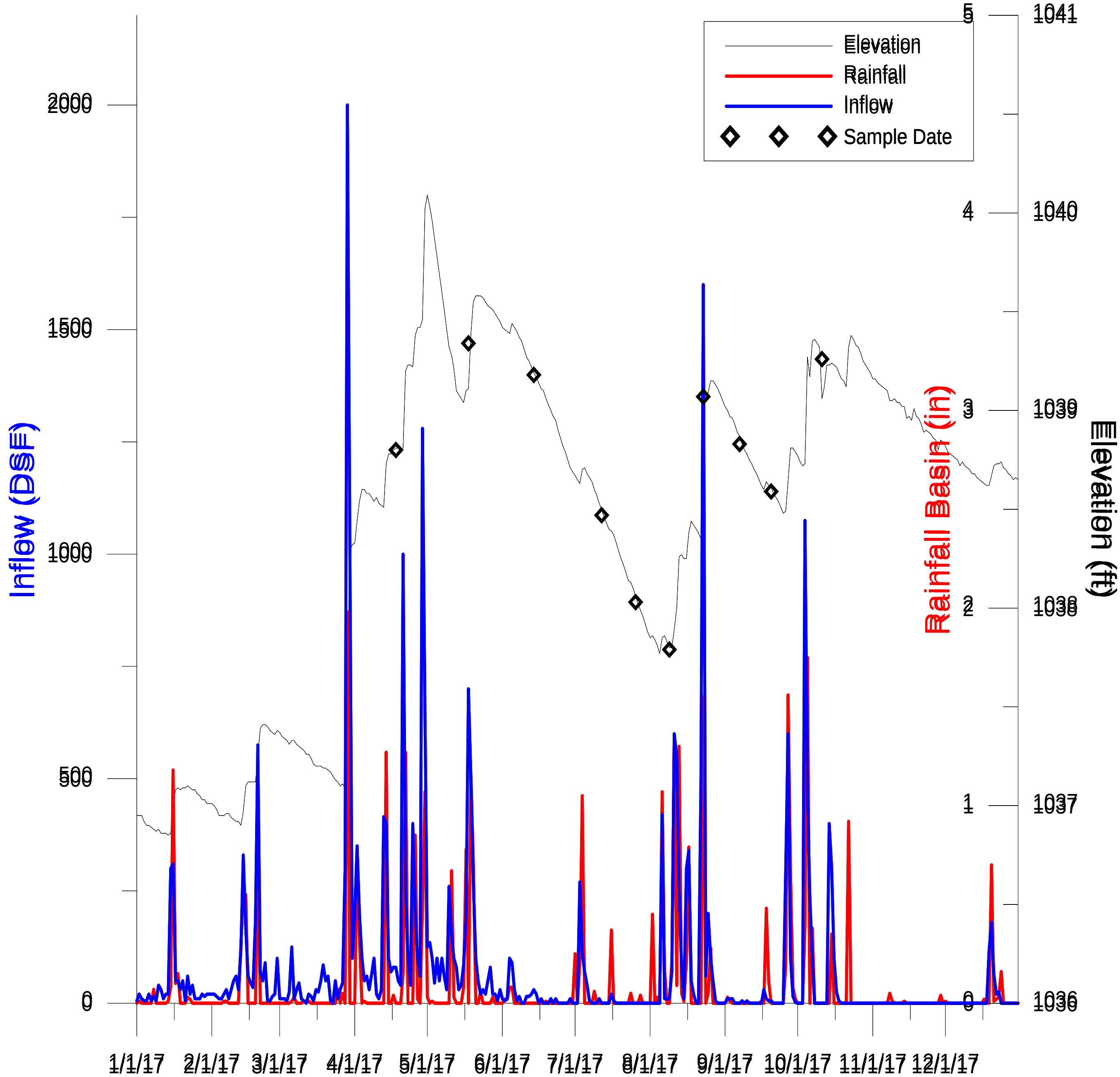


Figure 3. 2017 Inflow, Rainfall, and Elevation Data for Lake Thunderbird, with Sample Dates Indicated.

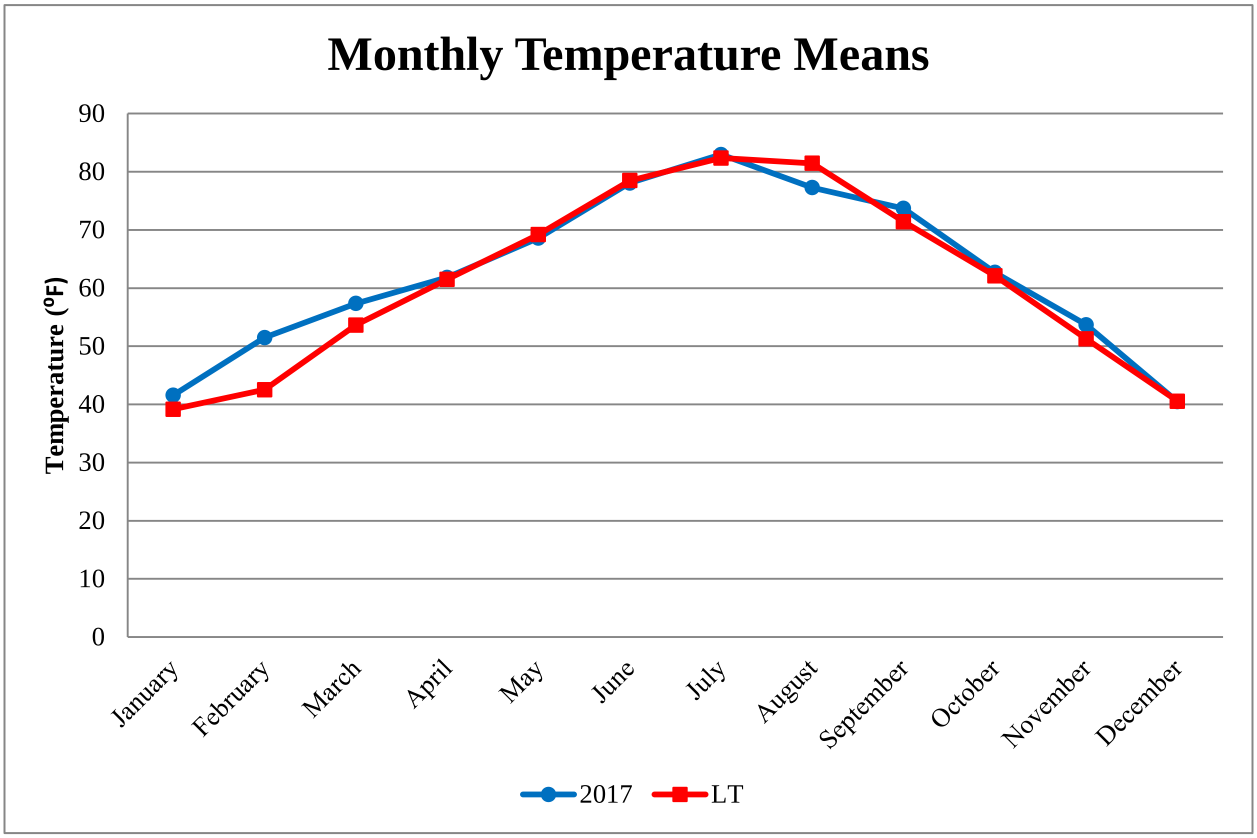


Figure 4. 2017 and Long Term (LT) Average Monthly Temperature at the Norman Mesonet Station.

Hydrologic Budget

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

Eq. 2 $$\frac{\Delta V}{\Delta t} = Q_{in} - Q_{out} + PA_s - E_v A_s - W_s$$

Where V is lake volume (acre-feet),
A_s is lake surface area (acres),
Q_{in} and Q_{out} are net flows into and out of the lake due to tributary inflows and gated releases,
P is the rainfall directly on the lake (feet),
E_v is the lake evaporation (feet),
W_s is the water exported for water supply use (acre-feet).

In other words, the rate of change in volume of water stored 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 released or exported (e.g. water supply) from the lake. For Lake Thunderbird, subsurface and groundwater flow is assumed close to calculated error and 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. Because the USACE's reported inflow term includes direct rainfall, we use USACE reported inflow minus calculated direct rainfall volume as the runoff term for the budget. Precipitation was calculated 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:

Eq. 3 $\boldsymbol{Q_p} = \mathbf{P}*\boldsymbol{A_s}$

Where Q_p is precipitation, $\mathbf{P}$ is rainfall amount, and $\boldsymbol{A_s}$ is the surface area of the lake.

Water outputs from Lake Thunderbird include gated dam releases, water supply withdrawals, and evaporation; USACE reports releases and withdrawals. Daily evaporation rates are calculated and reported by the USACE; their calculations relate solar radiation, wind speed, relative humidity, and average daily air temperature to estimate daily evaporation. The OWRB multiplies this rate by the daily average surface area of the lake to give the volume of water evaporated per unit time.

Eq. 4 $\boldsymbol{Q_e} = \boldsymbol{E_v}*\boldsymbol{A_s}$

Where Q_e is evaporation, $\boldsymbol{E_v}$ is the evaporation rate, and $\boldsymbol{A_s}$ is the surface area of the lake.

The lake volumes, corrected to elevation, were calculated and the daily differences summed to account for the change in volume for each month. The volumes used were derived from the OWRB's 2001 bathymetric survey (OWRB, 2001) elevation-capacity curves.

A summary of monthly water budget calculations for Lake Thunderbird is below, where 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 (**Table 2**). 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 so both terms were calculated and compared. The difference between the inputs and outputs is in the I-O column and the monthly change in volume, calculated as the sum of daily volume changes, is in ΔV column. Total monthly error is calculated as the difference between the change in lake volume based on elevation and change in lake volume based on inputs-outputs. Examination of the estimated water budget for Lake Thunderbird showed that estimated inputs and outputs were close to the actual volume changes that were calculated by change in pool elevation. The negative value reported for November inflow indicates the rainfall did not reach the lake likely due to soil infiltration in the watershed. **Figure 5** provides a visual summary of water gains and losses on a monthly basis. Here it is clear that the rainfall and runoff in April was released largely during May and that August had an unusually high rainfall.

Table 2. 2017 Lake Thunderbird Water Budget Calculations expressed in Acre-feet.

Month	INPUTS			OUTPUTS				ERROR TERM		
	Inflow	Rainfall	**Total Inputs**	Evaporation	Water Supply	Releases	**Total Outputs**	I-O	ΔV	Error
Jan	1,867	573	2,440	1,471	1,137	-	2,608	(169)	309	478
Feb	3,728	586	4,314	1,942	1,029	-	2,971	1,343	1,904	(561)
Mar	7,317	944	8,261	2,898	1,242	-	4,140	4,122	4,939	(818)
Apr	9,885	3,067	12,952	2,966	1,291	-	4,257	8,695	9,004	(309)
May	4,756	2,354	7,111	3,746	1,602	6,365	11,713	(4,602)	(3,344)	1,258
Jun	744	60	803	4,186	2,010	-	6,196	(5,392)	(3,910)	1,482
Jul	545	506	1,051	4,374	2,154	-	6,528	(5,477)	(4,168)	1,310
Aug	7,024	3,360	10,383	3,490	1,615	-	5,105	5,278	6,071	(793)
Sep	856	1,340	2,196	2,874	1,483	-	4,357	(2,161)	(1,235)	926
Oct	4,110	1,275	5,385	2,700	1,367	-	4,067	1,319	2,058	(739)
Nov	(59)	59	-	1,658	1,186	-	2,844	(2,844)	(1,698)	1,146
Dec	372	431	803	1,126	946	-	2,072	(1,269)	(154)	1,115
Total	41,145	14,555	55,700	33,431	17,062	6,365	56,858	(1,158)	9,776	4,494

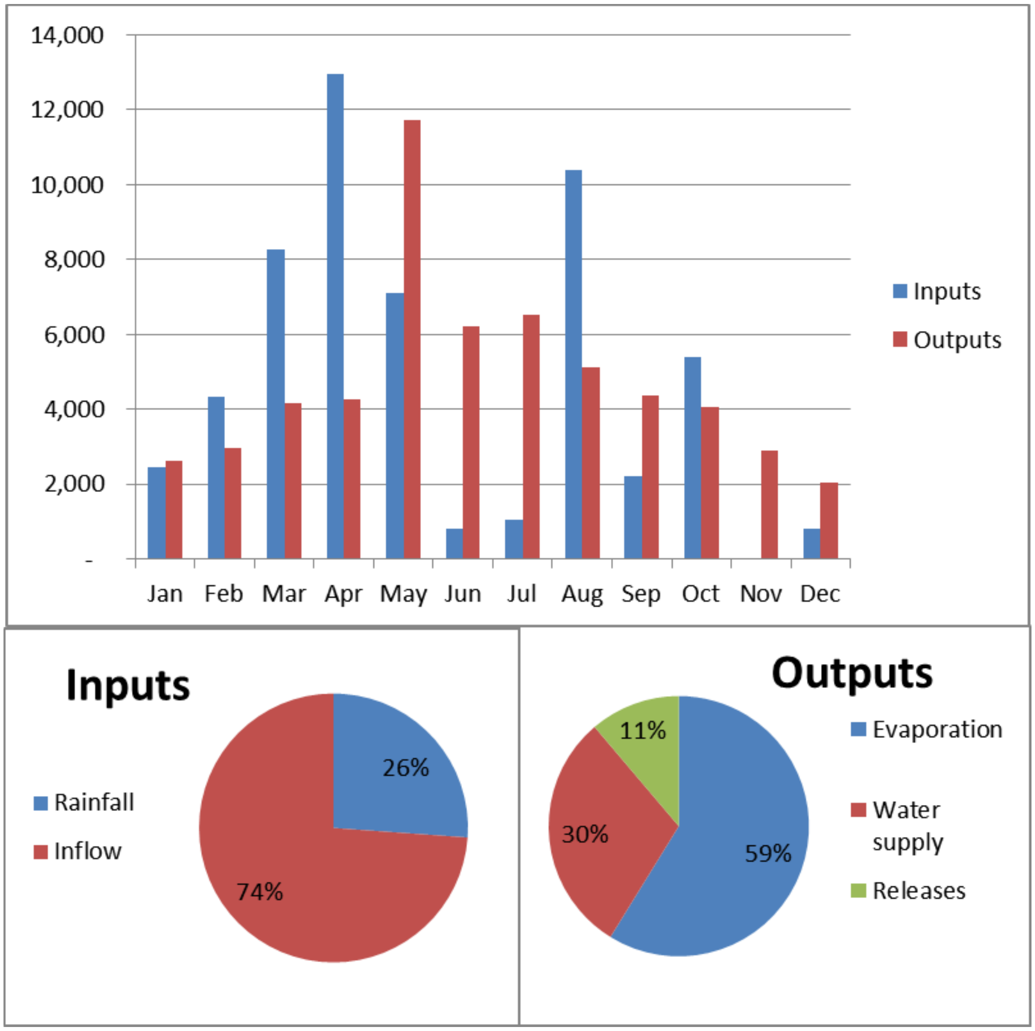


Figure 5. 2017 Lake Thunderbird water Input and Output sources by month, expressed as the percent of total.

Once a hydrologic budget is constructed, additional features of reservoir dynamics such as hydrologic retention time are estimated. The hydrologic retention time, tau, 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 4.52 years in 2017, with an average (2001 to 2017) hydrologic residence time of 3.93 years. The higher than average 2017 residence time is largely due to a dryer year than normal.

In the 2017, the hydrologic budget contains a cumulative annual error of 4,494 acre-feet, with an average monthly error of 374 acre-feet. Changes in bathymetry since the 2001 survey (OWRB 2002) are the likeliest explanations for error. Another source of potential error in these calculations is that the inflow values are estimated using change in elevation adjusted to volume and do not account for changes in bathymetry since the last update of area and capacity curves.

Volume and areas estimated above the conservation pool into the surge pool are 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 assessed the LiDAR and OWRB lake boundary to be compatible to estimate volumetric estimations.

According to the bathymetric survey completed by OWRB in 2001, a conservation pool sedimentation rate is estimated to be around 400 acre-feet per year in the time period since impoundment, although there is uncertainty in this rate. Should the estimated sedimentation rate prove correct and constant, newly deposited sediment is predicted to be mostly in the upper portion of the conservation pool, in the shallowest portions of the lake, with a loss of approximately 6,800 acre-feet since 2001 (OWRB, 2002). While not a great amount, the potential distribution of deposited sediment has consequences for in-lake processes such as sediment suspension and nutrient flux. 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, but limitations related to scope of this survey diminish the applicability of extrapolating this finding to the entire lake. Resurveying the whole reservoir using comparable survey methods to the 2001 study would allow for a more reliable estimate of sedimentation. A more current bathymetry data set could also significantly reduce errors for any future water quantity or quality modeling.

Any groundwater loss and gain to the lake is assumed negligible for this analysis and any actual measurable changes are aggregated into the inflow variable. It is possible to verify the exchange of groundwater (loss or gain) with the lake by performing seasonal groundwater level surveys and reviewing the geology of the area. However, such a survey is a considerable undertaking and is beyond the scope of work for this project.

Water Quality Evaluation

Thermal Stratification, Temperature, and Dissolved Oxygen

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

Isopleths are a graphical method to illustrate lake dynamics as they interpolate hundreds of data points into one figure to show variation in measured parameters over depth and time. The isopleths of temperature and DO, while not exact, illustrate the process of thermal stratification and the impact of stratification on DO. **Figure 7** displays all temperature and DO data from site 1, the deepest part of the lake near dam, over the monitoring period. Each line in **Figure 7** 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 red, graduating to blue as temperature gets cooler, while on the DO plot, the lowest DO values are colored red, graduating to blue at the highest DO. Some individual profiles of temperature and DO with respect to depth at site 1 are included to highlight aspects of the 2017 monitoring season. The remaining temperature and DO profile plots from site 1 are contained in **Appendix B.** Relative thermal resistance to mixing (RTR) calculations inform on the strength or intensity of stratification. This is a unit-less measure of temperature based density differences, indicating how likely the layers will mix. RTR calculations aid in determining the size of the epi-, meta- and hypolimnion (**Appendix C**).

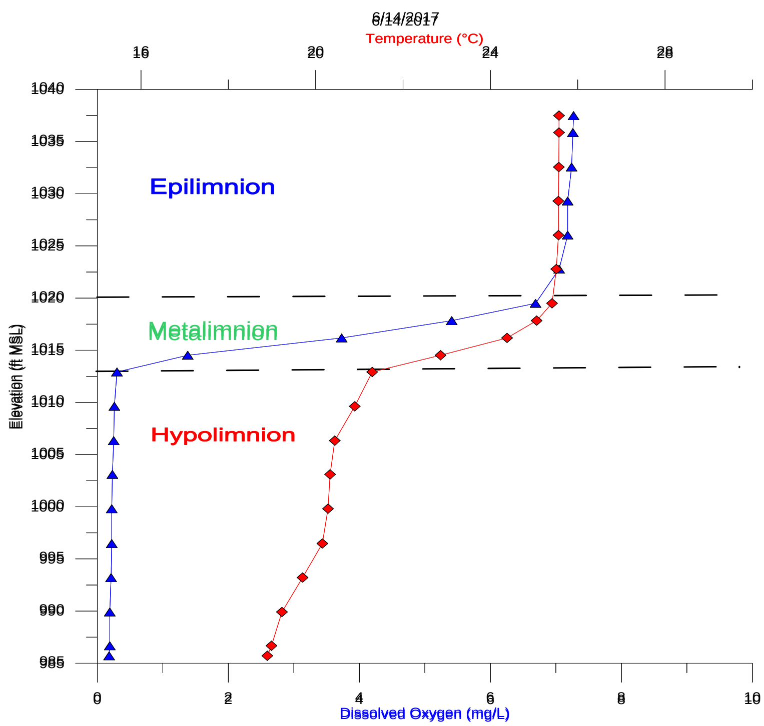


Figure 6. A typical Temperature (red, diamond) and Dissolved Oxygen (blue, triangle) vertical profile for Lake Thunderbird (June 14, 2017) approximate boundaries between the Epilimnion, Metalimnion and Hypolimnion are marked with dashed lines.

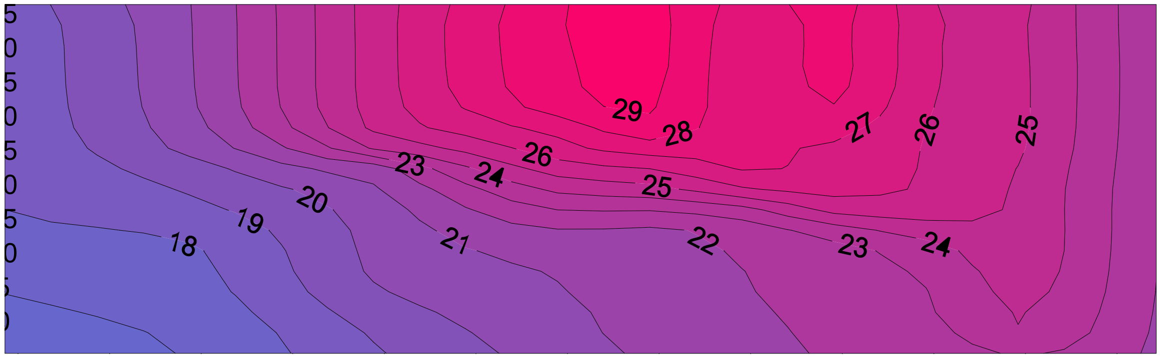


Figure 7. 2017 Isopleths of Temperature (°C) and Dissolved Oxygen (mg/L) versus Elevation (ft) at Site 1.

While little thermal difference with depth was noted on the first sample date, April 18, 2017 the difference was enough for dissolved oxygen to gradually decline with depth. By the second sample event, May 18, 2017, stratification, though weak, had strengthened with dissolved oxygen now anoxic at the sediment-water interface. By June 14, stratification had set up for the season with completely anoxic hypolimnetic waters and anoxia creeping into the metalimnion (**Figure 6**). As the season progressed from late spring through summer, epilimnetic warming continued until reaching a peak temperature of 29.6°C on July 26, 2017 (**Figure 8**). Also, notable about this event is the push of anoxic water through the metalimnion and into the bottom of the epilimnion. Cooling of the lake led to a deepening of the epilimnion and sharp reduction of the metalimnion by August 9, 2017. A brief warming period in late August again created a large mainly anoxic metalimnion and shallower epilimnion followed by a decreasing hypolimnion throughout the fall (**Figure 7**).

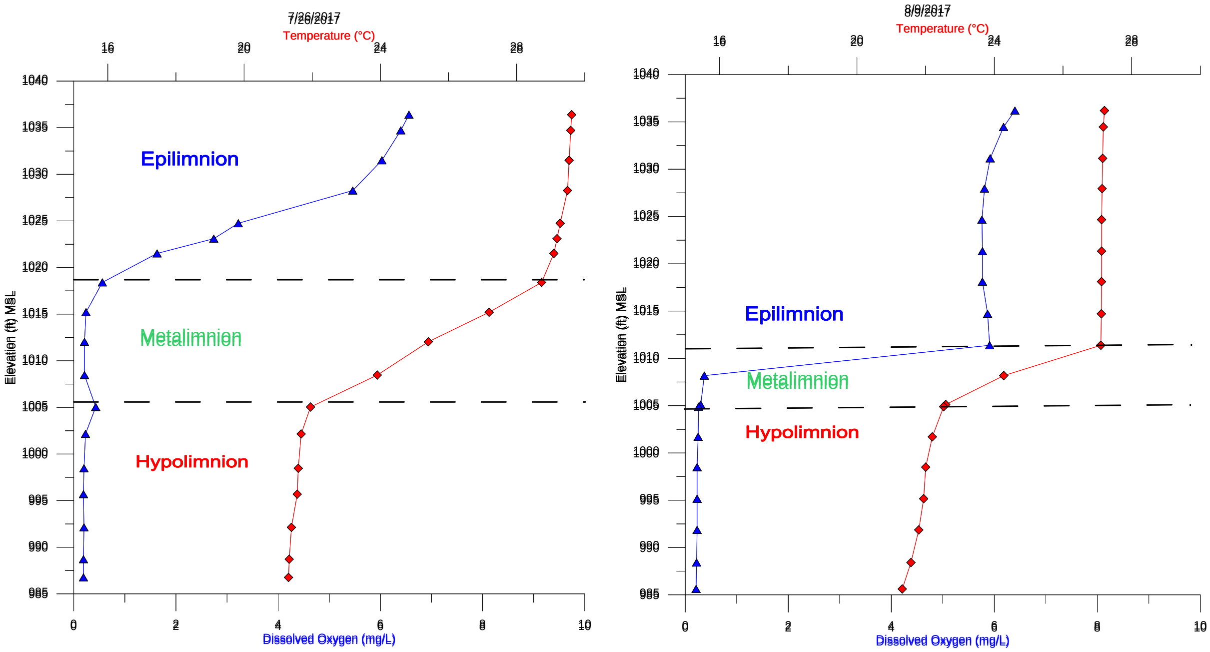


Figure 8. Temperature (red, diamond) and Dissolved Oxygen (blue, triangle) vertical profiles at Site 1 of July 26, 2017 and August 9, 2017.

Anoxic water in the metalimnion maintained a constant presence throughout the summer into late September when nominal thermal resistance to mixing began to decrease. On September 20, 2017, an oxygen "bulge" was centered approximately at the 1006' elevation, depicting increased dissolved oxygen levels. The nozzle of the Supersaturated Dissolved Oxygen (SDOX) system is centered at this elevation, suggesting this bulge is a positive indicator of SDOX performance (**Figure 9**). Higher ORP values measured at this event indicate less oxygen demand in the hypolimnion, allowing the observation of the SDOX oxygen load (**Figure 11**).

