Lake Thunderbird Water Quality

2018 Final Report

Submitted to

Central Oklahoma Master Conservancy District

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Submitted by

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Executive Summary

Lake Thunderbird is a multi-purpose reservoir located in the Cross Timbers Ecoregion of south-central Oklahoma in Cleveland County. It serves as the terminal reservoir for a largely agricultural 256 square mile watershed. Constructed by the Bureau of Reclamation, Lake Thunderbird began operation in 1966. The lake boasts a large state park, with many recreational opportunities including two marinas, campgrounds, two swim beaches, hiking trails, and a nature center. The lake itself is also a source of recreational activities, including a large boating presence, swimming, kayaking, and jet skiing. Under the authority of the Central Oklahoma Master Conservancy District (COMCD), Lake Thunderbird also serves as a major drinking water supply to three large metropolitan areas - Del City, Midwest City, and the City of Norman. COMCD has contracted with the Oklahoma Water Resources Board (OWRB) to monitor the lake for a variety of water quality parameters over the past eighteen years. In 2018, monitoring was conducted to identify any water quality concerns, assessment of water quality standards, and Supersaturated Dissolved Oxygen System (SDOX) efficacy.

In 2018, OWRB documented a typical thermal stratification pattern in the lake with the onset of stratification occurring in May and mixing in October. The hypolimnion experienced hypoxic conditions throughout the summer sampling season; the metalimnion also experienced hypoxia from May to September. While common in the hypolimnion, hypoxia in the metalimnion highlights the excessive algal growth and large oxygen demand of the lake bottom sediments. Nutrient concentrations were high throughout the sampling season, reaching peak levels in late summer. Hypolimnetically stored nutrients also accumulated through the monitoring season as a result of sequestration below the density gradient, internal release from anoxic sediment, and organic material buildup. Riverine nutrient concentrations were higher than in lacustrine areas, likely due to stormwater inflows and wind mixing through shallow areas creating consistent nutrient cycling.

Chlorophyll, a measure of algal biomass, decreased relative to previous years, but remained excessive. In 2018, mean chlorophyll at site 1 ranged from relatively low at 10.5 µg/L in April to peak mean chlorophyll at 30.07 µg/L in July. Taste and odor complaints, collected from City of Norman drinking water facility, were highest in winter months in 2018, rather than the usual September peak. Geosmin, an algal toxin related to taste and odor, peaked in winter as well, highlighting that there are active algal processes occurring in the winter. This is difficult to substantiate, as there is no monitoring data during these months.

The SDOX system was installed in Lake Thunderbird in 2011. It is designed to induce desirable physical and chemical conditions in the lake, such as increasing dissolved oxygen and oxidation-reduction potential in the hypolimnion, reducing phosphorus sediment load, and providing oxygen for breakdown of organic molecules including taste and odor compounds. Anoxic Factor, a metric used to analyze SDOX efficacy, shows a decrease in 2018, indicating less sediment phosphorus release than in previous years. While delivering the largest oxygen load to date (546,994 lbs), the SDOX's measurable positive effect is minimized by increased nutrient accumulation and algal productivity. Additional monitoring activities will be implemented in 2019 to further assess the efficacy of the SDOX.

Many stakeholders have a vested interest in Lake Thunderbird and its watershed. Efforts such as the Watershed Based Plan (WBP) (OCC, 2010), the Total Maximum Daily Load (TMDL) study (ODEQ, 2013), and COMCD's support of in-lake management measures and continued water quality monitoring have been implemented for the lake. These plans and actions provide a foundation, which could be the impetus to mitigating poor water quality conditions in this important waterbody. Additional investigative research is needed to improve understanding of water quality issues and potential remedies. Recommendations for further study are included in the Appendices of this report.

In general, in-lake and watershed mitigation measures need to be implemented in tandem to provide the best opportunity to improve water quality at Lake Thunderbird. An improved comprehensive plan emphasizing active in-lake and watershed management could help lead Lake Thunderbird to meet water quality standards for turbidity, chlorophyll-a, and dissolved oxygen. Current in-lake mitigation measures, such as the SDOX, should be continued, but have opportunities for improvement.

Introduction

Lake Thunderbird is a multi-purpose reservoir in the Cross Timbers Ecoregion of south-central Oklahoma in Cleveland County. Determined in the 2001 bathymetric survey, the lake's surface area is 5,439 acres and capacity is 105,838 acre-feet (OWRB, 2002). Its maximum depth is 58 feet near the dam in the lacustrine region of the lake; mean depth for the lake is 15.4 feet. Total volume and consequently, maximum depths represent a reduction since the lake's 1966 impoundment due to sedimentation.

Lake Thunderbird has a long history of water quality issues, documented in the long-term dataset from the water quality monitoring conducted by OWRB. It continues to be listed as impaired in the latest approved Oklahoma Integrated Water Quality Report for the Public and Private Water Supply beneficial use due to high chlorophyll-a, and the Fish and Wildlife Propagation beneficial use due to low dissolved oxygen and increased turbidity (ODEQ, 2016).

In order to combat the effects of cultural eutrophication in the reservoir, the COMCD gained funding through the American Recovery and Reinvestment Act to install and operate a SDOX in 2011. The goal of this system is to add oxygen to the deepest portion of the lake's anoxic hypolimnion, while maintaining thermal stratification. This added oxygen should limit the transfer of nutrients from the hypolimnion to the surface waters and decrease the internal load of phosphorus, among other ancillary benefits. OWRB provides the COMCD with some analysis on the efficacy of this system to accomplish these goals.

OWRB has provided water quality based environmental services for COMCD since 2000 and continues to conduct long-term water quality monitoring at the lake and provide analysis on lake condition. This report presents data and analysis from 2018.

Sampling Regime

In 2018, water quality sampling occurred from April 18 through October 10. Monitoring was conducted for the parameters listed in **Table 1** at the sites indicated in **Figure 1.** During each visit, all COMCD sites were sampled and were consistent with the OWRB Beneficial Use Monitoring Program (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, beneficial use assessment, and comparison between riverine and lacustrine zones.

In-situ water quality profiles for oxidation-reduction potential (ORP), dissolved oxygen (DO), temperature, specific conductance (SpC), 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 chlorophyll samples were collected at the surface of sites 1, 6, 8, and 11. Additionally, at-depth samples were collected with a Van Dorn sampler in 4-meter depth intervals at Site 1 from the surface to the bottom. Analyses performed on these samples included both a phosphorus (P) and a nitrogen (N) nutrient series listed in **Table 1**. Field observations, Secchi disk depth, surface chlorophyll, and turbidity samples were collected at all eight sites.

Table 1. 2018 Water quality sample dates and parameters.

SAMPLE VARIABLES		
General Water Quality –		
Chlorophyll-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) concentration	Dissolved Oxygen % saturation	Temperature
Specific Conductance (SpC)	Oxidation Reduction Potential (ORP)	pH
Field Observations -		
Air Temp	Wind (Direction/Speed)	Cloud Cover
Precipitation	Wave Action	Barometric Pressure
Site Depth		

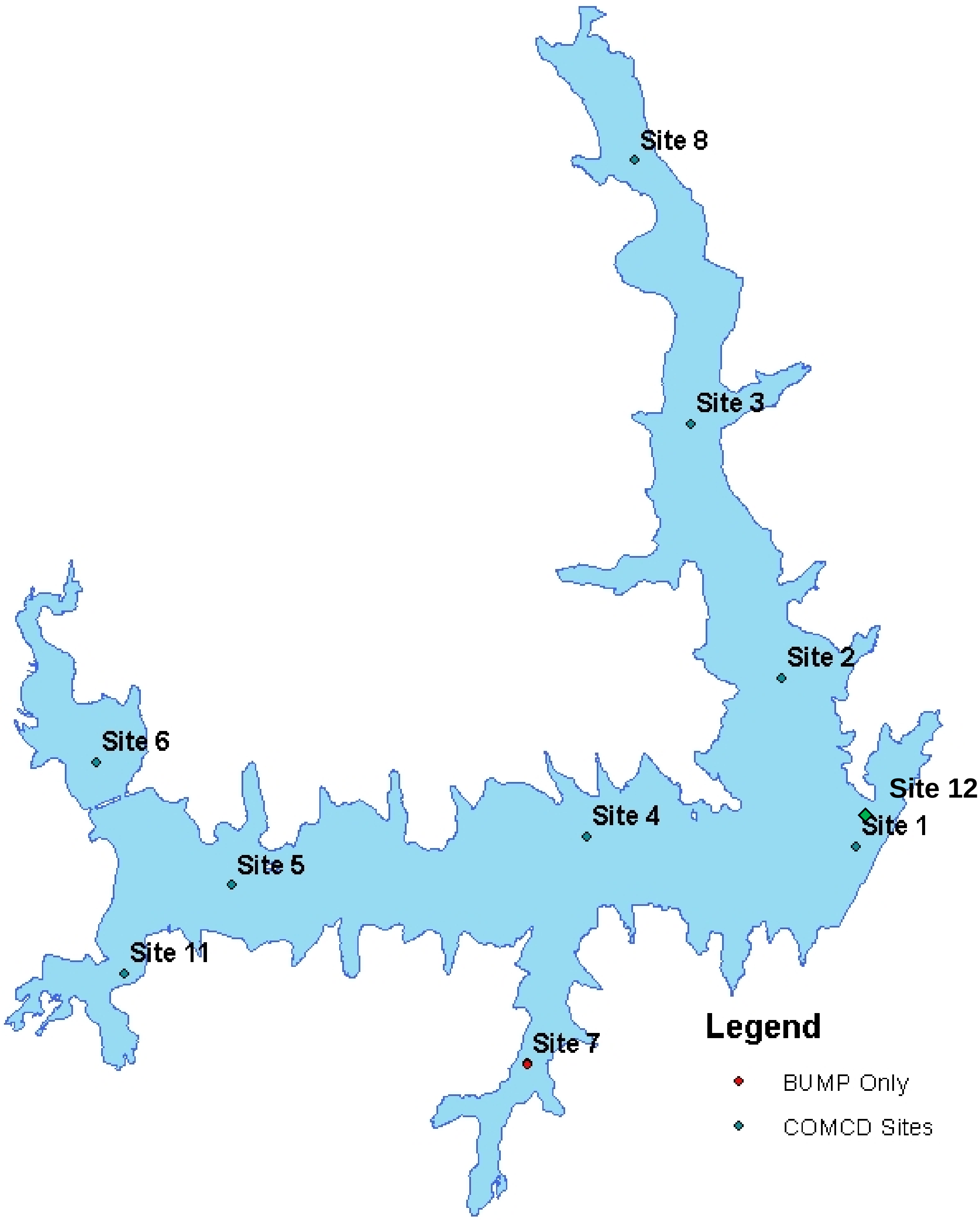


Figure 1. 2018 Lake Thunderbird sampling sites

Watershed

Lakes do not exist in isolation; they interact as part of a complex ecosystem contained within a watershed. A watershed is the area of land that drains rainfall and streams to a "pour point," which in Oklahoma this is usually a reservoir. **Figure 2.** Lake Thunderbird HUC 8 Watershed presents Lake Thunderbird's Hydrologic Unit Code 8 (HUC 8) watershed encompassing 256 square miles in the Cross Timbers Ecoregion of central Oklahoma. Lake Stanley Draper is within the same HUC 8 watershed as Lake Thunderbird, but their hydrologic connection to each other is minimal. Lake Stanley Draper is highly managed for water supply purposes and water is not permitted to be released downstream.

Lake Thunderbird is a Bureau of Reclamation multi-use reservoir with a surface area of 5,439 acres and a volume of 105,838 acre-feet. Major tributaries to the lake are the Little River and Hog Creek, each entering as an arm of the lake from the west and north, respectively. Water is released below the dam into the Little River, which has a confluence with the Canadian River roughly 85 miles downstream.

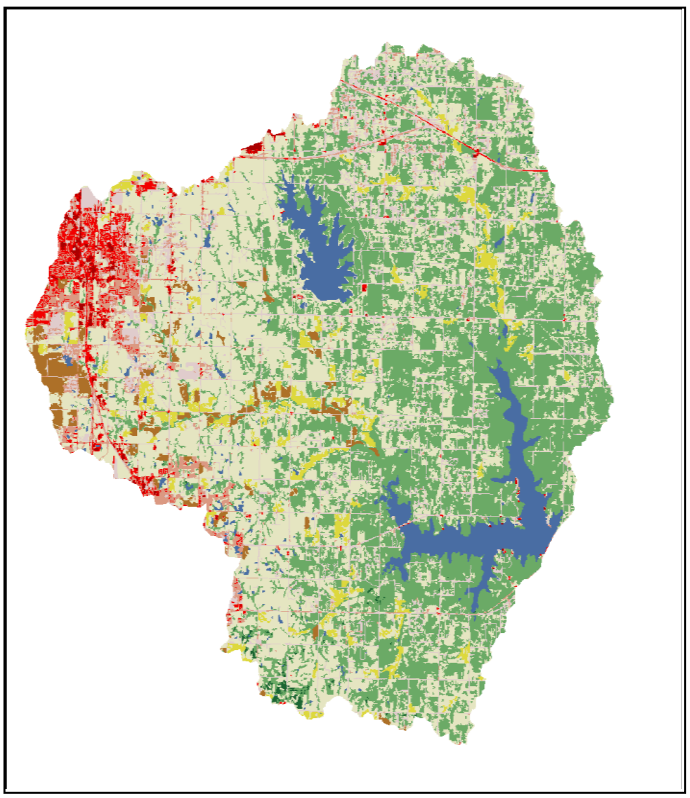


Figure 2. Lake Thunderbird HUC 8 Watershed

Land uses in the watershed of a waterbody are important when determining potential sources of nutrients, sediment, or other forms of pollution. **Table 2.** Land Use Acreage in Lake Thunderbird HUC 8 Watershed presents the land uses in the Lake Thunderbird watershed; the dominant categories are grassland and deciduous forest. Developed land makes up roughly 16% of the watershed, mostly in the northwest portion, encompassing parts of Oklahoma City, Moore, and Norman.

Table 2. Land Use Acreage in Lake Thunderbird HUC 8 Watershed

Category	Acreage	Percent of watershed
Open water	6,738	4.322%
Developed, open space	14,661	9.405%
Developed, low intensity	6,769	4.342%
Developed, medium intensity	3,102	1.990%
Developed, high intensity	661	0.424%
Barren Land	30	0.019%
Deciduous Forest	55,010	35.288%
Evergreen Forest	351	0.225%
Grassland/Herbaceous	59,765	38.338%
Pasture/Hay	5,452	3.498%
Cultivated Crops	3,341	2.143%
Emergent herbaceous wetlands	8	0.005%
Total Watershed	155,888	100%

Continuing development in the watershed underscores the need for Best Management Practices (BMPs) and opportunities for Low Impact Development (LID) measures that would support greater long-term watershed integrity.

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 inflow 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 a number of chemical and biological processes.

Figure 3 provides a graphical representation of Lake Thunderbird's rainfall, elevation, inflow, and sampling dates for calendar year 2018. Annual precipitation at Lake Thunderbird dam in 2018 totaled 38.77 inches, consistent with the lake's average of 38 inches, with peak rainfall events corresponding to increases in lake elevation. In general, 2018 had more inflow (from the watershed) events than in 2017. For example, 2017 inflow events never exceeded 2000 day-second-feet (DSF), whereas 2018 had three peak events higher than 2000 DSF. This becomes important when examining increasing nutrient levels and non-algal turbidity witnessed in the reservoir. These inflow events were predictably driven by relatively large rain events.

In addition to hydrology, air temperature can influence lake characteristics such as thermal stratification and nutrient availability, which subsequently influences primary productivity. **Figure 4** compares monthly mean temperatures in 2018 to the long-term monthly mean. Monthly average temperatures were similar to long term averages during most of the year, except for a cooler than average April and warmer than average May. In 2018, the lake experienced peak air and water temperature in July, coinciding with the lake's strongest stratification. Slight climatological variances from the norm were observed in 2018 and yet the lake's typical pattern and duration of thermal stratification was maintained in 2018.

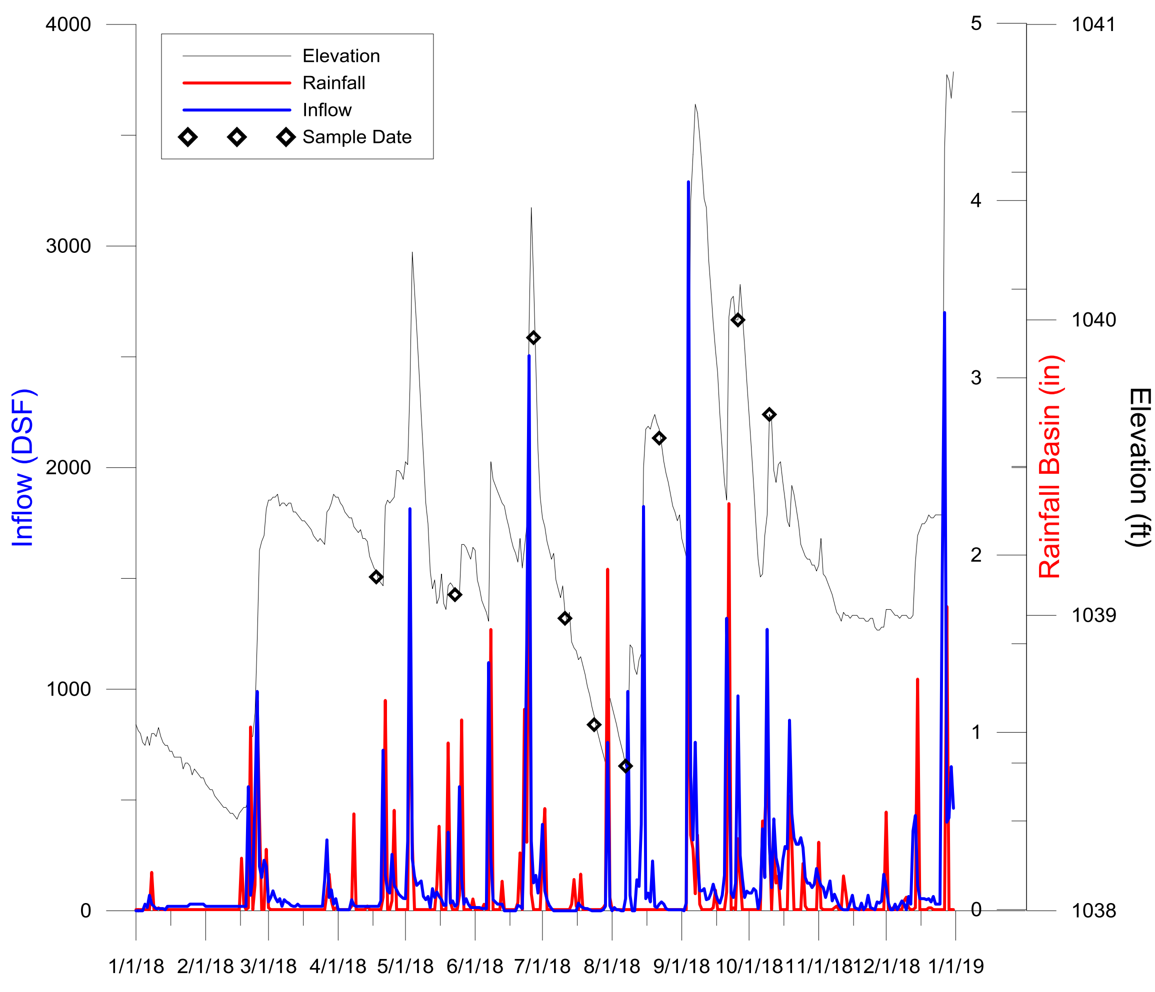


Figure 3. 2018 Inflow, Rainfall, and Elevation Data for Lake Thunderbird, with Sample Dates Indicated.

