Lake Thunderbird Water Quality

2019 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 twenty years. In 2019, monitoring was conducted to identify any water quality concerns, assessment of water quality standards, and Supersaturated Dissolved Oxygen System (SDOX) efficacy.

In 2019, 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 anoxic conditions throughout the summer sampling season; the metalimnion also experienced anoxia from July to September. While common in the hypolimnion, anoxia 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, increased relative to previous years and remained excessive. In 2019, mean chlorophyll at site 1 ranged from relatively low at 5.3 µg/L in August to peak mean chlorophyll at 48.1µg/L in October. Taste and odor complaints, collected from City of Norman drinking water facility, were low in 2019, and peaked in September. Geosmin and 2-methylisoborneol (MIB), algal toxins related to taste and odor problems, peaked in winter as well, highlighting that there are active algal processes occurring in the winter. OWRB will implement additional monitoring events in winter to investigate this dynamic.

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. Additional monitoring activities were implemented in 2019 to further assess the efficacy of the SDOX. This additional opportunity for analysis indicates that, due to the size limitation of the system and its capacity to oxygenate the hypolimnion, the SDOX does not appear to have any current effect on the lake processes.

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 2019.

Sampling Regime

In 2019, water quality sampling occurred from April 17 through October 9. Additional profiles were collected in November to book end the stratification period and collect data after lake mixing. 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, 11, and 12. 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 and at the bottom at site 12. 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 nine sites.

Table 1. 2019 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		

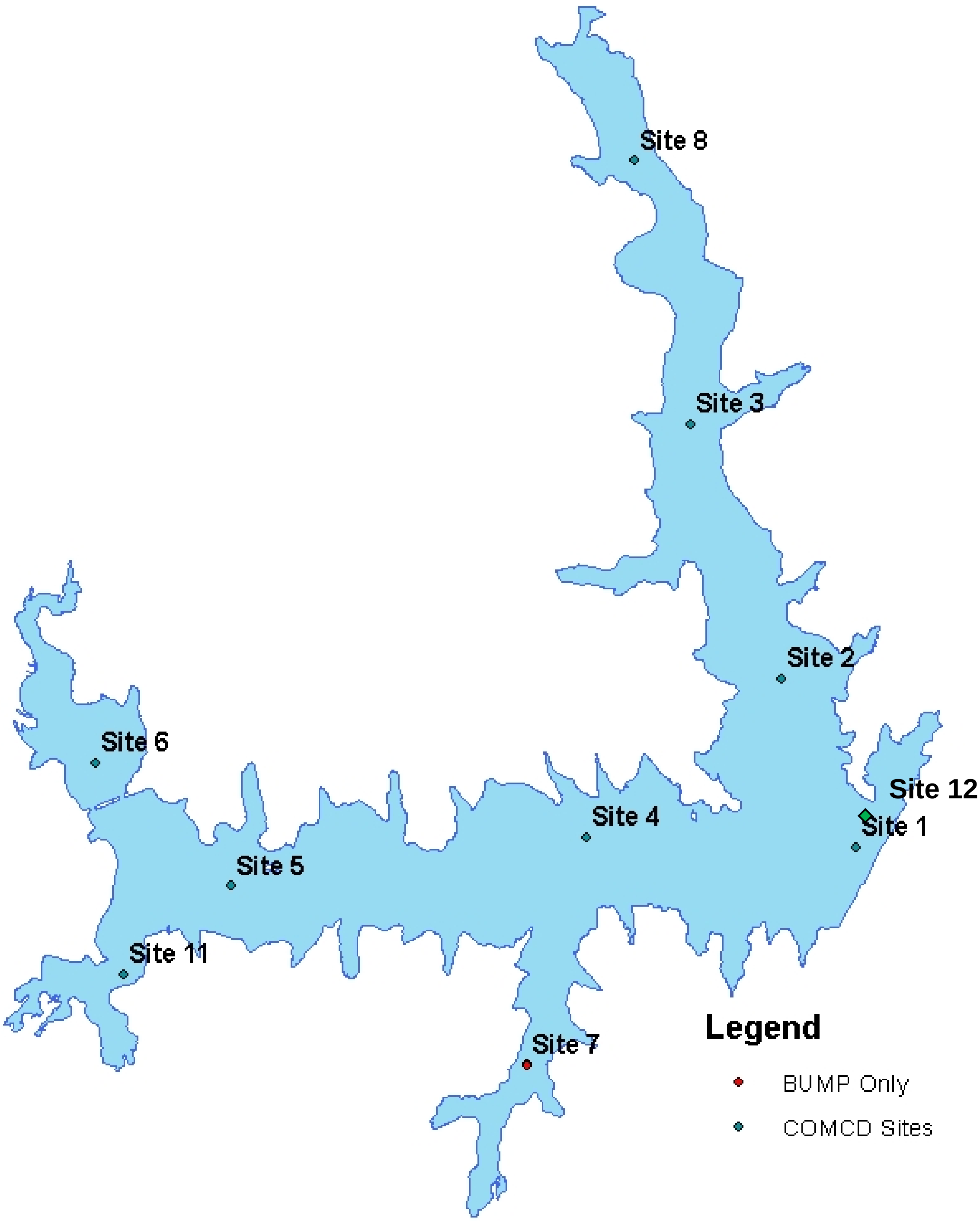

Figure 1. 2019 Lake Thunderbird sampling sites

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** 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.

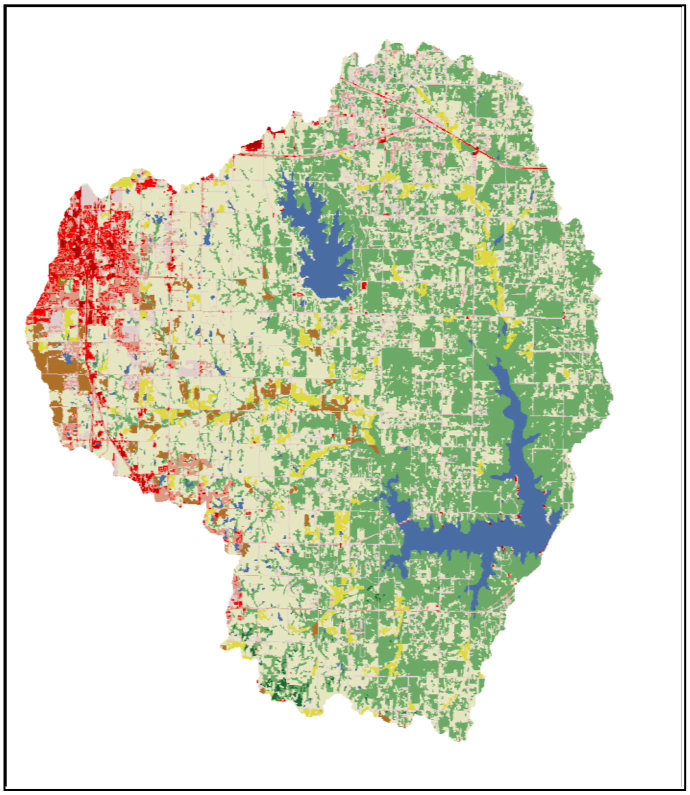

Figure 2. Lake Thunderbird HUC 8 Watershed

Land uses in the watershed of a waterbody are important when determining potential sources of nutrients, sediment, or other forms of pollution. **Table 2** presents the land uses in the Lake

Thunderbird watershed; the dominant categories are grassland and deciduous forest. Developed land makes up roughly 18% of the watershed, mostly in the northwest portion, encompassing parts of Oklahoma City, Moore, and Norman. New land cover data collected in 2016 was made available for this report, as such the percent change column represents the increase or decrease difference from the previous data collection in 2011.