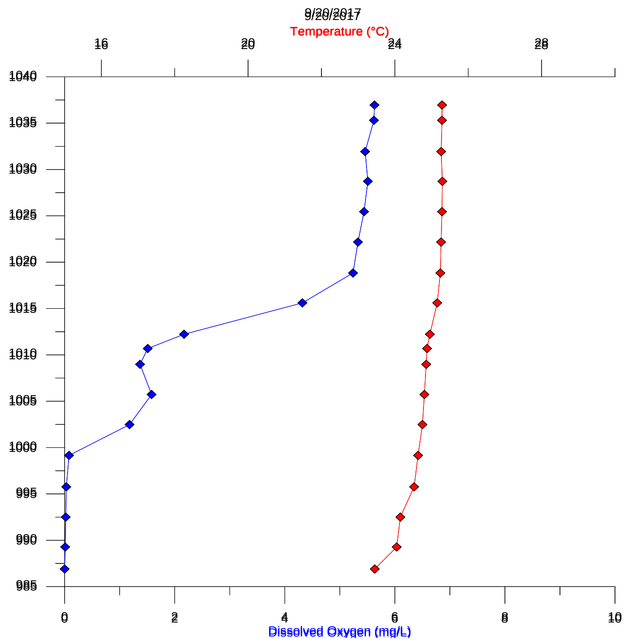


Figure 9. Temperature (red, diamond) and Dissolved Oxygen (blue, triangle) vertical profile at Site 1 September 20, 2017.

Epilimnetic (surface) DO increases during the day due to high photosynthetic rates and decreases at night when photosynthesis ceases and plant and animal respiration consumes oxygen faster than it can diffuse in from the atmosphere. The areas of violet at the surface in **Figure 7** represent algae growth driving dissolved oxygen percent of saturation above 100%, a condition referred to as supersaturation. The greatest supersaturation occurred in early July, coinciding with the highest period of chlorophyll values, as expected in this system. Epilimnetic waters with dissolved oxygen below the saturation point indicate respiration rates greater than the sum of photosynthetic oxygen production and diffusion of atmospheric oxygen into the water.

Metalimnetic anoxia, observed from June through September, is indicative of a hypereutrophic system, driven by a high organic load created largely by algal growth and die-off. These dead algal cells feed hypolimnetic bacteria that require an electron acceptor for survival. When strong anaerobic conditions are present, elements other than oxygen act as terminal electron acceptors in the decomposition process; resulting in the release of nutrients and other constituents from the sediment. When mixing events occur, these released nutrients migrate to the surface waters where they further stimulate algal growth. When examining the oxygen isopleths, the partial mixing events are evident as the blue area (higher oxygen content) pushes down toward the red area (lower oxygen content) in early August and early September.

General Water Quality: pH and Oxidation-Reduction (redox) Potential

Lake Thunderbird exhibited increases in surface pH during the summer months indicating high rates of photosynthesis. The lower hypolimnetic pH present in late summer and early fall is due to the buildup of bacterial respiration byproducts (**Figure 10**). 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 driving pH and ORP down. In general and as seen in 2017 data, peaks of higher epilimnetic and low hypolimnetic pH correspond with peaks in algal productivity. High rates of photosynthesis will temporarily elevate pH as carbon dioxide is stripped from the epilimnion, while catabolism of the settling algae depresses pH in the hypolimnion.

It is also important to note that, although not documented by our sampling regime, it is commonly accepted that epilimnetic pH has a daily variation of daylight elevation and nighttime lowering. Daily pH shifts follow oxygen concentration driven by algae, daytime photosynthesis, and nighttime respiration. In either case carbon dioxide is either produced (respiration) or consumed (photosynthesis) faster than replaced via atmospheric diffusion. Without any impinging biological processes such as photosynthesis and respiration, baseline pH for Lake Thunderbird would be the common pH of bicarbonate buffered systems, 8.2.

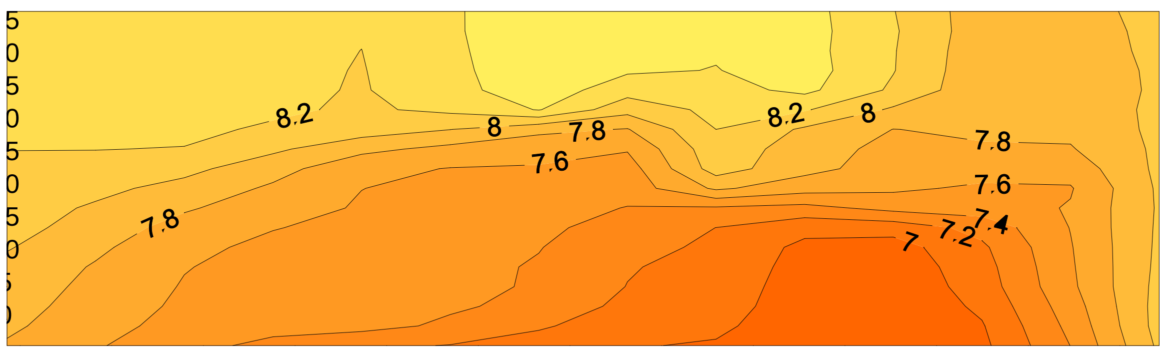


Figure 10. 2017 Isopleths of pH (S.U.) Versus Elevation (ft) at Site 1.

Complete anoxia of the hypolimnion was observed near the beginning of June (**Figure 7**), and a month later came low, 100mV or less, oxidation-reduction potential (ORP) (**Figure 11**). It is important to note that under anoxic conditions, other electron acceptors replace oxygen, such as iron and manganese. Production of sulfide and methane is also common as other electron acceptors for anaerobic metabolism become scarce. Under oxygenated conditions, redox potentials remain highly positive (300-500 mV) as oxygen is readily available as an electron acceptor during bacterial respiration. Normally, as aerobic bacterial communities consume oxygen until hypolimnetic anoxia, the bacterial community shifts to an anaerobic one that uses nitrate as the final electron acceptor for respiration. During this bacterial community composition shift, the water maintains a relatively positive redox. When nitrate is depleted, there is another shift in the bacterial community toward one that uses sulfate as the final electron acceptor. This shift is marked by a precipitous drop in ORP, buildup of incompletely decomposed organic matter and accumulation of sulfide and methane, bacterial waste products. Generally, as the ORP drops towards 100mV or lower (strongly reducing conditions), solids such as phosphorus and metals dissolve into the water column reflected in July data. The duration and extent of strong hypolimnetic reducing conditions are directly related to the accumulation of these compounds in the hypolimnion. Finally, low ORP 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.

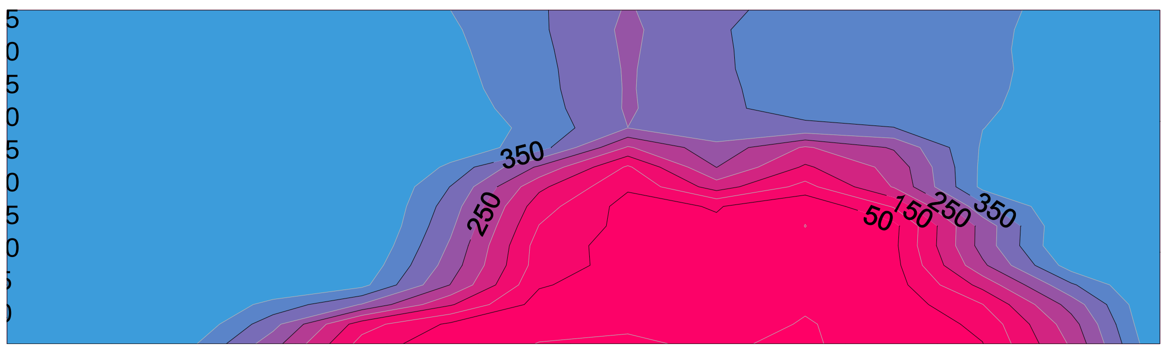


Figure 11. 2017 Isopleths of Oxidation-Reduction Potential (mV) versus Elevation (ft) at Site 1.

Nutrients

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 collected during monitoring visits, including dissolved and total forms. Dissolved nutrient concentrations consist of nutrients that are available for algal growth, such as ortho-phosphorus, ammonia, nitrate, and nitrite. High dissolved nutrient concentrations in the epilimnion generally indicate that nutrients are immediately available for, and therefore not limiting to, algal growth; while hypolimnetic concentrations are nutrients that could be available for future algal growth, especially during lake turnover in the fall. In general, when both N and P are readily available, neither is a limiting nutrient to algal growth, and excessive chlorophyll-*a* values can be expected. When high P concentrations are readily available in comparison to very low N concentrations, algal growth may be N-limited and vice versa. N limitation can give a competitive advantage to undesirable Cyanobacteria (blue-green algae) due to their ability to convert atmospheric N into a usable form by way of specialized cells called heterocysts. These blue-green algae have the ability to produce harmful toxins and compounds that cause taste and odor problems in public water supplies. Increasing eutrophication in Oklahoma reservoirs has increased the frequency and severity of blue-green algae blooms, resulting in measurable amounts of cyanotoxins found in afflicted waterbodies. Monitoring for blue-green algal blooms was not included in the scope of this project; however, the detection of taste and odor compounds, Geosmin and MIB, in recent years, confirms presence of nuisance blue-green populations in Lake Thunderbird.

Light can also be considered as a macronutrient capable of limiting algal growth, whether in the form of suspended solids in the water column discouraging photosynthesis or even as excessive algae shading its own potential growth deeper in the water column.

Phosphorus – P

Site 1 surface total phosphorus (TP) and ortho-phosphorus (ortho-P) are values consistent with those seen in eutrophic and hypereutrophic lakes (**Figure 12**). Epilimnetic ortho-P was generally at or below reporting limit for most of the summer followed by a fall increase to measurable amounts. Epilimnetic TP steadily increased through the fall and is largely due to the upward mixing of the ortho-P rich hypolimnion.

Hypolimnetic ortho-P increased throughout the stratification period before decreasing following lake mixing. Common in eutrophic systems, the buildup of hypolimnetic ortho-P is evidence of organic material settling from the epi- and metalimnion, in addition to active release from the anoxic sediment (**Figure 13).**

Phosphorus in the riverine portions of the lake was consistently higher than the open water lacustrine sites (**Figure 12** and **Figure 14**). Phosphorus levels were relatively similar across all riverine sites although the Little River, site 11, had the highest maximum and mean - driven by the high value in late July (**Figure 14**).

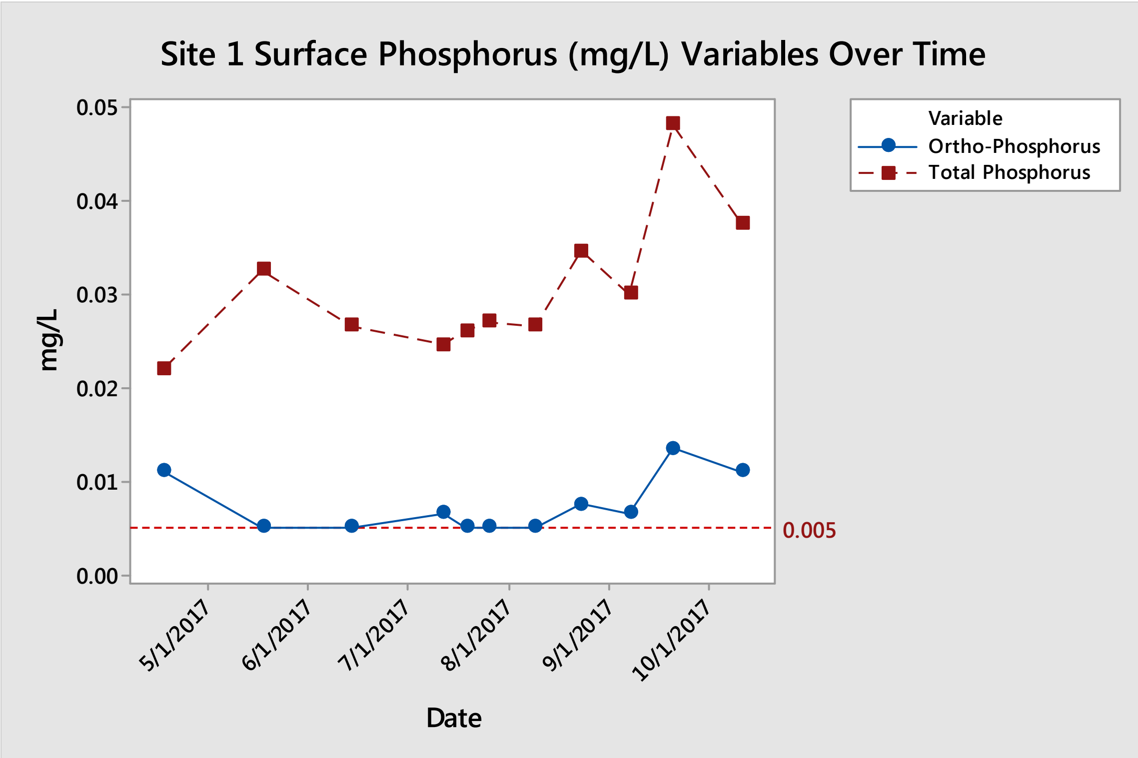
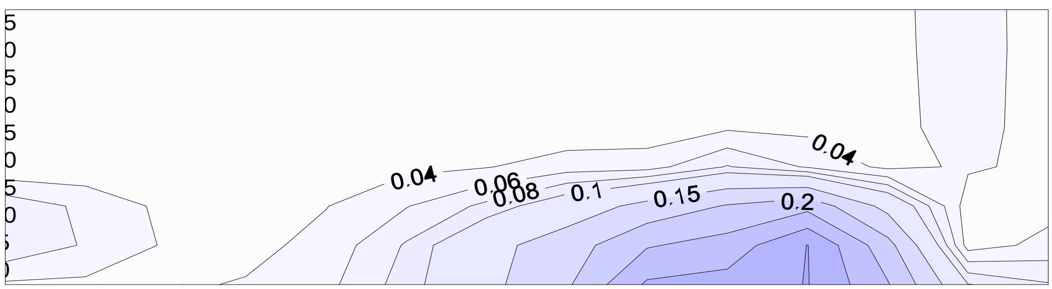


Figure 12. 2017 Surface Phosphorus Variables as P (mg/L) at site 1. Dashed Line represents the laboratory reporting limit (0.005 mg/L).



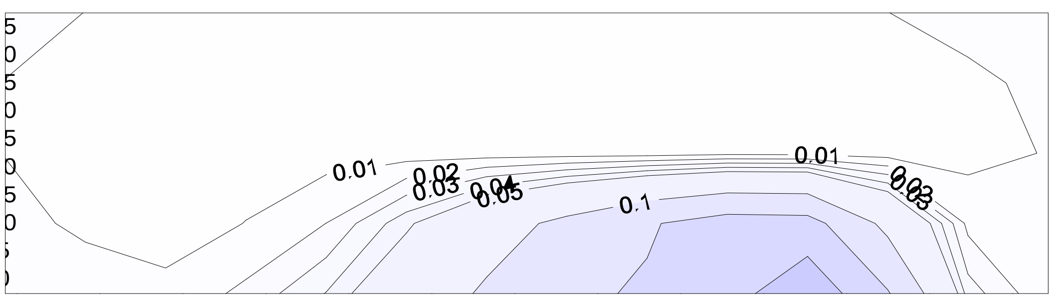


Figure 13. 2017 Isopleths of Total Phosphorus and Ortho-phosphorus versus Elevation (ft) at Site 1.

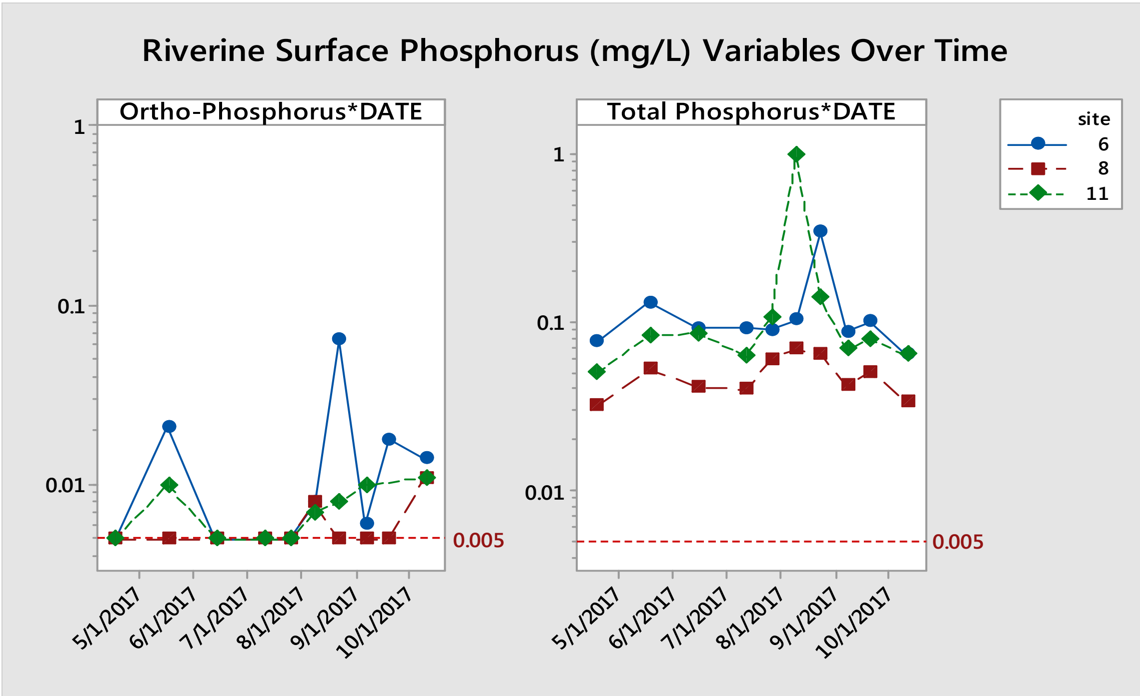


Figure 14. 2017 Surface Phosphorus (mg/L) variables from the three riverine sites. Dashed line represents the laboratory reporting limit (0.005 mg/L).

Phosphorus in the upper arms of the lake represents the potential for hypereutrophic algal growth and these areas have the potential to see the most positive impact of watershed BMP implementation. Site 11 returned the highest mean TP concentration of 0.172 mg/L and site 8 returned the lowest of 0.049 mg/L. Driving its high average, Site 11 also reported the maximum TP value measured, 0.978 mg/L, greater than any reported riverine sample in 2016. Site 6 consistently had highest TP concentrations at each sample event and recorded the highest ortho-phosphorus value at 0.064 mg/L. On a seasonal basis, there was no statistical difference detected between riverine sites. Both ortho-phosphorus and TP spikes are likely attributed to rainfall and subsequent inflow events in the watershed. These higher levels of phosphorus represent a greater risk for elevated phosphorus in the main lake body, potentially leading to higher algal growth.

In order to visualize phosphorus present within thermal layers of the lake, a phosphorus budget was constructed to integrate the water budget with monitored water quality data. Integration entails matching profile parameters with reservoir bathymetry to partition total phosphorus reports into epilimnetic, metalimnetic and hypolimnetic layers of the water column. Some interpolation is required to align elevations between sample events with care taken to minimize seasonal variation around each depth interval. The cumulative summation of these layers allows the estimated massing of phosphorus (P) for each sample date (**Table 3**). Focusing on one row (elevation), reading left to right the progression of phosphorus mass (and concentration) through the monitoring season is evident. The labeled rows at the bottom provide summaries of the conditions denoted above by highlight (thermal structure) and font color (anoxia). The massing of phosphorus is the first step to the modeling of a stressor-response model for algal growth as well as placing lake water quality in context of external inputs. Alone, this summary adds insight to internal and external factors driving a key macronutrient for algal growth.

Table 3. 2017 Lake Thunderbird Site 1 Phosphorus Mass (kg) at elevation by sample date (Bold red numbers represent anoxic layers while blue shaded cells represent the epilimnion, clear cells metalimnion and red shaded cells hypolimnion). Values in parentheses on May 18, represent the individual values making up the sum of 15 kg, highlighting anoxia present at the deepest point.

Average Elevation	4/18/2017	5/18/2017	6/14/2017	7/12/2017	7/26/2017	8/9/2017	8/23/2017	9/7/2017	9/20/2017	10/11/2017
1038.7	245	317	289	251	291	267	368	309	485	386
1037.0	244	393	278	274	273	271	387	296	467	403
1035.3	408	528	502	433	472	469	620	524	854	614
1032.1	362	534	455	363	445	377	556	446	706	583
1028.8	332	433	346	325	379	365	480	396	644	473
1025.5	283	390	337	306	322	301	432	356	580	455
1022.1	247	349	301	245	**285**	284	388	319	488	373
1019.0	213	277	115	**216**	**245**	228	**394**	253	420	332
1015.9	180	262	261	**168**			**347**	239	354	281
1014.8			**112**		**219**	192				
1012.4	150	196	**199**	**134**	**192**	158	**295**	193	195	246
1008.9	119	174	**180**	**227**	**324**	**273**	**514**	145	**331**	185
1005.8	83	114	**140**	**241**	**320**	**502**	**553**	**414**	**160**	124
1002.6	160	71	**99**	**195**	**289**	**339**	**481**	**572**	**103**	85
999.3	157	45	**65**	**176**	**190**	**265**	**359**	**367**	**60**	51
996.0	57	23	**34**	**75**	**106**	**155**	**169**	**204**	**28**	33
992.9	20	15 (10)	**23**	**78**	**67**	**97**	**109**	**199**	**31**	28
989.4		(4)								
986.5		(0.1)								
985.8		**(0.3)**								
TP mass	3260	4106	3735	3706	4420	4544	6452	5232	5905	4653
Anoxic TP mass	0	0	851	1509	2238	1631	3221	1756	713	0
% anoxic TP mass	0%	0%	23%	41%	51%	36%	50%	34%	12%	0%
Lake mean conc.	0.025	0.031	0.028	0.029	0.035	0.037	0.049	0.040	0.050	0.036
Epi P-conc	0.025	0.031	0.025	0.024	0.029	0.027	0.034	0.029	0.050	0.036
Hypo P-conc	NA	NA	0.038	0.144	0.068	0.170	0.167	0.297	0.074	NA

Red numbers within the metalimnetic white shaded areas indicate a large load of organic matter from the epilimnion feeding hypolimnetic bacterial growth, thus depleting oxygen in increasing volumes. This metalimnetic anoxia, combined with the intensity of epilimnetic oxygen demand, is a recent trend for Lake Thunderbird and was documented throughout the stratification period. Anoxia limited to the hypolimnion is the typical condition in eutrophic reservoirs. The three sample events of complete metalimnetic anoxia further underscore the excessive algal growth and subsequent oxygen demand in 2017. As anoxic volume increases, the area of sediment experiencing anoxic conditions increases in an approximate logarithmic fashion, thus exacerbating the consequences of sediment phosphorus release. The summary row titled "%

anoxic TP mass" reflects the increased volume of anoxic water and net release of phosphorus from the increased area of exposed sediment.

The constructed budget demonstrates pre-stratification lake P mass, in 2017, of approximately 3,259 kg; proximate but lower than the historical (2009 – 2016) pre-stratification average of 3,700 kg. The whole lake maximum of 6,450 kg coincides with the August 23, rainfall event and is followed by a net loss to 5,232 kg of phosphorus, due to sedimentation to the lake bottom. For the year, there is a net gain of about 1,400 kilograms.

The whole lake average epilimnetic phosphorus concentration of 0.045 mg/L is a relatively good starting point for the reservoir with respect to limiting algal growth. Epilimnetic phosphorus concentrations stay relatively steady over the season, punctuated by high levels associated with runoff events and hypolimnetic mixing.

Nitrogen – N

Total and dissolved nitrogen produced patterns somewhat atypical for seasonal ecological cycles in reservoirs (**Figure 15**). The normal seasonal pattern for Lake Thunderbird surface water has been seasonal increases of Kjeldahl nitrogen with ammonia and then nitrate/nitrite falling below reporting limit. In 2017, nitrate falls below reporting limit within the hypolimnion in June, followed by ammonia accumulation in August. Surface Kjeldahl nitrogen was variable with an epilimnetic peak mid- to late summer, likely associated with moderate August rainfall. In the epilimnion, nitrate/nitrite fell below reporting limit by mid-June and was not reported again until lake mixing in October. This portion of the seasonal pattern was normal; atypical was the consistent detection of epilimnetic ammonia throughout the sample season. Energetics of nitrogen assimilation by algae orders ammonia first, as it requires less energy and then nitrite, nitrate and finally dinitrogen. The expectation is then for ammonia to fall below reporting limit first then followed by nitrate as it takes less energy for algal uptake. The disparity between the data and ecological behavior is not easily reconciled.

Hypolimnetic Kjeldahl nitrogen peaked in late August coinciding with hypolimnetic ammonia accumulation. Average Total nitrogen values were similar to previous years, with the exception of 2016, which were considerably lower. Examination of ammonia distribution with depth and over time showed a general increase in ammonia in the hypolimnion. This is due to ammoniacal release from anoxic sediment and as the product of bacterial decomposition (**Figure 16**). The stepwise breakdown of thermal stratification mixed the ammonia rich hypolimnetic waters to the surface, a typical seasonal pattern in Lake Thunderbird. In the hypolimnion, nitrate serves as an electron acceptor in respiration as oxygen is absent; in 2017, nitrate did not fall below reporting limit until June coinciding with hypolimnetic anoxia. The low concentrations of nitrate in the hypolimnion suggest a shift to a bacterial community of sulfide and methane producers. The low redox potential associated with these communities predicts sediment release of ortho-phosphorus and ammonia.