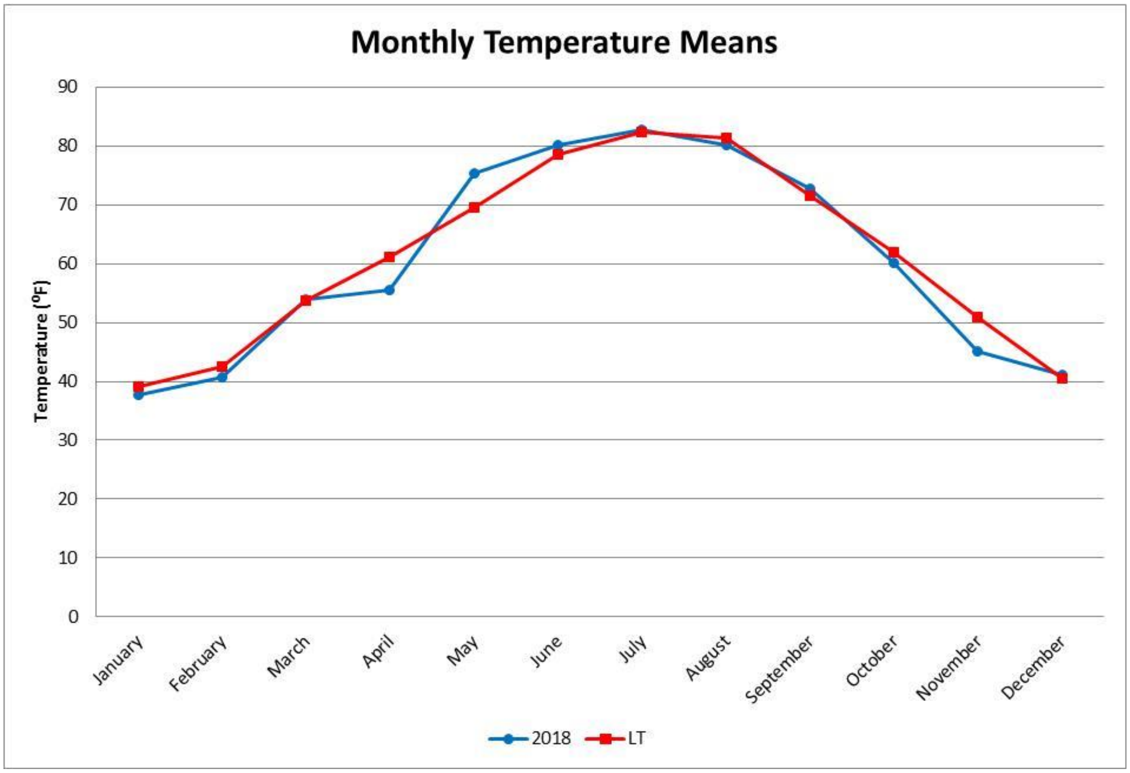


Figure 4. 2018 and Long Term (LT) Average Monthly Temperature at the Norman Mesonet Station.

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 (evaporation) and sub-surface 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 United States Army Corps of Engineers (USACE) 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 USACE. The precipitation contribution to the total inflows was 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 3**). 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 input and output terms were calculated then 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. Examination of the estimated water budget for Lake Thunderbird showed that estimated inputs and outputs were similar to the actual volume changes that were calculated by change in pool elevation. **Figure 5** provides a visual summary of water gains and losses on a monthly basis. Inputs and outputs were comparable throughout the entire season. Inflows were highest in September, October, and December. The inflowing water was largely released downstream in September and October; however, the December inflow was largely retained in the reservoir.

Table 3. 2018 Lake Thunderbird Water Budget Calculations expressed in Acre-feet. Parentheses indicate a negative value.

Month	INPUTS			OUTPUTS				ERROR TERM		
	Inflow	Rainfall	Total Inputs	Evaporation	Water Supply	Releases	Total Outputs	I-O	ΔV	Error
Jan	1,131	98	1,230	1,691	928	-	2,619	(1,389)	(978)	411
Feb	5,088	1,731	6,819	1,405	716	-	2,121	4,698	4,939	(242)
Mar	2,824	161	2,985	2,924	1,239	-	4,163	(1,178)	51	1,127
Apr	2,637	1,500	4,138	3,606	1,271	-	4,877	(740)	257	483
May	7,549	2,140	9,689	4,413	1,488	6,762	12,662	(2,973)	(1,904)	1,069
Jun	10,609	2,565	13,174	3,976	1,686	7,597	13,259	(85)	669	(584)
Jul	1,106	1,806	2,912	3,905	2,186	1,507	7,598	(4,687)	(3,241)	1,445
Aug	6,732	1,558	8,291	4,023	1,741	563	6,327	1,964	2,984	(1,020)
Sep	17,367	2,634	20,001	2,450	1,278	14,777	18,505	1,496	2,367	(870)
Oct	14,411	1,508	15,919	1,538	1,106	16,774	19,418	(3,499)	(2,624)	875
Nov	2,416	468	2,884	1,397	1,068	1,767	4,232	(1,348)	(875)	473
Dec	13,941	1,704	15,646	1,178	1,099	3,743	6,020	9,625	8,952	673
Total	85,814	17,874	103,688	32,506	15,806	53,490	101,803	1,885	10,599	3,840

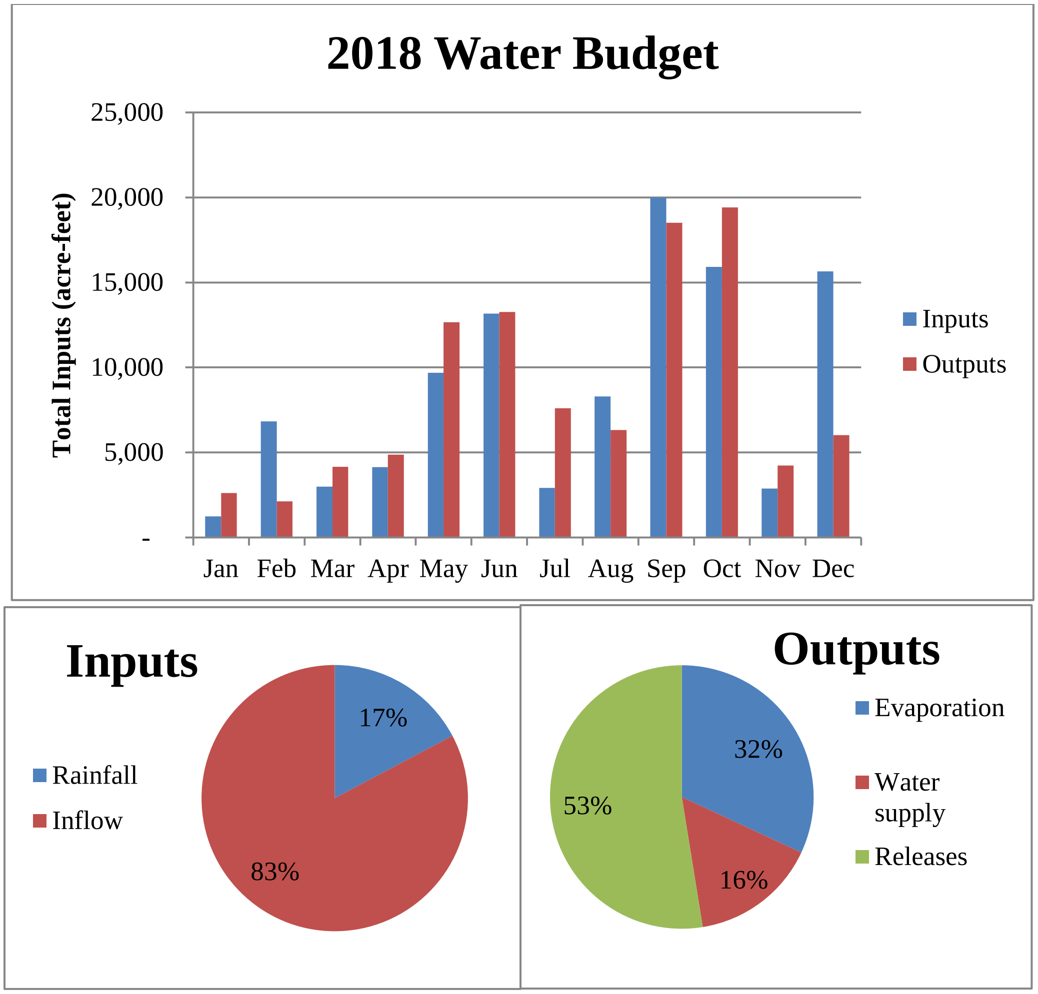


Figure 5. 2018 Lake Thunderbird water Input and Output sources by month, expressed as the percent of total.

Once a hydrologic budget is constructed, additional features of reservoir dynamics such as hydrologic retention time can be estimated. Tau, the hydrologic retention time, is the ratio of lake capacity at normal pool elevation to the annual exiting flow. This represents the theoretical time it would take a given molecule of water to flow through the reservoir. Lake Thunderbird's water had a hydrologic residence time of 1.53 years in 2018, with an average (2001 to 2018) hydrologic residence time of 3.79 years. The lower than average 2018 residence time is largely due to a higher volume of gated releases.

Total monthly error is the difference calculated between the change in lake volume based on elevation and change in lake volume based on inputs-outputs. In 2018, the hydrologic budget contains a cumulative annual error of 3,840 acre-feet, with an average monthly error of 320 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. 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, the conservation pool sedimentation rate is estimated to be around 400 acre-feet per year 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 7,200 acre-feet since 2001 (OWRB, 2002) or a loss of about 6.43% of total volume. 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 entire reservoir using comparable survey methods to the 2001 study would allow for a more reliable estimate of sedimentation. Additionally, 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. Thus, ongoing decomposition processes in the hypolimnion deplete dissolved oxygen and it is not replenished. The OWRB has documented this process at Lake Thunderbird each monitoring year since 2000.

Stratification and hypolimnetic anoxia are inevitable processes even without the extreme influence of outside forces.

Isopleths are a graphical method to illustrate lake dynamics 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 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. A few individual profiles of temperature and DO with respect to depth at site 1 are included to highlight aspects of the 2018 monitoring season and illustrate lake stratification layers (**Figure 6Figure 8**Figure 9). 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 are to mix. RTR calculations aid in determining the size of the epi-, meta- and hypolimnion layers (**Appendix C**: Relative Thermal Resistance Plots).

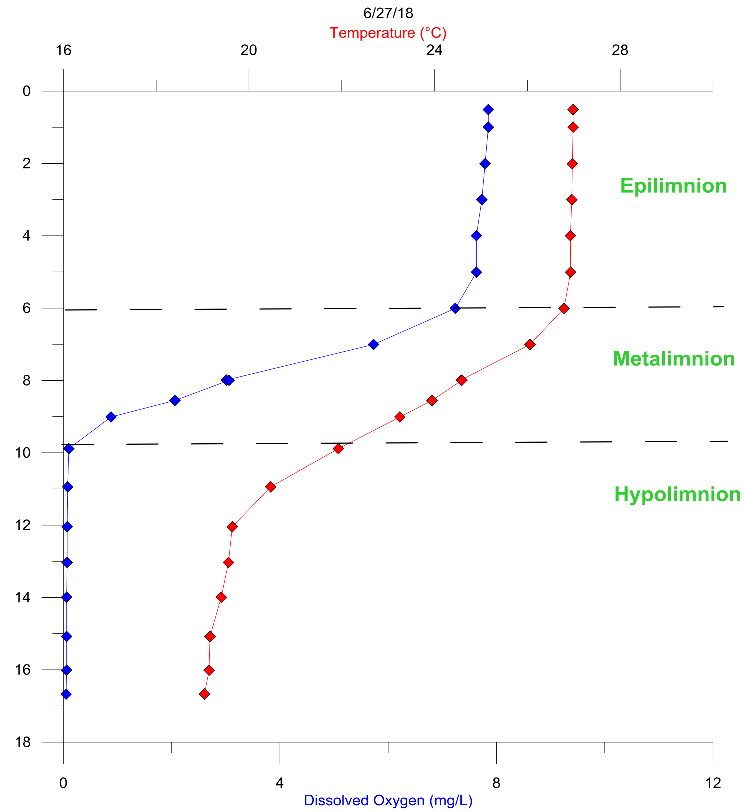
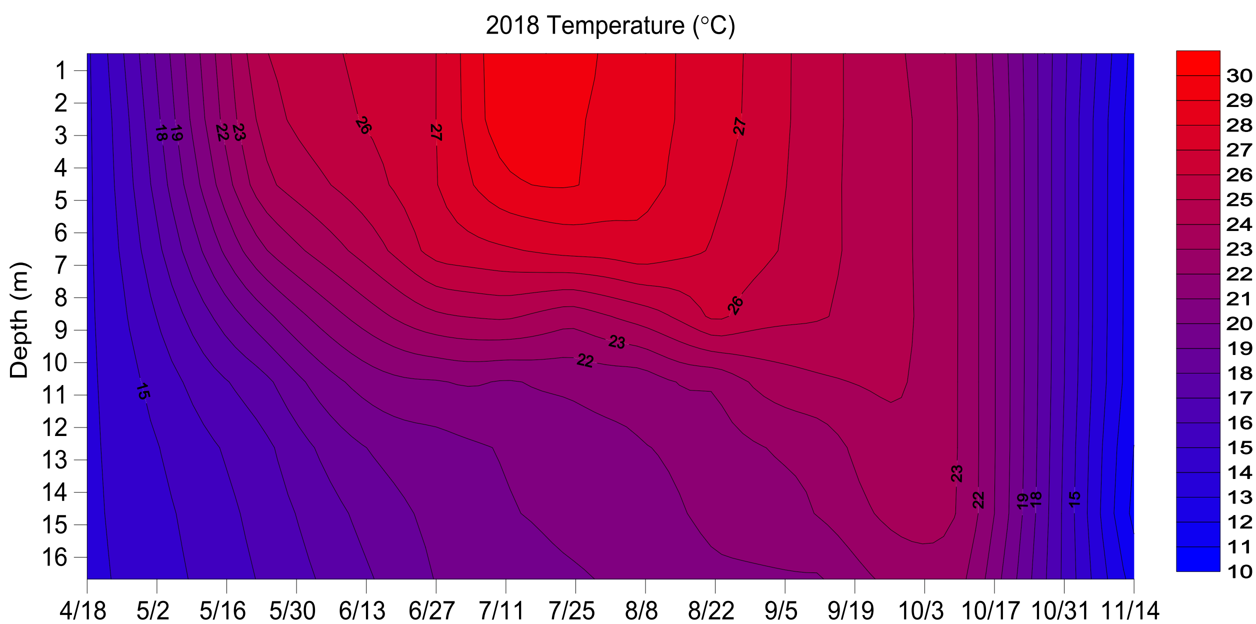


Figure 6. A typical Temperature (red, diamond) and Dissolved Oxygen (blue, triangle) vertical profile for Lake Thunderbird (June 27, 2018) approximate boundaries between the Epilimnion, Metalimnion and Hypolimnion are marked with dashed lines.



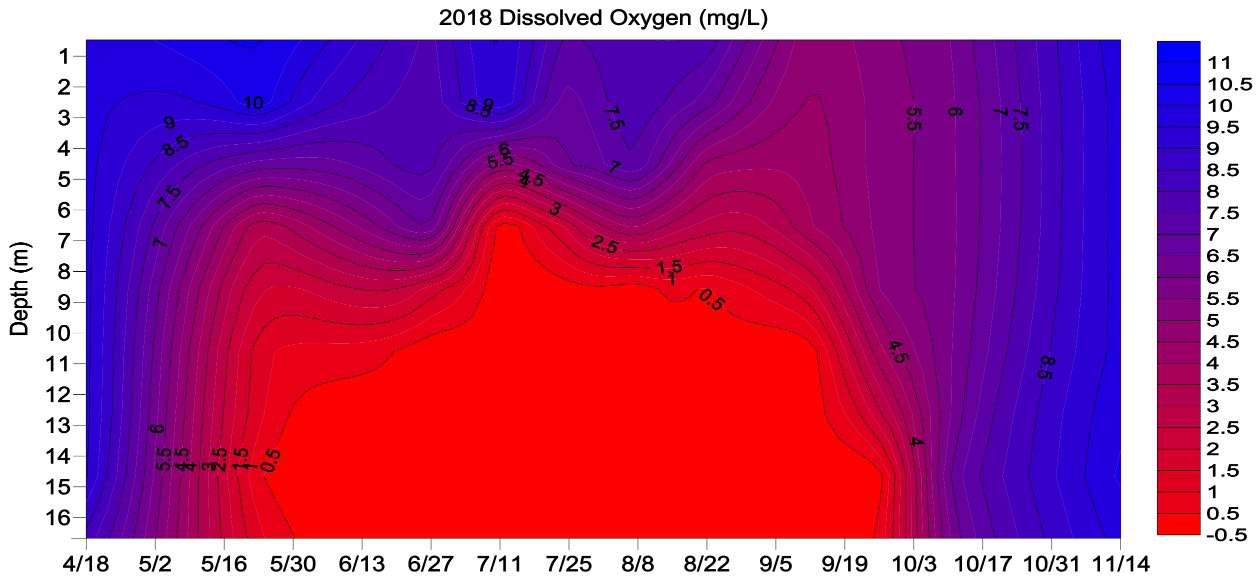


Figure 7. 2018 Isopleths of Temperature (°C) and Dissolved Oxygen (mg/L) versus Depth (m) at Site 1.

Little thermal difference with depth was noted on the first sample date, April 18, 2018, indicating a completely mixed system. By the second sample event, May 23, 2018, thermal stratification had strengthened exhibiting an 8°C temperature gradient from top to bottom. Dissolved oxygen dynamics had set up for the season with completely anoxic hypolimnetic waters and anoxia creeping into the metalimnion. As the season progressed, epilimnetic warming continued until reaching a peak temperature of 29.88°C on July 11, 2018 (**Figure 7**). In addition, evident at this event is the push of anoxic water upwards, completely dominating the metalimnion and hypolimnion. This is evidence of increased organic load, hypolimnetic water and sediment oxygen demand resulting from the eutrophication occurring in the lake. Anoxic water in the metalimnion maintained a constant presence throughout the summer into September when nominal thermal resistance to mixing began to decrease.

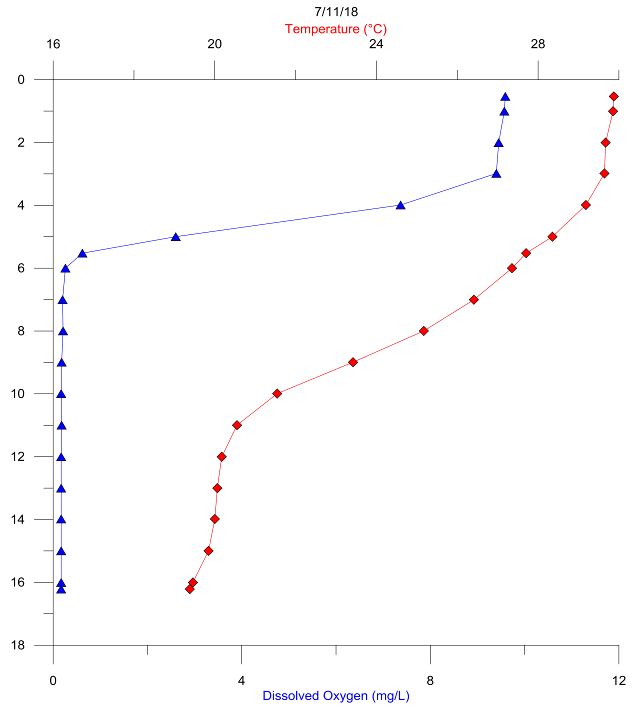


Figure 8 A Temperature (red, diamond) and Dissolved Oxygen (blue, triangle) vertical profile for Lake Thunderbird (July 11, 2018) highlighting an anoxic metalimnion and hypolimnion.

Epilimnetic water began to cool by the September 12th sampling event, thus deepening the epilimnion, although stratification still persisted, perpetuating the metalimnion and hypolimnion layers. By the October event, the water column was isothermal and the lake was considered mixed (**Figure 9**).

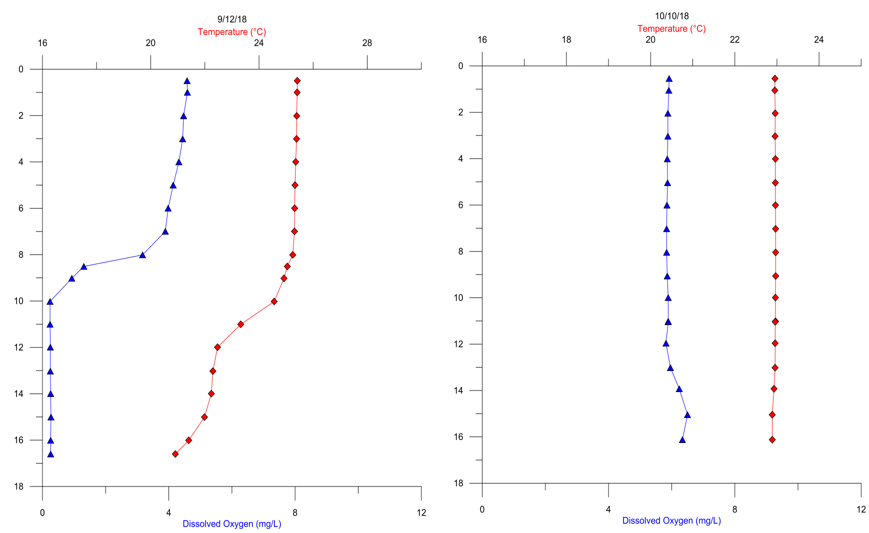


Figure 9 Temperature (red, diamond) and Dissolved Oxygen (blue, triangle) vertical profile at Site 1 September 12, 2018.

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 highest DO at the surface occurring, in July and early August, represent high levels of algal 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 at site one, as expected in this system.

Metalimnetic anoxia, observed from May through September, is indicative of a eutrophic 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 can further stimulate algal growth.

pH and Oxidation-Reduction (redox) Potential

Lake Thunderbird exhibited increases in surface pH during the summer months indicating high rates of photosynthesis. 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. (**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, driving pH and ORP down. In general and as seen in 2018 data, peaks of high epilimnetic and low hypolimnetic pH correspond with peaks in algal productivity.