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

Category	Acreage	Percent of Watershed	Percent Change
Open water	8,359	5.08%	+0.76%
Developed, open space	12,474	7.58%	-1.82%
Developed, low intensity	9,182	5.58%	+1.24%
Developed, medium intensity	6,080	3.70%	+1.71%
Developed, high intensity	1,376	0.84%	+0.41%
Barren Land	238	0.14%	+0.13%
Deciduous Forest	61,607	37.45%	+2.16%
Evergreen Forest	322	0.20%	-0.03%
Mixed Forest	163	0.10%	
Shrub Scrub	2842	1.73%	
Grassland/Herbaceous	55,237	33.58%	-4.76%
Pasture/Hay	4,926	2.99%	-0.50%
Cultivated Crops	1,533	0.93%	-1.21%
Emergent Herbaceous wetlands	20	0.01%	+0.01%
Total Watershed	164,505	100%	100.00%

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 chemical and biological processes.

Figure 3 provides a graphical representation of Lake Thunderbird's rainfall, elevation, inflow, and sampling dates for calendar year 2019. Annual precipitation at Lake Thunderbird dam in 2019 totaled 44.62 inches, more than the lake's average of 38 inches, with peak rainfall events corresponding to increases in lake elevation. Inflows volumes were greater in 2019 than in 2018, leading to the lake experiencing higher than normal elevations, peaking in May. This becomes important when examining increasing nutrient levels and non-algal turbidity witnessed in the reservoir.

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 2019 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 March and warmer than average September. In 2019, 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 2019 and yet the lake's typical pattern and duration of thermal stratification was maintained.

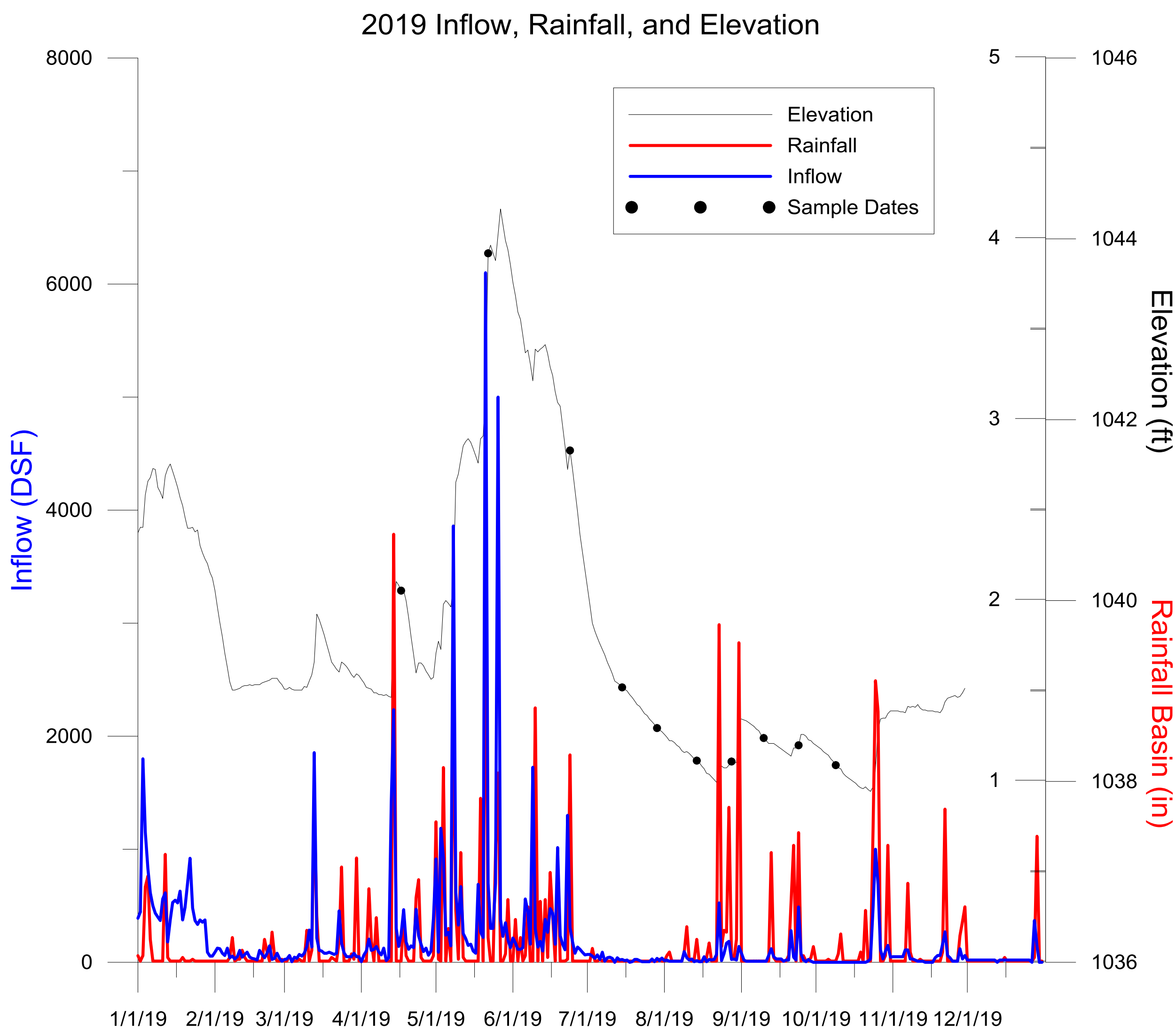

Figure 3. 2019 Inflow, Rainfall, and Elevation Data for Lake Thunderbird, with Sample Dates Indicated.

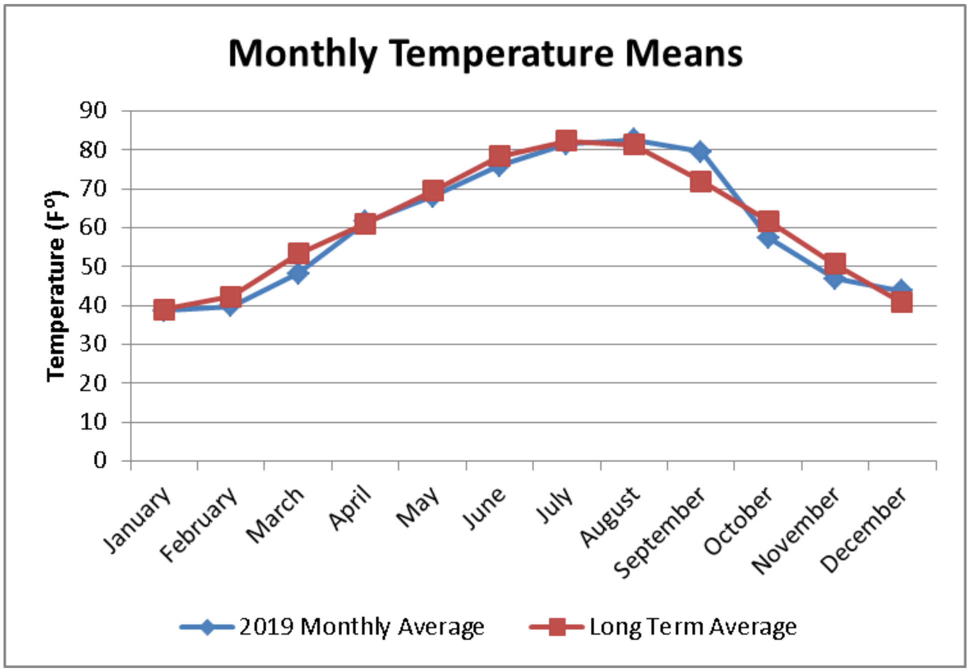

Figure 4. 2019 and Long Term (LT) Average Monthly Temperature at the Norman Mesonet Station.