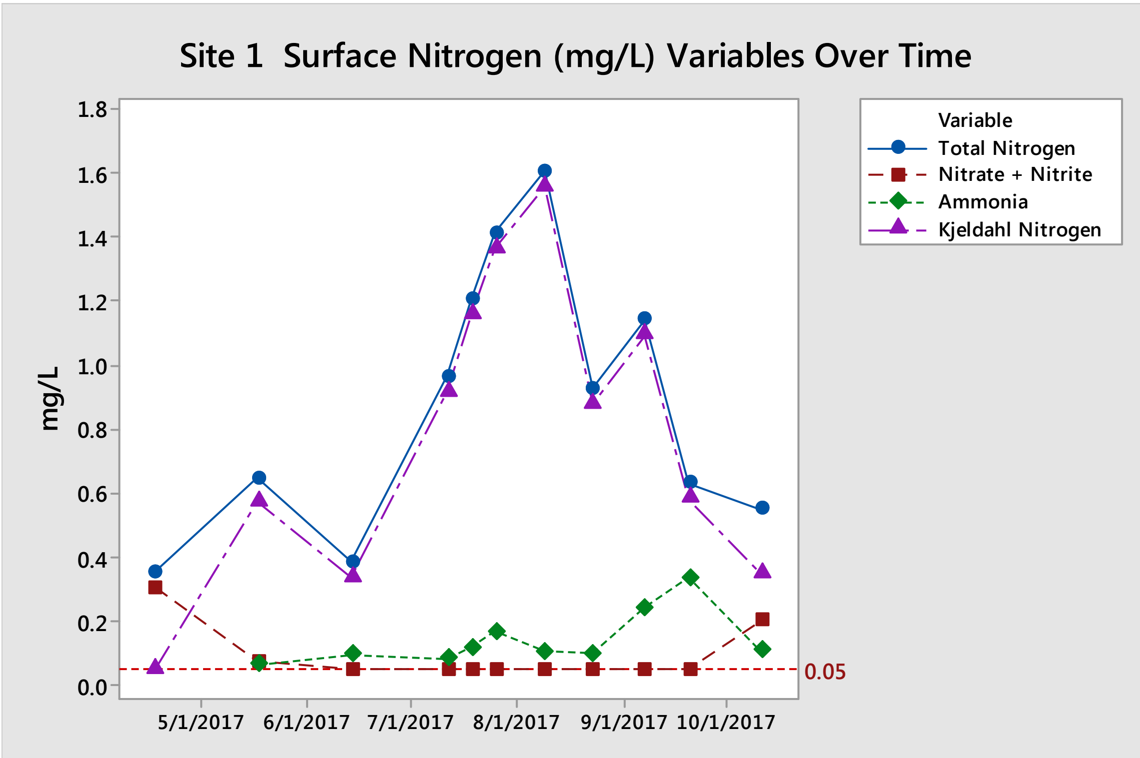


Figure 15. 2017 Surface Nitrogen (mg/L) series over time at Site 1. Dashed line represents reporting limit for all Nitrogen Variables (0.05 mg/L).

Figure 16. 2017 Isopleths of Total Kjeldahl Nitrogen, Nitrate/Nitrite, and Ammonia (mg/L) versus Elevation (ft) at Site 1.

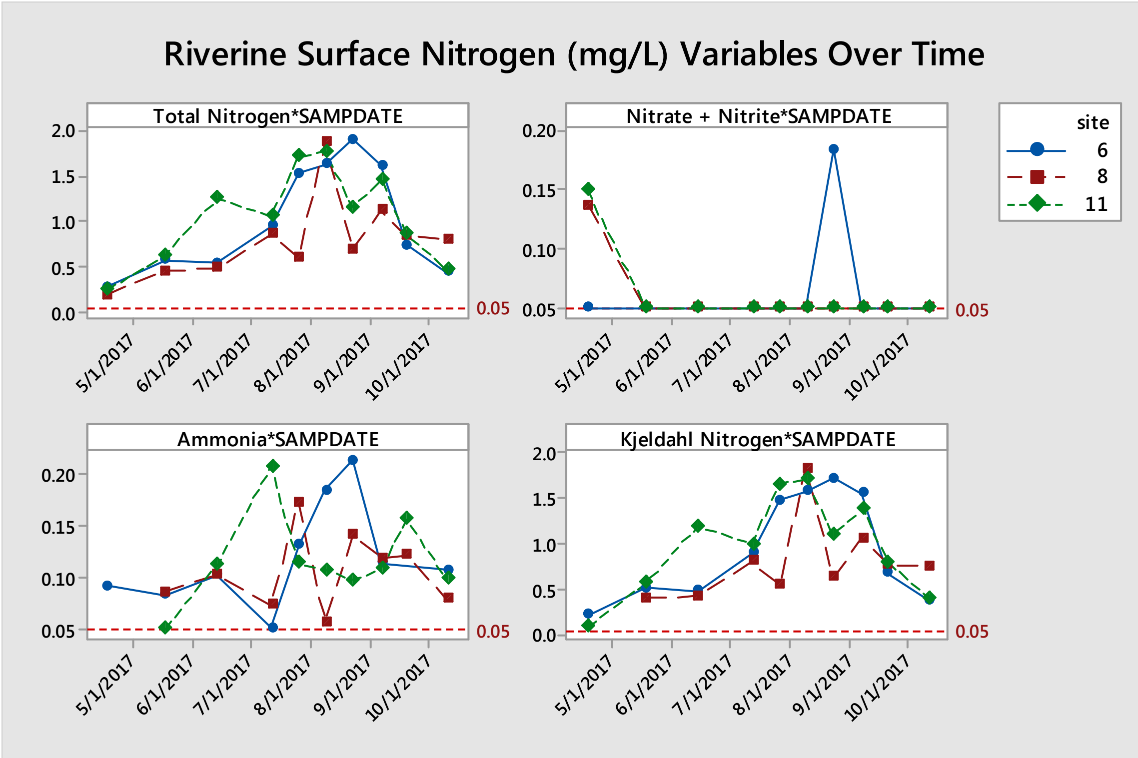


Figure 17. 2017 Surface Nitrogen Variables as N (mg/L) from the three riverine sites. Dashed line represents the laboratory reporting limit (0.05 mg/L) for all parameters.

Examination of the riverine sites for all monitored nitrogen parameters showed no seasonal statistical difference. Compared to the lacustrine zone, total nitrogen levels were generally higher suggesting the tributaries as a source of nitrogen (**Figure 17**). The abundance of ammonia, the most easily assimilated nitrogen nutrient, is unusual and contrasted to the 2014 data set when 32 of 35 riverine samples reported as below reporting limit.

In general, nutrients behaved similar to previous years with riverine inorganic nutrients generally greater than lacustrine values, hypolimnetic accumulation of dissolved nutrients such as ortho-phosphorus and ammonia, and seasonal buildup of epilimnetic total phosphorus and nitrogen. The consistent detection of ammonia combined with few seasonal detects for nitrite-nitrate at all surface sites is not easily explained by biological processes as ammonia is the preferential nitrogen species for plant uptake.

Algae

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. Algal biomass and subsequently biological production has many impacts to overall water quality including ecosystem stability, drinking water suitability, and recreational impacts related to water transparency.

Trophic state is a common designation used to classify lakes and reservoirs according to their level of productivity or algal biomass (Carlson, 1979). Recently Lake Thunderbird's classification has ranged from eutrophic to hypereutrophic; meaning it experiences high to excessive algae growth. Characteristics of hypereutrophic systems include an anoxic hypolimnion, potential for episodes of severe taste and odor issues, and potential for algal scum and low transparency (due to high algal biomass). Due to the problems presented by excessive algal growth, understanding the factors driving it and consequently determining the pathway to limit algal productivity are key to effective water quality management.

Biomass

In 2017, average chl-a values at site 1 reflect an increase of 7.2 µg/L over last sampling year and the highest single year's average since the installation of the SDOX device (**Figure 18**). For the 2017 sampling season, the average chl-a at Lake Thunderbird dam was 27.64 µg/L; just above the pre-SDOX (2007-2010 historical) average of 22.5 µg/L. Annual whole lake average for 2017 increased to 32.9 µg/L from 22.8 µg/L this monitoring year. Examining only the riverine sites yielded an average of 37.5 µg/L while lacustrine sites yielded an average of 29.2 µg/L; indicating that the overall higher values present in major tributaries, especially in July and August drive up the whole lake average. Similarly, the higher site 1 average is driven by high values measured in late July and August. However, all of these values exceed the 10 µg/L chl-a criteria set in place to protect the PPWS beneficial use of SWS lakes.

In 2016, algal bloom and die-off events, represented by high levels of pheophytin-a - a degradation product of chl-a - complicated the use of chl-a as a diagnostic tool. From an ecological assessment perspective, these events underscore the need for analysis of both pigments and that care should be taken when assessing the 2016 chl-a data or investigating inter-annual trends. Due to this uncertainty, it is difficult to definitively state whether the increase from 2015 to 2017 occurred as a sloped increase or as a sharp step, however an upward trend is emerging (**Figure 18**). This current trend of increasing chl-a is disturbing and represents a disappointing reversal of the oligotrophication from the post-SDOX years 2012 and 2013 and continued further degradation of Lake Thunderbird.

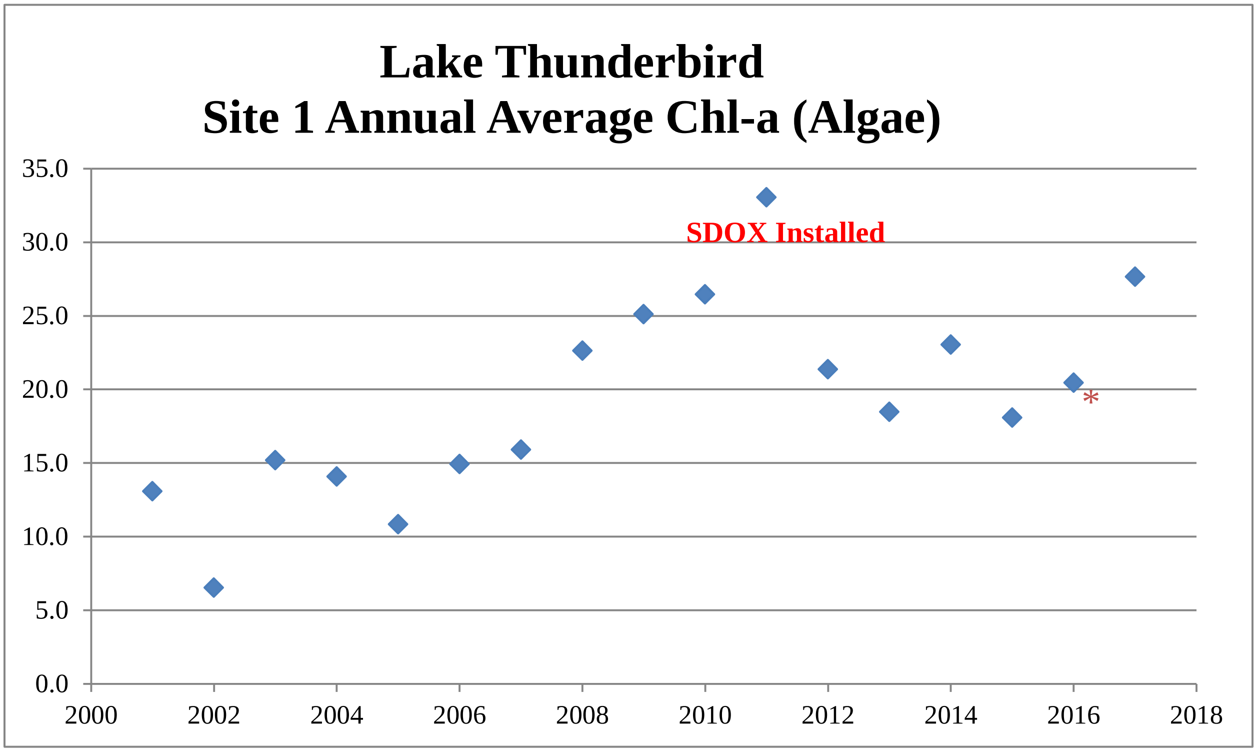


Figure 18. 2001 through 2017 Lake Thunderbird average surface chlorophyll-a (µg/L) at Site 1. Asterisk denoted season with documented algal die offs (excessive pheophytin-a and low chl-a).

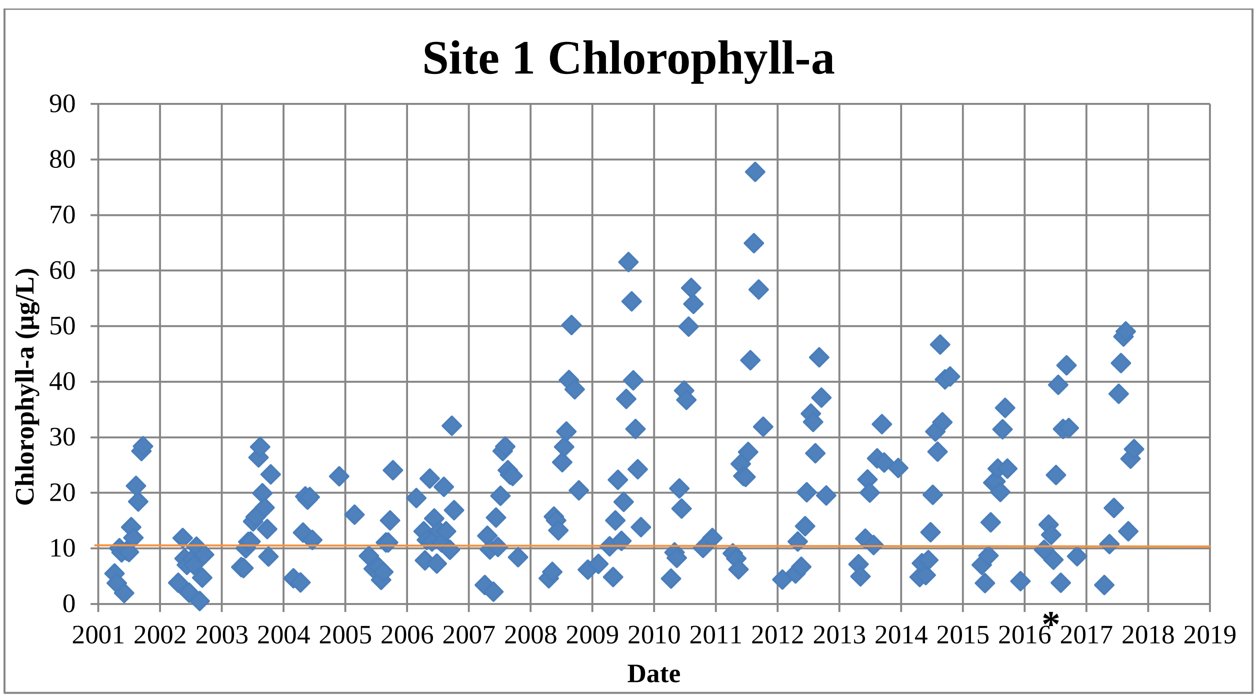
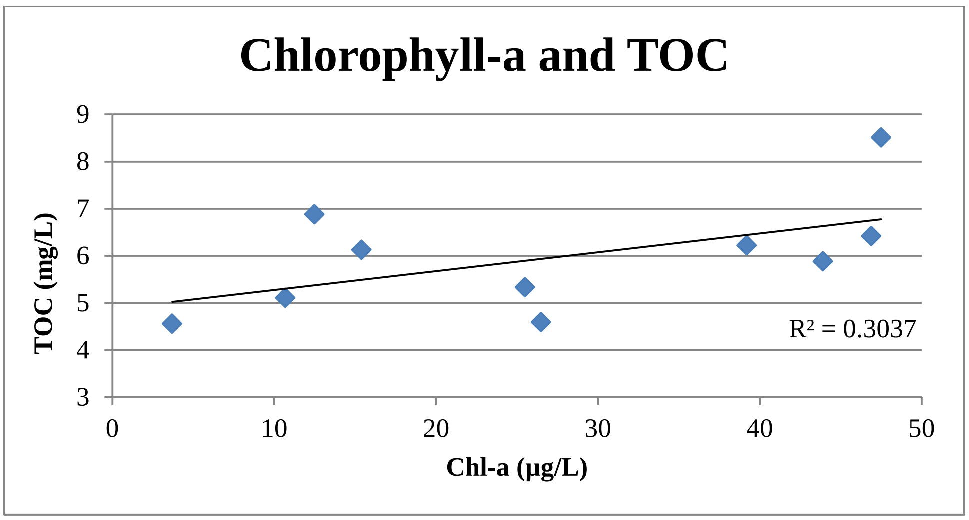


Figure 19. 2001-2017 Lake Thunderbird surface chl-a (µg/L) at Site 1. Orange line denotes SWS criteria of 10 µg/L

Total Organic Carbon - TOC

Total organic carbon (TOC), an important drinking water treatment parameter, is an additional measure of organic content. Algal growth, the process of creating organic compounds out of carbon dioxide, in eutrophic and hypereutrophic systems is related to TOC and is a useful measure to inform on organic content, used frequently by drinking water plants. Samples for TOC analysis were collected at the surface of Site 1 as part of the routine sample regime. Regression analysis shows chlorophyll-a and TOC to be related, indicating in-lake production of TOC via algal growth was significant (**Figure 20**). While a seasonal relationship is clear, with 30% of the TOC variability explained by chlorophyll-a¸ the precision and accuracy of predicting any one TOC value from chlorophyll-a value is low.



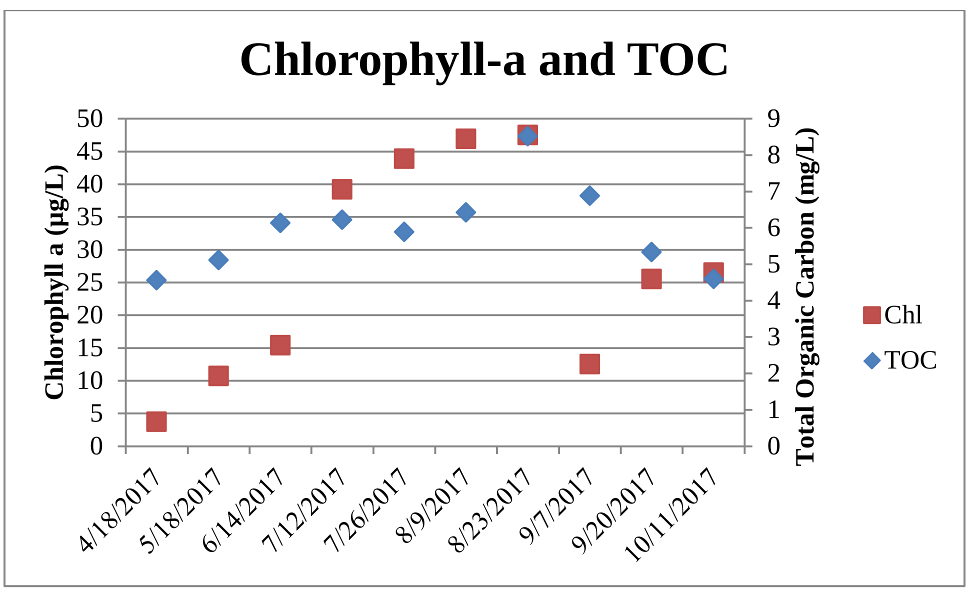


Figure 20. 2017 Lake Thunderbird surface TOC and chl-a at Site 1.

Taste and Odor Complaints

The City of Norman has provided data on the number of taste and odor complaints for our period of record (2000 – 2017) and more recently included Taste and Odor (T&O) compound analysis. Annual data has indicated that changes in lake water quality correlate well with customer complaints in the final finished water. Consumers at the tap can detect taste and odor causing compounds in extremely low concentrations (~ 5 ηg/L) (Graham et al 2008). Algae produce the majority of T&O compounds found in Oklahoma reservoirs. The most common problematic drinking water taste and odor compounds, Geosmin and 2-methylisoborneol (MIB), are produced primarily by Cyanobacteria.

Taste and odor (T&O) complaints in 2017, exhibited a pattern consistent with previous years, with complaints peaking in September corresponding with the beginning of lake turnover. The daily summary of T&O complaints confirms this normal trend for 2017 (**Figure 21)**. Causal factors point to the two strong mixing events around September. The large and mostly anoxic metalimnion seen on August 23 had mixed into the epilimnion by the September 7 sample event. Between September 7 and September 20 sample events, the lake had completely de-stratified mixing all hypolimnetic contents (**Figure 7**). These mixing events likely contributed to T&O events in two ways: epilimnetic release of previously hypolimnetically stored chemicals and increased epilimnetic algal die off, resulting in the large-scale release of T&O causing compounds. The compiled daily complaints from Norman's records show a strong spike in complaints on September 5 **(Figure 21)**. The City of Norman tracks Geosmin, MIB and chlorophyll-a in its raw lake water which allows us to draw a direct line from the algal die off documented September 7th 2017, to the number of complaints received about the finished drinking water. Comparing the daily complaints to the laboratory tests show Geosmin as the precursor and MIB as the cause of the September 5, 2017 T&O spike (**Figure 22**).

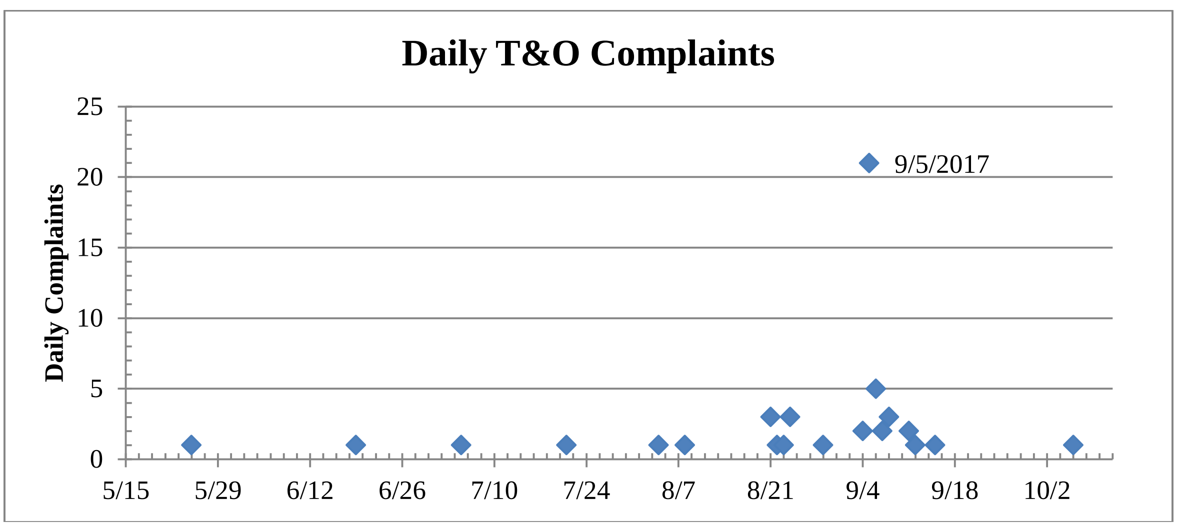


Figure 21. 2017 City of Norman compiled daily Taste and Odor complaints.

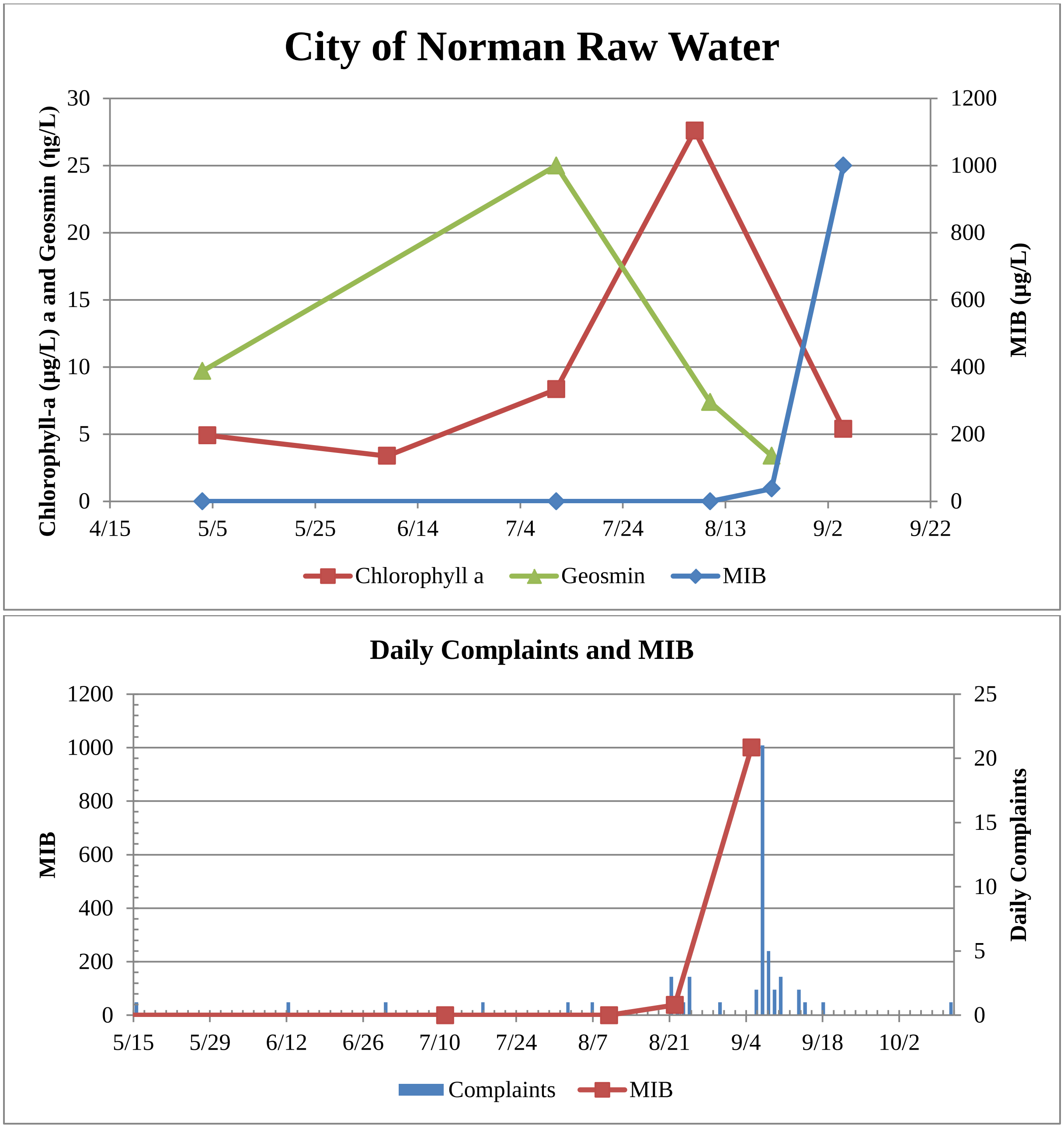


Figure 22. 2017 City of Norman raw water laboratory analysis.