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.

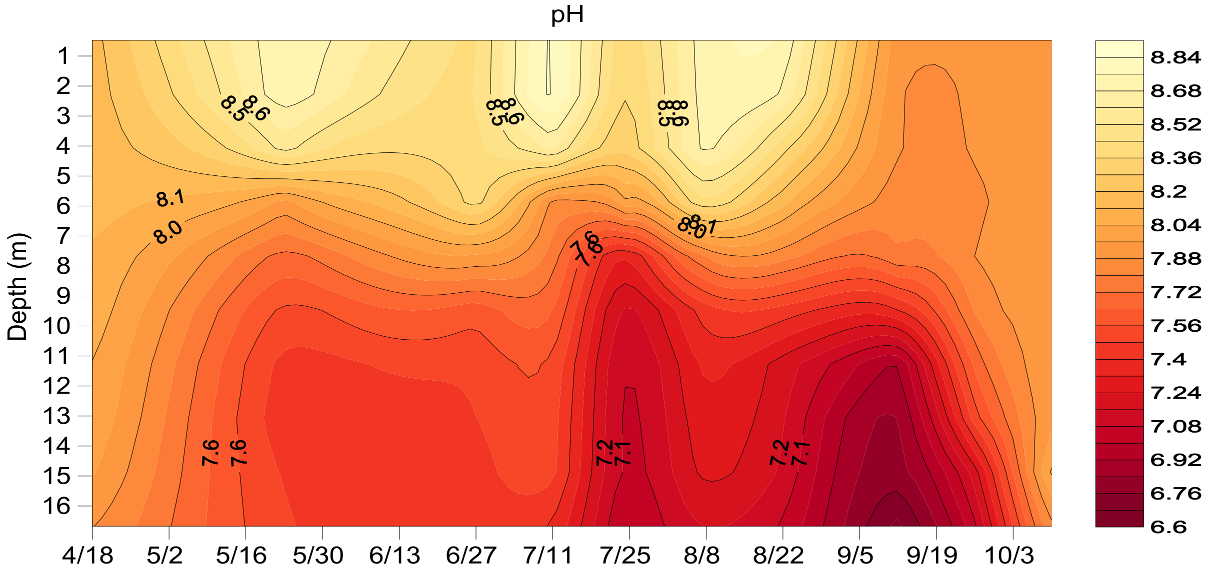


Figure 10. 2018 Isopleth of pH (S.U.) Versus Depth (m) at Site 1.

Complete anoxia of the hypolimnion was observed in May **(Figure 7**), and by mid-June, oxidation-reduction potential (ORP) was severely depressed at less than 100 mV (Figure 11). Under oxygenated conditions, redox potentials remain highly positive (300-500 mV) as oxygen is readily available as an electron acceptor during bacterial respiration. Normally, aerobic bacterial communities consume oxygen to the point of hypolimnetic anoxia, the bacterial community then 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. Generally, as the ORP drops towards 100mV or lower (strongly reducing conditions), sediment-bound phosphorus dissolves into the water column. 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 slow the oxidation (breakdown) of organic materials such as the contents of dead and dying algal cells providing another source of nutrients to accumulate in the hypolimnion.

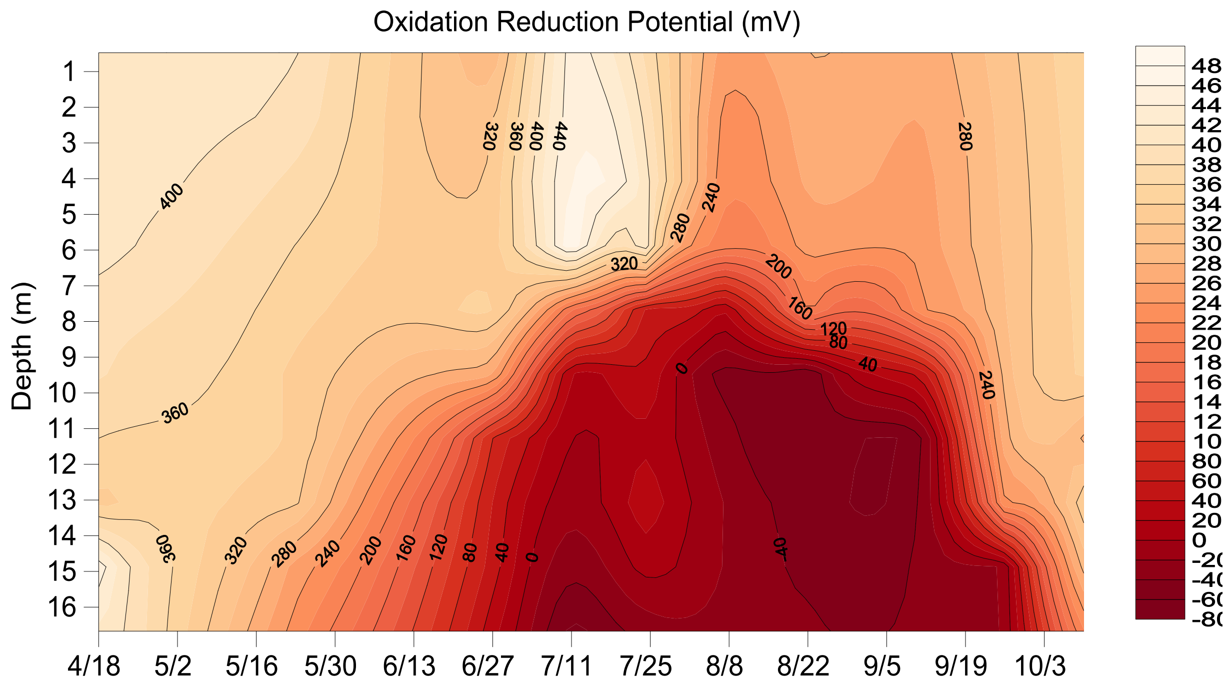


Figure 11. 2018 Isopleth of Oxidation-Reduction Potential (mV) versus Depth (m) at Site 1.

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 and phosphorus 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.

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 and therefore not limiting 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 nitrogen and phosphorus are readily available, neither is a limiting nutrient to algal growth, and excessive chlorophyll-a values can be expected. When high phosphorus concentrations are readily available in comparison to very low nitrogen concentrations, algal growth may be nitrogen-limited and vice versa.

Site 1 is examined to represent lacustrine nutrient values; additionally, nutrient levels in riverine areas are also examined because nutrient levels vary both spatially and seasonally. Nutrient graphs are presented here as a time series across three years to provide context across recent years.

Phosphorus – P

Total phosphorus (TP) is a measure comprised of particulate phosphorus and ortho-phosphorus and represents all phosphorus in the water sample. Ortho-phosphorus (ortho-P) is the bioavailable, dissolved form of phosphorus, used by algal communities for photosynthesis.

Epilimnetic TP was fairly consistent through the beginning of the monitoring season before increasing in the late summer and fall. Values ranged from 0.019 ug/L to a high of 0.047 ug/L in October. In 2018, epilimnetic ortho-P was generally at or below reporting limit for the majority of the sampling season (**Figure 12**).

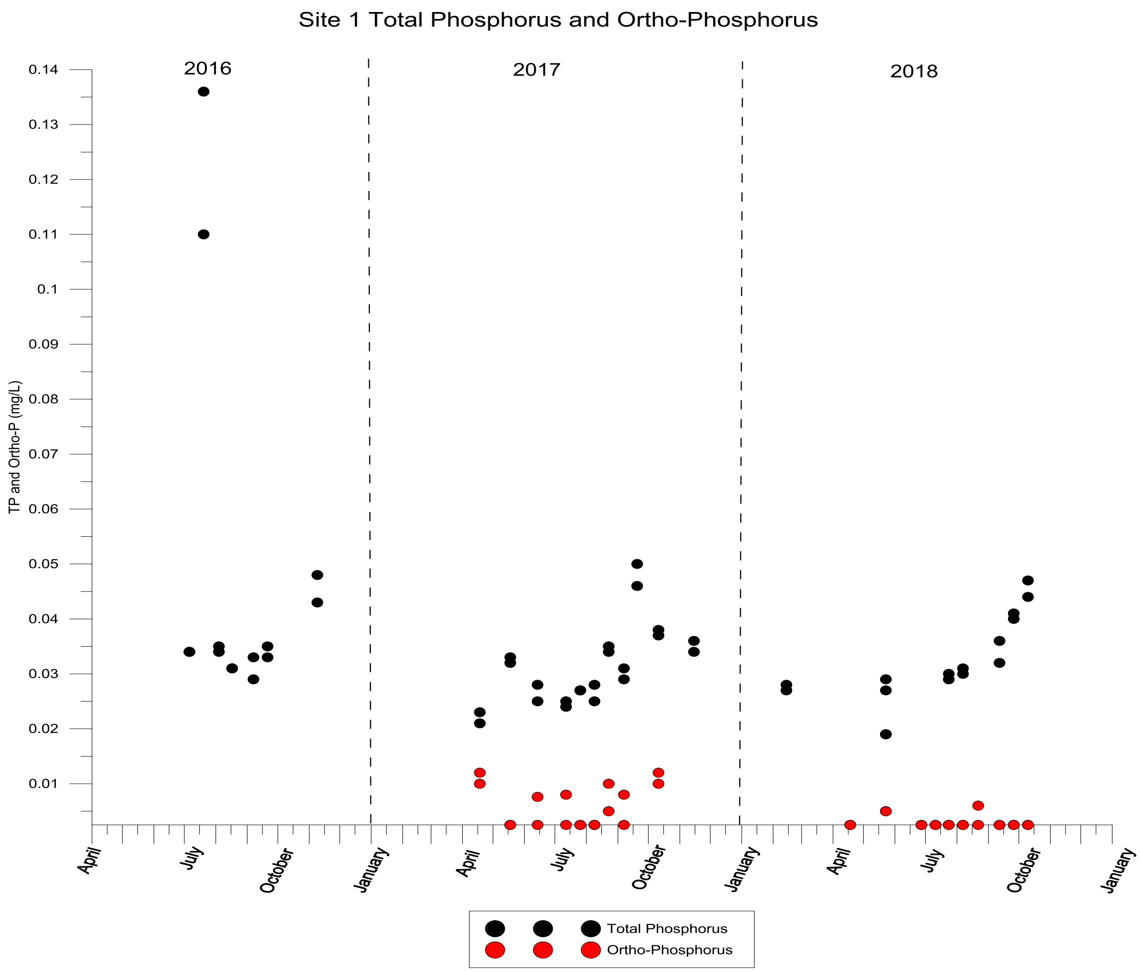


Figure 12. 2018 Surface Phosphorus Variables as P (mg/L) at site 1. Values on x-axis represent half the laboratory reporting limit (0.0025 mg/L). 2016 ortho-P values are omitted, as analytical methods were not comparable.

Physical characteristics, such as stratification driven by thermal dynamics and DO depletion, influence many chemical and biological lake processes. Differences in water temperature and densities keep nutrients sequestered in the hypolimnion where they often accumulate through the season. Anoxic water and reducing conditions in the hypolimnion also create an environment favorable to sediment nutrient release. Hypolimnetic ortho-P accumulated throughout the stratification period, driving increased TP, before a decrease following lake mixing. (**Figure 13).** Omitted values in April, June, and August were due to laboratory error and the QA/QC issue is further addressed in **Appendix A**.

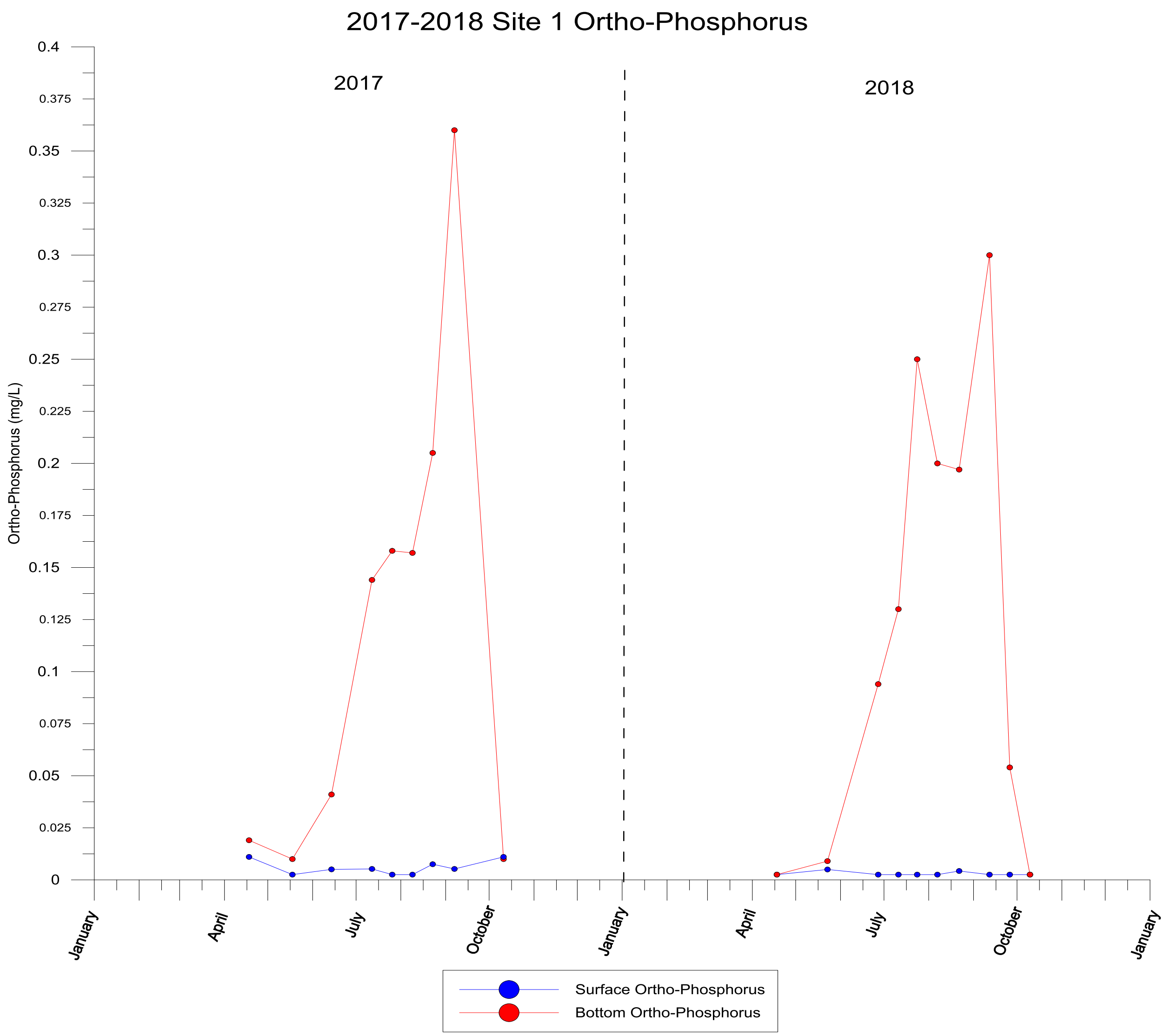


Figure 13. 2018 Site 1 Ortho-phosphorus at Surface and Bottom depth.

Riverine sites are much shallower than lacustrine sites and therefore do not stratify, allowing nutrients to continuously cycle through the water column and be available for algal uptake. Wind mixing and thus, nutrient and sediment resuspension are also common in these shallow, turbid areas. Lacustrine and riverine sites' nutrient concentrations are often disparate from each other; riverine values are consistently higher than in open water sites (**Figure 12** and **Figure 14**). In 2018, site 8 and 11 behaved very similarly and exhibited TP values slightly over the lacustrine sites. Site 6, near the Alameda Dr. bridge on the Little River arm, had the highest TP values and increased through the season, peaking in October at 0.283 mg/L.

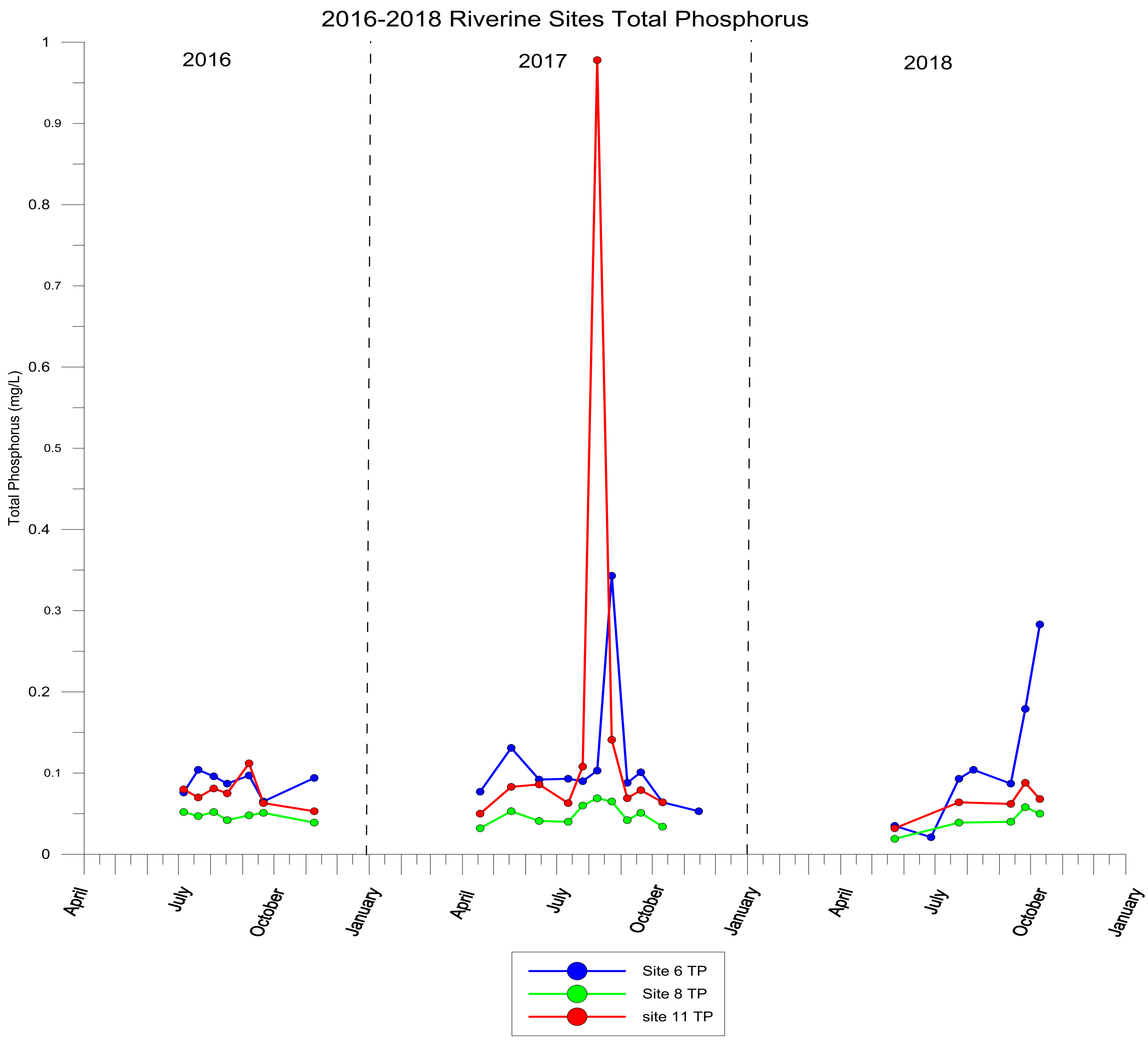


Figure 14. 2018 Surface Phosphorus (mg/L) from the three riverine sites.

Site 1 surface TP and ortho-P values are consistent with those seen in eutrophic and hypereutrophic lakes as well as similar to levels seen in previous years (**Figure 12**). 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.** 2018 Site 1 Ortho-phosphorus at Surface and Bottom depth.

Riverine areas are also susceptible to wind mixing and resuspension of sediment and nutrients. They are greatly impacted by storm flow events, likely driving the high site 11 phosphorus spike in 2017 and increasing fall concentrations in 2018. Site 6 usually exhibits the highest phosphorus concentration likely due to storm water bringing in nutrients and sediment to this shallow area. These higher levels of phosphorus represent a greater risk for elevated phosphorus in the main lake body, potentially leading to higher algal growth.

Nitrogen – N

Total nitrogen is a measure comprised of Kjeldahl nitrogen and nitrate/nitrite, representing all organic and inorganic nitrogen compounds in the sample. Values ranged from 0.487 mg/L to 1.725 mg/L, with an anomalous peak in late August. Surface total nitrogen was relatively consistent through the sampling season and was driven by organic nitrogen present in algae as opposed to ammonia (**Figure 15**). Omitted values in July were due to laboratory error and the QA/QC issue is further addressed in **Appendix A**.