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. 2019 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	30,985	503	31,488	1,233	1,357	32,741	35,331	(3,844)	(3,036)	808
Feb	3,400	250	3,650	1,138	1,216	7,978	10,331	(6,682)	(5,557)	1,125
Mar	7,412	2,029	9,441	2,135	1,408	6,575	10,119	(677)	617	60
Apr	14,248	1,775	16,022	3,254	1,445	11,627	16,326	(304)	720	(416)
May	47,270	3,854	51,124	3,213	1,413	17,423	22,049	29,075	21,146	7,929
Jun	16,879	2,700	19,579	4,461	1,543	35,619	41,623	(22,044)	(16,619)	5,425
Jul	1,880	-	1,880	5,062	1,994	5,381	12,437	(10,557)	(8,335)	2,222
Aug	1,323	2,029	3,352	4,188	2,190	-	6,378	(3,026)	875	2,151
Sep	2,255	780	3,035	3,526	2,051	-	5,577	(2,542)	(1,441)	1,101
Oct	3,043	2,203	5,246	2,397	1,733	-	4,130	1,116	1,955	(839)
Nov	2,051	944	2,995	1,332	1,157	-	2,489	506	1,338	(832)
Dec	1,629	374	2,003	1,459	855	-	2,314	(311)	978	(667)
Total	132,376	17,440	149,816	33,400	18,362	117,344	169,106	(19,290)	(7,357)	18,068

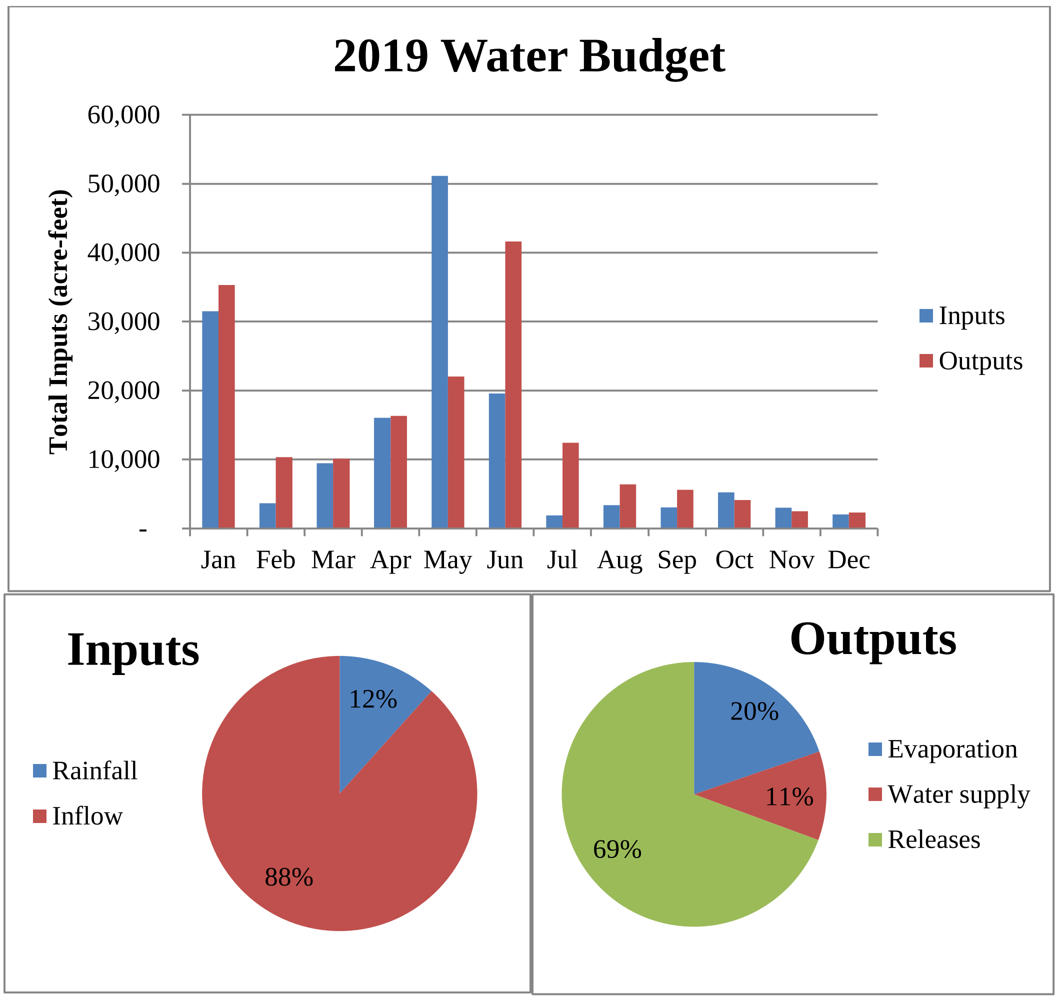

Figure 5. 2019 Lake Thunderbird Water Input and Output sources by month, expressed as the percent of total.

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 0.78 years in 2019, with an average (2001 to 2019) hydrologic residence time of 3.53 years. The lower than average 2019 residence time is largely due to a higher volume of gated releases, representing the second highest volume of releases since 2001.

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 2019, the hydrologic budget contains a cumulative annual error of 18,068 acre-feet, with an average monthly error of 1,506 acre-feet, a large increase compared to 2018 error. 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 Light Detection and Ranging (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 7,600 acre-feet since 2001 (OWRB, 2002) or a loss of about 7.2% 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 (**Appendix E**). 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 profiles of temperature and DO with respect to depth at site 1 are included to highlight some elements of the sampling season and illustrate lake stratification layers (**Figure 6**). The remaining temperature and DO profile plots from site 1 and 12 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 and can be found in Error! Reference source not found..

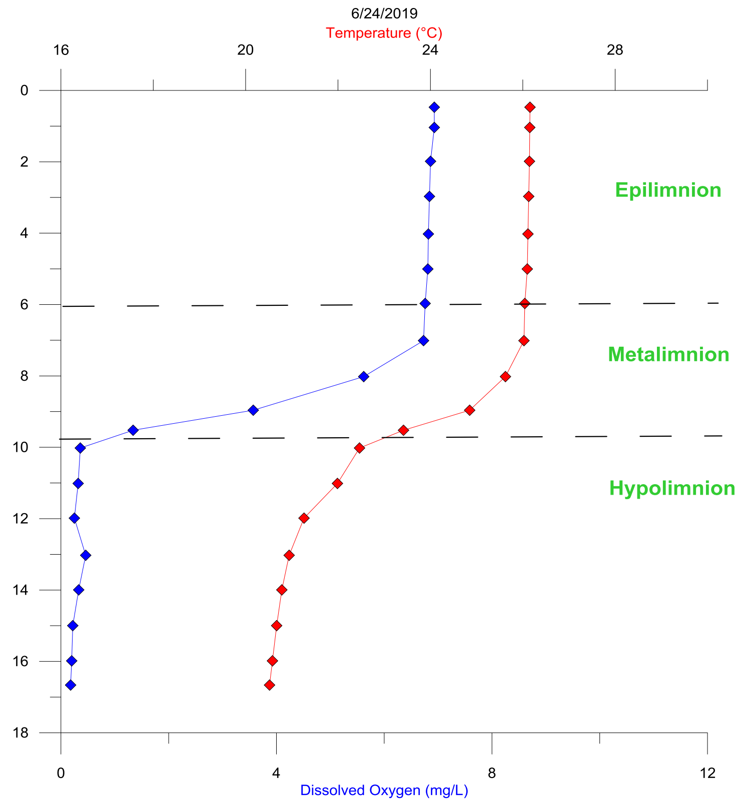

Figure 6. A typical Temperature (red, diamond) and Dissolved Oxygen (blue, triangle) vertical profile for Lake Thunderbird (June 24, 2019) approximate boundaries between the Epilimnion, Metalimnion and Hypolimnion are marked with dashed lines.