Trophic State Index – TSI

Trophic state is defined as a measure of primary productivity. This concept has been expanded over time in an attempt to classify each lake into a particular trophic state based on a series of metrics. These metrics in turn are used to assess biological processes and water quality trends; comparing each metric can shed light on what drives algal growth. Carlson's trophic state indices (TSI) are the most common measure of algal biomass (Carlson, 1977) and were compared in this analysis to examine algal growth. Three surface parameters, chlorophyll-a (CHL), Secchi depth (SD) and total phosphorus (TP) are indexed to estimate algal biomass (Carlson 1977, Kratzer 1981). Of these three, chl-a yields the most accurate TSI value, as it is the most direct measure of algal biomass. TSI based on secchi depth is historically the most inaccurate index at Lake Thunderbird as high-suspended solids will lead to relatively low water clarity, thus clouding the impact of algal biomass on the TSI value. Trophic states are categorized by their TSI(CHL) values as follows: 0 to 40 as oligotrophic or low algal growth, 41 to 50 as mesotrophic or increasing algal growth, 51 to 60 as eutrophic or high algal growth to finally ≥ 61 as hypereutrophic or excessive algal growth.

Lake Thunderbird's TSI for each of the three lacustrine variables are displayed in **Figure 23** ranging from 42-69 throughout 2017. TSI(CHL), a reflection of actual or realized algae growth, showed site 1 to have been mesotrophic in April steadily increasing to the hypereutrophic range by the start of July and continuing through the end of the sample season. The exception to this was the mid-September event when all three variables approximated each other and were in the eutrophic range. Also notable, is the observation that TSI(TP) over-predicted TSI(CHL) until mid-July, then TSI(TP) consistently under predicted TSI(CHL) through August suggesting TP is not a stable predictor of chl-a levels. This time-period also indicates when TSI(CHL) transitions to a hypereutrophic state. Overall, the TSI(CHL) matrices calculated on monitored chl-a results indicates excessive (hypereutrophic) lacustrine algal growth as values are above 61 for much of the summer. TSI matrices at the riverine sites did not show a seasonal pattern, but did indicate realized algal growth, as TSI(CHL) was in the hypereutrophic range throughout the season (**Figure 24**). TSI(SD) over predicted TSI(CHL), likely caused by high turbidity, while TSI(TP) and TSI(CHL) generally varied together in the riverine sites suggesting that TP is a better predictor of algal growth in these areas.

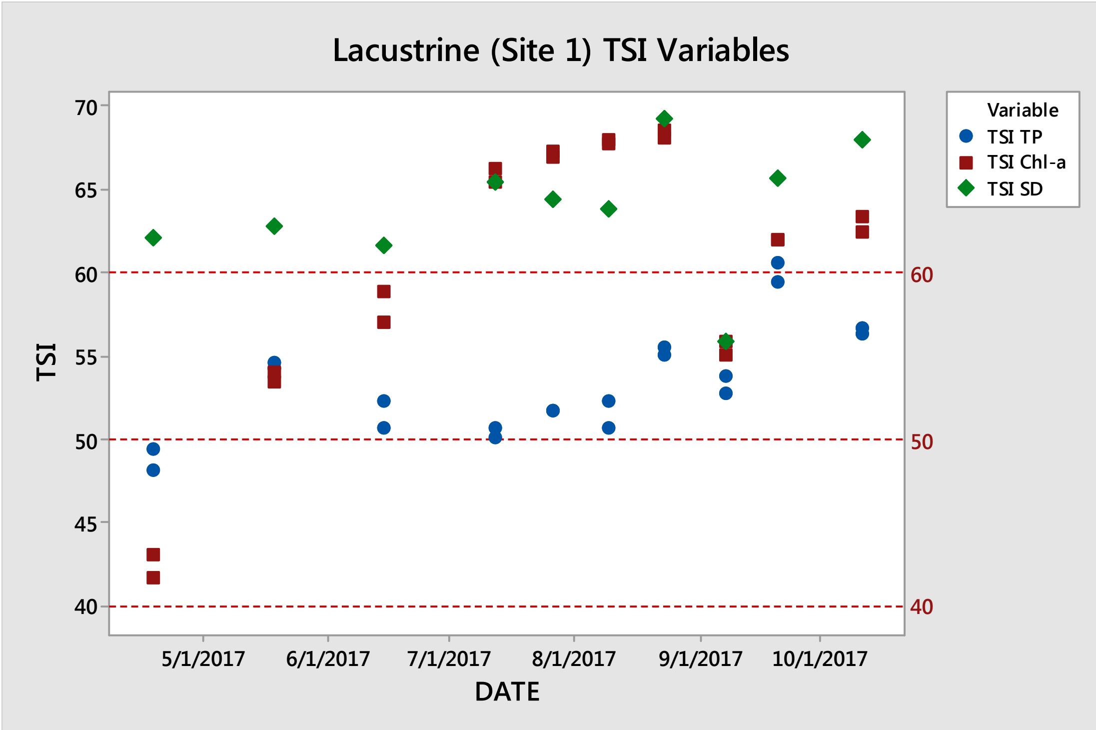


Figure 23. 2017 Carlson's Trophic State Index values for Lake Thunderbird at Site 1 including QA samples 1(12) and 1(22). Red dashed lines delineate ranges for trophic states.

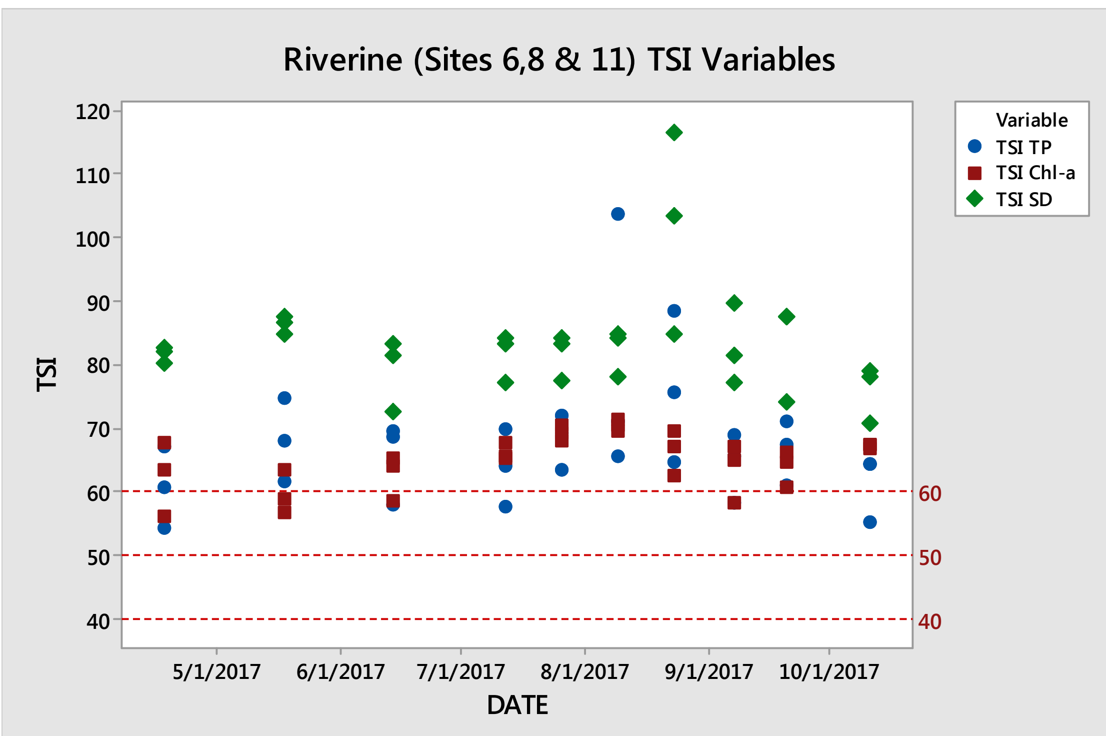


Figure 24. 2017 Carlson's Trophic State Index values for riverine sites (sites 6, 8, and 11) for Lake Thunderbird. Red dashed lines delineate ranges for trophic states.

Indicators of Algal Nutrient Limitation

To develop effective mitigation measures it is critical to understand causal factors of excessive algae growth. To this end, the OWRB has employed a variety of diagnostic tools examining the relationship between algal macronutrients (phosphorus, nitrogen, and light) and measures of algal biomass. The three separate tools applied to the 2017 data set are multivariate plot analysis, Total Nitrogen to Total Phosphorus ratio (N/P) and linear regression analysis.

Multivariate Plot

By examining the interrelationships between TSI variables one can also discern factors affecting algal limitation such as light or phosphorus (Carlson, 1991). This multivariate plot takes the result of TSI(CHL) - TSI(TP) and TSI(CHL) - TSI(SD) for each sample and plots these with TSI(CHL) – TSI(TP) on the vertical axis versus TSI(CHL) - TSI(SD) on the horizontal. Application of the multivariate plot requires combining the use of three axes (X, Y and diagonal) to develop a general view of the relationships between these three TSI variables. Samples to the right of the y-axis can indicate algal cells and/or zooplankton grazing influencing light transparency while samples to the left of the y-axis can indicate that inorganic turbidity exerts a greater influence on light transparency. Finally, samples below the x-axis suggest that phosphorus is not the primary chemical nutrient limiting algal growth while samples above the x-axis can indicate phosphorus as limiting algal growth. Samples on or near the diagonal running from the lower left corner to the upper right corner can indicate that turbidity may limit algal growth while phosphorus is bound to clay.

For site 1, representing the lacustrine zone of the lake, most samples fell to the left of the y-axis indicating inorganic turbidity influences transparency greater than organic turbidity (an abundance of algal cells) (**Figure 25**). Lacustrine samples also were largely above the x-axis suggesting that phosphorus exerts influence on algal growth. Finally, all samples follow the diagonal, but are shifted to the left of y-axis about 6 TSI units, a relatively significant deviation. Without including any other analyses, the conclusion would be that algal growth trends toward light and phosphorus limitation. Comparison of the seasonal trend to individual data points does not support the concept of phosphorus limitation, because the two samples most negative on the y-axis are the April samples with the lowest chlorophyll-a, in the mesotophic range; predicted less likely to be phosphorus limited. Additionally, the samples most positive on the y-axis are from the dates with the highest chlorophyll-a, in the hypereutrophic range; predicted most likely to be phosphorus limited. Therefore, when algal growth was the greatest, phosphorus limitation is predicted as more probable as a limiting factor and when algal growth is the lowest, phosphorus was predicted as less likely to be limiting. These predictions detract from the credibility of the general conclusion based on this multivariate plot. Interpretation of these plots leads to a tendency towards inorganic turbidity as the most probable algal limiting nutrient, however, inorganic turbidity measurements were not high, therefore it is likely that at higher chlorophyll levels algal turbidity is a contributer to its own limitation.

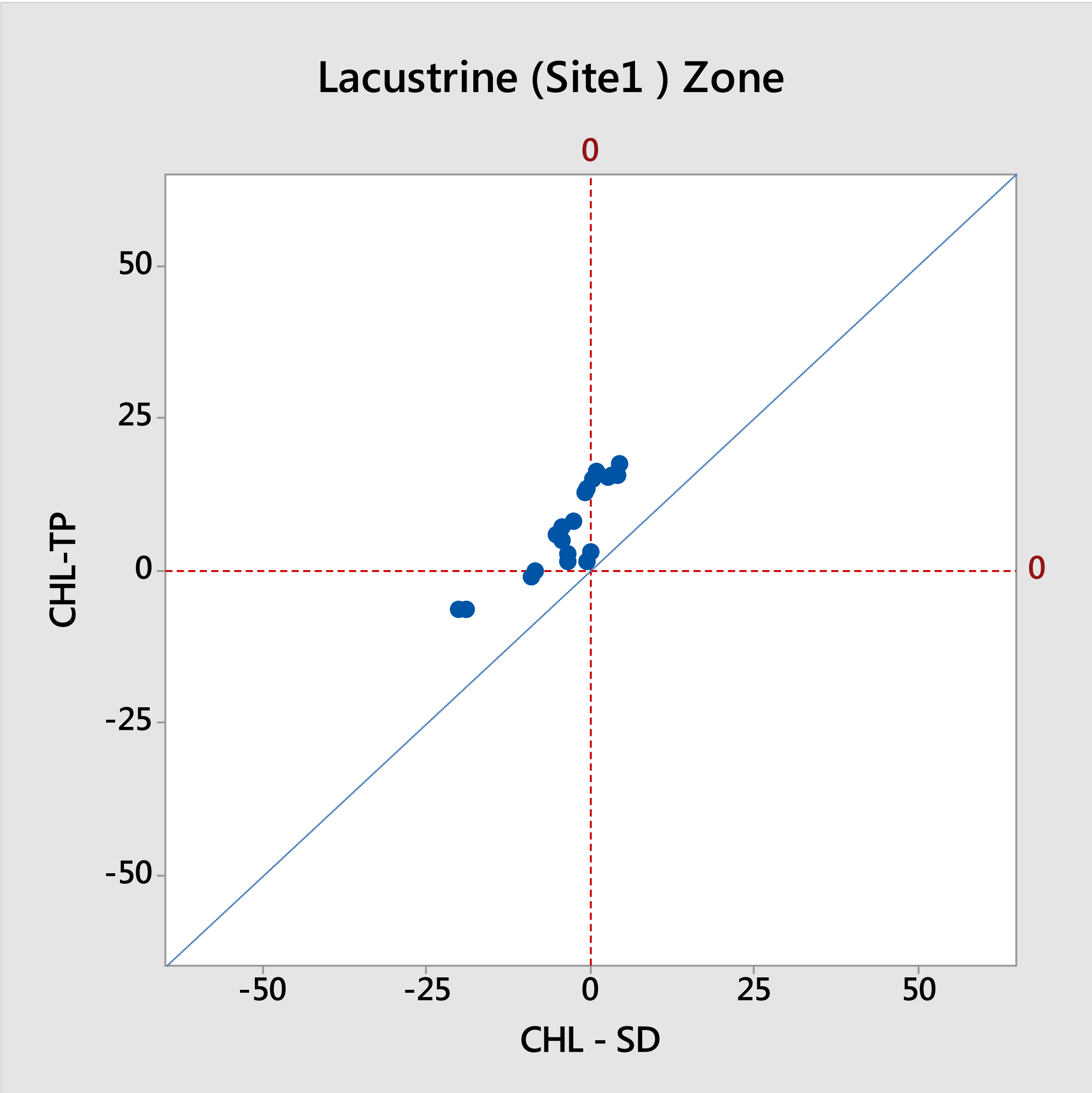


Figure 25. 2017 Trophic State Indices (TSI) plot of TSI(TP) and TSI(SD) deviation from the TSI(CHL) used to suggest means of algal growth limitations at Site 1. Diagonal line represents when turbidity may limit algal growth if phosphorus is bound to clay.

The shape of the riverine multivariate plot is similar to the lacustrine, but shifted approximately left 15 and down 10 TSI units (**Figure 26**). Keeping in mind the lack of seasonal variance and that most of the samples were in the hypereutrophic range, a general conclusion would be that inorganic turbidity has a greater influence on transparency than seen in the lacustrine zone. Low secchi depth measurements and high turbidity measurements support this conclusion.

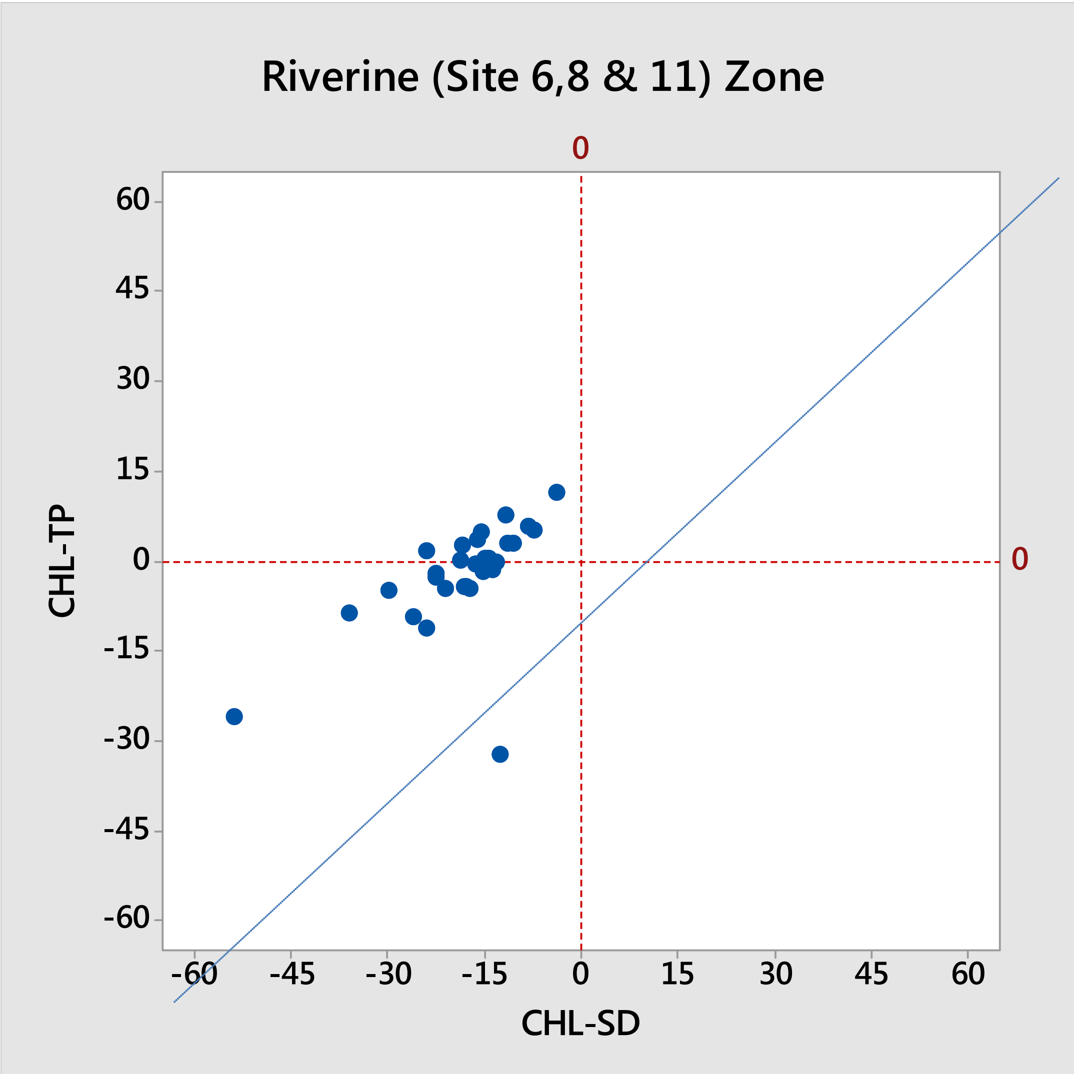


Figure 26. 2017 Trophic State Indices (TSI) plot of TSI(TP) and TSI(SD) deviation from the TSI(CHL) used to suggest means of algal growth limitations of the riverine sites. Diagonal line represents when turbidity may limit algal growth if phosphorus is bound to clay.

Total Nitrogen to Total Phosphorus (N/P) Ratio

Phosphorus as the limiting nutrient for most freshwater systems is desirable because under phosphorus limiting conditions, green algae will typically be predominant. This is opposed to a blue green algae predominance, which can cause a multitude of issues commonly associated with recreation, drinking water supply and fish community structure. Total nitrogen to total phosphorus (N/P) ratios are used to predict whether nitrogen or phosphorus is the most likely nutrient to limit algal growth. Dzialowski *et al.* (2005) has divided the molecular ratio of total nitrogen to total phosphorus into three ranges, wherein a N/P ratio of less than or equal to 18 indicates a nitrogen-limited waterbody, ratios of 20-46 indicate a co-limitation of nitrogen and phosphorus, and waters having ratios greater than 65 are regarded as phosphorus-limited. In most eutrophic Oklahoma reservoirs, a co-limitation prediction turns out to be no chemical nutrient limitation, because both nutrients are readily available in significant amounts and produce high productivity. Lake Thunderbird has generally had N/P ratios in the 40's to 60's over the years, indicating the lake was phosphorus to co-limited. Historically, average total nitrogen values have been on the continuous rise since 2006, with a crash in 2016 and rebound in 2017. For 2017, N/P ratios were split evenly between co-limitation and phosphorus as the predicted limiting chemical nutrient **(Figure 27**). The 2017 average N/P molar ratio is at the upper end of the co-limitation range. High total nitrogen values and relatively average total phosphorus values at site one in late July through early September drive these higher ratios. Examination of the corresponding dissolved nutrient values shows the consistent presence of the inorganic nutrients, ammonia and ortho-phosphorus. The presence of readily available nitrogen and phosphorus suggests that should algal growth have a limiting nutrient it is more likely to be light, rather than the chemical macronutrients of nitrogen and phosphorus.

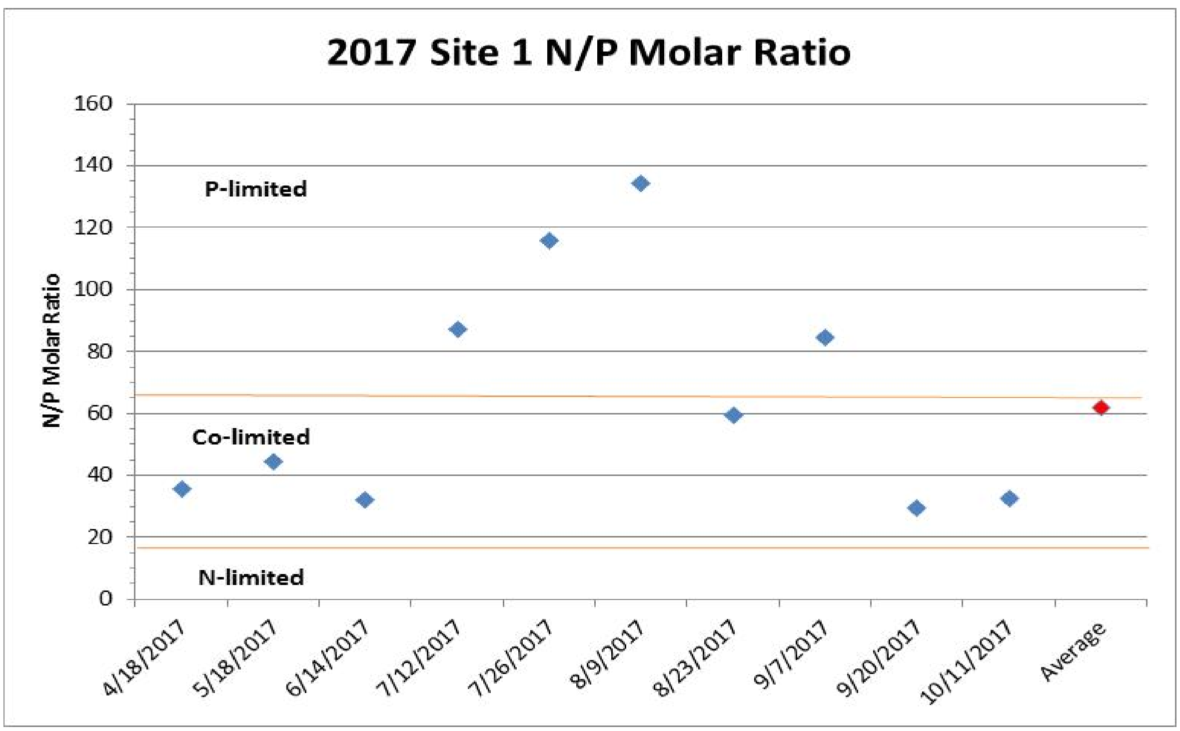


Figure 27. 2017 Site 1 surface N/P molecular ratio. Lines represent approximate divisions between phosphorus, co-limitation, and nitrogen predictors. Red symbol at far right hand side of plot represents the annual average value.

Regression Analysis

The use of regressions is an empirical means to detect relationships between stressors and response variables. Each of the three algae macronutrient variables, light as represented by secchi depth, nitrogen, and phosphorus, were examined for a statistically significant relationship to chl-a using regressions. Of these three stressor variables, only phosphorus did not show a significant relationship to chl-a (**Figure 28).** While several individual variables showed statistical significance, Secchi disk depth, total nitrogen, and organic nitrogen showed the most significance with p-values of 0.006, 0.002, and 0.001 and R^2 of 30.9, 42.0, and 44.6 respectively. Application of a multiple regression scheme included all potential stressor variables (n=8) concluding with a two variable quadratic model with organic nitrogen and Secchi disk depth as providing the best fit. This conclusion was backed up by a R^2 of 89.9% and p-value <0.001 (**Figure 29**). In summary, almost 90% of the chl-a variability is explained by the parameters organic nitrogen and Secchi disk depth.