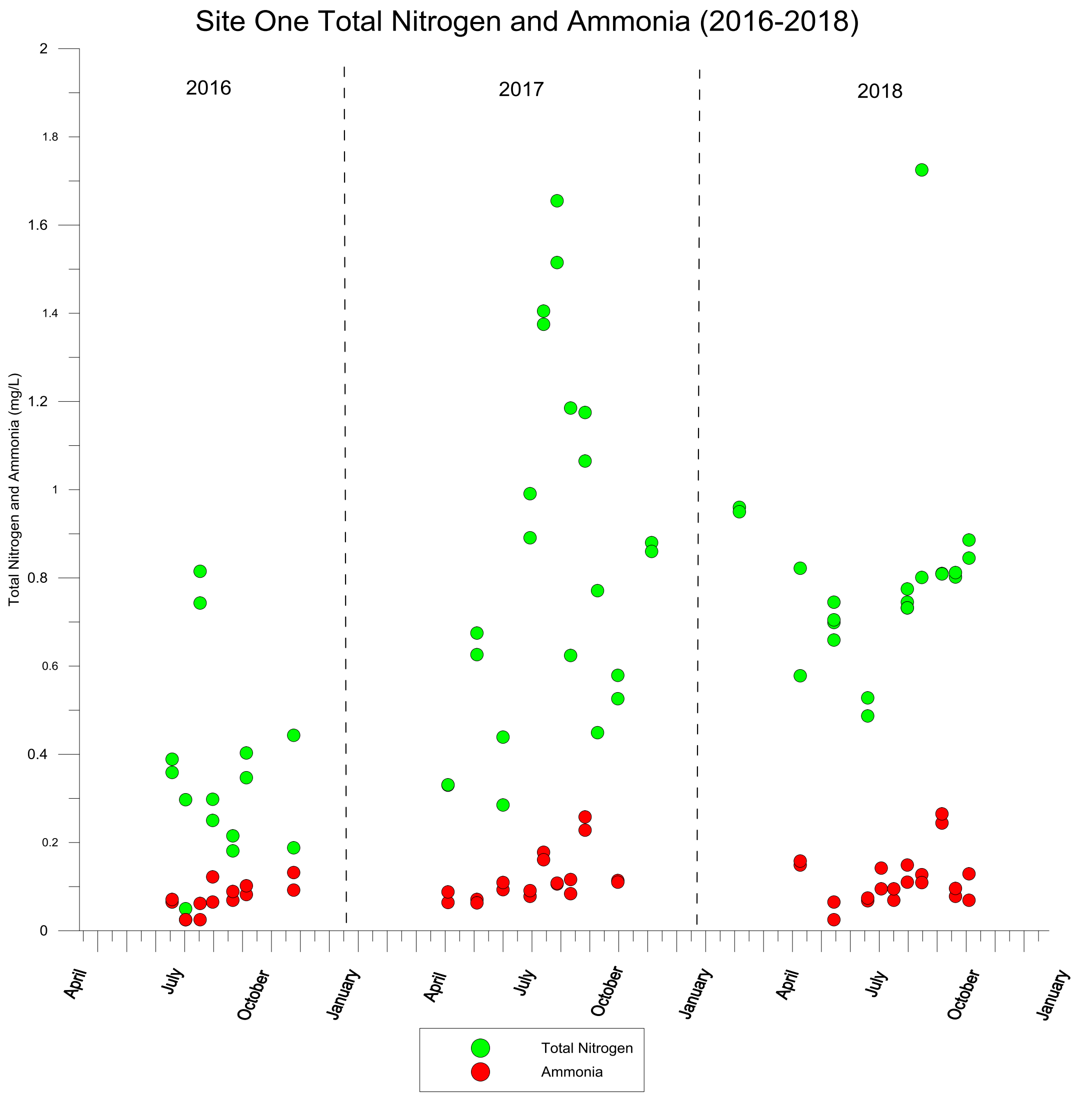


Figure 15. 2018 Surface Total Nitrogen (mg/L) over time at Site 1.

The typical pattern for Lake Thunderbird surface water has been seasonal increases of Kjeldahl nitrogen with ammonia and then nitrate/nitrite falling below reporting limit. In 2018, epilimnetic nitrate/nitrite fell below reporting limit in mid-May and remained undetectable until late September at the end of the algal growing season. Detection of ammonia however, occurred across the entire season with a peak of 0.265 mg/L in early September.

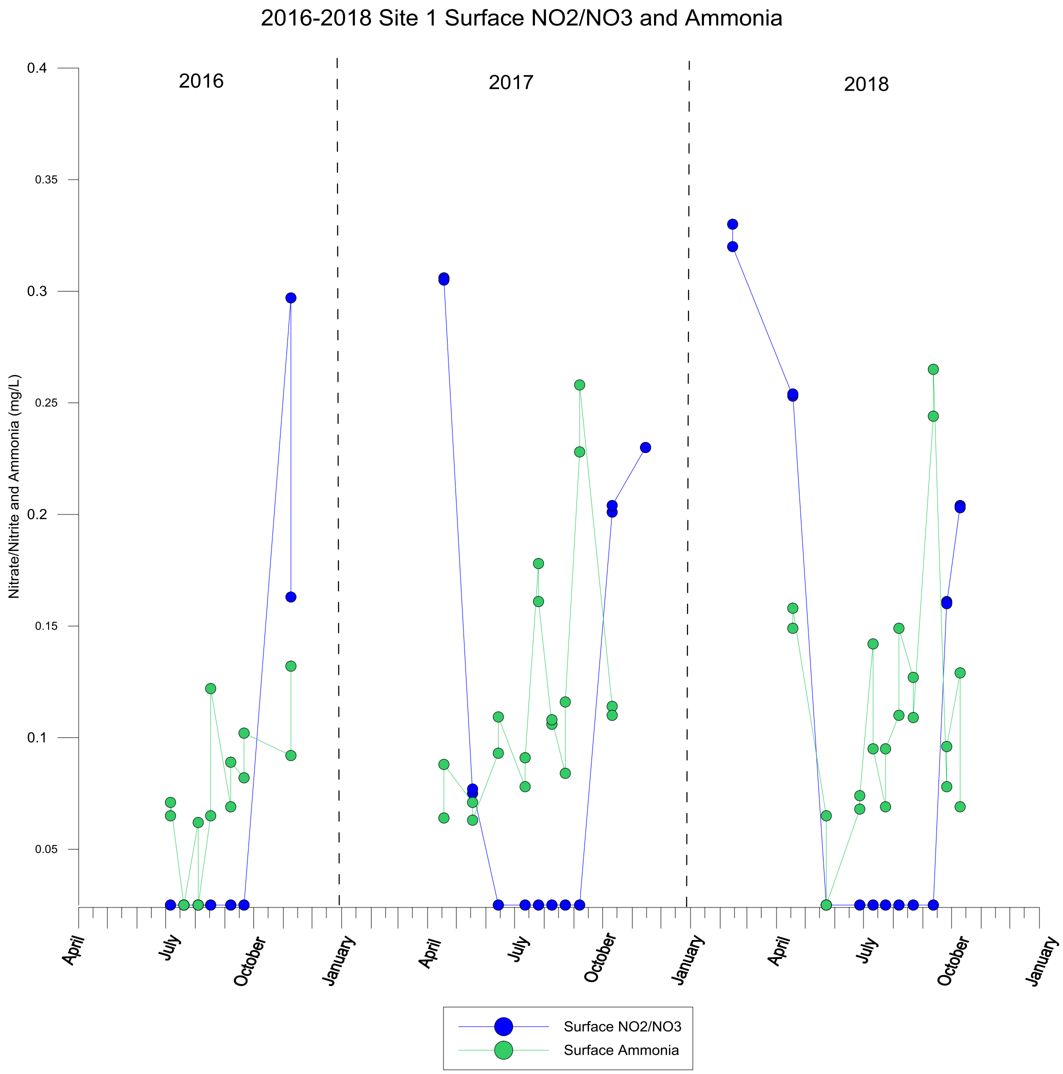


Figure 16. 2018 Surface Nitrate/Nitrite and Ammonia (mg/L) at Site 1. Values on x-axis represent half the laboratory reporting limit (0.025 mg/L).

Hypolimnetic total nitrogen peaked in early September coinciding with hypolimnetic ammonia accumulation. Examination of ammonia distribution with depth and over time showed a general increase in ammonia in the hypolimnion during summer months when hypolimnetic waters were anoxic followed by a decrease in the fall (**Figure 17** 2018 Site 1 Ammonia at Surface and Bottom Depth).

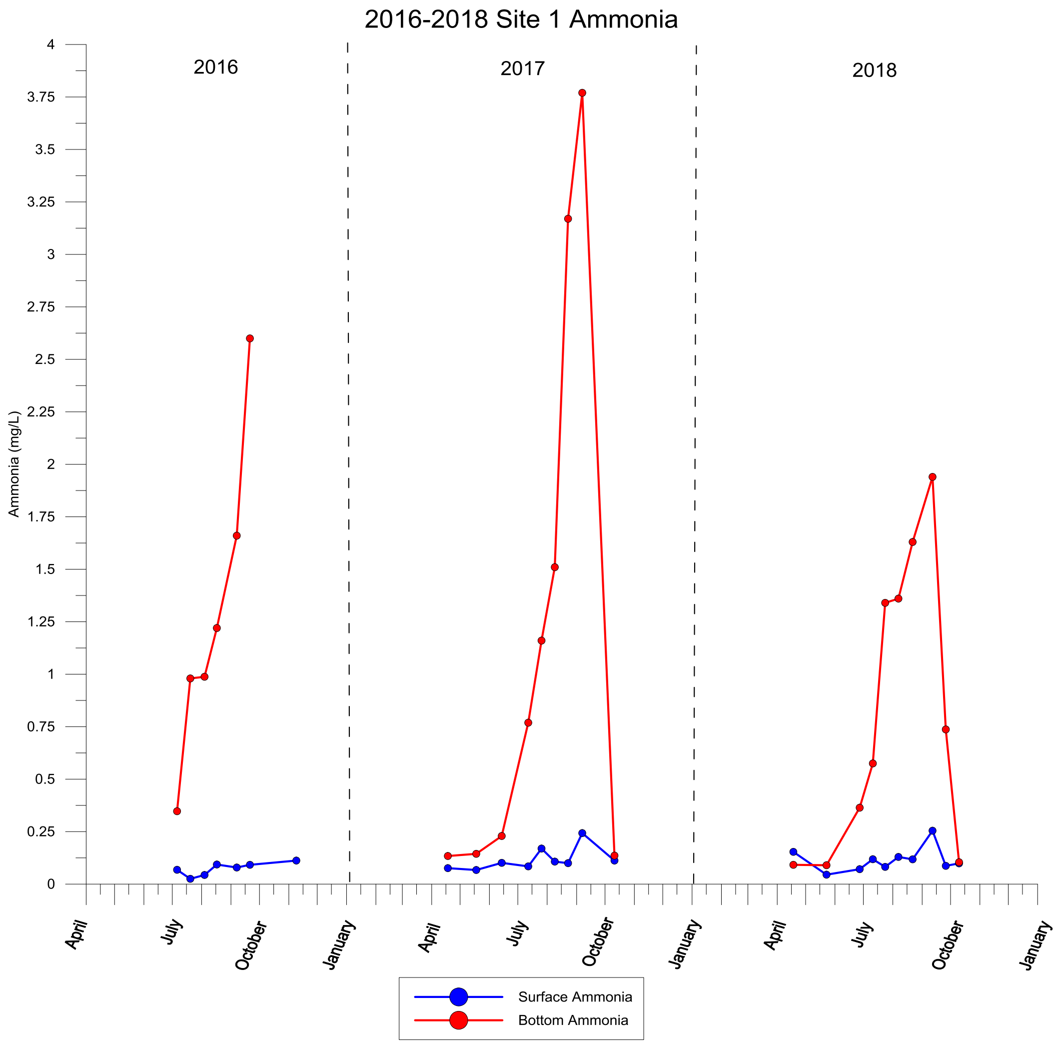


Figure 17 2018 Site 1 Ammonia at Surface and Bottom Depth

Compared to the lacustrine zone, riverine total nitrogen levels were higher suggesting the tributaries are an important source of nitrogen (**Figure 18**). Nitrogen in the riverine sites increased throughout the season and generally varied together with the exception of a lower value observed in April at site 6. As in lacustrine sites, peak total nitrogen in river sites were lower than in 2017.

Lacustrine and riverine sites' nutrient concentrations are often disparate from each other; riverine values are consistently higher than in open water sites. In 2018, site 8 and 11 behaved very similarly and exhibited TN values slightly over the lacustrine sites. All sites' nitrogen concentrations generally increased through the season and followed a similar peak and fall pattern. Site 6 had the highest TN values peaking in October at 1.251 mg/L.

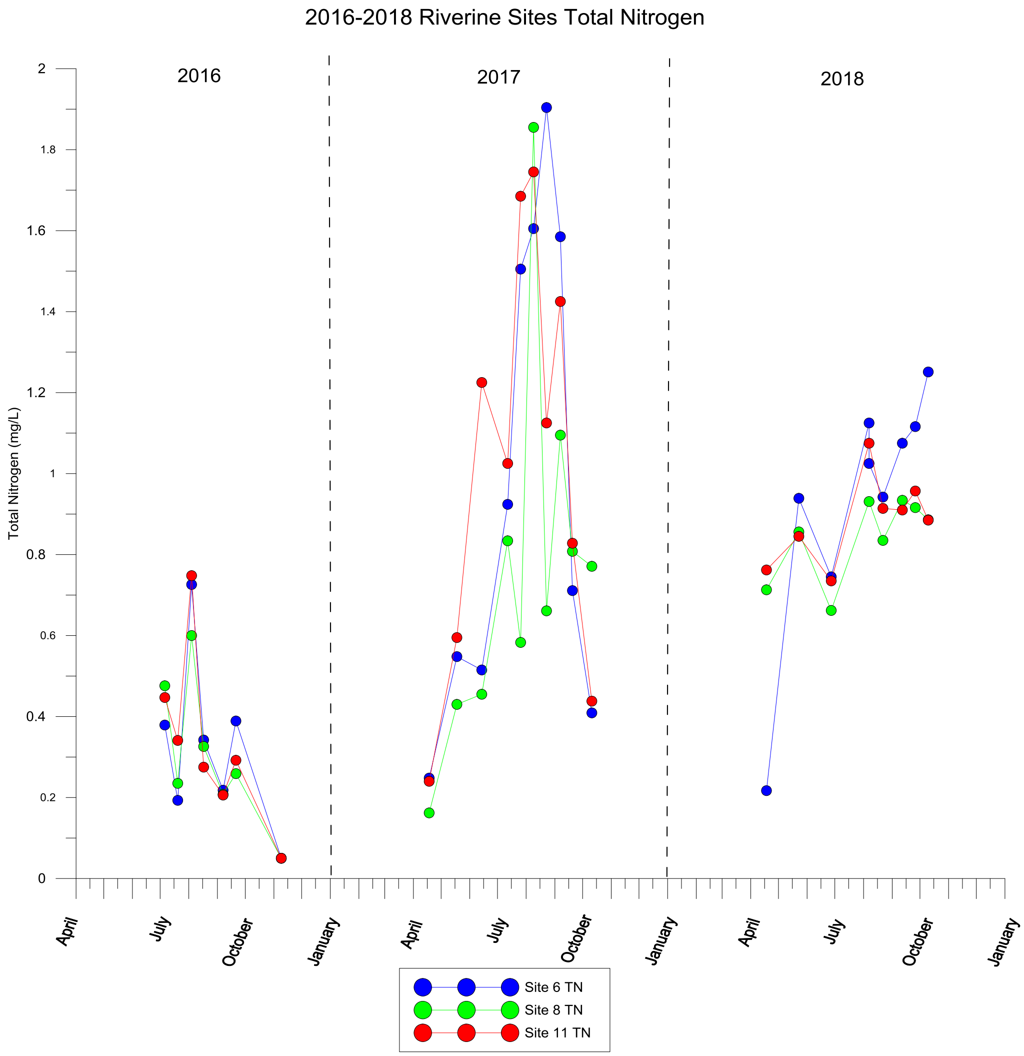


Figure 18. 2018 Surface Total Nitrogen Variables as N (mg/L) from the three riverine sites.

Average site 1 epilimnetic total nitrogen values were similar to previous years and are in the range of eutrophic reservoirs in Oklahoma. Epilimnetic ammonia was detected throughout the monitoring season and represents an atypical occurrence, as energetics of nitrogen assimilation by algae orders ammonia first. Ammonia requires less energy for uptake, followed by nitrite, nitrate and finally dinitrogen. The expectation is then for ammonia to fall below reporting limit first, then nitrate, however the opposite was observed in 2018 (**Figure 16**). The disparity between the data and ecological behavior is not easily reconciled.

Hypolimnetic ammonia accumulated through the season, due to sequestration by density gradient and release from lake-bottom sediment. The stepwise breakdown of thermal stratification in the fall mixed the nutrient rich hypolimnetic waters to the surface, decreasing hypolimnetic concentration.

Riverine nitrogen concentrations peaked at the same time as lacustrine values and were measured a slightly higher than in lacustrine areas throughout the season. Site 6 exhibited the highest nitrogen values, likely attributed to storm water bringing nutrients into this shallow area of the lake.

In general, nutrients behaved similarly 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.

Algae

Chlorophyll-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. 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.

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.

Algal Biomass

Chlorophyll concentrations vary spatially and seasonally and therefore, are presented as lacustrine and riverine sites over time. Lacustrine chlorophyll values began the monitoring season at relatively low levels, mostly lower than the 10 µg/L water quality criterion, until June when the lake began to stratify (**Figure 19.** 2018 Lake Thunderbird surface chlorophyll (µg/L) at lacustrine sites. Black line denotes SWS criteria of 10 µg/L). Warmer epilimnetic waters as well as a greater amount of sunlight and nutrients lead to increased production of algae during summer months. This is a trend observed each year in Lake Thunderbird and many other reservoirs in Oklahoma. After the May 23rd event all samples were measured well over the 10 µg/L criterion. Chlorophyll values were relatively similar among lacustrine sites throughout the spring and early summer and they all gradually increased. In September, site 3 values spiked and represented the highest observed values in 2018, at 48.1 µg/L.

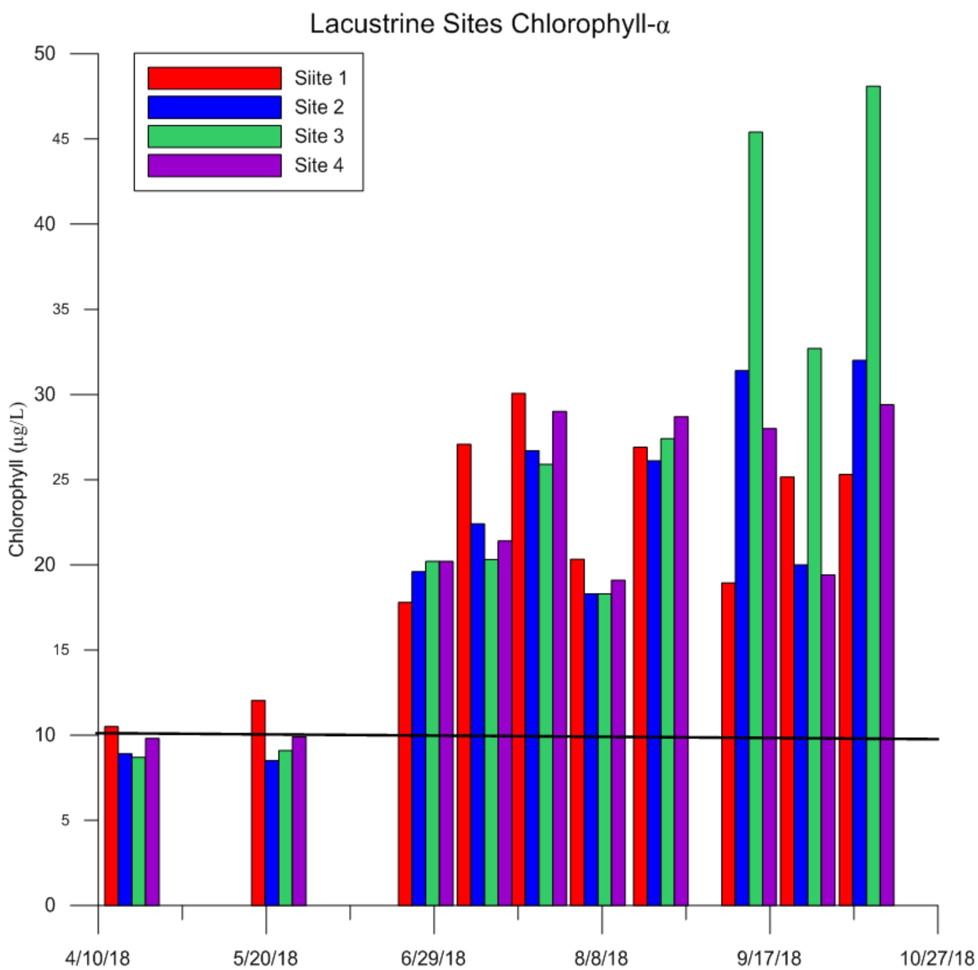


Figure 19. 2018 Lake Thunderbird surface chlorophyll (µg/L) at lacustrine sites. Black line denotes SWS criteria of 10 µg/L

Chlorophyll in riverine sites followed similar patterns as chlorophyll in lacustrine sites, although at a higher magnitude (**Figure 20**). Sites 8 and 11 began the season close to the 10 µg/L criterion, with site 6 exceeding. Site 6 and site 11 sharply increased over early summer and site 8 increased more gradually. Seasonally, we see a general increase among all riverine sites compared to lacustrine values; however, geographically these sites are more spatially spread out, so the comparison between them is more varied than values recorded among the lacustrine sites. Nutrient availability is greater in riverine areas, providing algae more production potential. Inorganic turbidity is higher in these areas as well, due to inputs from the tributaries and watershed, which likely suppresses algae from blooming to even higher levels.