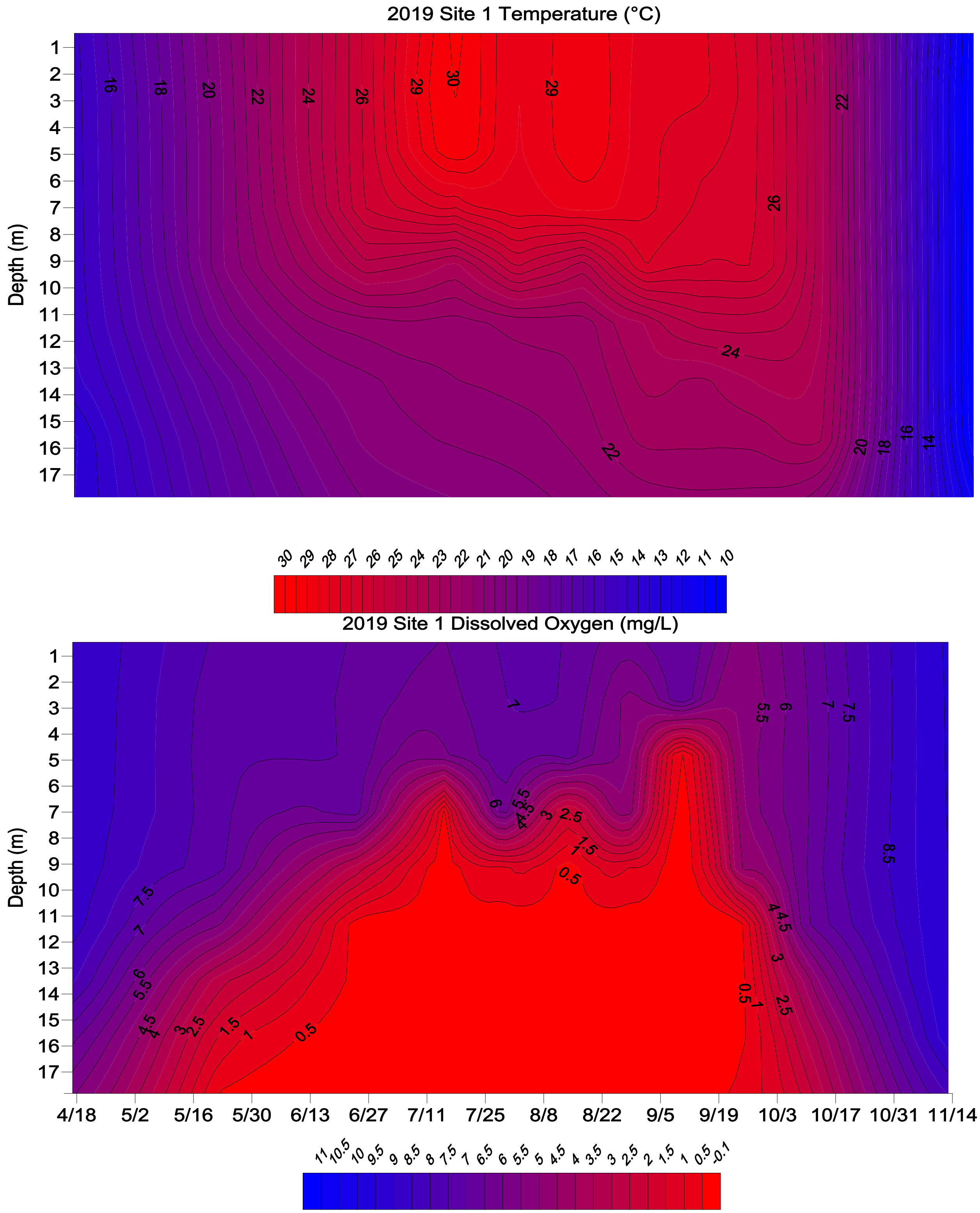

Figure 7. 2019 Isopleths of Temperature (°C) and Dissolved Oxygen (mg/L) versus Depth (m) at Site 1.

Little thermal difference with depth was noted on the first sample date, April 17, 2019, indicating a mixed water column. By the second sample event, May 22, 2019, thermal stratification had strengthened exhibiting a 3°C temperature gradient from top to bottom. Dissolved oxygen dynamics had begun to set up for the season with mostly anoxic hypolimnetic waters. As the season progressed, epilimnetic warming continued until reaching a peak temperature of 29.665°C on July 15, 2019 (**Figure 8**). Evident at this event is the push of anoxic water upwards, creeping into the metalimnion and dominating the hypolimnion. This is evidence of increased organic load, and a high hypolimnetic water and sediment oxygen demand. Anoxic water in the metalimnion was observed variably through the summer into September, but not as the constant presence seen in 2018.

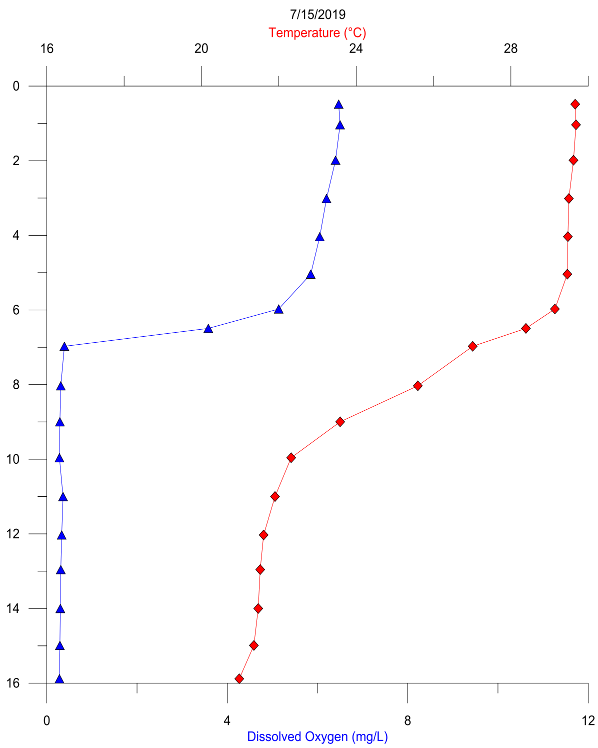

Figure 8 A Temperature (red, diamond) and Dissolved Oxygen (blue, triangle) vertical profile for Lake Thunderbird (July 15, 2019) highlighting a mostly anoxic metalimnion and anoxic hypolimnion.

Epilimnetic water began to cool by the September 24th sampling event, thus deepening the epilimnion, although slight stratification still persisted as well as some hypoxia in the hypolimnion. This marks the onset of lake mixis and by the November event, the water column was isothermal and the lake was considered mixed (**Figure 9**).