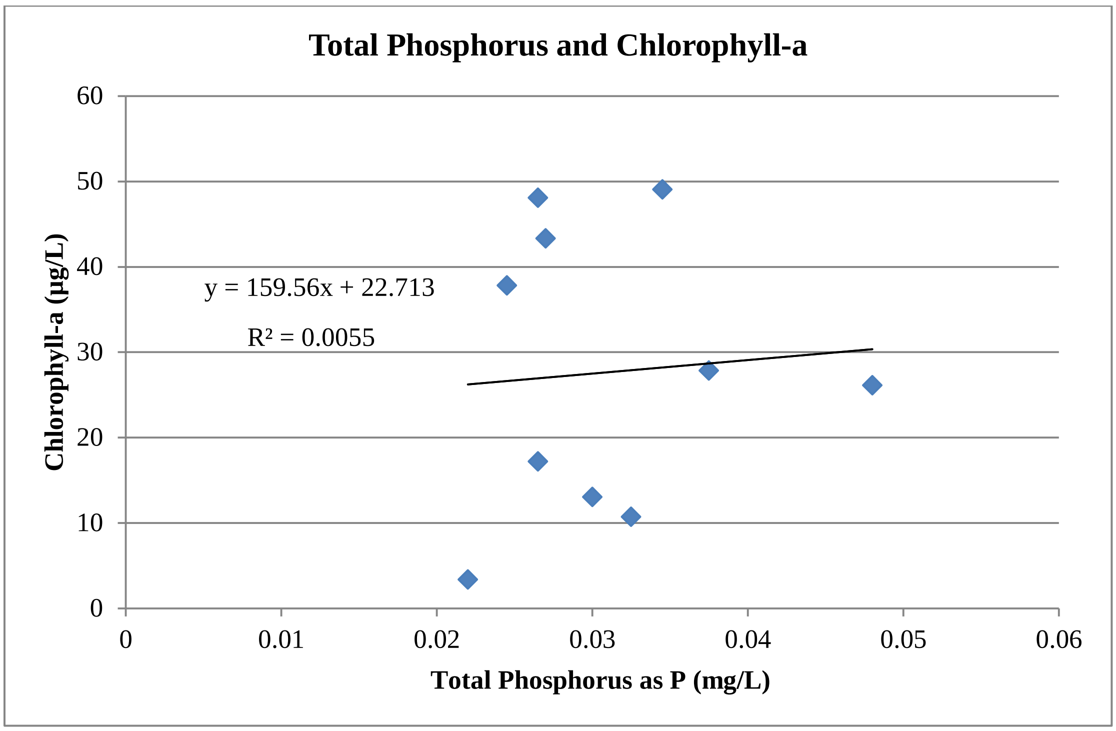


Figure 28. Graphical summary of chlorophyll-a versus Total Phosphorus regression analysis.

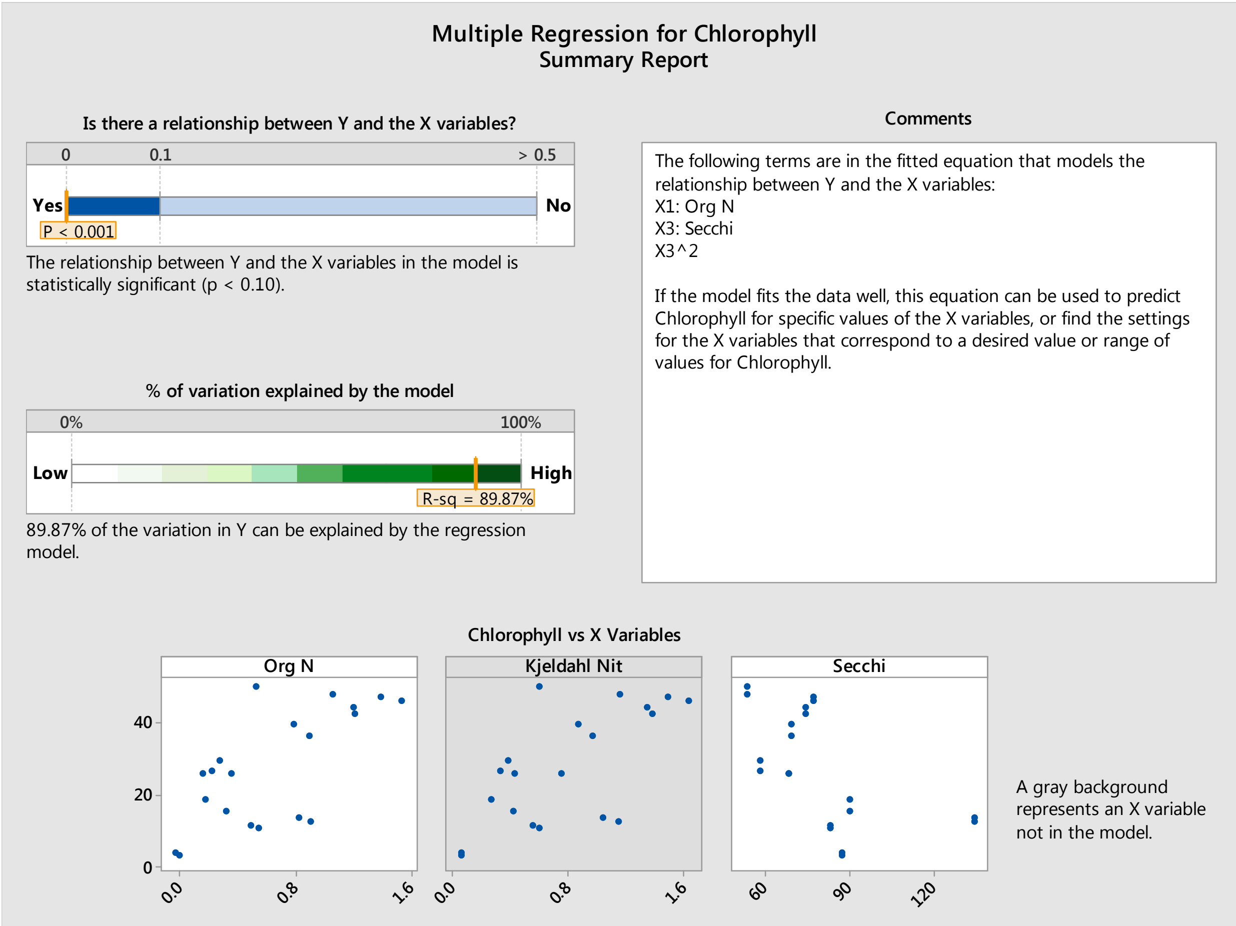


Figure 29. Statistical summary of multiple regression analysis.

Summary

Factors affecting or limiting algal growth are not always directly apparent and can have many confounding influences; therefore, data was examined using three methods: multivariate plot, N/P ratio, and multiple regression analyses. Results of the multivariate plot analysis pointed toward phosphorus and light as factors limiting algal growth. Closer examination clearly refuted a conclusion of phosphorus limitation, which, through this analysis, left inorganic turbidity (light) as primary limiter of algal growth in the lacustrine zone. As inorganic turbidity measurements were relatively low through the season, this conclusion is not entirely explanatory and it is more likely that algae was self-shading (organic turbidity). Application of the N/P ratio to predict between nitrogen, phosphorus, or co-limitation did not provide a clear linkage to the limiting nutrient. Of the three methods, regression analysis was perhaps the most thorough, as all measured water quality parameters were evaluated against the response variable, chlorophyll-a. Multiple regressions resulted with a best-fit equation that explained almost 90% of the variability using two stressor parameters, Secchi disk depth and organic nitrogen. Reporting of the model construction showed that Secchi disk depth had the greatest contribution to explaining chlorophyll-variability than any other parameter (**Figure 30**). While organic nitrogen is a key component used to explain the variability of chlorophyll-a, this parameter does not fit into the scheme of limiting algal growth in 2017. The best explanation of inclusion of organic nitrogen in the regression is as a reflection of the existing algal content. This is because algae are autotrophs – they use solar energy to create their own nitrogen - and therefore organic nitrogen will vary with chlorophyll, but does not explain the variability. The most common denominator for these three methods suggests that if any macronutrient limits algal growth, it is light, as indicated by Secchi disk depth (transparency).

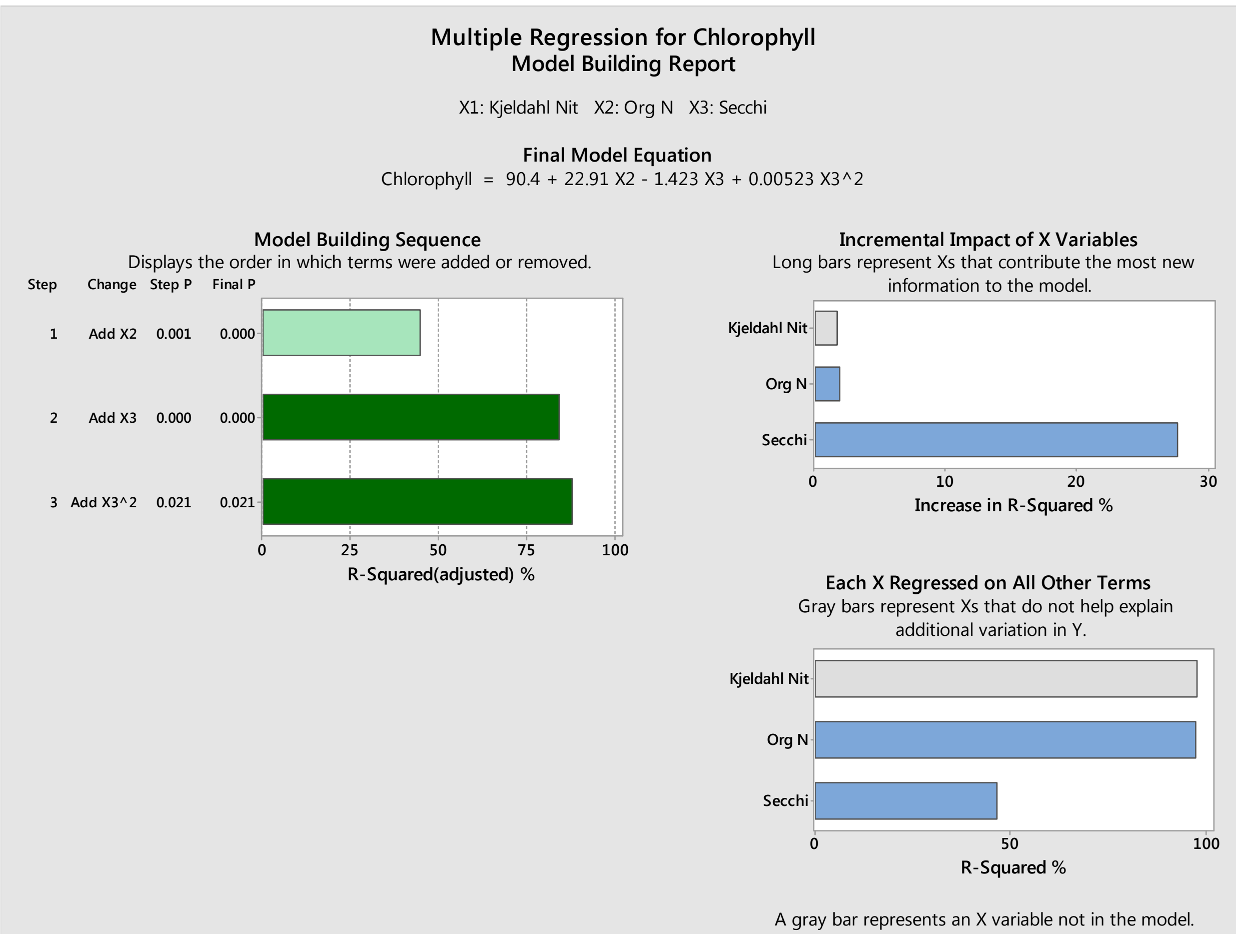


Figure 30. Summary report of multiple regression model equation and incremental impact of select parameters to explain response parameter variability.

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 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 are listed in the OWQS Appendix A for Lake Thunderbird and in the introduction of this report. Physical, chemical, and biological data on Lake Thunderbird were used to ascertain the condition of lake waters and determine if lake water quality supports its assigned beneficial uses.

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. Discussion of Lake Thunderbird's water quality parameters are in the following sections, with an emphasis on their accordance with 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 lake tributaries, but are not a part of the traditional BUMP sample regime and therefore not used for BUMP reporting purposes. However, these sites were included in the following OWQS assessment, as they are pertinent to whole lake analysis for this project.

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 DO criteria is a seasonal threshold of 4.0 mg/L during the summer months and 5.0 mg/L in spring and fall; the volumetric criteria examines one-time events with a threshold of volume (50%) as anoxic (< 2 mg/L DO).

No surface water violations occurred in 2017, as the minimum surface DO registered at 4.41 mg/L at site 1 September 7, 2017, one month before the previous year's minimum surface DO.

This 4.41 mg/L was slightly above the summer minimum surface criteria, but signified a recent hypolimnetic mixing event corroborated by associated nutrient data. Lake Thunderbird did not violate the volumetric criteria as it exhibited a maximum 38% of anoxic volume on June 26, 2017.

Chlorophyll-a – Chl-a

Oklahoma surface water drinking supplies are sensitive and vulnerable to eutrophication - high biological productivity driven by excess nutrients. Communities can experience substantial hardship and high costs to treat water 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 microcystin – a known hepatotoxin. OWQS have provided additional protections from new point sources and protection against additional loading from existing point sources by identifying these at-risk reservoirs as Sensitive Water Supplies (SWS). Lake Thunderbird has this SWS designation 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 2017 sampling season, the lake wide chl-a average in Lake Thunderbird was 32.98 µg/L, with 95% of the samples exceeding 10 µg/L, whereas samples collected in 2016 had a lake wide average of 22.83 µg/L with 81% of samples exceeding **(Figure 31**). The long term ten-year lake-wide average is 26.9 µg/L, with 83% of samples exceeding 10 µg/L. Based on these calculations, Lake Thunderbird’s beneficial use of Public and Private Water Supply would be considered as non-supporting/impaired with respect to chlorophyll-a.

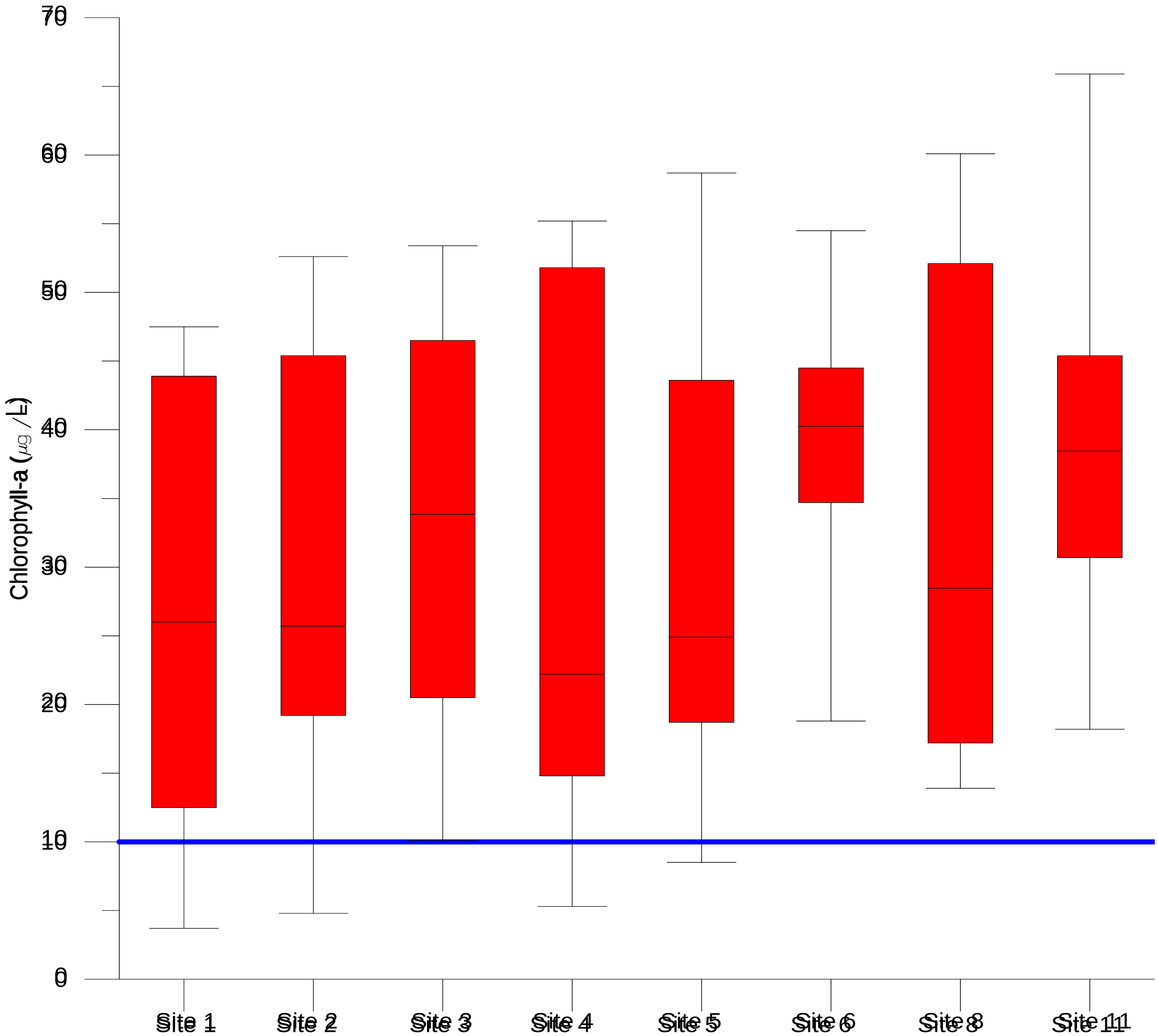


Figure 31. 2017 Lake Thunderbird chlorophyll-a (µg/L) by Site, where boxes represent 25% of the data distribution both above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Blue line represents SWS criteria of 10 µg/L.

Water Clarity

Turbidity and Secchi disk depth are methods of measuring water clarity and the amount of suspended particles in a lake. While natural to pristine lakes often have Secchi disk depths of several meters, Oklahoma reservoirs typically have depths measuring less than one meter. In Lake Thunderbird, Secchi disk depths ranged from a 2017 mean of 17.1 centimeters at Site 6 to a mean of 79.3 centimeters at Site 1. Whole lake average of Secchi depth was 48.6 centimeters.

The lacustrine sites (1, 2, and 4) had the deepest Secchi depths, while the riverine sites (6, 8, and 11) had the shallowest, as is typical of riverine portions of Oklahoma reservoirs (**Figure 32**).

The criterion for turbidity, a measure of water transparency used as criterion for the protection of the beneficial use of Fish and Wildlife Propagation, is set at 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 not supporting its beneficial use, and is thus impaired for turbidity. For the 2017 sampling season, the lake wide turbidity average in Lake Thunderbird was 34.6 NTU, with 31.3% of the samples exceeding 25 NTU **(Figure 33**), compared to 81% of last year's samples. The long- term ten-year lake-wide average is 24.8 NTU, with 26.7% of those samples exceeding 25 NTU. Based on these calculations, Lake Thunderbird is not supporting for the Fish and Wildlife Propagation beneficial use with respect to turbidity.

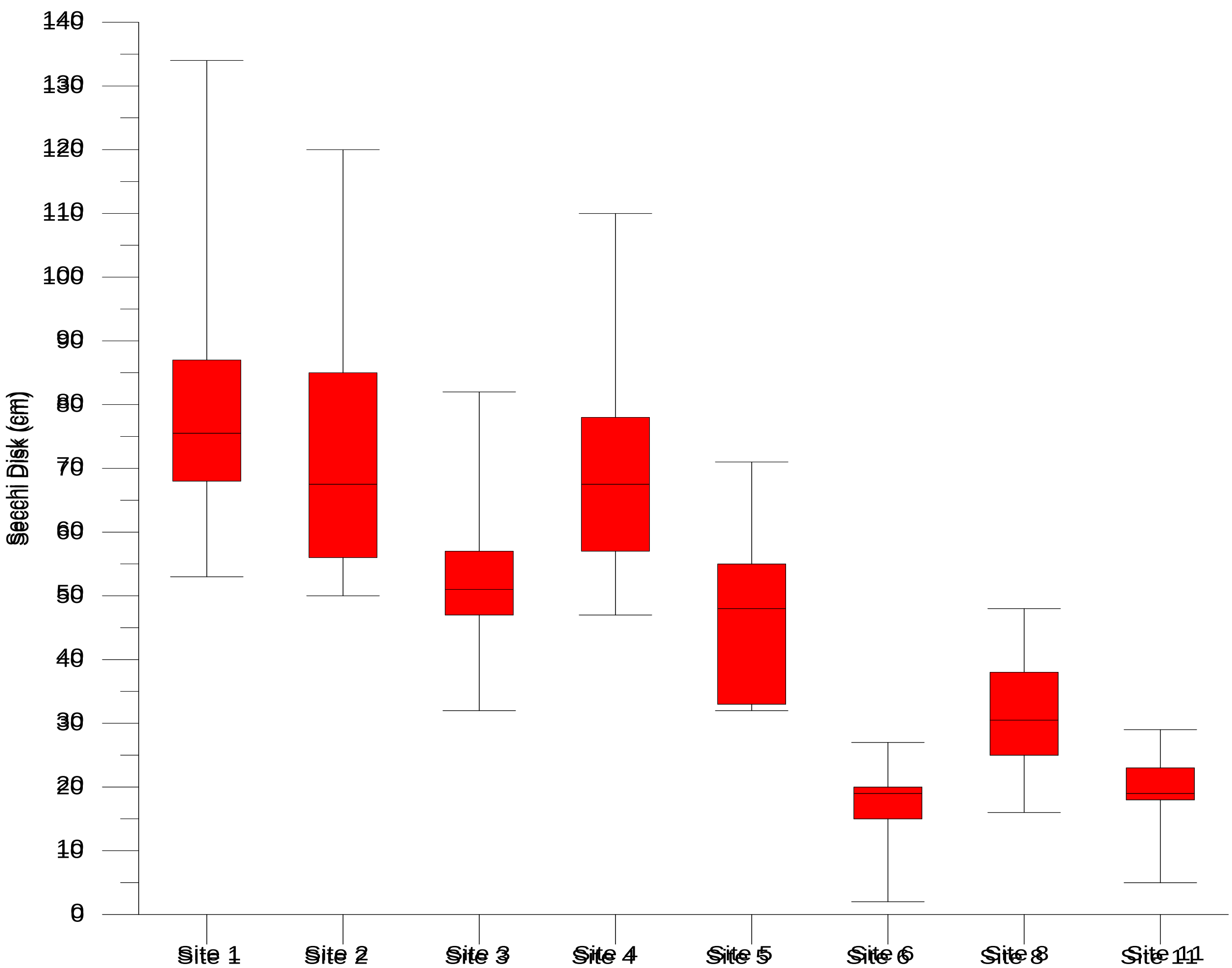


Figure 32. 2017 Lake Thunderbird Secchi Disk Depth (in centimeters) by Site, where boxes represent 25% of the data distribution both above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values.

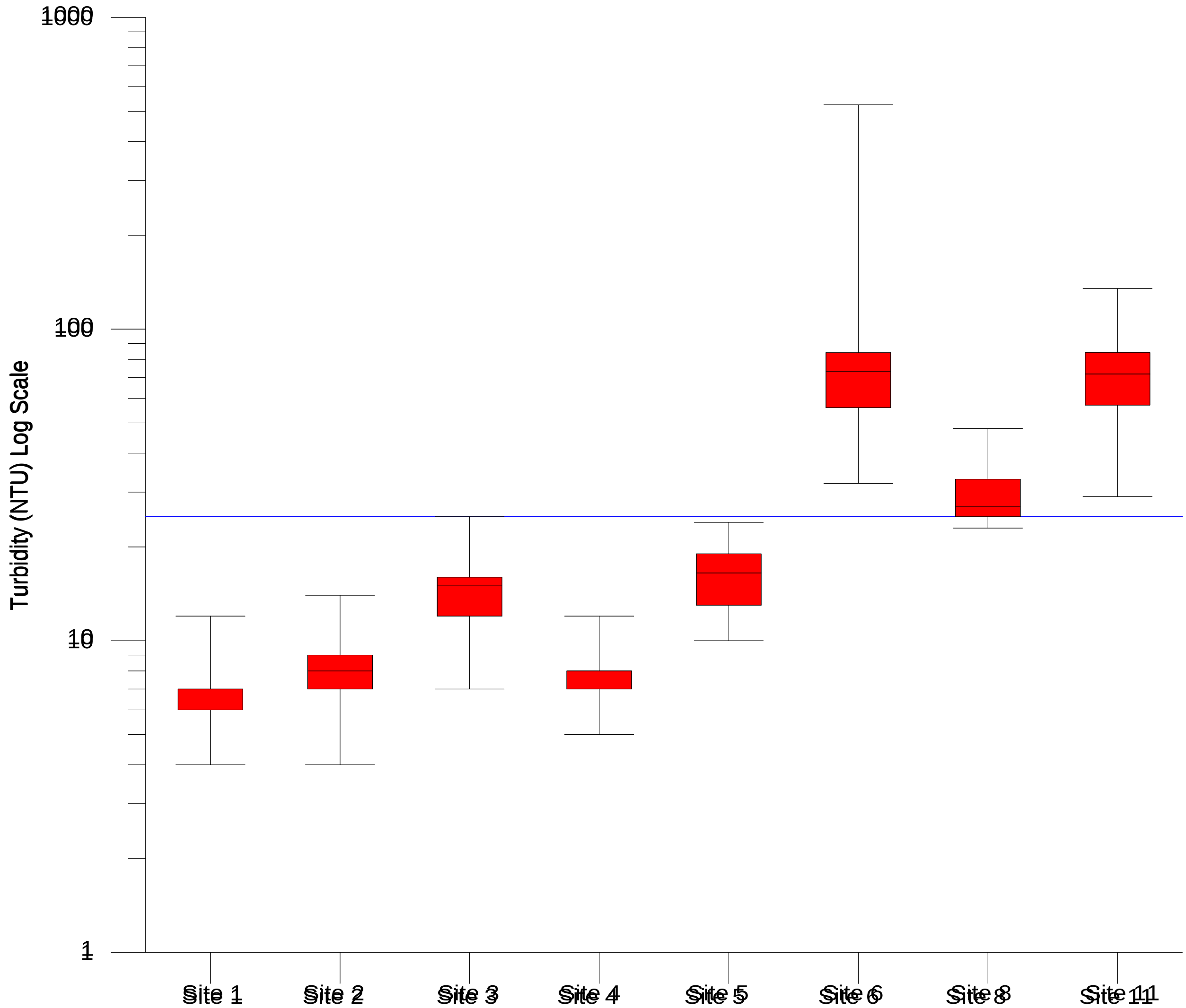


Figure 33. 2017 Lake Thunderbird Turbidity (NTU), by Site, where boxes represent 25% of the data distribution both above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Solid blue line indicates the 25 NTU water quality standard.