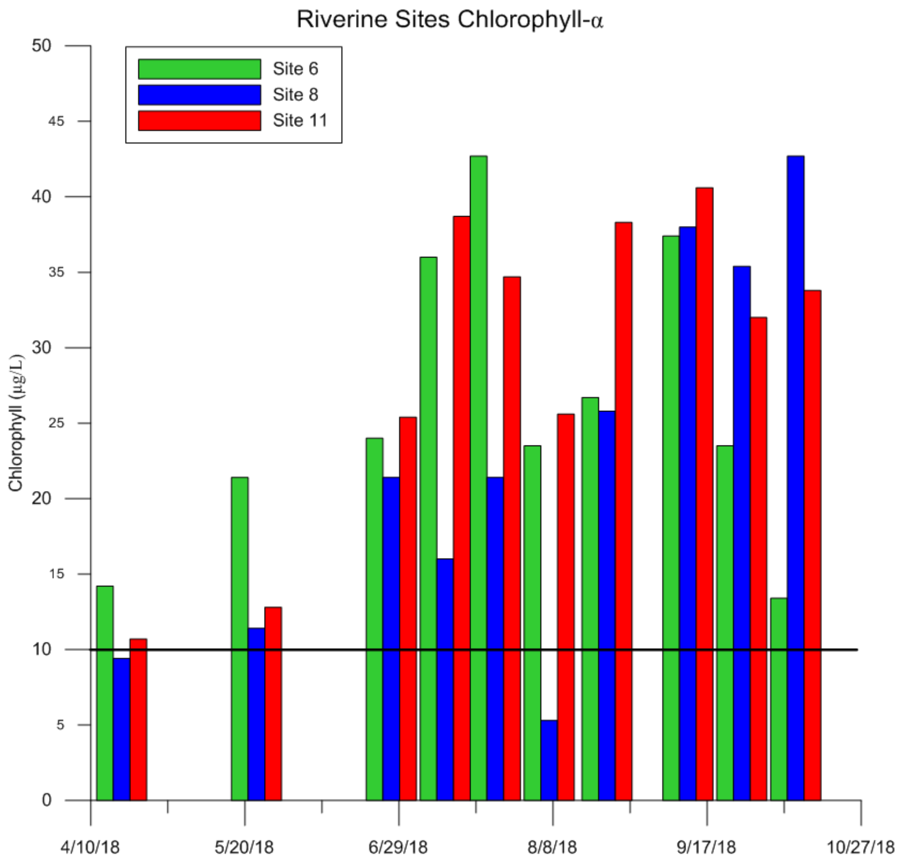


Figure 20. 2018 Lake Thunderbird surface chlorophyll (µg/L) at riverine sites. Black line denotes SWS criteria of 10 µg/L

Algal 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 and nitrogen), and measures of algal biomass.

Nutrients

Phosphorus is desirable as the limiting nutrient for most freshwater systems, 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. A common tool for examining the limiting nutrient relationship is Total Nitrogen to Total Phosphorus (TN/TP) ratio.

TN/TP 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 TN/TP 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 algal productivity.

In the 2018 monitoring season concurrent nitrogen and phosphorus data was not available due to the aforementioned laboratory quality assurance problems. Thus, a 2018 TN/TP ratio is not presented. Historically, Lake Thunderbird has been in the co-limitation range, as both nutrients were readily available for algal growth.

Light

In 2018, Lake Thunderbird's non-algal turbidity was calculated to examine its effect on algal limitation using this equation derived from BATHTUB model (Walker, 1999)

Eq. 5 $T = 1/ Z_{SD} - 0.025 \text{ Chl a}$

Of the samples analyzed for non-algal turbidity (T) influence on algal growth, 60.3% were found to have a T value greater than one. This indicates that at these sites, allochthonous particulates are potentially important and the expected algal response to nutrients is likely to be low. According to Canfield and Bachmann (1981), *"predictions of algal densities and water transparency are less reliable in artificial lakes, as the phosphorus-chlorophyll and chlorophyll-Secchi depth relationships are less precise. This seems to be due to the influence of non-algal particulate materials."* These insights could help explain why chlorophyll values were lower than would be expected by the high amount of nutrients present in the system. More investigation is needed and additional monitoring and analysis will be conducted in 2019.

Trophic State Index – TSI

Trophic state is a measure of primary productivity used to classify waterbodies as oligotrophic, mesotrophic, eutrophic or hypereutrophic. 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 developed the most commonly used biomass-related trophic state indices (TSI) (Carlson, 1977). The Carlson TSI metrics were compared in this analysis to examine algal growth. Three surface water quality parameters, chlorophyll (CHL), Secchi depth (SD) and total phosphorus (TP) aid in estimating algal biomass (Carlson 1977, Kratzer 1981). Of these three, chlorophyll yields the most relatable TSI value, as chlorophyll is the most direct measure of algal biomass, which is the measure of primary productivity that the trophic state seeks to classify. TSI based on Secchi depth is historically the poorest predictor of trophic state at Lake Thunderbird because high-suspended solids lead to relatively low water clarity. This clouds the impact of algal biomass on the TSI value. Trophic states, categorized by their TSI(CHL) values, are 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 parameters are displayed in **Figure 21** ranging from 46.6-69.4 throughout 2018. TSI(CHL), a reflection of actual or realized algae growth, showed site 1 to have been eutrophic in April steadily increasing to the hypereutrophic range by July and maintaining that state through the rest of the sampling season with only a small retreat to eutrophy in September. TSI(TP) under-predicted TSI(CHL) throughout the season suggesting that TP is not a stable predictor of trophic state and additional factors are driving algal growth. TSI(SD) consistently over-predicted TSI(CHL) likely influenced by higher inorganic turbidity values. Overall the TSI(CHL), which is calculated based on monitored chlorophyll results, indicated high lacustrine algal growth as values were above 50 for the whole monitoring period, corresponding to a eutrophic state.

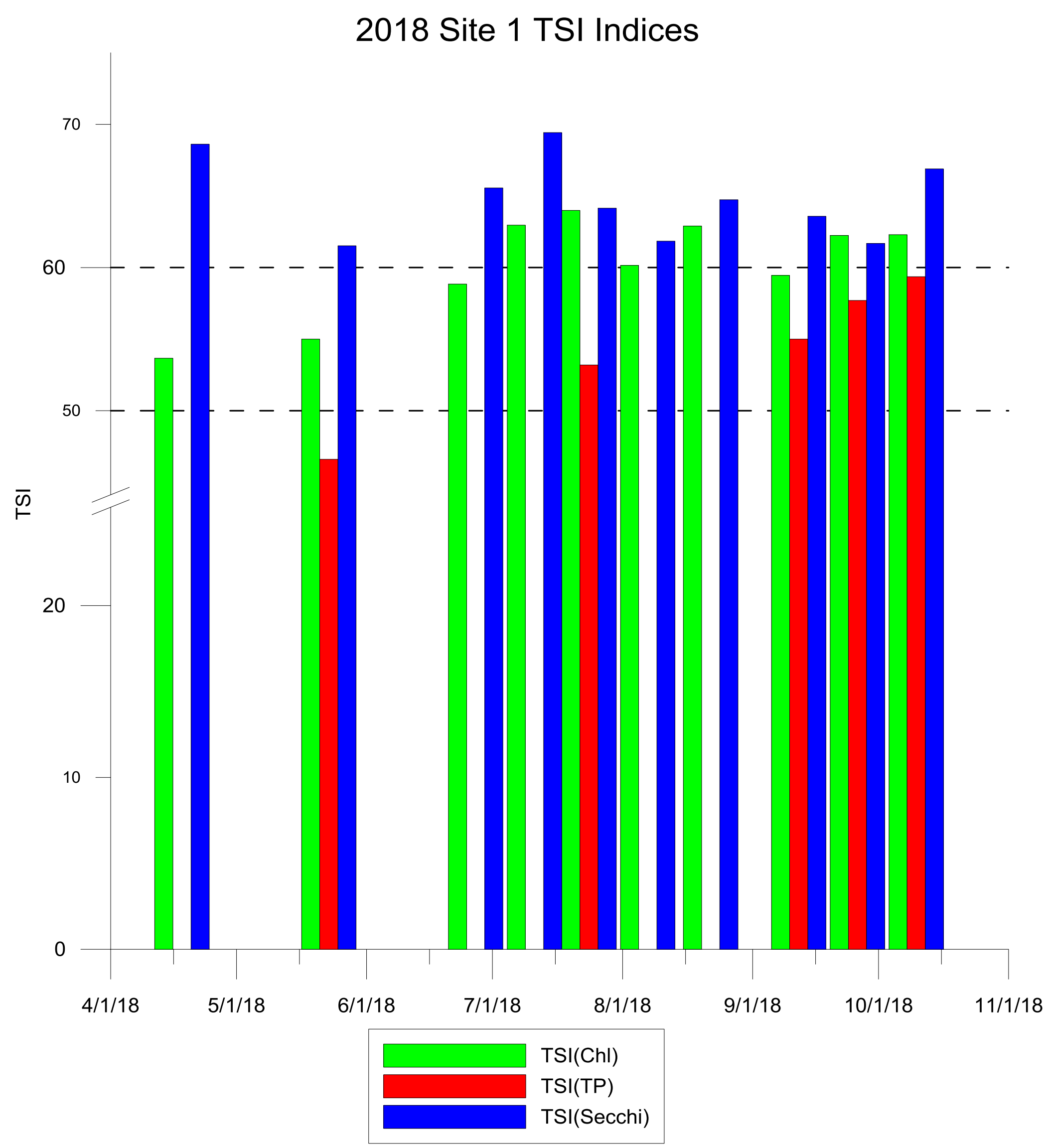


Figure 21. 2018 Carlson's Trophic State Index values for Lake Thunderbird at Site 1. Dashed lines delineate ranges for trophic states. Axis is broken from 25 to 45 to emphasize relationships between variables.

In a similar pattern as site 1, TSI(CHL) at the riverine sites increased from eutrophic to hypereutrophic conditions in July. TSI(CHL) varied between sites and were consistent with realized chlorophyll in the system (**Figure 22**Error! Reference source not found.).

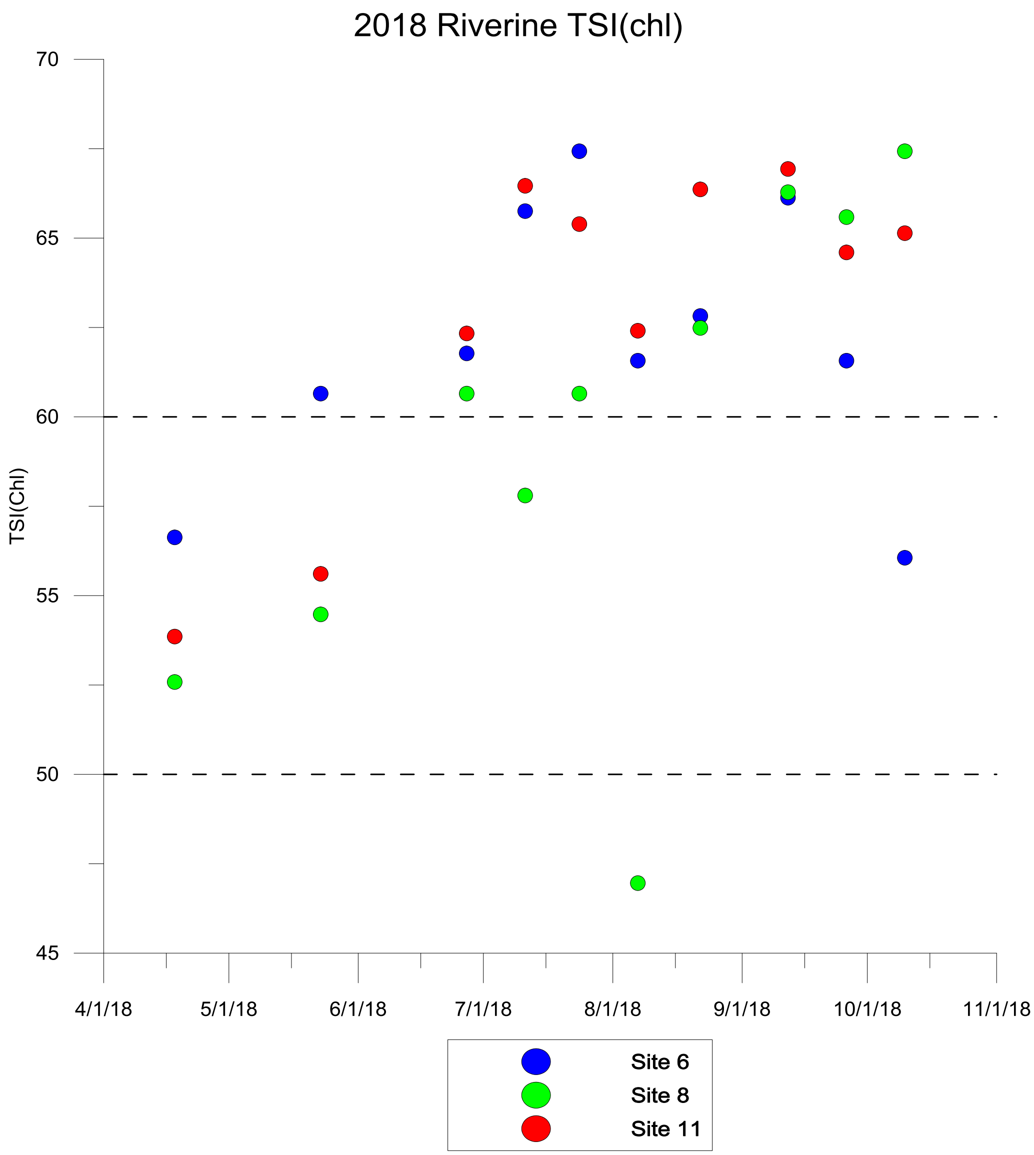


Figure 22. 2018 Carlson's Trophic State Index values for riverine sites (sites 6, 8, and 11) for Lake Thunderbird. Dashed lines delineate ranges for trophic states.

Total Organic Carbon - TOC

Total organic carbon (TOC) is a measure of all the carbon containing compounds present in a water sample, allowing insight to the amount of organic material present. Sources of these organic compounds include soil and plant detritus and to a lesser degree, even carbon present in living material such as bacteria and plankton (Wetzel, 2001). Wetzel presents median organic carbon content for eutrophic lakes as 12.0 mg/L, oligotrophic lakes as 2.2 mg/L, and rivers as 7.0 mg/L (2001). In 2018, Lake Thunderbird TOC values ranged from 4.68 to 5.17 mg/L with a mean value of 4.945 mg/L (**Table 4** 2018 Lake Thunderbird Total Organic Carbon (mg/L)). In 2018, TOC was not easily relatable to algal content, likely due to pheophytin and sediment from the watershed contributing to carbon sources.

TOC is an especially important measure for water treatment plants to inform on potential creation of Disinfection By-Products (DBPs). Chlorine compounds used in disinfection can react with organic matter to creating by-products that could be carcinogenic (TCEQ, 2002). Reducing TOC in the source water could lead to reducing the drinking water treatment cost.

Table 4 2018 Lake Thunderbird Total Organic Carbon (mg/L)

Total Organic Carbon (mg/L)	
4/18/2018	5.17
5/23/2018	4.98
6/27/2018	4.86
7/11/2018	5.03
7/24/2018	5.04
8/7/2018	4.68
8/22/2018	4.93
9/12/2018	4.68
9/26/2018	5.02
10/10/2018	5.06

Taste and Odor Complaints

The City of Norman has provided data on the number of taste and odor complaints for the period of record (2000 – 2018) and more recently included taste and odor 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 taste and odor 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 complaints in 2018, exhibited a different pattern from previous years, with complaints peaking in January rather than the typical September peak (**Figure 23**). In past years, taste and odor complaints coincided with lake mixing events cycling hypolimnetic chemicals into the water column. In 2017, complaints peaked when MIB values were highest at over 1,000 ηg/L. In 2018, MIB peaked in September when epilimnetic DO was lowest prior to destratification. Interestingly, Geosmin peaked in December of 2018 (**Figure 24**). It is clear that various algae processes are active throughout the winter months; however, it is impossible to evaluate the winter season nutrient dynamics and algal processes because monitoring is not conducted in the winter months.

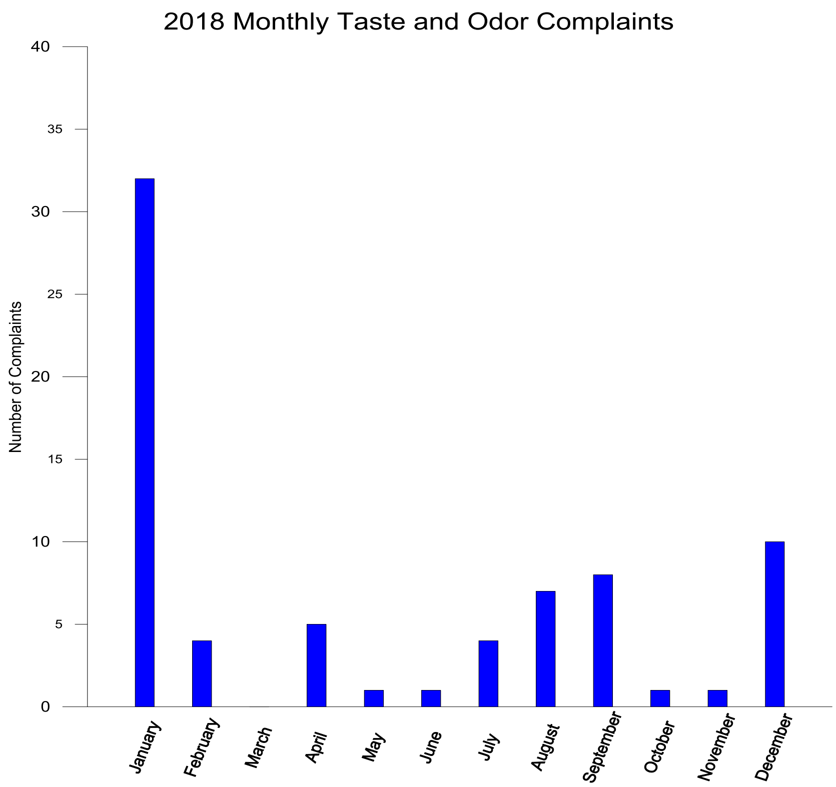


Figure 23. 2018 City of Norman compiled daily Taste and Odor complaints. March complaints not recorded.

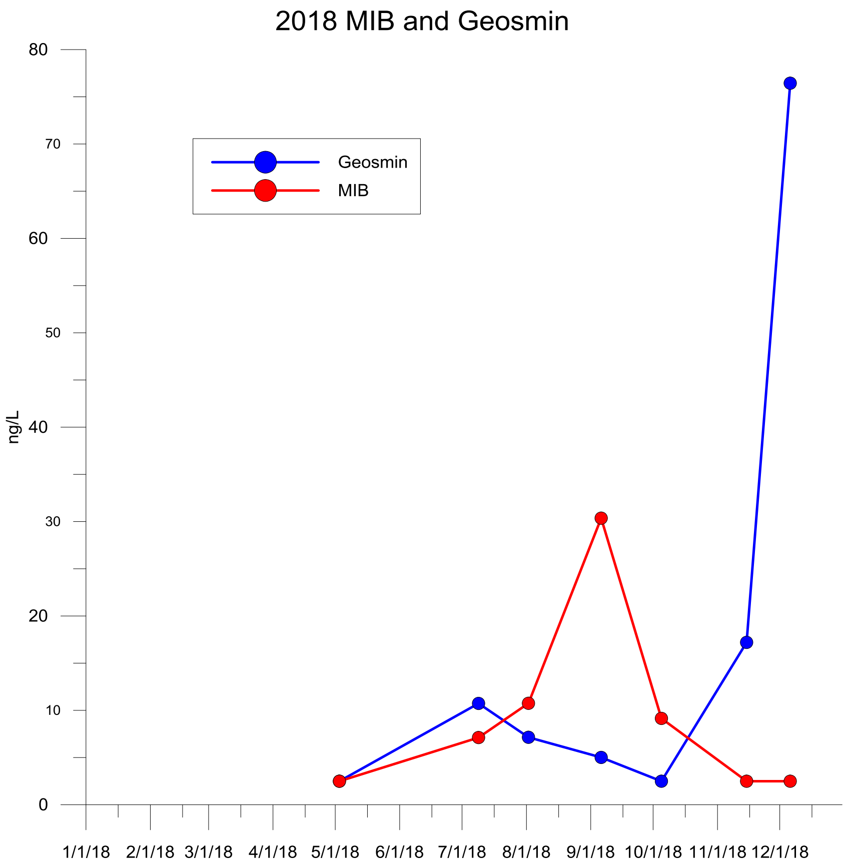


Figure 24. 2018 City of Norman raw water laboratory analysis.