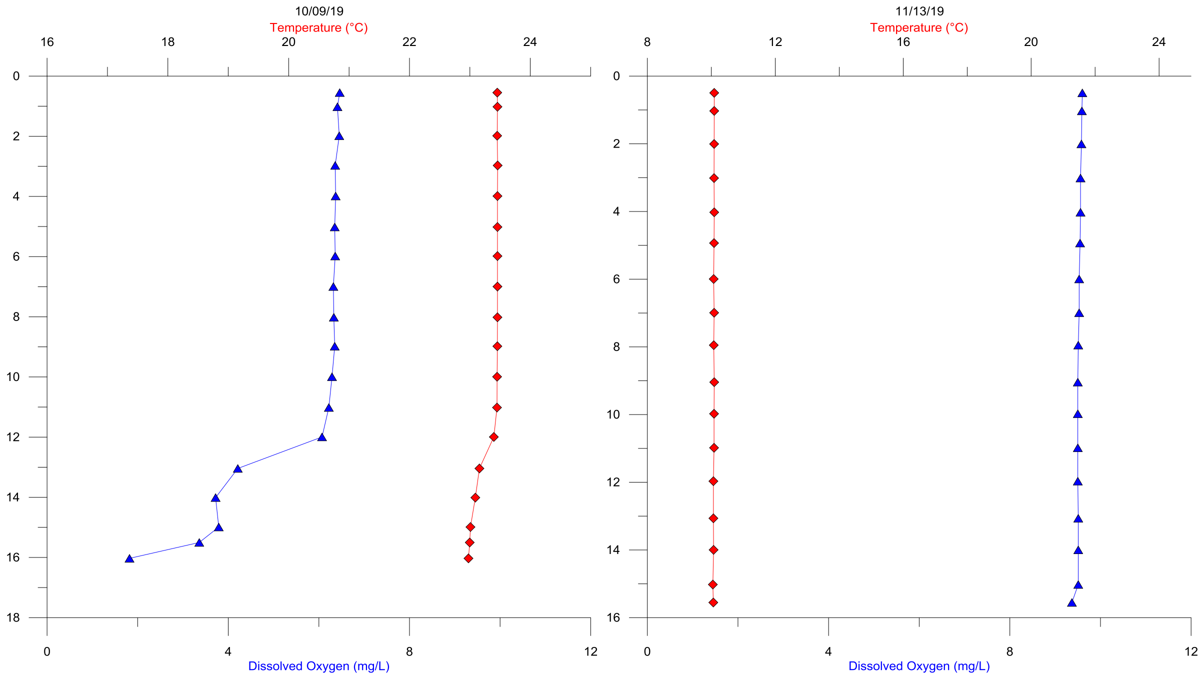

Figure 9 Temperature (red, diamond) and Dissolved Oxygen (blue, triangle) vertical profile at Site 1 September 12, 2018.

Metalimnetic anoxia, experienced in Lake Thunderbird in 2019, 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 2019 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.

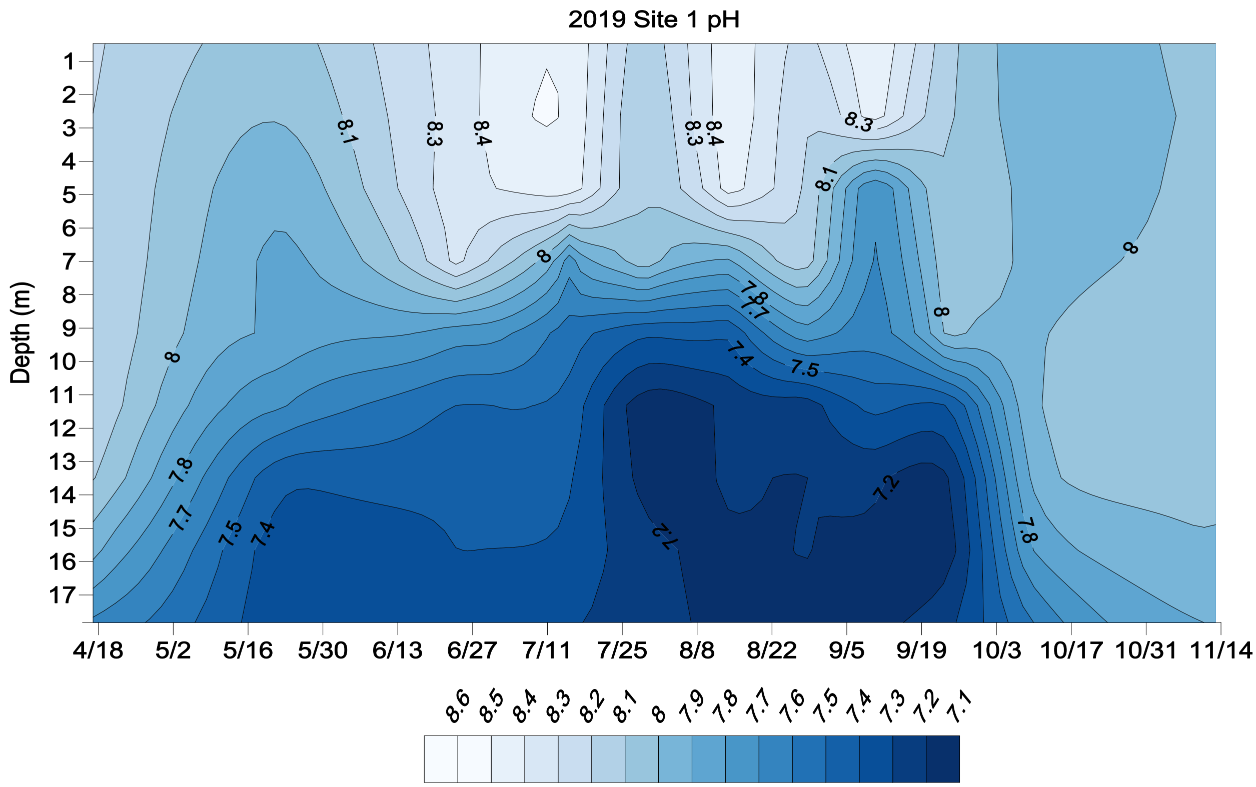

Figure 10. 2019 Isopleth of pH (S.U.) Versus Depth (m) at Site 1.

Partial anoxia of the hypolimnion was observed in May (**Figure 7**), and by July, 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.