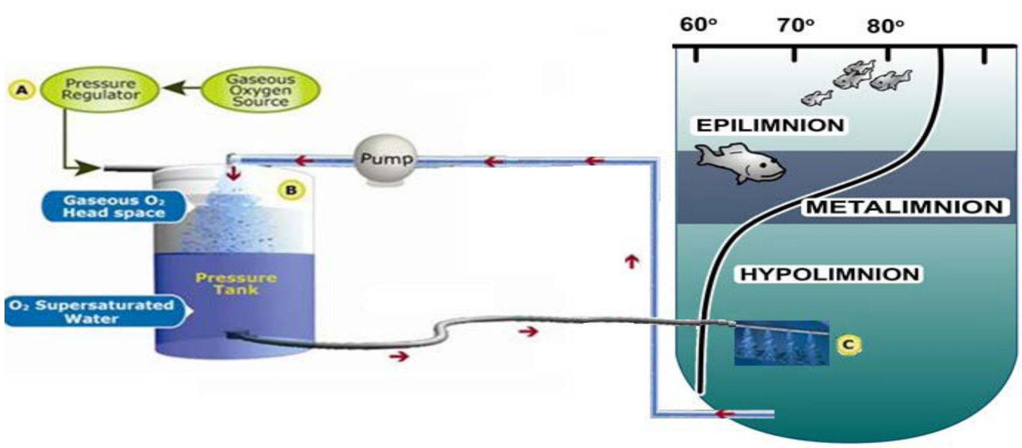
Supersaturated Dissolved Oxygen Injection System (SDOX)

Sample year 2017 marked the seventh season of operation for the supersaturated dissolved oxygen injection system (SDOX) installed in Lake Thunderbird. It is designed to operate throughout the entire stratification period, oxygenating the bottom five meters of the lake without disrupting thermal stratification (**Figure 34** and **Figure 35**). The system withdraws water from the deepest area of the hypolimnion approximately 16 meters in depth (at conservation pool), supersaturating this water with oxygen under pressurized conditions, and then re-injecting it at a separate location 13 meters deep, approximately 996.3’ elevation. At full capacity, this system will treat 1,536 gallons per minute while delivering 5,202 lb. DO/day. By this design, SDOX should provide oxidant to the bottom 902 acre-feet of lake, encompassing 243 acres of nutrient rich sediment.

This monitoring season marked the fifth 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 intense vertical mixing within the water column (OWRB, 2012). After reviewing all options with the system owner/operator, COMCD, and manufacturer, BlueInGreen, the decision to redesign the discharge nozzle adding additional openings to diffuse the force of reinjection was made. 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 operated with these modifications since July 2012. The SDOX delivered at an average rate of 4,400 pounds of oxygen per day during 2017, a bit higher than in 2016 and significantly greater than 2015 and 2014.

When present, oxygen is the terminal electron acceptor in respiration, allowing the oxidation-reduction potential in the hypolimnion to stay in an oxidized state and not drop into a reduced state. Reducing conditions reflected by low redox potential, below 100 mV, increases the solubility of a wide range of nutrients and metals; the resulting sediment release of these compounds further stimulates algal growth. If the SDOX system is able to provide an oxidated hypolimnion, potential benefits include reduction of the internal nutrient load by minimizing the recycling of nutrients from the sediment, consequently, mitigating peak chl-a values. The introduction of oxygen in the hypolimnion should also lower dissolved metal release, such as iron and manganese, into the water column.

Figure 34. Conceptual illustration of the SDOX System at Lake Thunderbird



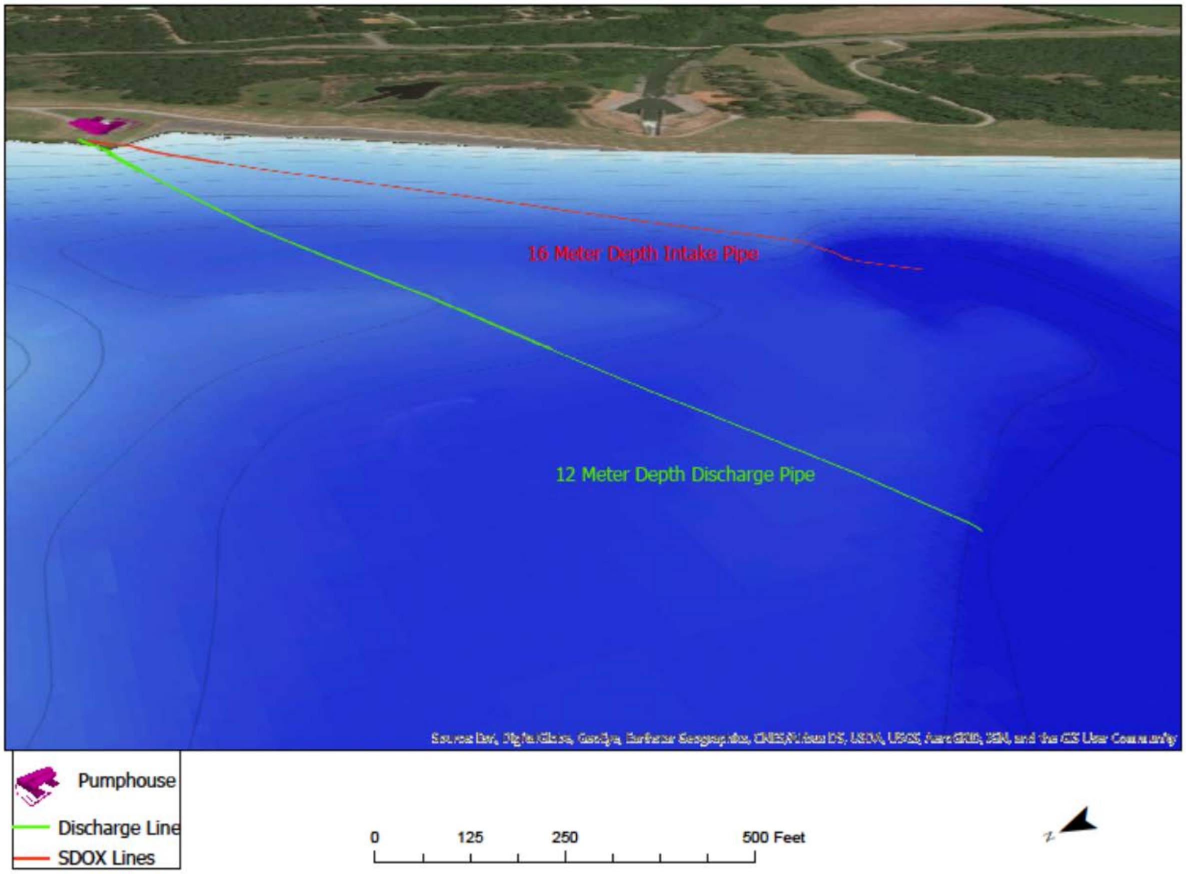


Figure 35. Map highlighting SDOX location and current configuration.

Thermal Stratification

One of the advertised advantages of SDOX over traditional aeration techniques is the ability to oxygenate 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. The hypolimnetic temperature continually increased throughout the entire summer of 2011, until isothermal conditions were reached, precipitating a much earlier than normal turnover event. In 2012, a somewhat similar situation was observed where hypolimnetic water was warmer than normal and heated at a higher rate than what is documented in the historical dataset. Enough data has been collected to average hypolimnetic warming rates broken into three periods, bracketing SDOX installation and use (**Table 4)**. Three years prior to SDOX installation the averaged warming rate was 0.014 °C/day. During the first season of operation, 2011, the hypolimnetic warming rate increased more than four-fold to 0.065°C/day. Following system modifications occurring early July 2012, the rate of temperature increase at the bottom slowed noticeably to almost half the initial post-SDOX installation rate, an average of 0.036 °C/day. However, the rate in 2015 increased to 0.059 °C/day, represented an anomalous season for hypolimnetic warming, and was not included in the average rate. Post-SDOX installation rates show a reduced amount of induced mixing, although SDOX operation still influences hypolimnetic temperature.

Examination of Relative Thermal Resistance to mixing (RTR) plots (**Appendix C**) showed a strengthening of thermal stratification and homogenization of the hypolimnion following SDOX startup. The top of the hypolimnion varied between the 10 and 11 meter mark until late September when significant weakening of stratification occurred. For most of the stratification season, a homogenous region in the hypolimnion centered approximately 2 meters above the SDOX outlet. RTR plots at site 12 reinforce the indications that the SDOX induces slight upward mixing of water due to reinjection of saturated water and is explanatory of continued hypolimnetic warming.

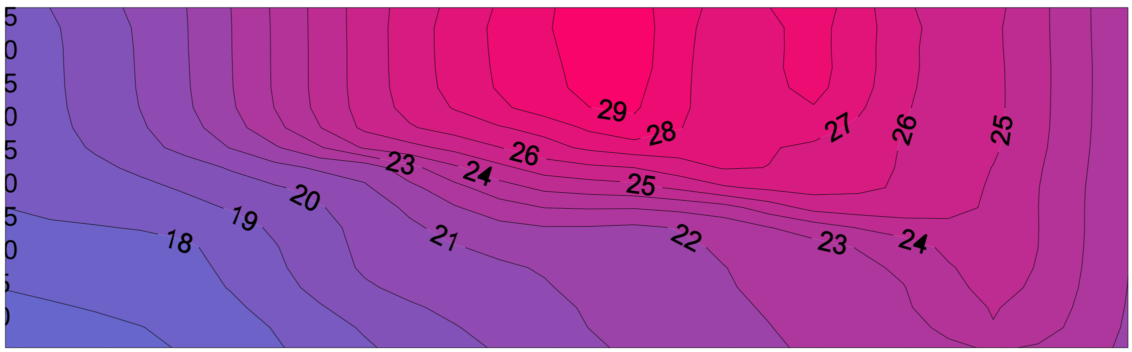
Table 4. Hypolimnetic temperature change bracketing SDOX Installation. 2015 value not included in average warming rate

Time Period	Year	Rate (°C/day)
Pre-install	2008	0.015
Pre-install	2009	0.023
Pre-install	2010	0.005
Install	2011	0.065
Post-install	2012	0.043
Post-install	2013	0.030
Post-install	2014	0.037
Post-install	2015	0.059
Post-install	2016	0.030
Post-install	2017	0.038

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

The main goal of the SDOX system is to provide an oxygenated hypolimnion from 12 meters in depth and below through much of the summer. While not designed to prevent anoxia (< 2mg/L DO) within the entire hypolimnion, it is expected to raise DO levels in the deepest 902 acre-feet of the lake. If DO levels increased, it is expected that ORP values would increase as well due to the availability of oxygen as an electron acceptor. However, low ORP (< 100mV) followed onset of anoxia by about three weeks and was concurrent with hypolimnetic nitrate depletion (**Figure 36 and Figure 16)**. This indicates a quick shift from an aerobic bacterial community producing carbon dioxide as the primary waste product to an anaerobic community producing sulfide and methane as waste products.

The duration of low ORP, just short of four months in 2017, was about 2 weeks less than pre-installation years. However, the volume of water experiencing reducing conditions did not encompass the entire hypolimnion as during pre-installation years. Duration and volume of low ORP was less than that experienced in 2016, indicating increased efficacy of the SDOX at creating oxidizing hypolimnetic conditions. In summary, while the stated oxygen goal was not realized, it is clear that the SDOX exerted a positive effect on hypolimnetic water quality.



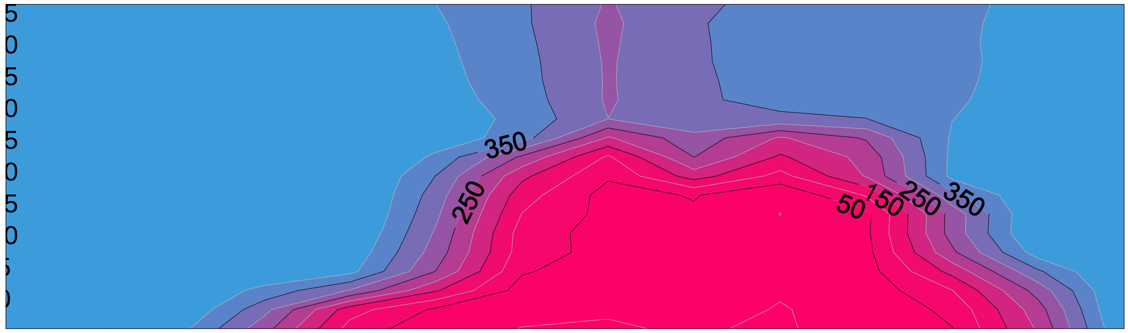


Figure 36. 2017 Isopleths Temperature, Dissolved Oxygen, and Oxidation-Reduction Potential (ORP) versus Elevation at Site 1; highlighting the temporal disparity between onset of stratification (Temperature), Anoxia (Dissolved Oxygen), and reducing conditions (ORP).

Another metric well suited to measure SDOX performance is the anoxic factor (AF) which 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 as seen in Equation 5.

Eq. 5 $$AF = \sum_{i=1}^{n}(t_i * a_i)/A_o$$

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 elevation at which anoxia is first encountered is used to ascertain corresponding area from the 2001 area-depth table. Analysis for sediment phosphorus content allows the estimate of sediment phosphorus release rate (RR), important for estimating internal loading to the lake. Multiplication of the RR by AF provides an estimate of sediment phosphorus load. Comparison of these equations to the historical dataset provides insight to SDOX performance trends (**Table 5**). The average of 2005 – 2009 represents pre-SDOX conditions as a baseline comparison against AF calculated for the following years. A marked reduction, lower AF, occurred during the first three full seasons of operation (2011 – 2013) indicating less phosphorus release from sediment. In 2014, a shift occurred and anoxic factor was higher than the 2005-2009 baseline and every year since 2015, the estimated P-load to the lake has increased relative to the baseline. As oxygen delivery was the highest since installation, the increase in AF and P-load of the last four years are a clear indicator of increased organic load to the hypolimnion, beyond the mitigation capacity of the SDOX.

Table 5. Summary of Anoxic Factor (AF) and sediment Phosphorus load (P-load) by year (2011 – 2017) with Relative Percent Difference (RPD) as it relates to 2005-2009 baseline average.

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	47.06	42%	4,552	28%
2017	47.13	43%	4,440	25%

Nutrients, and Chlorophyll-a

The SDOX system induces physical changes, such as increased dissolved oxygen and oxidation-reduction potential in the hypolimnion; it is meant to reduce phosphorus sediment loading and to provide oxidant for complete breakdown of organic molecules including taste and odor compounds. In 2017, as well as documented in previous years, the sediment nutrient load fuels chl-a during the late-summer/fall turnover, 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.

Examination of the 2017 chl-a values suggests that the process of oligotrophication has ceased, as algal biomass trends towards pre-SDOX years. It may be that the sharp increase in post-installation algal biomass began in 2016, however, the exact degree may have been clouded by the large quantities of pheophytin-a documented throughout that monitoring season.

Sediment Phosphorus

Sediment phosphorus concentration has traditionally 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 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 are 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 an inexact use of a terrestrial metric to index aqueous sediment dynamics. However, as iron is primary factor binding phosphorus and aluminum plays a role in aqueous phosphorus dynamics, examination of the PSR poses merit for tracking sediment binding ability in Lake Thunderbird. These make the PSR attractive as an option to track potential effects of the SDOX system and of the continual rain of organic matter to the phosphorus dynamics of the lake bottom.

Sample collection occurred at four sites in Lake Thunderbird on April 18, and October 11, of 2017. Sediment collected at site 1 represents the lacustrine portion of lake-bottom most affected and targeted by the SDOX system. Sediment collected at sites 6, 8, and 11 provides a contrast of riverine sediment to lacustrine sediment. Sediment cores were divided into two sub-samples: the top 2 centimeters of the core (surficial) and the underlying 5 to 10 centimeter intermediate zone. The surficial values are used to calculate sediment phosphorus load while molar values of both sediment layers are inputs for the PSR equation:

Eq. 6 $PSR_{Ox} = (\text{Oxalate-P}) / [(\text{Oxalate-Fe}) + (\text{Oxalate-Al})]$

The underlying assumption is that the oxalate extraction represents a reasonable measure of aluminum and iron ability to bind phosphorus. Terrestrial application of the PSR suggests values greater than 0.25 are samples saturated with phosphorus. The simplest interpretation of the PSR would be the lower the value the greater the ability of the sediment to bind phosphorus.

All sediment PSR values were well below 0.25 with a low of 0.034 at site 8 and maximum of 0.125 at site 6 (**Figure 37**). Differences between riverine sites were statistically significant as a group of site 8 and 11 results were statistically separate from other sites. Sites 1 and 6 the most similar exhibiting no measurable, statistical difference. These values suggest that sediment at sites 1 and 6 have less capacity to bind phosphorus than site 8 and 11. When compared to overlying water quality (**Figure 13**), a relationship of lower sediment PSR (greater ability to bind phosphorus) to lower overlying aqueous phosphorus concentration is seen.

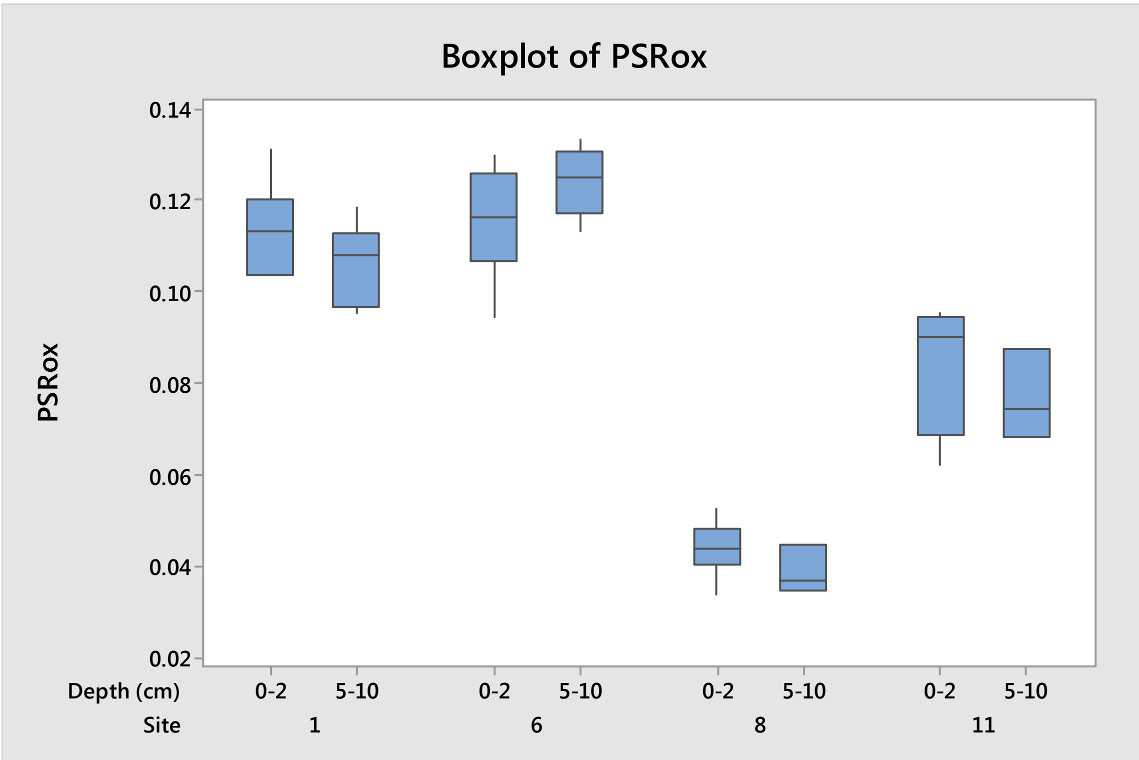


Figure 37. 2017 box and whisker plot of Phosphorus Saturation Ratio by site and depth range.

Discussion

For the past 17 years, OWRB has documented the water quality of Lake Thunderbird; observing the consequences of cultural eutrophication and degrading 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. Flooding in 2015 and in 2016 hampered the oligotrophication process, in part due to high organic content in floodwaters and associated inflowing nutrients. In 2017, excessive algal growth continues its upward trend to reach pre-SDOX levels, averaging only 5.46 µg/L less than the highest average on record. Data collected by Norman’s Drinking water treatment plan shows a clear connection between excessive algae, excessive taste and odor compounds, and spikes in complaints by drinking water customers. It is clear that degraded raw water quality has increased the cost of producing potable water.

Climactically, Lake Thunderbird experienced a slightly warmer winter and a wetter, cooler August than usual, resulting in peak epilimnetic temperature in July, rather than typical August. Inputs to the lake remained relatively equal with total outputs, resulting in an overall static water level. Relatively large inflows in late August caused a slight disruption to thermal stratification; however, the overall pattern of stratification remained similar to previous years. Weak stratification was observed at the May sample event and had fully set up by June, coinciding with a completely anoxic hypolimnion. Indicative of a hypereutrophic system, complete metalimnetic anoxia was evident by July 12, persisting through the summer until thermal mixing in late September. This recent trend of metalimnetic anoxia further underscores the excessive algal growth and the urgent need for addressing the water quality impairments in the lake.

Dissolved and total forms of nutrients, primarily nitrogen and phosphorus, were examined with respect to their spatial and temporal trends, as well as their role in limiting algal growth. Total phosphorus values were consistent with those typically reported in Lake Thunderbird during recent years, but are higher than they should be to effectively curb excess biological productivity. Lacustrine phosphorus measures were generally lower than riverine surface phosphorus, suggesting delivery of a large load of this nutrient is attributed to runoff from the watershed. Late summer and early fall hypolimnetic phosphorus values were high, stemming from increased bacterial decomposition of organic matter and release from anoxic sediment. Nitrogen, another nutrient important for algal growth, was also readily available in 2017, returning to the higher levels of previous years rather than the decreased values documented last year. Nitrogen dynamics were a little confounding this year, as ammonia was detected in the epilimnion throughout the year; ammonia requires the least amount of energy for assimilation by algae so should be used first and one would expect levels below the reporting limit. However, nitrate/nitrite, the second most easily assimilated form of nitrogen, were below reporting limit first this year. Lacustrine nitrogen measures were generally lower than riverine nitrogen, again suggesting the tributaries as an important source of both nitrogen and phosphorus inputs. Hypolimnetic accumulation of TKN and ammonia was evident in late summer and early fall precipitated by increased bacterial decomposition of organic matter and release from anoxic sediment. Neither nutrient was found to be substantially limiting algal growth in 2017, as they were present in abundant amounts. Data collected in 2017 and documented relationships in scientific literature demonstrate the connection from excess nutrients to degraded raw water quality, therefore it remains imperative to meet TMDL nutrient reduction targets.

The TMDL developed by ODEQ in 2013 sets nutrient and sediment load reduction targets that, if met, would improve water quality in the lake to meet designated uses. It suggests a 35% load reduction rate for Total Nitrogen, Total Phosphorus, and Suspended Solids. This waste load allocation is divided amongst the three primary municipalities in the watershed: Moore, Norman and Oklahoma City (ODEQ, 2013). This document also provides suggestions of management strategies to aid in meeting reduction targets and the attainment of Lake Thunderbird's beneficial uses.

Chlorophyll-a is used as a proxy to measure algal biomass and it's important to understand the factors driving growth, due to its potential to cause drinking water and recreation issues. Lake Thunderbird's SWS designation requires average chl-a to be less than 10 µg/L; a use for which it is consistently impaired. Average chlorophyll-a values increased again in 2017, an ongoing trend since 2015, representing a need for algal biomass mitigation. In order to control biological populations, it is important to understand what is driving their growth. Data for 2017 was examined with respect to factors driving algal growth in three primary ways: multi-variate TSI plots, Total Nitrogen to Total Phosphorus ratio, and multiple regression analysis. Of the three, multiple regression analysis proved to be the most enlightening in determining factors limiting algal growth. It suggested that light, rather than nutrients, was the most limiting to algal growth, explaining almost 90% of the variability of chlorophyll-a values using two stressor parameters – secchi disk depth and organic nitrogen. Observed, continued eutrophication of Lake Thunderbird highlights the need for mitigation to meet impaired beneficial uses, as well as to improve and sustain suitability of a major drinking water source.

Another consequence of cultural eutrophication that can lead to many environmental problems is the proliferation of Harmful Algal Blooms (HABs). Several species of Cyanobacteria, or blue-green algae - a known contributor to HABs, occur in and dominate phytoplankton communities in many 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 reporting limits in the treatment process. The City of Norman has historically received taste and odor complaints in finished drinking water in September following significant lake mixing events; in 2017, as in other years, these complaints are directly attributable to the presence of these compounds. These mixing events contributed to taste and odor complaints through the process of hypolimnetically stored compounds mixing up and releasing in the epilimnion and through the epilimnetic algal die-off causing release of MIB and Geosmin. In addition to their causal relationship to T&O events, blue-green algae have the capability to produce multiple toxins that can cause skin irritations or lethality to humans, livestock, and pets that drink from untreated contaminated water sources.