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 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. Identification and protection of beneficial uses are vital to water quality standards implementation. Beneficial use designations for Lake Thunderbird are Public and Private Water Supply (PPWS), Fish and Wildlife Propagation (FWP), Agriculture, Recreation, and Aesthetics.

Lake Thunderbird is listed in the latest approved Oklahoma Integrated Water Quality Report as impaired due to low dissolved oxygen, excessive turbidity, and excessive chlorophyll (ODEQ, 2016). In order to address these impairments, Lake Thunderbird has undergone Total Maximum Daily Load (TMDL) development by the ODEQ with the resultant report approved by the Environmental Protection Agency (EPA) in 2013. The TMDL analysis requires a 35% long-term average load reduction of total nitrogen, total phosphorus, and total suspended solids from the 2008-2009 watershed load estimates in order to restore the lake's beneficial uses. Implementation of the TMDL is underway and point source and non-point source measures are outlined in the Final TMDL Report (Dynamic Solutions, 2013).

The Oklahoma Water Quality Standards Implementation Rules contain Use Support Assessment Protocols (USAP) for Oklahoma waterbodies. This USAP is the statewide methodology for integrated report water quality assessments (i.e. 305(b) and 303(d) reports). The 2018 water quality data was assessed in accordance with the USAP to evaluate current conditions relative to OWQS attainment or nonattainment. Physical, chemical, and biological data on Lake Thunderbird were used to assess the lake condition and determine if lake water quality supports its designated beneficial uses and are outlined below.

Dissolved Oxygen – DO

Dissolved oxygen criteria are designed to protect the diverse aquatic communities found throughout Oklahoma waterbodies. For warm water aquatic communities, such as Lake Thunderbird, two assessment methodologies apply to protect Fish and Wildlife Propagation beneficial use: 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 less than 50% of the lake volume measured as anoxic (< 2 mg/L DO).

One surface water violation occurred in 2018, as the minimum surface DO registered at 3.57 mg/L at site 2 on September 26, 2018. Lake Thunderbird did not violate the volumetric criteria in 2018 as it exhibited a maximum 41.21% of anoxic volume on July 11.

Chlorophyll-a

Oklahoma surface water drinking supplies are vulnerable to eutrophication - high biological productivity driven by excess nutrients. Communities can experience substantial hardship and high costs to treat water affected by eutrophication. 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 average chlorophyll concentration of 10 µg/L at a depth of 0.5 meters. For the 2018 sampling season, the lake wide chlorophyll average in Lake Thunderbird was 22.5 µg/L, with 84% of the samples exceeding 10 µg/L, whereas samples collected in 2017 had a lake wide average of 32.98 µg/L with 95% of samples exceeding (**Figure 25**). The long term ten-year lake-wide average is 26.6 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.

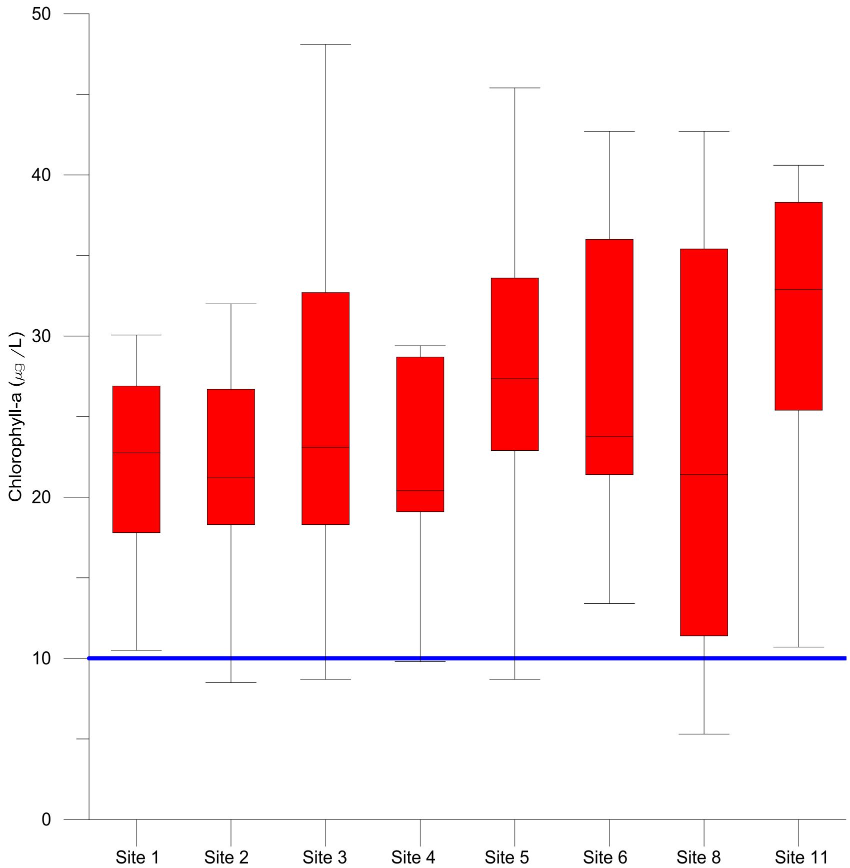


Figure 25. 2018 Lake Thunderbird chlorophyll-a (µg/L) by Site, where boxes represent 25% of the data distribution both above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Blue line represents 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. Oklahoma reservoirs typically have depths measuring less than one meter. In Lake Thunderbird, Secchi disk depths ranged from a 2018 mean of 17.9 centimeters at Site 6 to a mean of 72.9 centimeters at Site 1. Whole lake average of Secchi depth was 49.01 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 26**).

The criterion for turbidity, a measure of water transparency, for the protection of the beneficial use of Fish and Wildlife Propagation, is set at 25 Nephelometric Turbidity Units (NTU). If at least 10% of collected samples exceed this value in the most recent 10-year dataset, the lake is not supporting its beneficial use, and is thus impaired for turbidity. For the 2018 sampling season, the lake wide turbidity average in Lake Thunderbird was 23.82 NTU, with 23.7% of the samples exceeding 25 NTU **(Figure 27**), compared to 31.3% of last year's samples. The long-term, ten-year, lake-wide average is 24.9 NTU, with 26.9% 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.

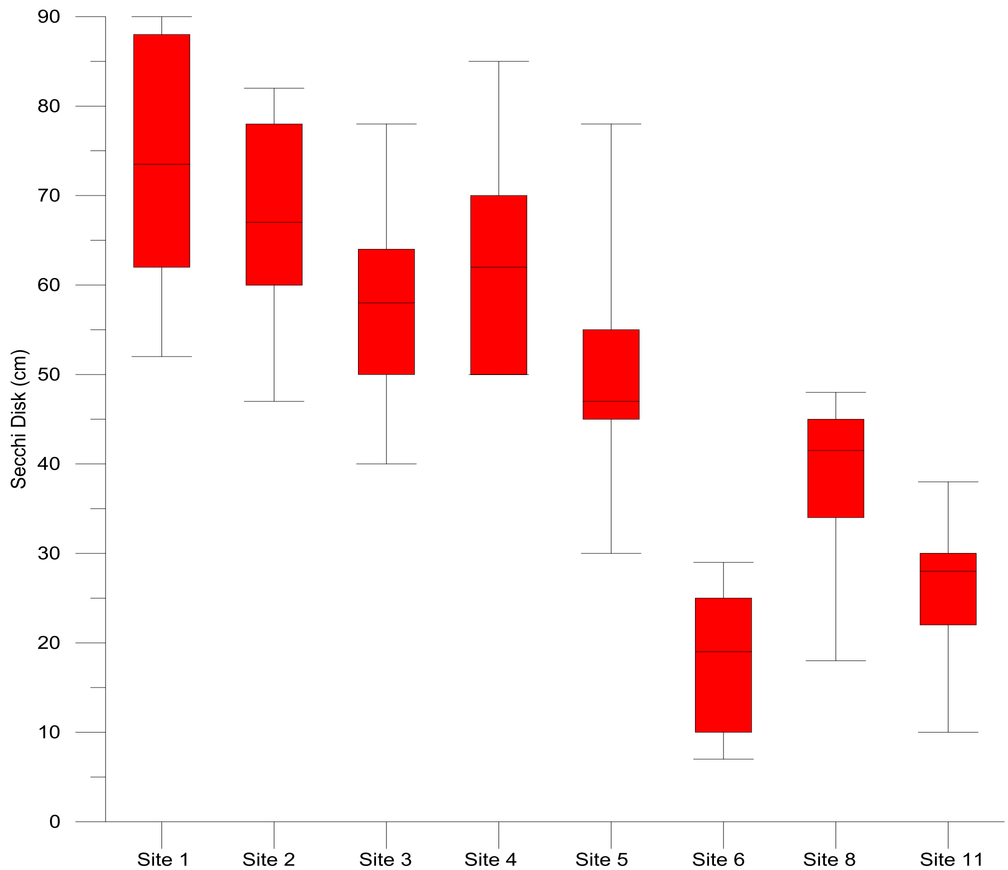


Figure 26. 2018 Lake Thunderbird Secchi Disk Depth (in centimeters) by Site, where boxes represent 25% of the data distribution both above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values.

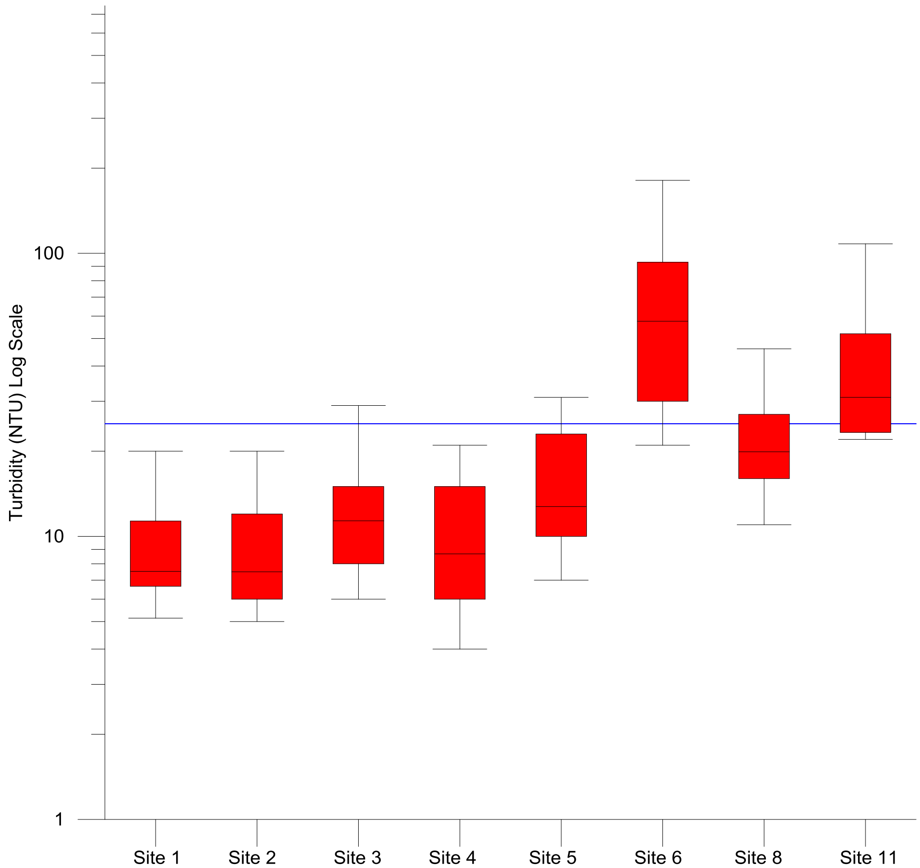


Figure 27. 2018 Lake Thunderbird Turbidity (NTU), by Site, where boxes represent 25% of the data distribution both above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Solid blue line indicates the 25 NTU water quality standard.

Supersaturated Dissolved Oxygen Injection System (SDOX)

Sample year 2018 marked the eighth season of operation for the SDOX installed in Lake Thunderbird. It is designed to operate throughout the entire stratification period and provide oxygen to the hypolimnion. The system withdraws water from the deepest area of the hypolimnion approximately 16 meters in depth, supersaturating this water with oxygen under pressurized conditions, and then re-injecting it at a separate location 12 meters deep (**Figure 29**).

This monitoring season marked the sixth year of operation at optimal design, as large modifications occurred in both the system's components and operation early on. The SDOX delivered 546,994 lbs. of oxygen at an average rate of 3,256 pounds per day in 2018, a higher amount, but lower rate than in 2017.

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 can further stimulate algal growth. If the SDOX system were able to provide an oxygenated hypolimnion, potential benefits would include reduction of the internal nutrient load by minimizing the recycling of nutrients from the sediment, consequently, mitigating peak chlorophyll values. The SDOX system should induce physical changes, such as increased dissolved oxygen and oxidation-reduction potential in the hypolimnion and reducing phosphorus sediment load and providing oxidant for breakdown of organic molecules including taste and odor compounds.

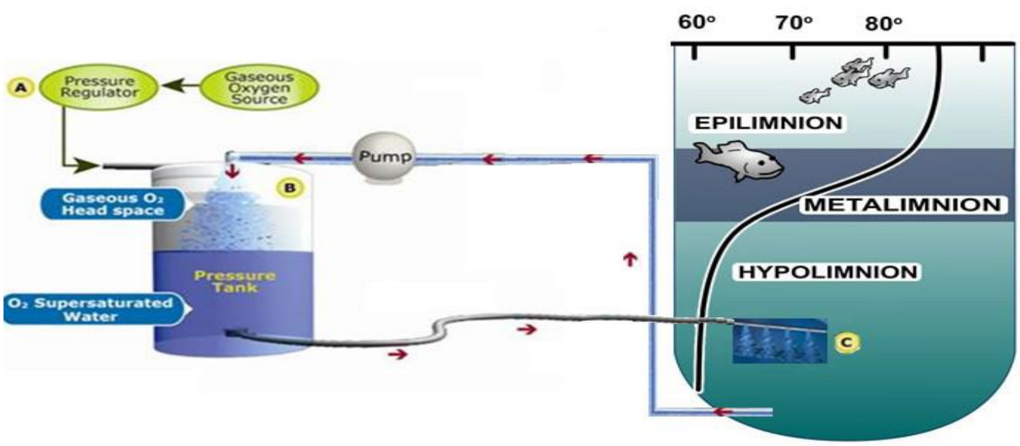


Figure 28. Conceptual illustration of the SDOX System at Lake Thunderbird

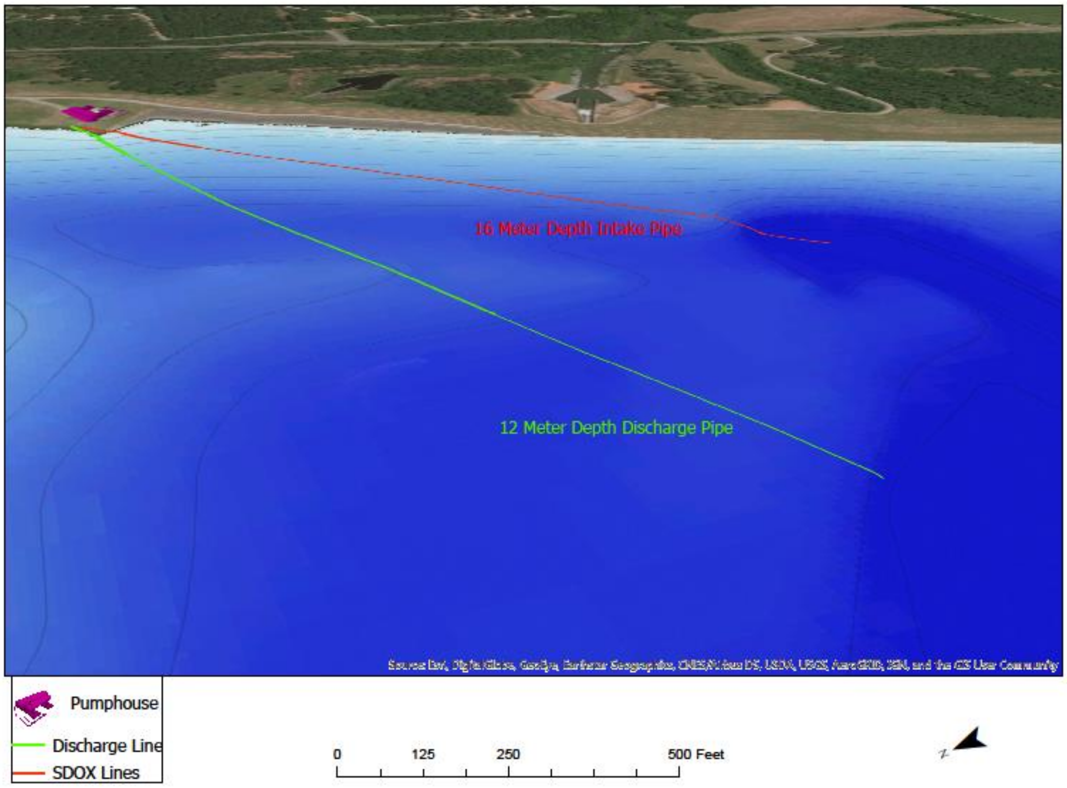


Figure 29. Map highlighting SDOX location and current configuration.

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.

Examination of Relative Thermal Resistance (RTR) to mixing plots (**Figure 30**) showed only a nominal difference between stratification patterns at sites 1 and 12, the output nozzle site. This indicates that the SDOX is not inducing a significant disruption of thermal stratification. In May, stratification was beginning to set up at both sites, by late July the lake was at peak stratification and resistance to mixing was highest. The remainder of RTR plots are in **Appendix C**: Relative Thermal Resistance Plots.

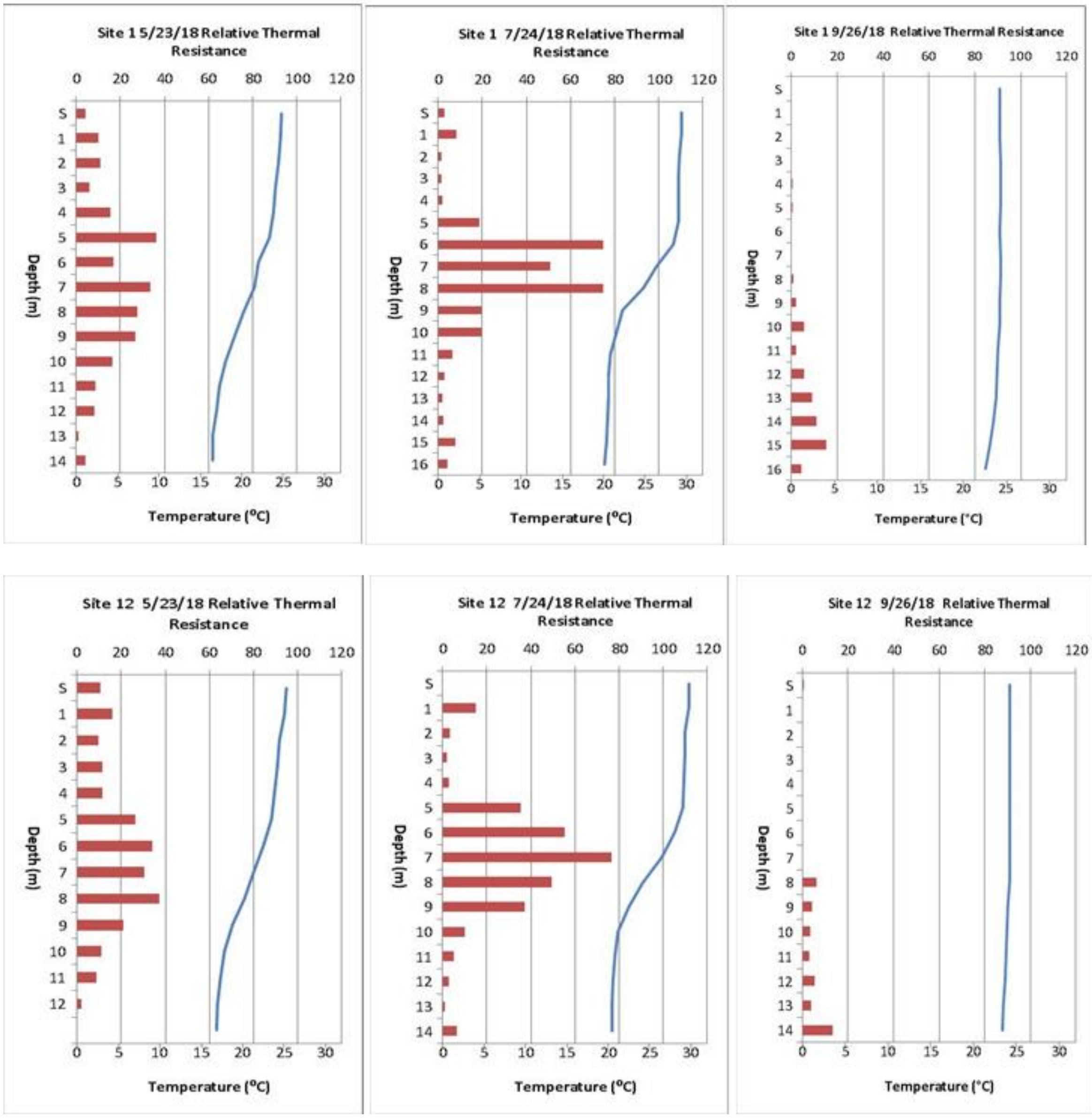


Figure 30. Relative Thermal Resistance plots at sites 1 and 12.