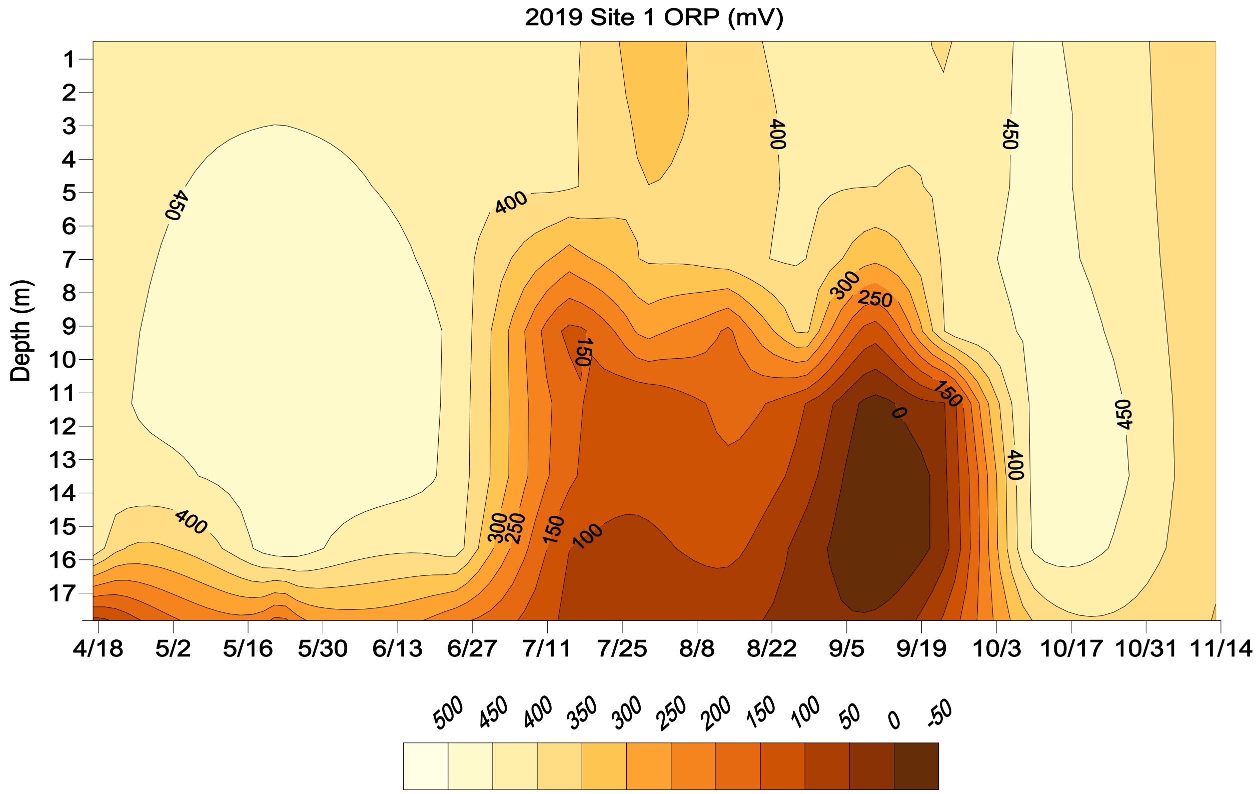

Figure 11. 2019 Isopleth of Oxidation-Reduction Potential (mV) versus Depth (m) at Site 1.

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 present in comparable levels to previous years through the beginning of the monitoring season before increasing in the late summer and fall. Values ranged from 0.023 ug/L to a high of 0.056 ug/L in October. Predictably, epilimnetic ortho-P was below the laboratory reporting limit for the summer; this is the height of the growing season where algae will consume all ortho-P (**Figure 12**).

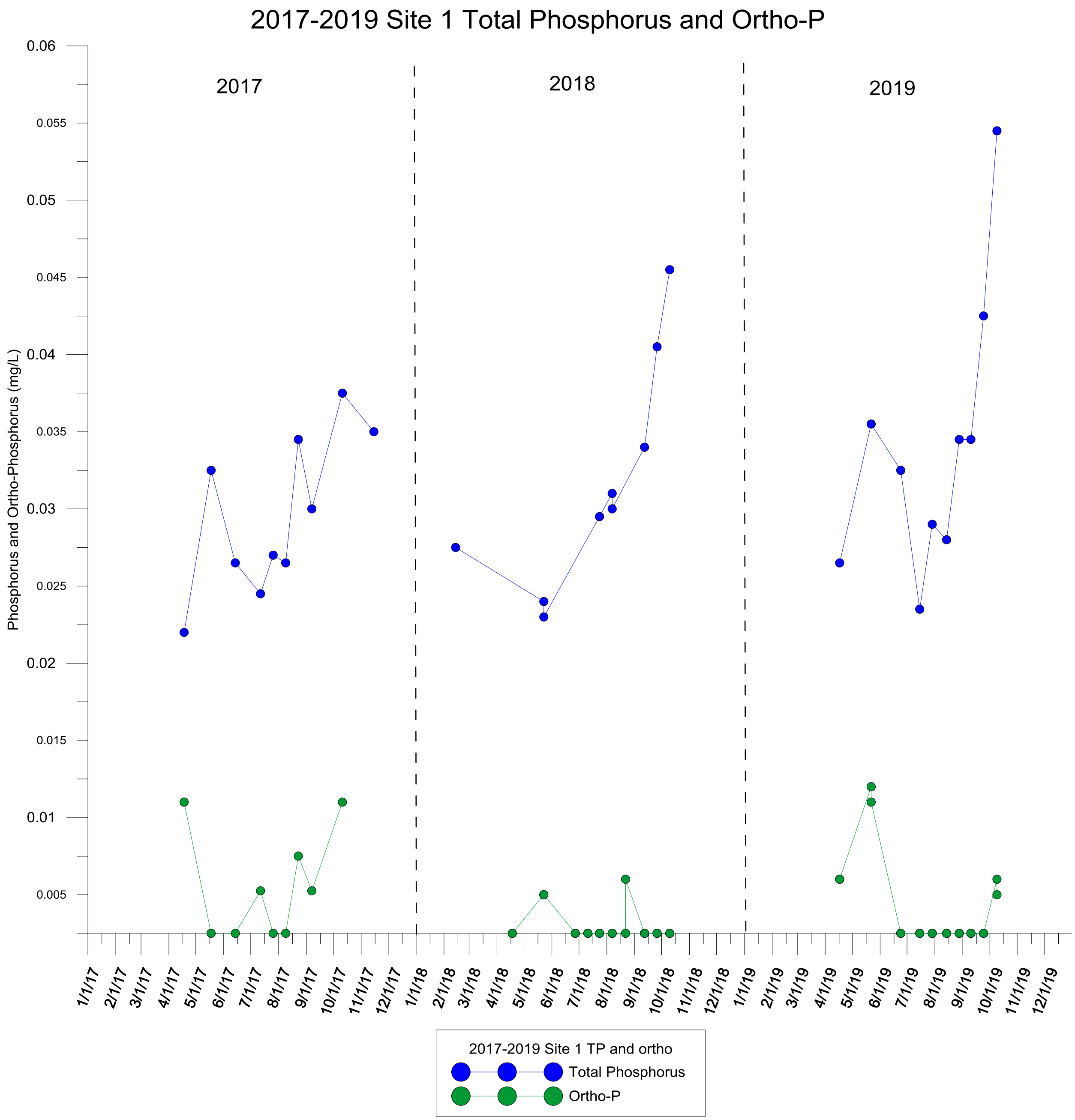

Figure 12. 2019 Surface Phosphorus Variables as P (mg/L) at site 1. Values on x-axis represent half the laboratory reporting limit (0.0025 mg/L).

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 after lake mixing. (**Figure 13).**