Lake Thunderbird is 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 identified by the ODEQ TMDL as excess nitrogen and phosphorus. OWRB has thoroughly analyzed these impairments and tracks the interplay of all macronutrients (including light) throughout the years. An important observation in 2017 is a shift from chemical nutrient limitation to light limitation, as nutrients were abundant enough to not hinder algal growth. This underscores the urgency for necessary nutrient reductions within the lake and the watershed. Monitoring data, collected in 2017, 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 criterion 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 installation of a hypolimnetic oxidation system in 2010 was an important step in an effort to mitigate excessive algae growth in the lake. The strength of a hypolimnetic oxidation system is direct delivery of oxygen to hypolimnion, increasing ORP, and thus enabling bacterial breakdown of organic detritus. The efficacy of this in-lake mitigation tool is enhanced with changes in land use behaviors within the watershed. Positive changes in water quality were seen in the first several years of SDOX operation, however the last two years have experienced a decline of water quality towards pre-SDOX levels. The increase in anoxic factor and sediment derived phosphorus load observed the last two years are a clear indicator of increased organic load (algal growth). The last several years of monitoring have reinforced the need to increase oxygen delivery into the lake bottom and ran at 85% capacity this year, the highest since installation. It is important to consider that all oxygen delivered (441,969 lb.) was utilized, enabling the breakdown of organic detritus and limiting its potential to affect future algal growth. A dissolved oxygen bulge was seen on the September 20 event, centered near the 1006' elevation, suggesting positive SDOX impact. This effect could be observed once hypolimnetic oxygen demand abated enough to allow the SDOX's ability to oxygenate the hypolimnion to show through, highlighting the need to determine hypolimnetic oxygen demand to more accurately manage SDOX and in-lake processes (**Appendix D**). It is also likely the SDOX has dampened the impact of algal growth on the amount of taste and odor chemicals stored in the hypolimnion. So, while peak and average chlorophyll-a in 2017 are as high as any time since OWRB monitoring, the lake still benefits from SDOX implementation. Other positive impacts of the SDOX, such as a DO bulge on September 20 and a decreased time period and volume of hypolimnetic water exhibiting low ORP, were observed in 2017. The lake management strategy in terms of water quality, including both in-lake and watershed measures, needs to be more aggressive in order to facilitate effective, measurable mitigation in the future. The first few years following installation of the SDOX highlighted the value of the hypolimnetic oxidation to not only provide aerobic lake habitat, but also improve the quality of raw drinking water for municipalities and reduce recreational health risks due to the growth of harmful algae. Unfortunately, ongoing eutrophication indicates SDOX operation alone will not provide the relief Lake Thunderbird needs to recover its attainment of beneficial uses.

Recommendations

Past years have shown hypolimnetic oxygenation to be an effective mitigation tool, but current sediment and water oxygen demand has increased past the ability of the SDOX. Assessment of current oxygen demand (the water column and sediment) for the anoxic zone and hypolimnion is an important planning effort toward optimizing oxidation efficiency. The OWRB has developed a Scope of Work outlining objectives, methods and cost to assess hypolimnetic oxygen demand in 2018 (**Appendix D**). Monitoring for the assessment of 2018 oxygen load provides a baseline level to weigh future hypolimnetic oxidation modifications. The ability to target the lowest portion of lake is necessary to increase the effectiveness of any oxygen delivery system, therefore a proposal to pilot a Speece cone installation utilizing the existing infrastructure is recommended (**Appendix E**). Speece cones produce a relatively laminar flow with high oxygen transfer efficiency, optimizing cost effectiveness and minimizing upward mixing from outlet flow.

Updating the lake's bathymetric survey is an important step towards minimizing error when estimating SDOX DO load assessment and increases the accuracy of any future water quality (nutrient enrichment, eutrophication, or sediment transport) response models. **Appendix F** details the Scope of Work for the OWRB to complete a bathymetric survey in 2018.

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 continue to be minimized. Aggressive watershed BMP implementation is necessary to reduce nutrient and solids movement to waterways and into Lake Thunderbird. Elevated nutrients and low water transparency of the riverine sites underscore this need to meet TMDL reduction targets. 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)

Another avenue to improve Lake Thunderbird's water quality health is to foster cooperation and collaboration between all stakeholders within the watershed to assist in reducing runoff from construction activities and urban land uses. The COMCD is in a good position to play a protective role for the health of Lake Thunderbird; upon formation, COMCD was designated with jurisdictional authority regarding construction activities within the watershed. Accessing the Clean Water State Revolving Fund (CWSRF) to offer prioritized financial incentives would be a direct, positive means of exercising the COMCD’s authority and role toward protecting Lake Thunderbird.

References

Carlson, R. (1977). A trophic state index for lakes. *Limnology and Oceanography, 22,* 361-369.

Carlson, R. (1979). *Lake and Reservoir Classification Systems.* United States Environmental Protection Agency. Washington D.C.: United States Environmental Protection Agency.

Carlson, R. (1991). Expanding the trophic state concept to identify non-nutrient limited lakes and reservoirs. *Enhancing the States' lake management programs* (pp. 59-71). Chicago: USEPA.

COMCD. (2006). *Rock Creek Watershed Analysis and Water Quality Evaluation.* Norman, OK: Central Oklahoma Master Conservancy District.

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

EPA. (2009). *National Lakes Assessment: A collaborative survey of the nation's lakes.* United States Environmental Protection Agency, Office of Water and Office of Research and Development. Washington D.C.: USEPA.

Gantzer, P. (2008). Controlling Oxygen, Iron, and Manganese in Water-Supply Reservoirs Using Hypolimnetic Oxygenation. Virginia Polytechnic Institute and State University.

Graham, J. L., Loftin, K., Ziegler, A., & Meyer, M. (2008). *Guidelines for design and sampling for cyanobacterial toxin and taste-and-odor studies in lakes and reservoirs.* Reston, VA: U.S. Geological Survey Scientific Investigations Report.

Lerman, A., & Baccini, P. (1978). *Lakes-Chemistry, Geology, Physics.* Verlag, NY: Springer.

Low Impact Development (LID) Urban Design Tools. (2014). Retrieved March 2, 2016, from Low Impact Development Center, Inc: http://lid-stormwater.net/index.html

Low Impact Development Center. (2014). Retrieved March 2, 2016, from Low Impact Development Center, Inc.: http://www.lowimpactdevelopment.org/index.htm

Nair, V. D., Harris, W. G., & Chakraborty, D. (2010). *An Indicator of Risk of Phosphorus Loss from Sandy Soils.* Retrieved from University of Florida Institute of Food and Agricultural Sciences Extension: http://edis.ifas.ufl.edu/ss539#FOOTNOTE_1

Nurnberg, G. (1994). Phosphorous Release from Anoxic Sediments: What we know and how we can deal with it. *Limnetica, 10*(1), 1-4.

OAC. (2008). Title 785, Oklahoma Water Resources Board: Chapter 45 , Oklahoma's Water Quality Standards; Chapter 46, Implementation of Oklahoma's Water Quality Standards. *Oklahoma Administrative Code*. Oklahoma City,, OK.

OCS. (2015). *Rainfall Summary Statistics for 2015*. Retrieved from Oklahoma Climatological Survey: http://climate.ok.gov/index.php

ODEQ. (2013). *Lake Thunderbird Report for Nutrient, Turbidity, and Dissolved Oxygen TMDLs.* Oklahoma City, OK: Oklahoma Department of Environmental Quality.

ODEQ. (2014). *The State of Oklahoma 2014 Water Qualit Assessment Integrated Report.* Oklahoma City, OK: Oklahoma Department of Environmental Quality.

OWRB. (2002). *Lake Thunderbird Capacity and Water Quality 2001 for the Central Oklahoma Master Conservancy District*. Oklahoma City, OK: Oklahoma Water Resources Board.

OWRB. (2010). *Clean Water State Revolving Fund Loan and American Recovery and Reinvestment Act ORF-09-0027-CW: Lake Thunderbird Water Quality Monitoring 2010-2012*. Oklahoma City, OK: Oklahoma Water Resources Board.

OWRB. (2011). *Devloping In-Lake BMPs to Enhance Raw Water Quality of Oklahoma's Sensitive Water Supply.* Oklahoma Water Resources Board. Oklahoma City, OK: OWRB.

OWRB. (2012). *Lake Thunderbird Water Quality 2012*. Oklahoma Water Resources Board. Oklahoma City, OK: OWRB.

Wetzel, R. G. (2001). *Limnology: Lake and River Ecysystems* (Third Edition ed.). Cambridge, MA: Academic Press.

Zhang, H., Schroder, J. L., Fuhrman, J. K., Basta, N. T., Storm, D. E., & Payton, M. E. (2005). Path and Multiple Regression Analyses of Phosphorus Sorption Capacity. *Soil Science Society of America Journal, 69*, 96-106.

Appendix A
Quality Control Data

Tabular Summary of 2017 Chlorophyll-a Quality Control Samples: Site 1 duplicate samples labeled as 1(12) & 1 (21) with summary statistics.

Date	Site 1 (12)	Site 1 (21)	Average	sd
4/18/2017	3.7	3.2	3.45	0.25
5/18/2017	10.7	10.1	10.4	0.3
6/14/2017	15.4	17.8	16.6	1.2
7/12/2017	39.2	38	38.6	0.6
7/26/2017	43.9	43.9	43.9	0
8/9/2017	46.9	51.6	49.25	2.35
8/23/2017	47.5	49.8	48.65	1.15
9/7/2017	12.5	13	12.75	0.25
9/20/2017	25.5	27.3	26.4	0.9
10/11/2017	26.5	27.6	27.05	0.55

sd – standard deviation

Tabular Summary of 2017 Blank Quality Control Sample Reports, labeled as site 1 (31).

Date	Total Kjeldahl Nitrogen mg/l	Nitrite+ Nitrate mg/l	Ammonia mg/l	Ortho-P mg/l	Total P mg/l
4/18/2017	<0.050	<0.050	<0.050	<0.005	<0.015
5/18/2017	0.086	<0.050	<0.050	<0.005	<0.015
6/14/2017	<0.050	<0.050	<0.050	<0.005	<0.015
7/12/2017	0.622/<0.05	<0.050	0.068/<0.050	<0.005	<0.015
7/26/2017	0.218	<0.050	<0.050	<0.005	<0.015
8/9/2017	<0.050	<0.050	<0.050	<0.005	<0.015
8/23/2017	<0.050	<0.050	<0.050	<0.005	<0.015
9/7/2017	<0.050	<0.050	<0.050	<0.005	<0.015
9/20/2017	<0.050	<0.050	<0.050	<0.005	<0.015
10/11/2017	<0.050	<0.050	<0.050	0.02	<0.015

BPQL – Below Practicable Quantification Limit

Tabular Summary of 2017 Replicate Sample Results Labeled as 1 (12) & 1 (22)

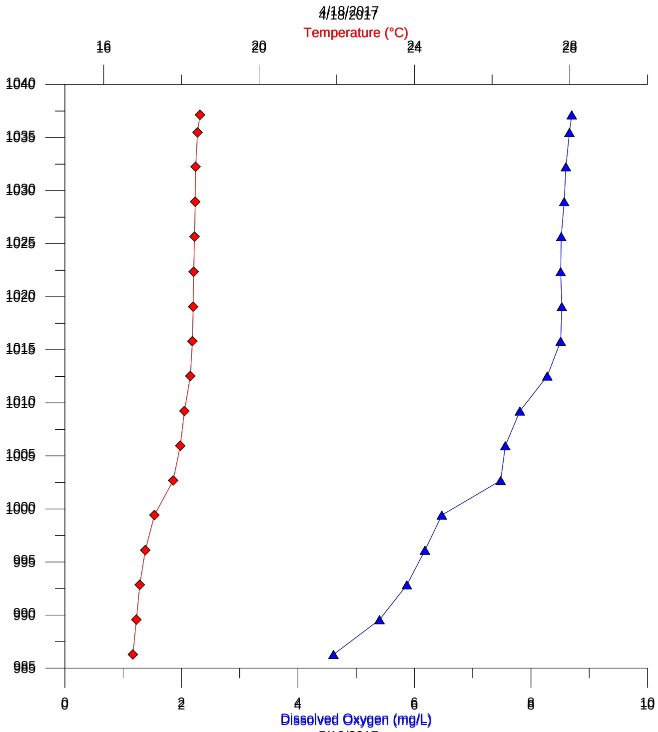
Date	Site	Total Kjeldahl Nitrogen mg/l	Nitrite+ Nitrate (mg/l)	Ammonia mg/l	Ortho-P mg/l	Total P mg/l	Chlorophyll-a µg/L
4/18/2017	1(12)	<0.050	0.305	0.088	0.012	0.023	3.7
5/18/2017	1(12)	0.598	0.077	0.063	<0.005	0.033	10.7
6/14/2017	1(12)	0.414	<0.050	0.105	<0.005	0.028	15.4
7/12/2017	1(12)	0.866	<0.050	0.091	0.008	0.024	39.2
7/26/2017	1(12)	1.35	<0.050	0.161	<0.005	0.027	43.9
8/9/2017	1(12)	1.49	<0.050	0.108	<0.005	0.025	46.9
8/23/2017	1(12)	1.16	<0.050	0.116	0.005	0.035	47.5
9/7/2017	1(12)	1.15	<0.050	0.258	<0.005	0.031	12.5
9/20/2017	1(12)	0.661	<0.050	0.402	0.02	0.05	25.5
10/11/2017	1(12)	0.322	0.204	0.11	0.01	0.038	26.5

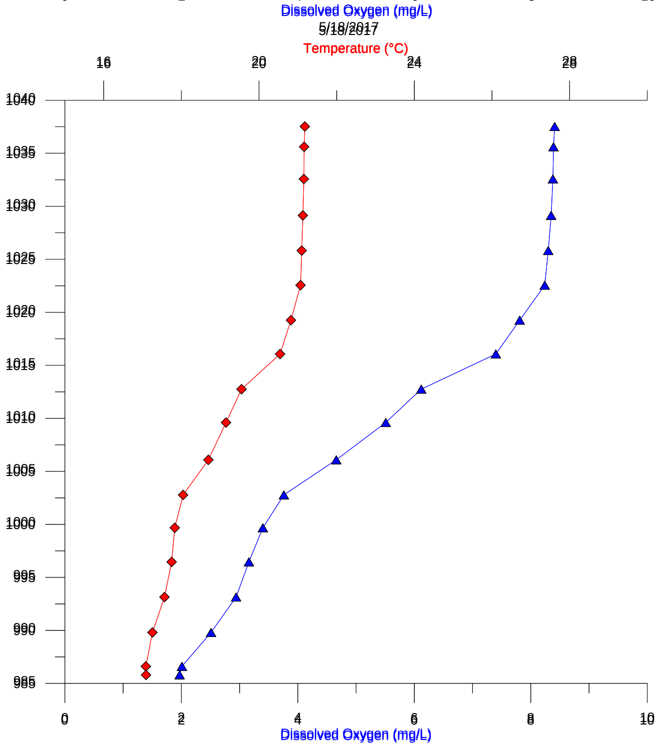
4/18/2017	1(22)	<0.050	0.306	0.064	0.01	0.021	3.2
5/18/2017	1(22)	0.551	0.075	0.071	<0.005	0.032	11.3
6/14/2017	1(22)	0.26	<0.050	0.093	<0.005	0.025	18.4
7/12/2017	1(22)	0.966	<0.050	0.078	<0.005	0.025	36.2
7/26/2017	1(22)	1.38	<0.050	0.178	<0.005	0.027	42.1
8/9/2017	1(22)	1.63	<0.050	1.06	<0.005	0.028	45.7
8/23/2017	1(22)	0.599	<0.050	0.084	0.01	0.034	49.8
9/7/2017	1(22)	1.04	<0.050	0.228	0.008	0.029	13.6
9/20/2017	1(22)	1.26	<0.050	0.273	0.007	0.046	25.5
10/11/2017	1(22)	0.378	0.201	0.114	0.012	0.037	29.4

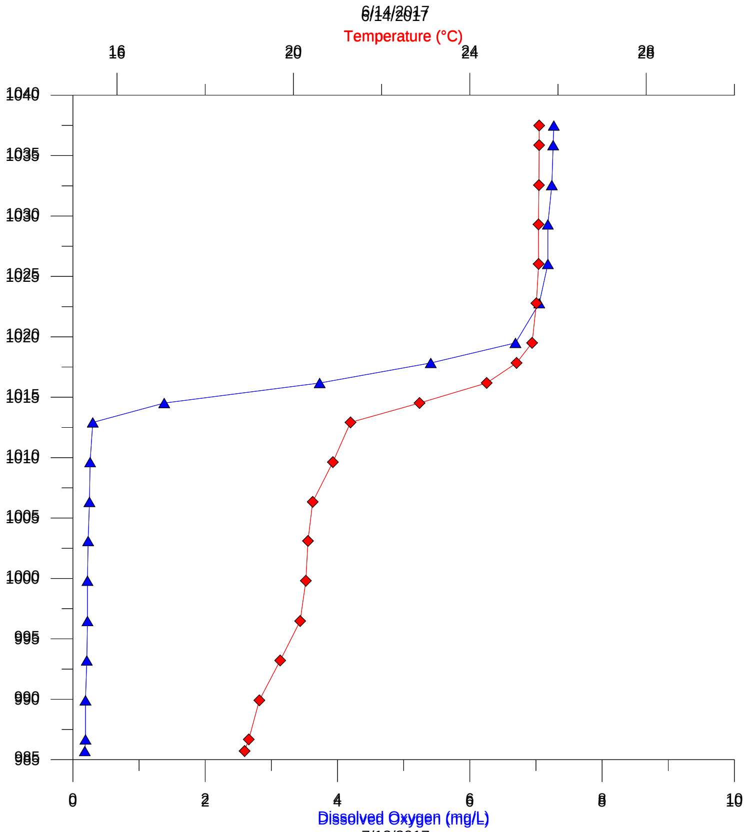
Appendix B

Temperature and Dissolved Oxygen versus Depth at Site 1

Temperature is denoted as Red Diamond Markers while Dissolved Oxygen is denoted as Blue Triangle Markers