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

The main objective of the SDOX system is to provide oxygen to the hypolimnion through much of the monitoring season. While not designed to prevent anoxia (< 2mg/L DO) within the entire hypolimnion, it is expected to raise DO levels. If DO levels increased, the expectation is that ORP values would increase as well due to the availability of oxygen as an electron acceptor. Low ORP (<100mV) was first observed at the sample event following when DO conditions were hypoxic (**Figure 31)**. This indicates that while DO levels were below 2 mg/L at the May event, oxidizing conditions persisted in the hypolimnion until the June event. This could be a sign of SDOX efficacy at creating these conditions.

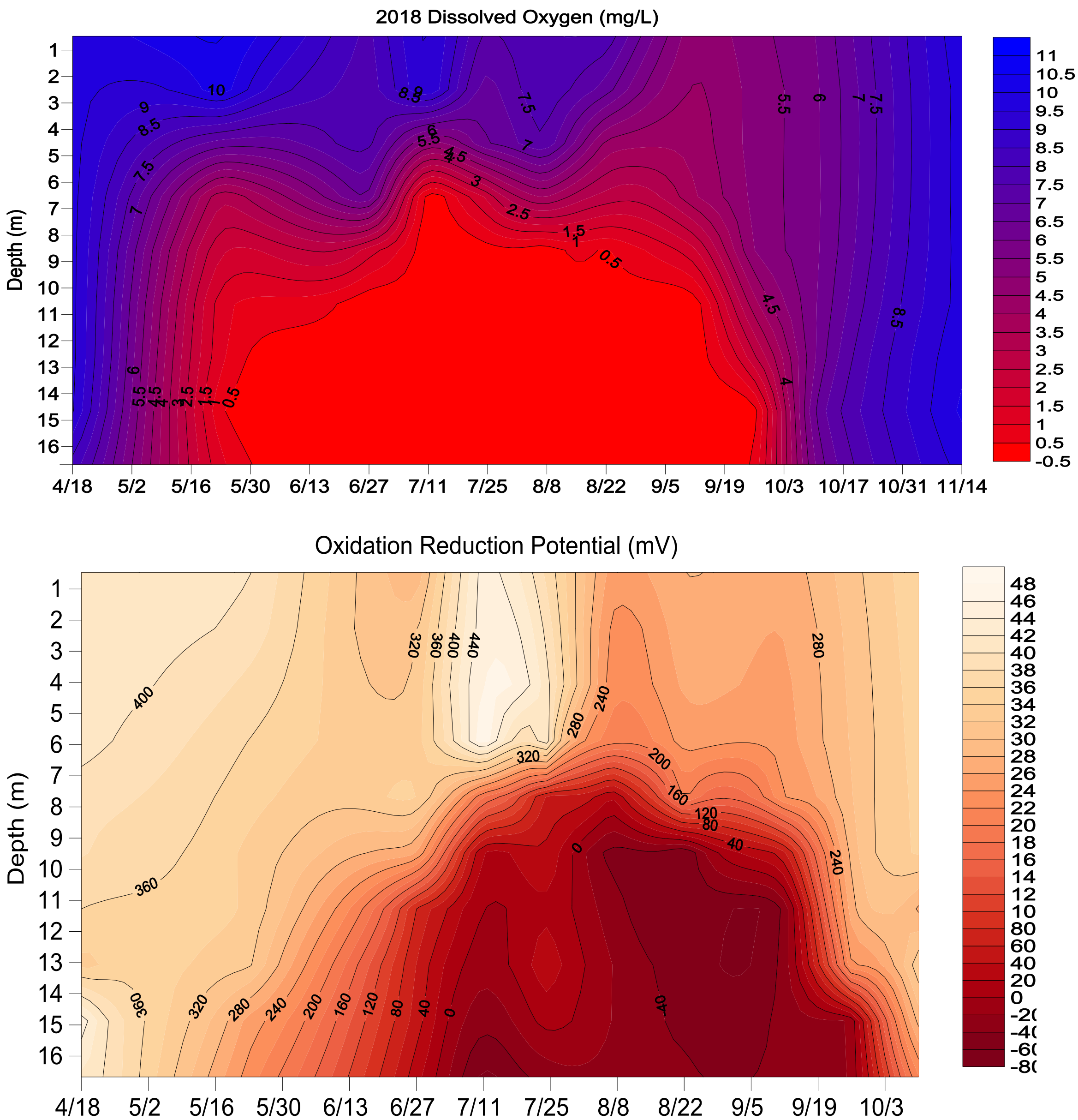


Figure 31. 2018 Isopleths of Dissolved Oxygen, and Oxidation-Reduction Potential (ORP) versus Depth at Site 1; highlighting the temporal disparity between Anoxia (Dissolved Oxygen), and reducing conditions (ORP).

A 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 6.

Eq. 6 $$AF = \sum_{i=1}^{n}(t_i * a_i)/A_o$$

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 and capacity vs. depth table (OWRB, 2002). 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 5Error! Reference source not found.). The average of 2005 – 2009 represents pre-SDOX conditions as a baseline comparison against AF calculated for the following years. Lower AF was seen from 2011 to 2014 indicating less phosphorus release from sediment relative to the baseline average. In 2015, a shift occurred and anoxic factor was higher than the 2005 - 2009 baseline; historic flooding also occurred in 2015, potentially affecting SDOX efficacy. 2018 was the first year to see a reversal of this increasing AF trend. The increase in AF and P-load from 2015 to 2017 is a clear indicator of increased organic load to the hypolimnion beyond the mitigation capacity of the SDOX. In 2018, the reversal of this trend is promising as it indicates less internal phosphorus loading.

Even though there was a decrease in the AF this year, the amount of anoxic water present at the nozzle site relative to the amount of oxygen pumped into the system, it is clear that there is a large sediment oxygen demand driving the consumption of oxygen. This demand should be evaluated and SDOX operation adjusted to limit phosphorus release from the sediment and subsequent mixing through the water column to limit algal growth and thus improve the lake's water quality. In summary, while the stated oxygen goal was not realized, it is appears that the SDOX exerted a positive effect on hypolimnetic water quality.

Table 5. Summary of Anoxic Factor (AF) and Sediment Phosphorus load (P-load) by year (2011 – 2018) 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	34.94	0%	3,753	0%
2010	46.22	28%	4,965	28%
2011	21.70	-47%	2,332	-47%
2012	25.61	-31%	2,751	-31%
2013	18.68	-61%	2,007	-61%
2014	30.67	-13%	1,809	-70%
2015	41.24	17%	4,312	14%
2016	39.72	13%	3,926	4%
2017	36.46	4%	3,434	-9%
2018	32.41	-8%	3,131	-18%

Discussion

For the past 18 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 increased development in the watershed, high levels of nitrogen and phosphorus especially in riverine areas, and increasingly high chlorophyll leading to beneficial use impairments.

Climactically, Lake Thunderbird experienced a slightly cooler April and a warmer than average May in 2018. Epilimnetic water temperature peaked in July. Water inputs to the lake remained relatively equal with total outputs, resulting in an overall static water level through the monitoring season. The overall pattern of stratification remained similar to previous years. Thermal stratification was observed at the May sample event coinciding with an anoxic volume in the hypolimnion. Indicative of a hypereutrophic system, anoxia was creeping into the metalimnion by June 27, persisting through the summer until thermal mixing in late September. This recent trend of metalimnetic anoxia further underscores the excessive algal growth and high sediment oxygen demand and the urgent need for addressing the water quality impairments in the lake. Reducing conditions in the hypolimnion, indicated by very low oxidation-reduction potential, occurred from June to September and encompassed a large volume of water, slowing the breakdown of organic materials. This provides a larger amount of material mixed into the water column after thermal stratification has broken down.

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 optimum to effectively curb excess biological productivity. Late summer and early fall hypolimnetic phosphorus values were high, stemming from the effect of thermal stratification and internal release from anoxic sediment. In fall, hypolimnetically stored nutrients mixed into the water column resulting in higher epilimnetic values. Ortho-P, the biologically available form of phosphorus, was not detectable in the epilimnion, due to uptake by algae. Hypolimnetic ortho-P accumulated through the season before mixing in the fall. Lacustrine phosphorus measures were generally lower than riverine surface phosphorus, suggesting delivery of a large load of this nutrient is entering the system as runoff from the watershed. Riverine areas also allow for the continuous cycling and resuspension of nutrients, due to their shallow depths being susceptible to wind mixing.

Nitrogen, another nutrient important for algal growth, was also readily available for algae in 2018. Nitrogen dynamics were a little confounding again this year, with detection of ammonia in the epilimnion throughout the year; ammonia requires the least amount of energy for assimilation by algae and therefore, should be used first by algae for metabolic processes. Thus, one would expect ammonia nitrogen concentrations to decrease below the reporting limit first. However, nitrate/nitrite, the second most easily assimilated form of nitrogen, was below reporting limit first this year and remained below until after peak growing season. 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 ammonia was evident in summer and early fall stemming from the effect of thermal stratification and release from anoxic sediment. Neither nutrient was likely to be substantially limiting algal growth in 2018, as they were present in abundant amounts. Data collected in 2018 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 such that designated beneficial uses are attained. 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).

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 classification requires average chlorophyll to be less than 10 µg/L; chlorophyll concentrations in the lake are consistently greater than 10 µg/L.

In 2018, average chlorophyll-a values decreased from 2017 values, but remained excessive, representing a need to mitigate conditions driving increased algal biomass. Riverine sites experienced higher chlorophyll levels than lacustrine areas, but high turbidity likely limited algal growth and prevented even higher chlorophyll values. In order to control biological populations, it is important to understand what is driving their growth. A new technique was employed this year to look at light's effect on algal growth, Walker's (1999) analysis on non-algal turbidity. Results would indicate that allochthonous particles did have a negative effect on algal growth, but more analysis is needed and will be expanded in the 2019 monitoring and analysis. Trophic State Indices were also examined and the most stable index, TSI(CHL), determined that the lake would be classified as eutrophic, increasing to hypereutrophic in peak summer months. Examining other TSI parameters, showed that factors other than TP are driving growth, and that high inorganic turbidity affects results.

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. 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. However, in 2018, January exhibited the peak number of taste and odor complaints and Geosmin levels peaked in December. This highlights that there is an interesting relationship between complaints and algal toxins occurring in winter months that should be investigated further. 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 2016 303(d) list of the Water Quality Integrated Report as impaired due to low dissolved oxygen and chlorophyll-a, with the driver of these impairments identified by the ODEQ TMDL as excess nitrogen and phosphorus. OWRB has thoroughly analyzed these impairments. Monitoring data, collected in 2018, 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 chlorophyll criterion for Sensitive Water Supply (SWS) 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. 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.

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. Positive changes in water quality were observed in the first several years of SDOX operation. In 2018, anoxic factor decreased relative to the calculated baseline value for the first time in several years. This indicates a measured positive influence of the SDOX and a decrease of estimated phosphorus load from lake sediments. Even though there was a decrease in anoxic factor this year, the volume of anoxic water present at the nozzle site relative to the amount of oxygen pumped into the system, it is clear that there is a large hypolimnetic oxygen demand. This demand should be precisely measured and SDOX operation adjusted to limit phosphorus release from the sediment and subsequent mixing through the water column to limit algal growth and thus improve the lake’s water quality. Based on this analysis, and OWRB experience monitoring this lake, the SDOX is not a silver bullet that is solving the eutrophic conditions of Lake Thunderbird. However, it is likely mitigating some of the internal phosphorus loading. That is an important aspect of maintaining water quality and not allowing further degradation, while the long-term goal is improved water quality and beneficial use attainment.

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. Hypolimnetic oxidation is a worthwhile exercise 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

In past years, the monitoring strategy has been modified many times for a multitude of reasons, not the least of which is budgetary concerns. This has led to a somewhat disjointed monitoring plan that does not always address areas of concern. To that end, the water quality monitoring strategy will be altered for 2019, at no cost to COMCD. Alterations include:

- Conducting additional DO transects around SDOX site
- Adding at depth nutrient samples at SDOX site
- Implementing a Depth Integrated Sampler (DIS) for sample collection
- Removing riverine sediment sampling sites

Additional DO transects around the SDOX nozzle during pre-stratification and peak stratification will establish baseline DO conditions and allow comparison to peak stratification conditions. This will aid in assessing presence and extent of SDOX influence on DO and subsequently ORP.

Additional nutrient profiles at the SDOX site will aid in SDOX effectiveness assessment by examining its potential effects on nutrient accumulation and release. A DIS will be implemented in order to capture a composite water sample from the lake's photic zone, determined at each site by doubling the secchi depth. Sediment sampling has been beneficial in previous years, to analyze anoxic factor and release rate of phosphorus from the sediments, but is most effective at lacustrine sites, thus sediment samples will not be collected at the riverine sites in 2019.

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** details the Scope of Work for the OWRB to complete a bathymetric survey in the future.

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**).

A major stated goal of the SDOX is to limit sediment nutrient release by adding super-saturated oxygen to the hypolimnion. Internal loading is a potential source of nutrients added to the reservoir that has only been estimated through sediment P concentrations in the past. An internal

P-loading study needs to be performed to accurately determine the amount of nutrients coming from the lake bottom rather than from the watershed. This would allow a better understanding of the nutrient budget and could lead to better management decisions taking into account allocating budgetary resources.

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 and sediment erosion further contributing to nutrient loads.
- 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
- Encourage municipalities within the watershed to incorporate LID into any new construction within the watershed (Low Impact Development Center, 1999)
- Encouraging community involvement through outreach, education, Watershed Management Groups, grassroots neighborhood "Protect our Lake" groups, river cleanups etc.

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 has an opportunity to act in a leadership role for the health of Lake Thunderbird.

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Appendix A
Quality Assurance and Quality Control Data

Water quality sampling followed the agency-specific Standard Operating Procedures (SOPs) (OWRB, 2017 and 2018). Several types of Quality Assurance/Quality Control (QA/QC) measures were employed to ensure quality data as part for the 2018 monitoring year, in the categories of collection, post-processing, and laboratory checks. These include:

- Timely review process of SOPs
- Calibration of field equipment
- Acid-washing and Blanking Van Dorns before sample collection
- Sampler training and audits for field collection and sample processing
- Geographic site and depth verification to locate SDOX nozzle site
- Multiple stage review process for profile, field and lab data flowing to database
- Reviewing analytical lab data for flags and abnormal data
- QA/QC sample collection

Several types of QA/QC samples were collected including replicates, duplicates, laboratory blanks, and analytical blanks. 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 a split sample. Replicate samples primarily control for the collection of a representative sample, but these results also include a measure of uncertainty from laboratory analysis.

Replicate samples were collected at the surface of the site 1 for each parameter and designated as Site 1(12) and Site 1(22) for environmental and replicate samples respectively (**Table 6**). In addition, the Site 1 chlorophyll sample was split to produce duplicate samples designated as Site 1(12) and Site 1(21), post processing was completed at the OWRB, then analyzed at Accurate Labs (**Table 9**).

Table 6. Summary of 2018 Replicate Sample Results Designated as 1 (12) & 1 (22)

Date	Site	TKN (mg/L)	NO2/NO3 (mg/L)	Ammonia (mg/L)	Ortho-P (mg/L)	TP (mg/L)	Chlorophyll-a (µg/L)
4/18/2018	1(12)	0.568	0.254	0.158	<0.005	NO DATA	10.7
5/23/2018	1(12)	0.634	<0.05	<0.05	0.005	0.019	12
6/27/2018	1(12)	0.462	<0.05	0.074	<0.005	NO DATA	16
7/11/2018	1(12)	NO DATA	<0.05	0.095	<0.005	NO DATA	NO DATA
7/24/2018	1(12)	NO DATA	<0.05	0.095	<0.005	0.029	29.7
8/7/2018	1(12)	0.707	<0.05	0.149	<0.005	NO DATA	18.3
8/22/2018	1(12)	0.776	<0.05	0.109	<0.005	NO DATA	27.9
9/12/2018	1(12)	0.785	<0.05	0.265	<0.005	0.036	20

Date	Site	TKN (mg/L)	NO2/NO3 (mg/L)	Ammonia (mg/L)	Ortho-P (mg/L)	TP (mg/L)	Chlorophyll-a (µg/L)
9/26/2018	1(12)	0.651	0.16	0.096	<0.005	0.041	23.4
10/10/2018	1(12)	0.641	0.203	0.069	<0.005	0.044	24.9
4/18/2018	1(22)	0.325	0.253	0.149	<0.005	NO DATA	10.1
5/23/2018	1(22)	0.674	<0.05	0.065	0.005	0.019	13.4
6/27/2018	1(22)	0.503	<0.05	0.068	<0.005	NO DATA	18.2
7/11/2018	1(22)	NO DATA	<0.05	0.142	<0.005	NO DATA	26.7
7/24/2018	1(22)	NO DATA	<0.05	0.069	<0.005	0.03	30.8
8/7/2018	1(22)	0.707	<0.05	0.11	<0.005	NO DATA	18.3
8/22/2018	1(22)	NO DATA	<0.05	0.127	0.006	NO DATA	26.1
9/12/2018	1(22)	0.784	<0.05	0.244	<0.005	0.032	17.4
9/26/2018	1(22)	0.642	0.161	0.078	<0.005	0.04	24.7
10/10/2018	1(22)	0.683	0.204	0.129	<0.005	0.047	24.3

*No Data results were invalidated per discussion above

Table 7. Summary of 2018 Chlorophyll-a (mg/L) Quality Control Samples Designated as 1(12) and 1(21)

Date	Site 1 (12)	Site1 (21)	RPD
4/18/2018	10.7	10.7	0.00%
5/23/2018	12	10.7	11.45%
6/27/2018	16	19.2	18.18%
7/11/2018	2	27.4	172.79%
7/24/2018	29.7	29.7	0.00%
8/7/2018	18.3	24.4	28.57%
8/22/2018	27.9	26.7	4.40%
9/12/2018	20	19.4	3.05%
9/26/2018	23.4	27.4	15.75%
10/10/2018	24.9	26.7	6.98%

The relative percent difference (RPD) statistic is calculated to describe the precision of each laboratory parameter based on the comparison of replicate and duplicate sample pairs.

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

Equation 1 was applied to each replicate and duplicate sample for each reported parameter. In **Table 8**, the acceptable precision limit for each parameter and the percent of sample events meeting that limit are listed.

Table 8. Acceptable Limits for Laboratory Precision of Contract Laboratory Measured Parameters and Percent of Samples meeting those based on Relative Percent Differences of Replicate Samples at Site 1

Parameter	Acceptable precision for laboratory replicates	Number of Sample Events Meeting RPD Threshold	Percent of Sample Events Meeting RPD Threshold
Total Kjeldahl Nitrogen	± 20%	9	90%
Nitrate/Nitrite	± 10%	10	100%
Ammonia	± 20%	4	40%
Total Phosphorus	± 10%	9	90%
Ortho-Phosphorus	± 20%	10	90%
Chlorophyll-*a*, Sestonic Replicate	± 10%	6	60%
Chlorophyll-*a*, Sestonic Duplicate	± 10%	5	50%

Ammonia values had the most replicate pairs not meeting the acceptable precision limits based on RPD. Chlorophyll replicates and duplicates met precision limits for the majority of the time, but were still higher than other parameters. Chlorophyll is a biological parameter that is extracted under extreme care, however, a high degree of variability in the chlorophyll pigment and other pigments between various algal species and individual algal cells is expected. Additionally, chlorophyll is analyzed using optical methods (i.e. spectrophotometric or fluorometric), which at times may over or underestimate chlorophyll concentrations due to the overlap of absorption and fluorescence bands of co-occurring pigments. Thus, it is not unexpected that a greater percentage of samples would not meet the RPD threshold for chlorophyll (**Table 9**).