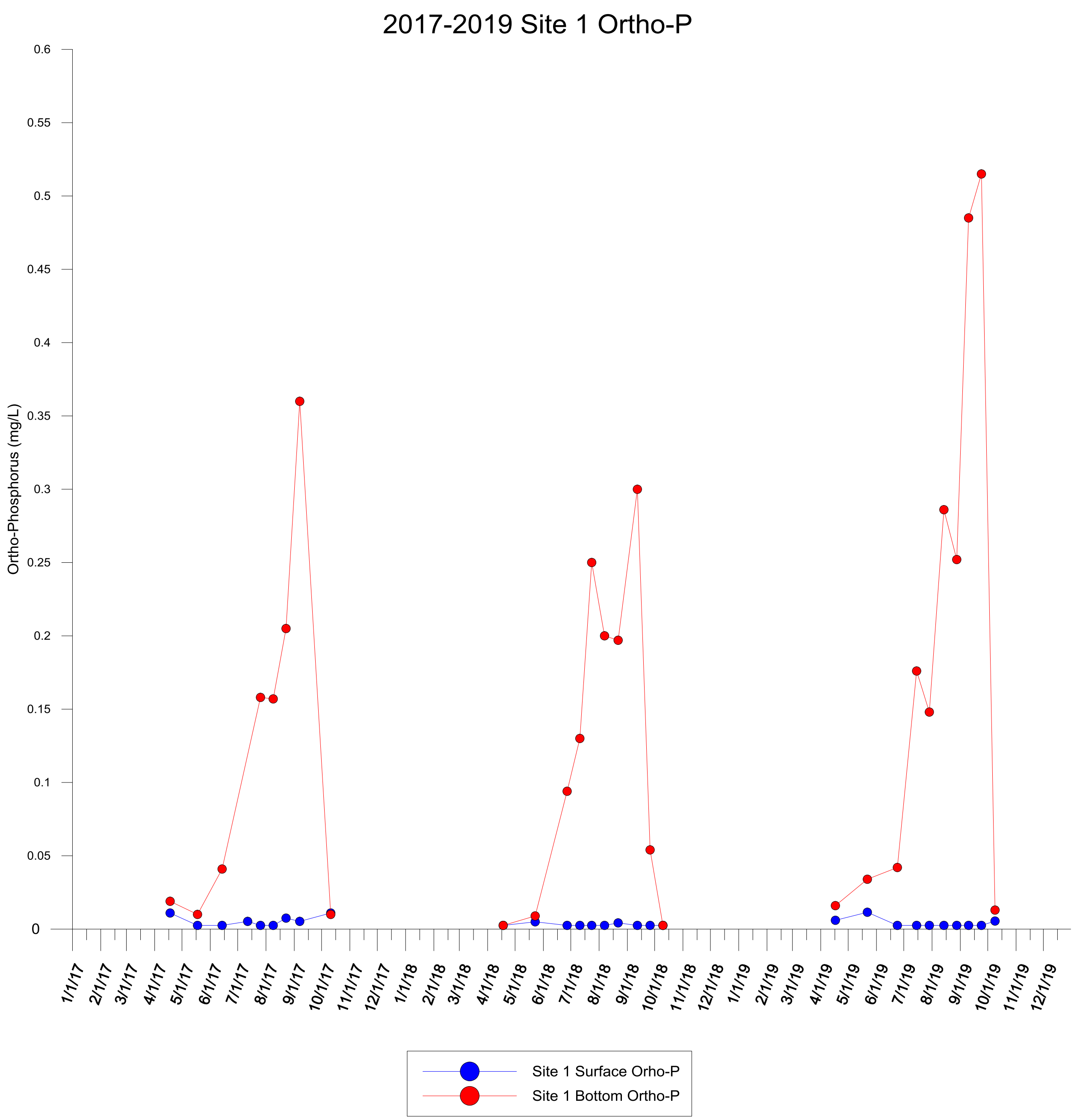

Figure 13. 2019 Site 1 Ortho-phosphorus at Surface and Bottom depth.

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 2019, site 8 and 11 behaved very similarly and exhibited TP values slightly over the lacustrine sites. Site 6, near the Alameda Drive bridge on the Little River arm, had the highest TP values and increased through the season, peaking in May at 0.265 mg/L. This is slightly atypical for Lake Thunderbird, as the TP usually peaks later in the season, although, there was a large inflow event in May that contributed to the early peak.

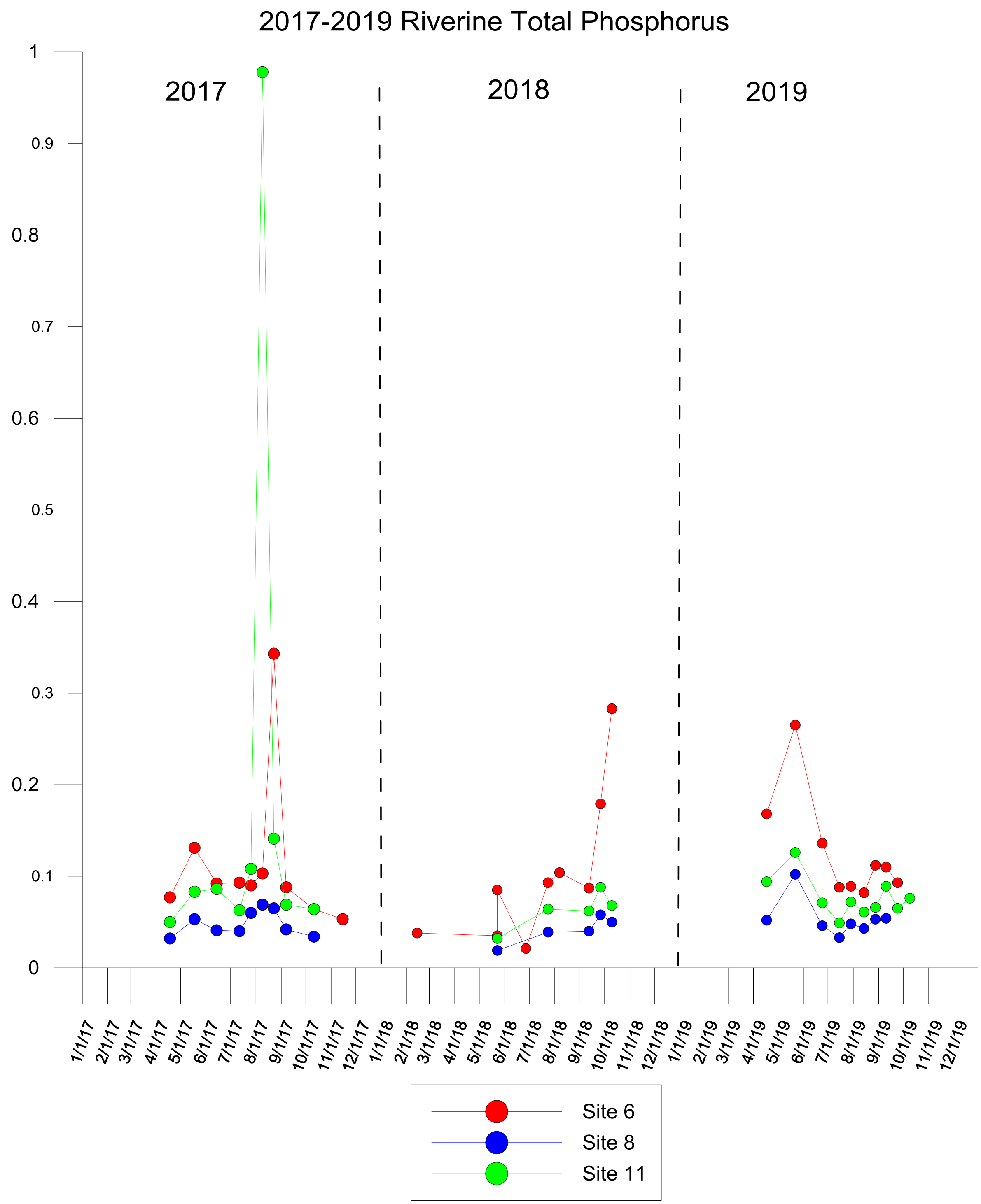

Figure 14. 2019 Surface Phosphorus (mg/L) from the three riverine sites.

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**).

Riverine areas are susceptible to wind mixing and resuspension of sediment and nutrients. They are greatly impacted by storm flow events, likely driving the early peak in TP in Spring. Site 6 does usually exhibit the highest phosphorus concentration likely due to storm water bringing in nutrients and sediment to this shallow area and this was observed this year. 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 at site 1 ranged from 0.525 mg/L to 0.92 mg/L, increasing through the season and was driven by organic nitrogen present in algae as opposed to ammonia (**Figure 15**).