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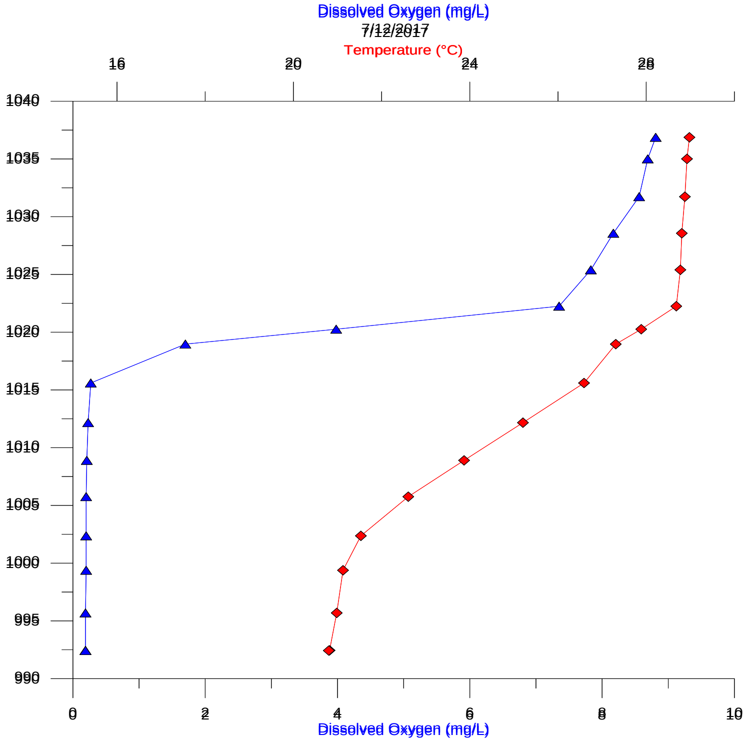
Dissolved Oxygen (mg/L)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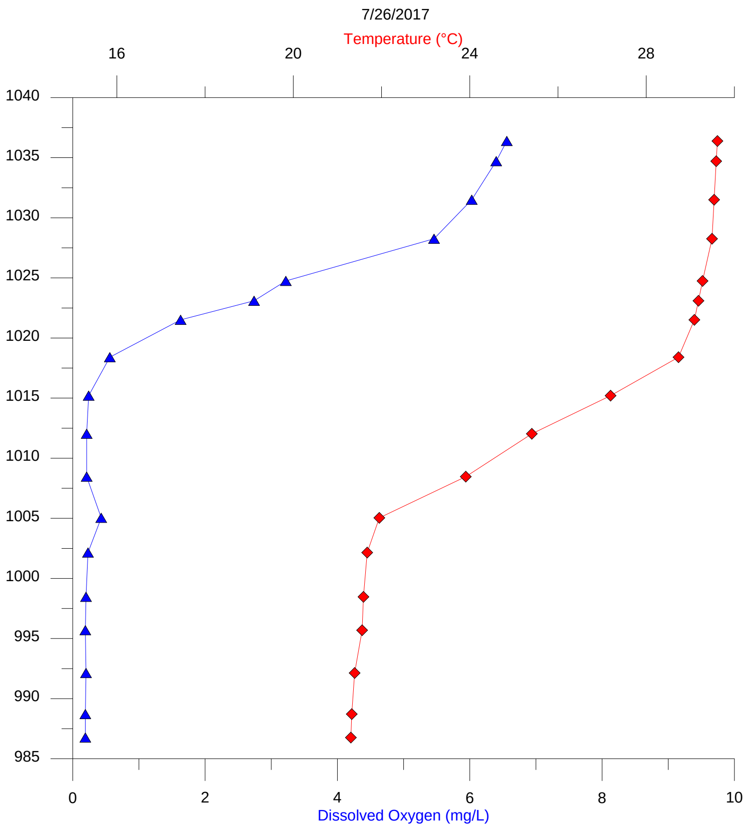
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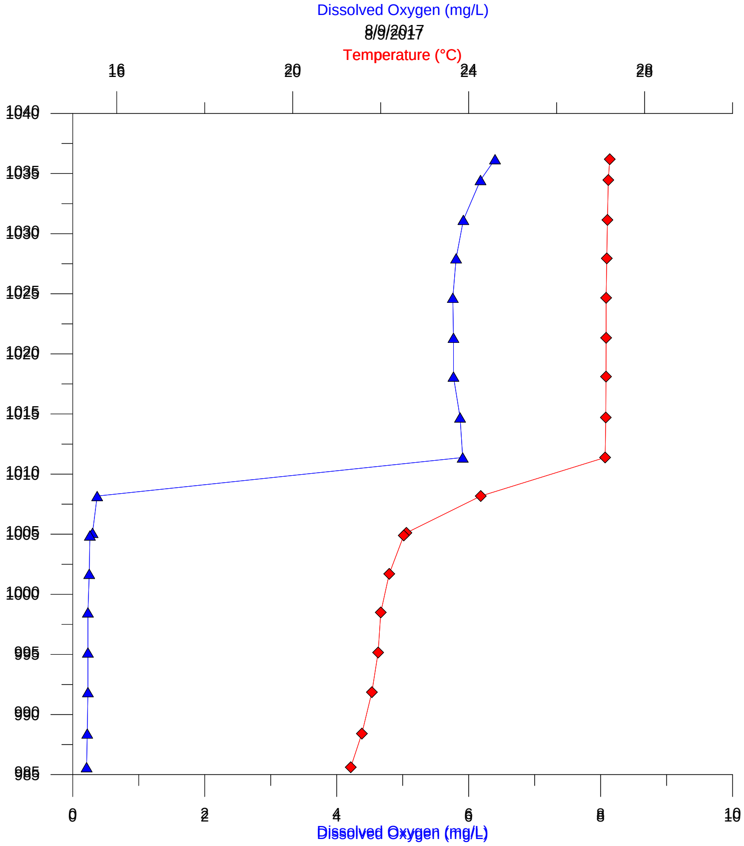
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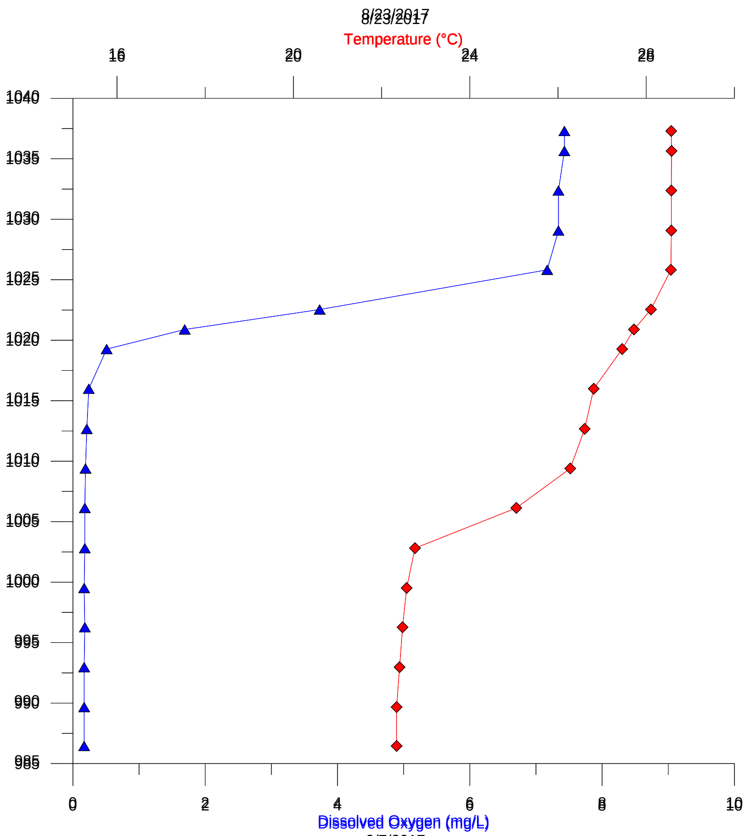
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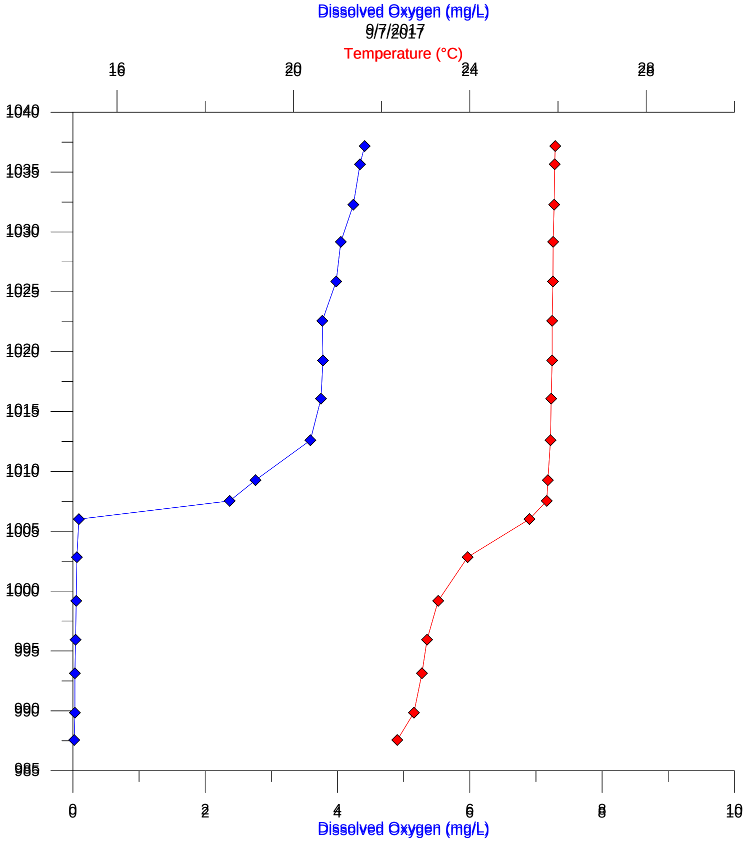
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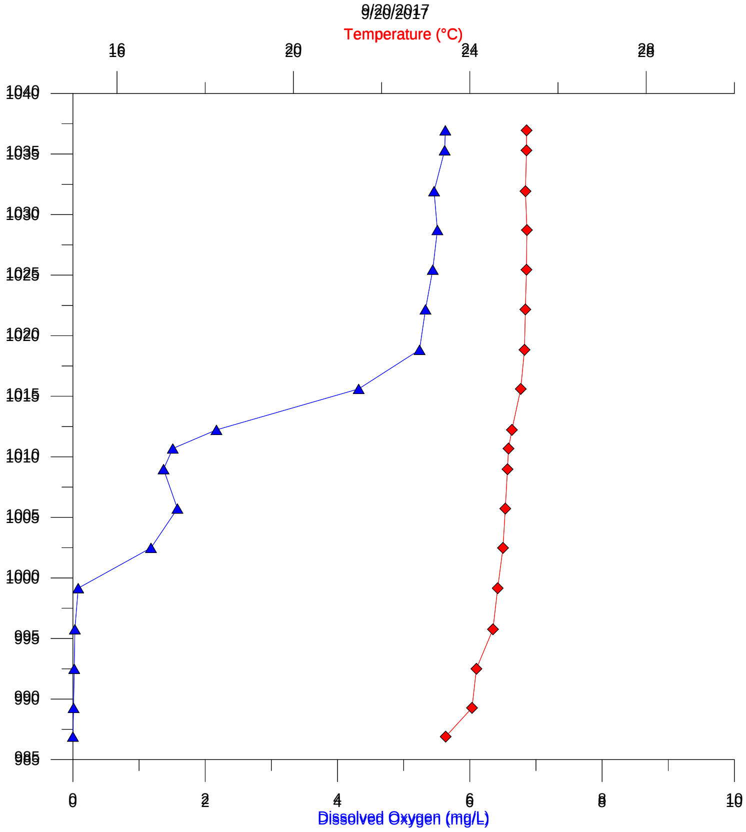
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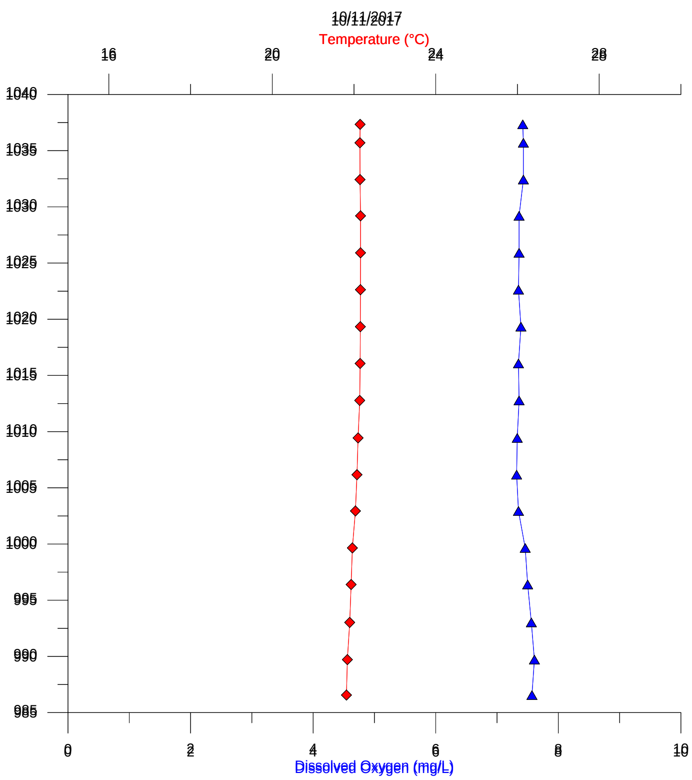
Dissolved Oxygen (mg/L)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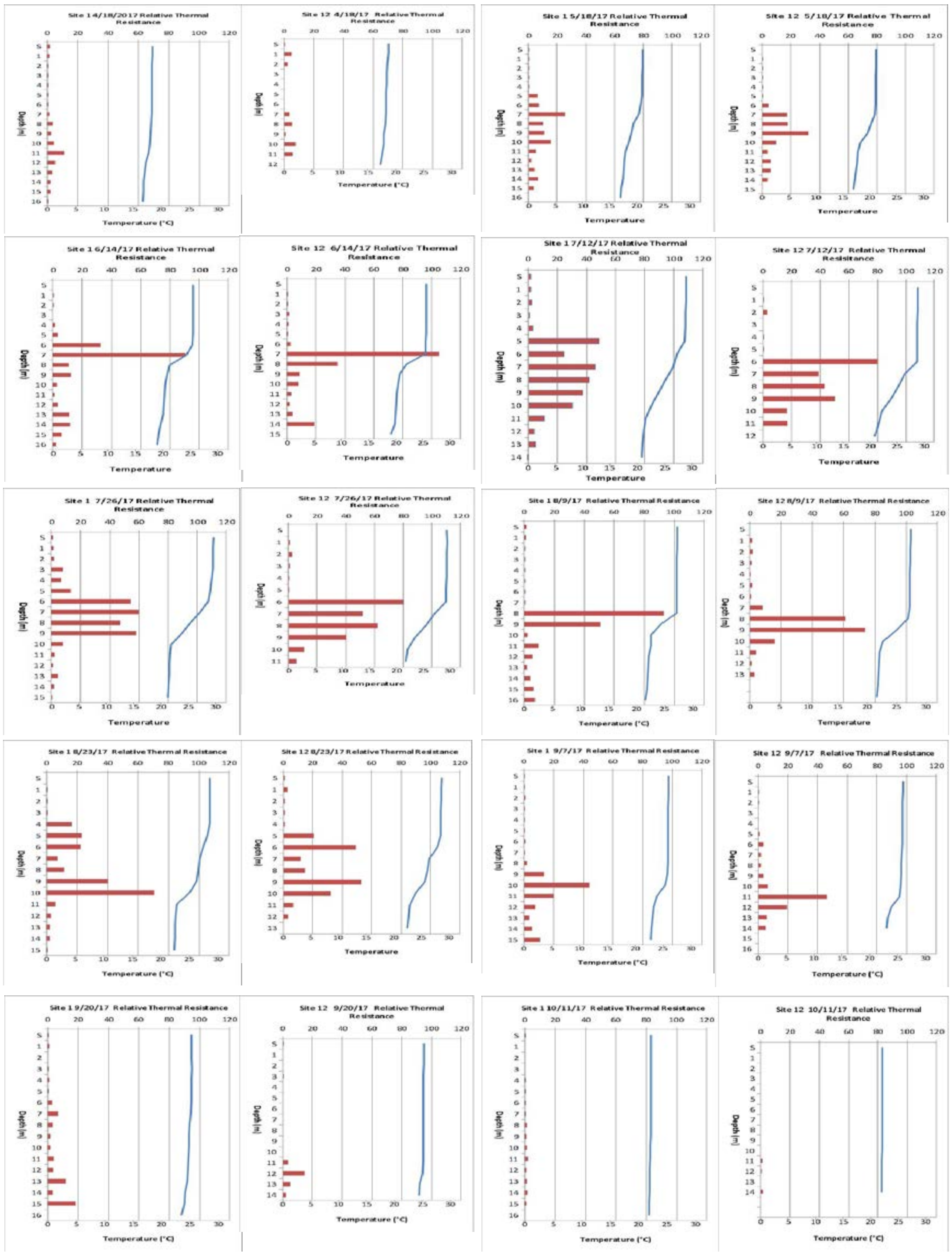
Dissolved Oxygen (mg/L)

Appendix C
Thermal Stratification (RTR) Plots



Appendix D

Planning Proposal for Quantifying

Hypolimnetic Oxygen Demand of Lake Thunderbird 2018

Introduction

The goal of this Intergovernmental Agreement is to provide information in fiscal year 2018 as described herein. This document outlines a cost-effective means of estimating the oxygen delivery required for sufficient hypolimnetic oxidation to meet performance expectations of the installed SDOX device. This work will provide critical information for any oxidation device to meet its outlined performance measures. Monitoring and reporting will occur as detailed below. Two costs have been developed for implementing this monitoring and reporting scheme in the fiscal year 2018: one using a wastewater procedure using our contract laboratory and the other, a more accurate procedure, using a field and laboratory method employing an OSU Graduate student. Table 1 outlines the costs for these two options.

Monitoring:

The field sampling regime includes both water and sediment samples collected at four planned sample events already conducted through OWRB routine monitoring: mid- June, mid-August, late August, and September. Five water quality samples will be collected at site 1 with the same distribution as the current routine monitoring project, and vertical water quality profiles will be measured at sites 1 and 4. Sediment samples will be collected at a range of elevations, correlating to depths in SDOX target zone, in order to better define sediment oxygen demand and SDOX performance. All sediment samples will be analyzed for Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD).

Reporting:

BOD and COD results will be integrated with water quantity measurements and collected water quality data to estimate hypolimnetic oxygen demand. The data collected over four sample events in the growing season will be used to assess peak and average oxygen required to meet a range of water quality based endpoints for 2018. Evaluation will take into account the existing oxidation system, which will be included in the OWRB's annual report as well as recommendations for future mitigation efforts.

Fiscal Year 2018 Budget:

2018 Quantify Hypolimnetic Oxygen Demand OWRB Lab			
Personnel	**Person Yrs.**		**Expenditure**
Total Person Years =	0.04	**Sub-total =**	$ 4,800
Laboratory			
Oxygen Demand in Water & Sediment			$ 2,092
		Contractual Sub-total =	$ 2,092
		TOTAL PROJECT COST =	**$ 6,892**

2018 Quantify Hypolimnetic Oxygen Demand OSU			
Personnel	**Person Yrs.**		**Expenditure**
Total Person Years =	0.025	**Sub-total =**	$ 3,202
Laboratory			
Oxygen Demand in Water			$ 1,100
Oxygen Demand in Sediment			$ 10,000
		Contractual Sub-total =	$ 11,100
		TOTAL PROJECT COST =	**$ 14,302**

Appendix E
Proposal to Pilot Speece Cone Hypolimnetic Oxidation

Hypolimnetic Oxygenation System

For Water Quality Improvements

Lake Thunderbird, OK

January 19, 2018

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Paul Koenig
Oklahoma Resources Water Board
Paul.Koenig@owrb.ok.gov

Re: ECO_2 SuperOxygenation System Lease for a 5,200 lbs/day Hypolimnetic Oxygenation System for Lake Thunderbird, OK

Dear Paul,

Thank you for your interest in the ECO2 "Speece Cone" SuperOxygenation System. The ECO_2 SuperOxygenation System is the world's most efficient oxygen transfer device with a proven average oxygen transfer efficiency of 95%. ECO2 has over 75 installations in the water and wastewater field with a 100% success rate. Two case studies for comparable hypolimnetic oxygenation systems are included in Appendix 2.

Upon review of the provided information for the existing oxygenation system at Lake Thunderbird, we're pleased to provide a solution that will indeed add the required amount of oxygen to Lake Thunderbird.

The less than satisfactory results in the lake over the last five years were caused by the existing malfunctioning oxygenation equipment. The ECO2 SuperOxygenation System is far superior, as it employs no moving parts other than the side stream pump, uses large openings that are not prone to scaling or clogging, and has a proven average oxygen transfer efficiency of 95%.

We would therefore like to provide you with a lease proposal for a system that will reliably add the 5,200 lbs/day to Lake Thunderbird during the 2018 summer season. To minimize cost, we may be able to re-use the existing 250 HP side stream pump, but operate it at a higher efficiency, resulting in reduced energy consumption. The pump curve of the existing pump is within our design range; however, it is unclear if the NPSH of the pump is suitable for the current equipment arrangement. The existing side stream piping will need to be inspected to determine whether it can be re-used. Typically, an ECO2 system in this arrangement would require a discharge pipe with small diameter nozzles spaced every 8-10 ft and pointed in an appropriate direction to spread the oxygenated water across the sediment. The system provided under the suggested lease proposal includes the ECO2 Speece Cone and simple Oxygen Flow Controls. One of our engineers will be available on-site for installation questions and system start-up.

ECO_2 is looking forward to working with you on this project.

Best regards,

Kevin Jacobs, P.E.
Director of Engineering
Eco Oxygen Technologies, LLC
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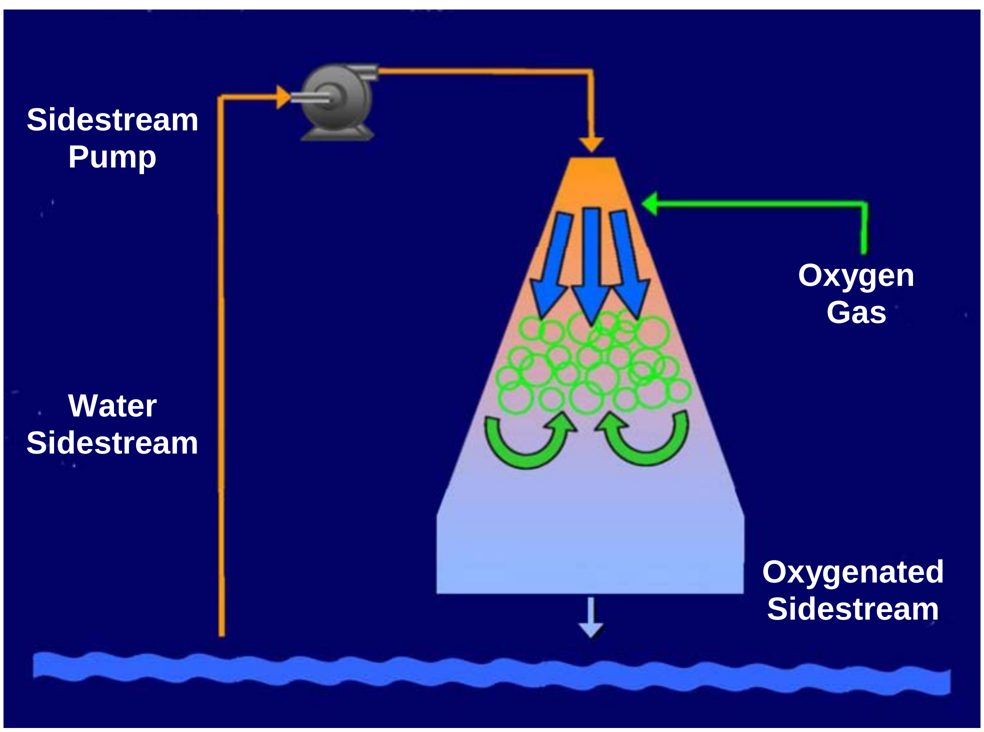
ECO$_2$ System

The ECO$_2$ Technology is based on Henry's Law and works by trapping pure oxygen bubbles inside the ECO$_2$ cone until they are dissolved. The system operates by pumping a side stream of water through a conical shaped oxygen transfer reactor, also known as the Speece Cone. Gaseous oxygen is fed into the cone and broken up into an intense bubble swarm by the velocity of the wastewater. This action creates an exceptionally large oxygen / water interface. The cone shape design provides sufficient contact time for the oxygen to fully dissolve in the water. The cone does NOT employ a pressurized pure oxygen headspace. The high oxygen transfer efficiency of >90% is achieved through the bubble swarm action in the cone.

The ECO$_2$ SuperOxygenation system can be installed in a small footprint on shore or can be submerged in the reservoir.



The proposed system will take a side stream and oxygenate it before sending the oxygenated water back into the hypolimnion of the lake.

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Budget Lease Proposal

ECO2 will provide a SuperOxygenation system, consisting of a Speece Cone and Oxygen Flow Controls, capable of dissolving 5,200 lbs/day of oxygen. The oxygen is dissolved into a side stream that is pulled from the hypolimnion of Lake Thunderbird, oxygenated and returned into the hypolimnion horizontally across the sediment. The proposed system may be able to reuse the existing side stream pump and possibly the existing intake and discharge piping, but further analysis is required.

Pump Pressure (ft of head)	140	175	200
Side Stream Flow Rate (gpm)	3,000	2,400	3,000
Target Oxygen Addition (lbs/day)	5,200	5,200	5,200
Maximum Oxygen Addition Capability (lbs/day)	5,200	5,200	6,700

*Site elevation assumed at 1,000 ft above MSL and water temperature of 22 deg C.

The discharge piping is what will need to be designed/adjusted to create the back pressure on the ECO2 system. For example, 15 one (1) inch diameter nozzles could be added to the pipe to create 200 ft of back pressure. The nozzles could be spaced and oriented to push the oxygenated water into different areas of the reservoir.

It is crucial for hypolimnetic oxygenation during summer stagnation to start the oxygenation before the DO is starting to drop in the hypolimnion. We therefore offer a 7 month seasonal lease for the Summer 2018 season (April – October) to demonstrate what the ECO2 System can do for Lake Thunderbird. We believe that the design of 5,200 lbs/day of oxygen addition should be sufficient to maintain aerobic conditions within the hypolimnion, it is just a matter of reliably adding the required amount, which the ECO2 System will do.

The monthly lease for the ECO2 System and Controls is $9,000, based on a 7 months lease period.

In order to have the system operational by next spring, we suggest the following steps:

- A site visit to review the existing pump and diffuser and determine flow rate and pressure capabilities.
- A meeting to go through the demonstrations goals and a discussion of how to proceed after the demonstration (purchase, continued lease, removal), etc.

Operational Considerations and Performance Criteria

Oxygen Transfer Efficiency (OTE):

The ECO_2 system has a proven average oxygen transfer efficiency (OTE) of 95%. This means that roughly 95% of the oxygen fed into the ECO_2 system gets dissolved and thus is available to sustain aerobic conditions. The high OTE is critical in comparing the life cycle costs of different oxygen transfer equipment.

Hypolimnetic Oxygenation

Hypolimnetic Oxygenation means that already dissolved oxygen is delivered directly into the hypolimnion – the bottom layer of a lake that has no access to atmospheric oxygen during the summer stratification. Oxygen is consumed rapidly in this layer, resulting in anaerobic conditions and the solubilization of iron and manganese, as well as phosphorous from the sediment. Trying to address this problem with surface aerators requires mixing of the entire lake volume and destratisfying the lake to bring oxygenated water from the surface to the lower levels. Aeration systems that bubble air into the lake have to deal with the low oxygen transfer rate and the fact that bubbles rise to the surface, making the oxygen not necessarily available in the lower levels of the lake where it is needed. Both technologies destroy the natural stratification of the lake.
The ECO_2 System on the other hand is a very effective technology that delivers dissolved oxygen horizontally to the hypolimnion, creating an "aerobic cap" above the sediment that prevents sulfide formation and locks in Fe, Mn and P.

Maintenance and Life Expectancy

The ECO_2 system has very little required maintenance costs. The ECO_2 cone is fabricated from stainless steel and has no moving parts. It requires no regular maintenance and has a life expectancy of 20+ years. The only service item is the side stream pump which is a standard industrial water pump. Other transfer devices that have small orifices and nozzles are prone to clogging leading to high maintenance costs and unreliable service.

Experience & Guarantee

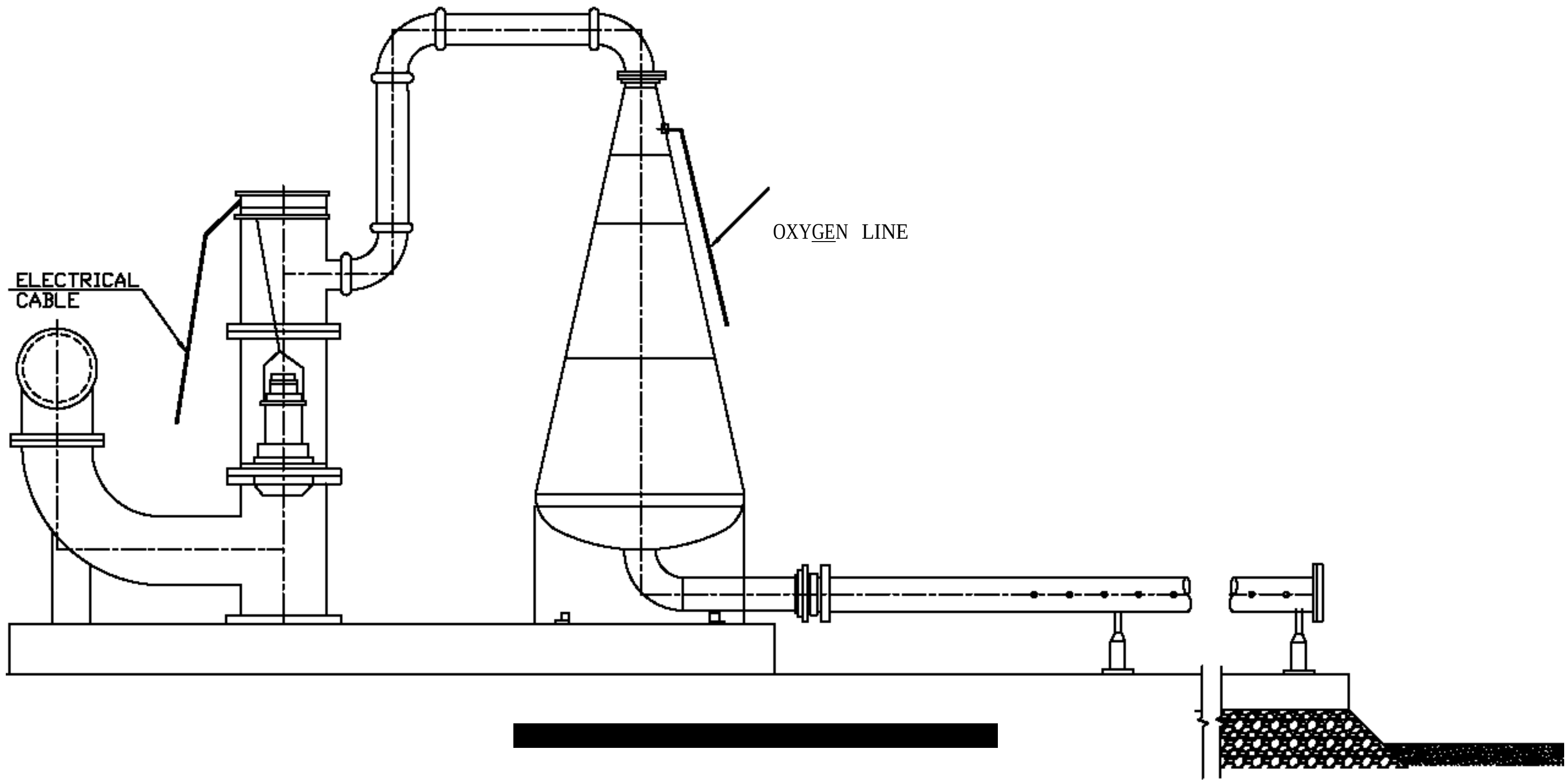
ECO_2 has over 75 systems installed throughout the US. All systems run continuously and reliably with a minimum amount of maintenance required. ECO_2 stands behind superior quality and guarantees each system to perform at a minimum of 90% oxygen transfer efficiency.

ECO2

Appendix 1

ECO_2 – Generic Drawing

Typical Lake Installation



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EC02
SUPEROXYGENATION TECHNOLOGY

DRAWING:
SHEET: 1 OF **1**
DATE:
8-10-2010

Appendix F

Lake Thunderbird Hydrographic Survey Scope of Work

The objective of this survey is to collect hydrographic data of Lake Thunderbird when the reservoir is at or near conservation pool elevation. An area capacity table and associated figures will be computed along with an estimated sedimentation rate using modern hydrographic technology. OWRB will collect a hydrographic dataset using Differential Global Positioning System (DGPS) for location and a dual frequency Echosounder for depth. Resurveying Thunderbird with current equipment will allow the comparison of updated area and capacity numbers with the previous 2001 survey to calculate sedimentation rates, as well as give a more precise area and capacity calculations achievable with updated techniques and increased coverage. The output of this work is a full report with updated contour and shaded relief maps and calculations.

PROJECT BUDGET			
Personnel	**Person Yrs.**		**Expenditure**
Total Person Years =	0.30	**Total=**	$ 36,057
Supplies			
Data Processing Materials			$ 1,300
Equipment Maintenance			$ 1,600
Supplies Sub-total =			$ 2,900
TOTAL PROJECT COST =			**$ 38,957**