Table 9. Summary of 2018 Chlorophyll-a (mg/L) Quality Control Samples Designated as 1(12) and 1(21)

Date	Site 1 (12)	Site1 (21)	RPD
4/18/2018	10.7	10.7	0.00%
5/23/2018	12	10.7	11.45%
6/27/2018	16	19.2	18.18%
7/11/2018	2	27.4	172.79%
7/24/2018	29.7	29.7	0.00%
8/7/2018	18.3	24.4	28.57%
8/22/2018	27.9	26.7	4.40%
9/12/2018	20	19.4	3.05%
9/26/2018	23.4	27.4	15.75%
10/10/2018	24.9	26.7	6.98%

Analytical blank samples, designated Site 1(31), collected from reagent grade water at OWRB were also submitted to the laboratory for analysis (**Table 10**). The vast majority of analytical blank samples were within acceptable range; however, the analytical blank samples on May 23, 2018 showed a low-level TKN contamination.

Table 10. Summary of 2018 Blank Quality Control Sample Results Designated as site 1 (31)

Date	NO2/NO3 (mg/L)	Ammonia (mg/L)	TKN (mg/L)	TP (mg/L)	Ortho-P (µg/L)
4/18/2018	<0.050	<0.050	<0.050	<0.015	<0.005
5/23/2018	<0.050	<0.050	0.162	<0.015	<0.005
6/27/2018	<0.050	<0.050	<0.050	<0.015	<0.005
7/11/2018	<0.050	<0.050	<0.050	<0.015	<0.005
7/24/2018	<0.050	<0.050	<0.050	<0.015	<0.005
8/7/2018	<0.050	<0.050	<0.050	<0.015	<0.005
8/22/2018	<0.050	<0.050	<0.050	<0.015	<0.005
9/12/2018	<0.050	<0.050	<0.050	<0.015	<0.005
9/26/2018	<0.050	<0.050	<0.050	<0.015	<0.005
10/10/2018	<0.050	<0.050	<0.050	<0.015	<0.005

Quality Assurance and Quality Control Issues

Some data QA/QC issues were identified in the 2018 monitoring year. These issues and actions taken upon their discovery are described below.

Upon review of sample results from April 18th, June 27th, July 11th, August 7th, and August 22nd, it was noted that TP concentrations were reported as below detection however, ample algal biomass, measured as chlorophyll, was present. Chlorophyll values ranged from approximately 10 – 25 µg/L for these sampling events. Phosphorus is an essential nutrient for all living organisms; for example, it is essential for DNA, cellular energy, and plant cell walls. Thus, it is not possible for algal biomass (i.e. phytoplankton) to be present in the lake and at the same time have no detectable total phosphorus. As an additional line of evidence, Lake Thunderbird TP and chlorophyll data from previous years was reviewed and this irregularity of TP below detection and algal biomass present was not found. The 2018 contradiction between TP and chlorophyll analytical results clearly indicates a problem with the laboratory total phosphorus analysis.

A key step in total phosphorus analysis is an acid digestion, which converts organically bound phosphorus to the orthophosphate form for analysis. It seems clear that on the sampling dates listed above a problem occurred in the acid digestion step of the analysis. Furthermore, because the intention of the digestion process is to convert all phosphorus in the sample to orthophosphate and the laboratory quality assurances checks utilize orthophosphate there is no way to identify a digestion problem concurrent with sample analysis. A sample digestion problem can only be identified upon data review, such as it was in this case. The erroneous total phosphorus results (April 18th, June 27th, July 11th, August 7th, and August 22nd) were excluded from all analysis in this report.

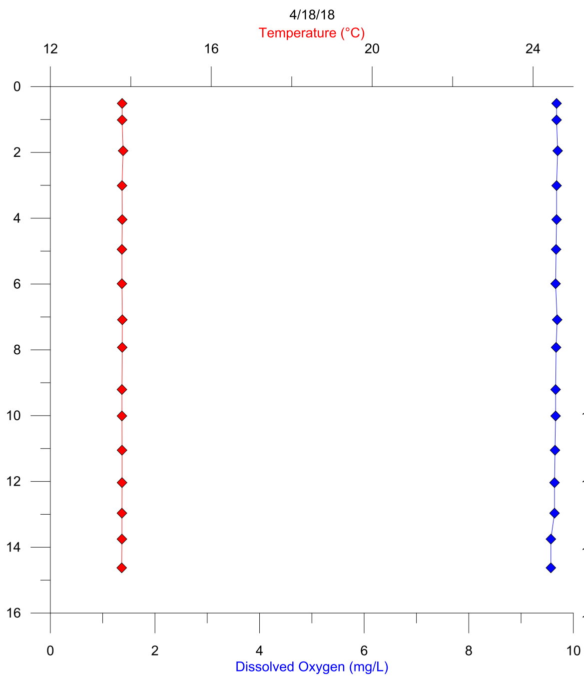
The nitrogen data from July and August showed ammonia to be higher than TKN values, which should be impossible because TKN is the sum of present organic nitrogen and ammonia. Accurate Labs was informed of the discrepancy and discovered expired reagents as the likely cause of the analysis error. The laboratory reanalyzed the August samples and results satisfied the required quality assurance checks and were more consistent with expected values. The sample holding time for the July TKN samples had expired and these samples were not able to be reanalyzed. Therefore, TKN values from the July sampling events were excluded from analysis in this report.

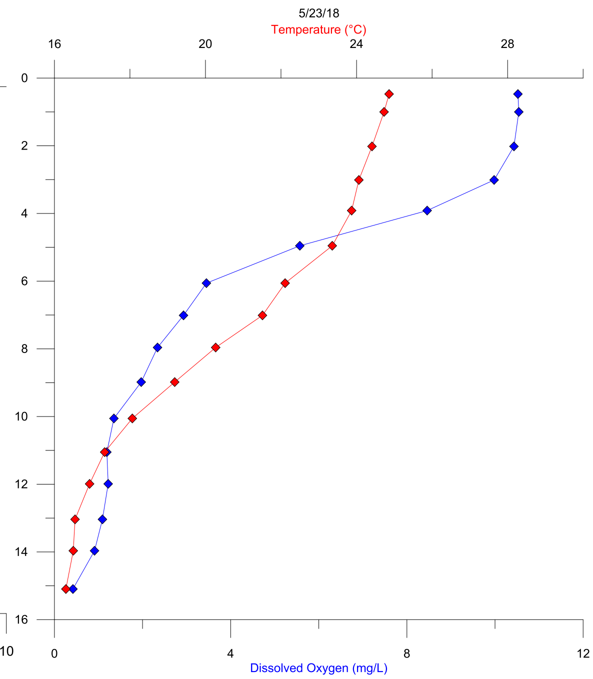
Accurate Labs performs its own internal quality control analysis in accordance with environmental lab accreditation practices, which is then verified by OWRB. The laboratory provides these QC analyses with each sample report and they are available upon request.

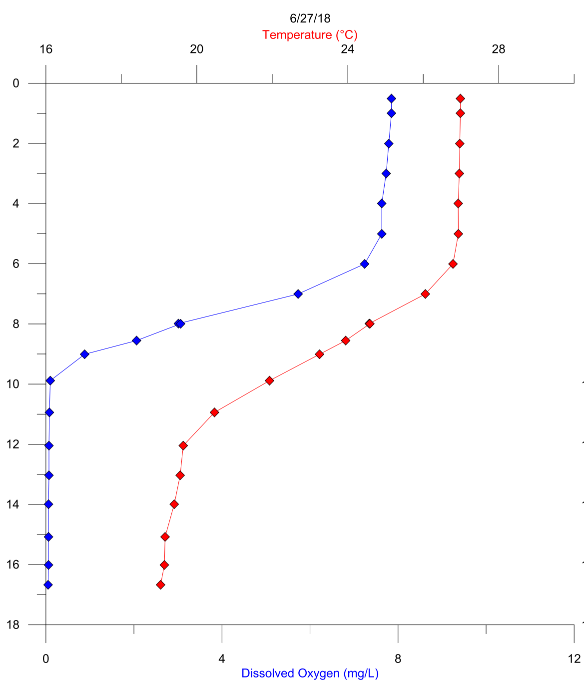
Appendix B

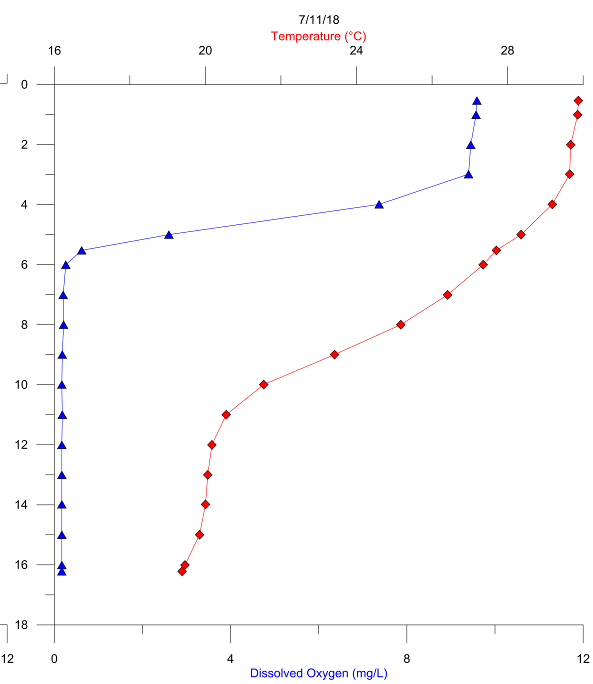
Temperature and Dissolved Oxygen versus Depth at Site 1

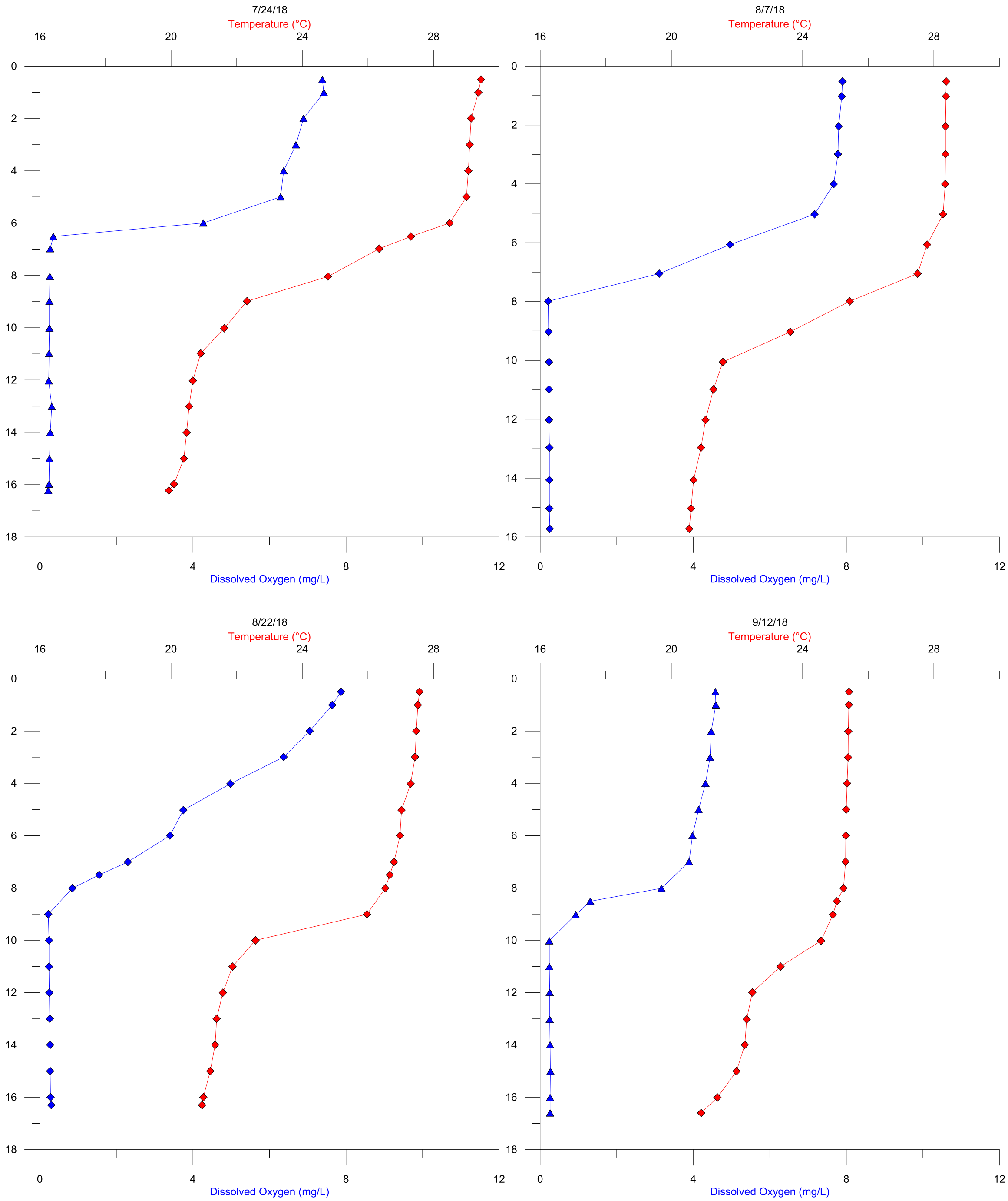
Temperature is denoted as Red Diamond Markers while Dissolved Oxygen is denoted as Blue Triangle Markers

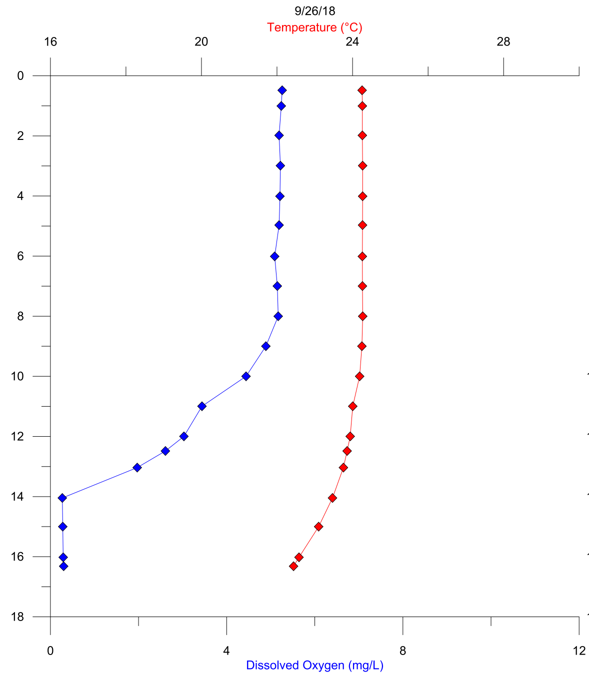


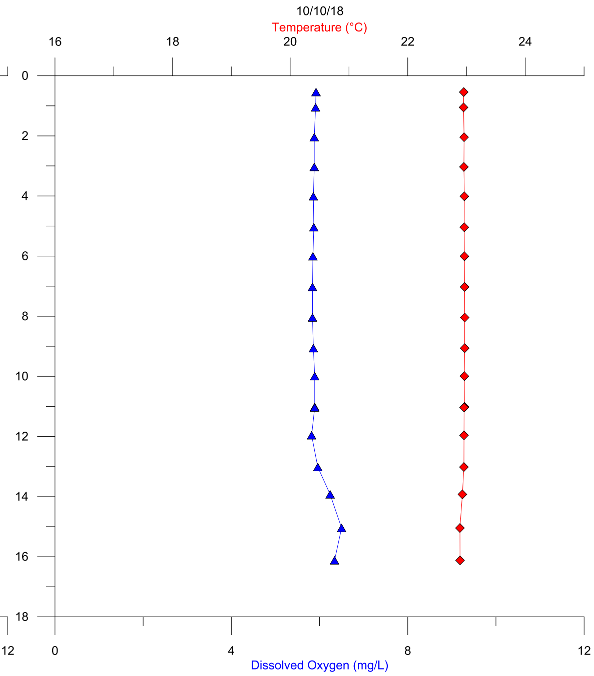




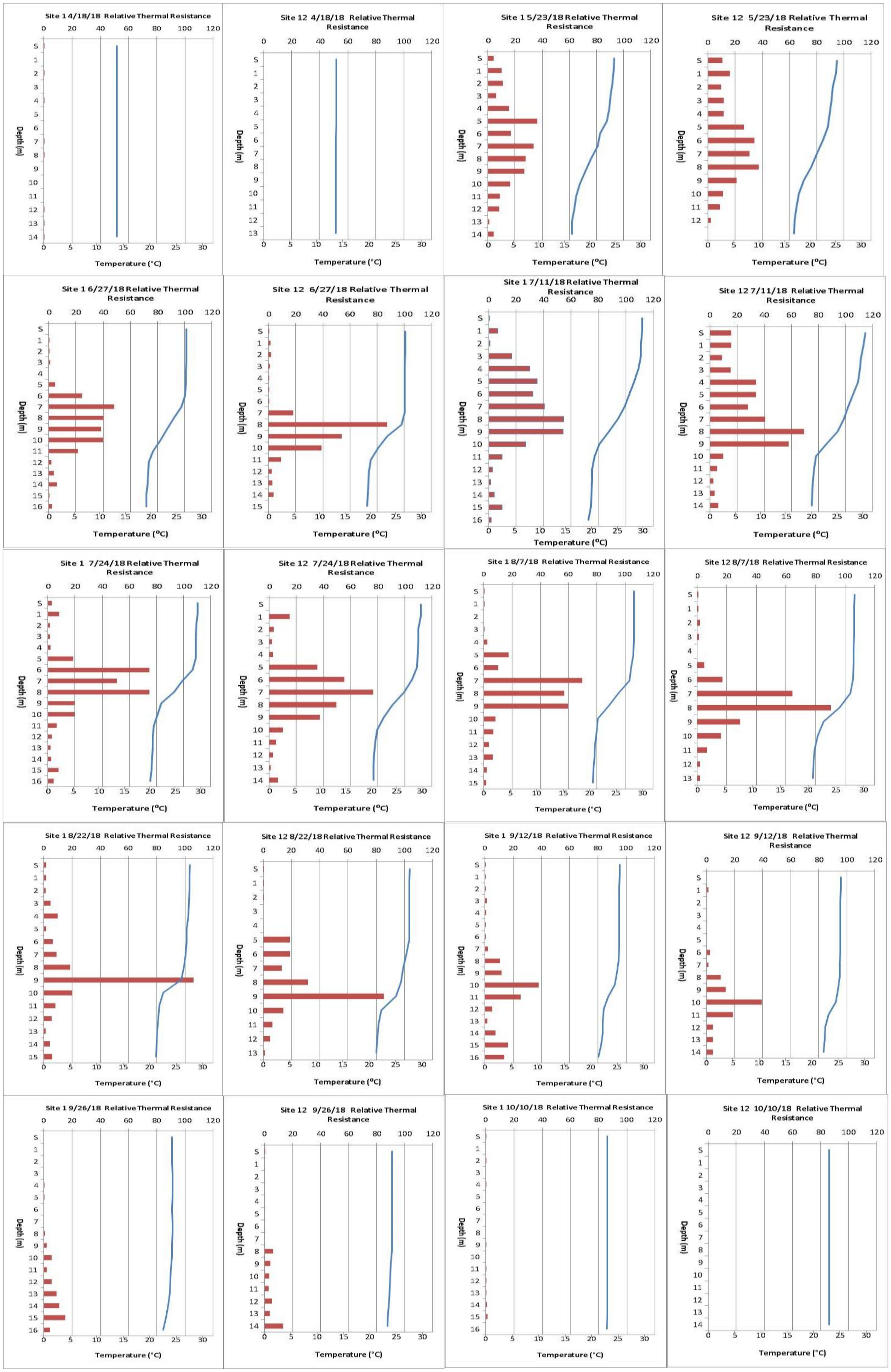



7/24/18
Temperature (°C)
16
20
24
28
0
2
4
6
8
10
12
14
16
18
0
4
8
12
Dissolved Oxygen (mg/L)
8/7/18
Temperature (°C)
16
20
24
28
0
2
4
6
8
10
12
14
16
0
4
8
12
Dissolved Oxygen (mg/L)
8/22/18
Temperature (°C)
16
20
24
28
0
2
4
6
8
10
12
14
16
18
0
4
8
12
Dissolved Oxygen (mg/L)
9/12/18
Temperature (°C)
16
20
24
28
0
2
4
6
8
10
12
14
16
18
0
4
8
12
Dissolved Oxygen (mg/L)


9/26/18
Temperature (°C)
16
20
24
28
0
2
4
6
8
10
12
14
16
18
0
4
8
12
Dissolved Oxygen (mg/L)


10/10/18
Temperature (°C)
16
18
20
22
24
0
2
4
6
8
10
12
14
16
18
0
4
8
12
Dissolved Oxygen (mg/L)

Appendix C: Relative Thermal Resistance Plots



Appendix D

Planning Proposal for Quantifying

Hypolimnetic Oxygen Demand of Lake Thunderbird

Introduction

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: 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. The budget below 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. 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.

Budget:

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**

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**

Location	Field Days	Persons	Lodging	Per Diem	Total
In-state	0	0	$ -	$ -	$ -

Appendix E

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**