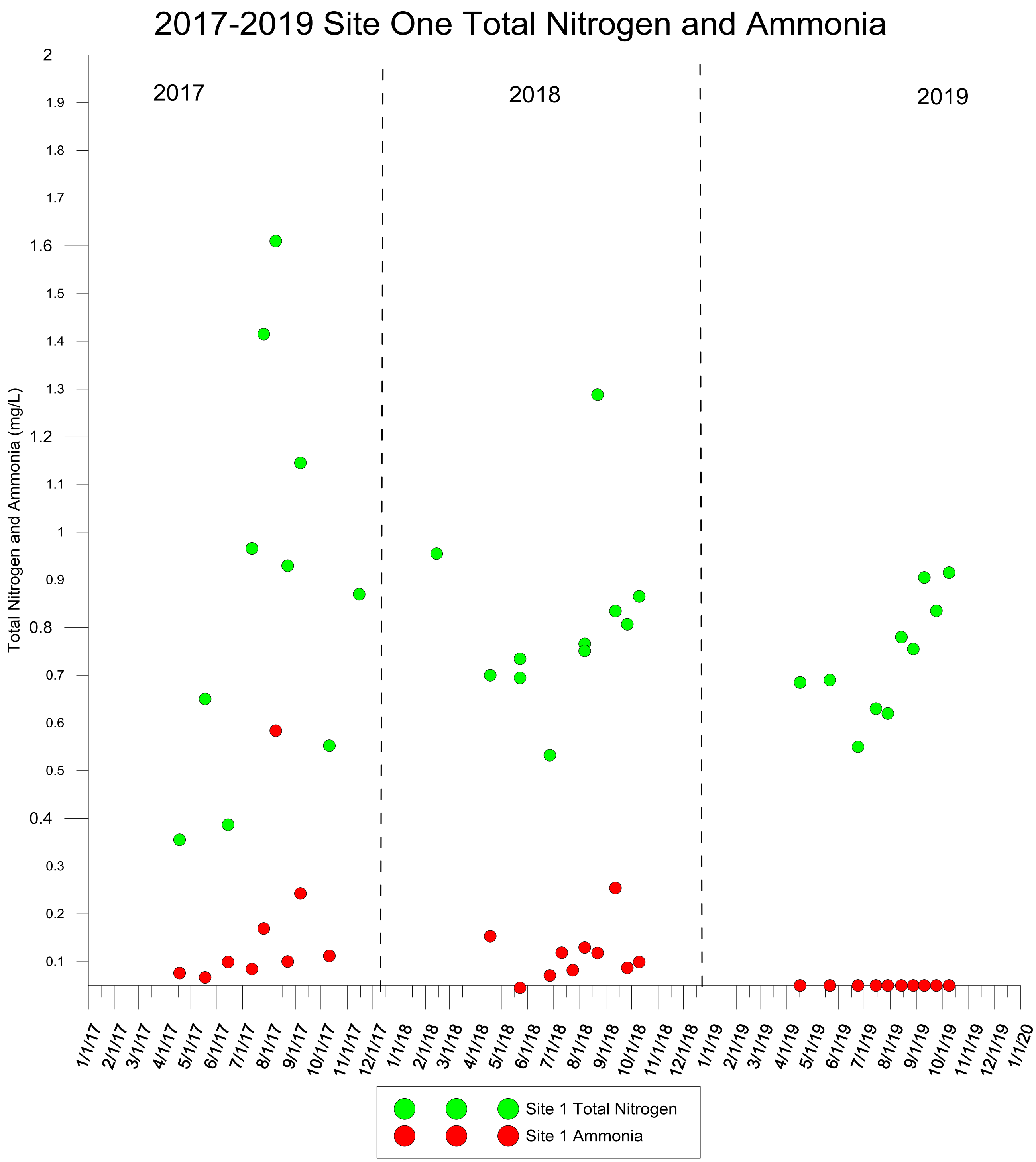

Figure 15. 2019 Surface Total Nitrogen (mg/L) over time at Site 1.

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 2019, epilimnetic nitrate/nitrite fell below reporting limit in June and remained undetectable until late September at the end of the algal growing season. Interestingly ammonia was not detectable throughout the season; this has not been the case historically, but as ammonia is preferentially used by algae, it follows that in a eutrophic reservoir it is depleted quickly.

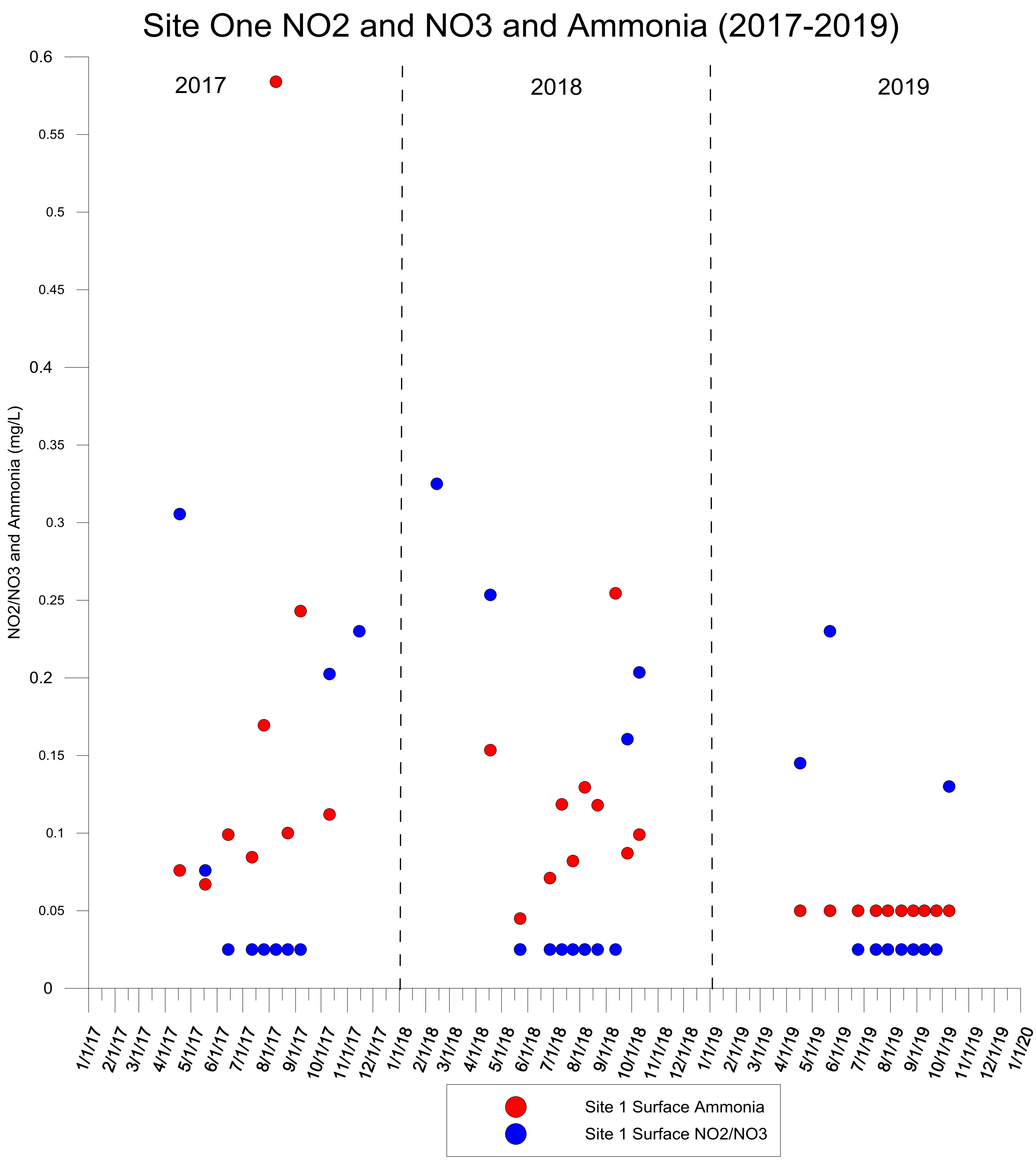

Figure 16. 2019 Surface Nitrate/Nitrite and Ammonia (mg/L) at Site 1. Values for 0.025 mg/L for NO2/NO3 and 0.05 mg/L for ammonia represent half the laboratory reporting limit.

Hypolimnetic total nitrogen peaked in 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**).

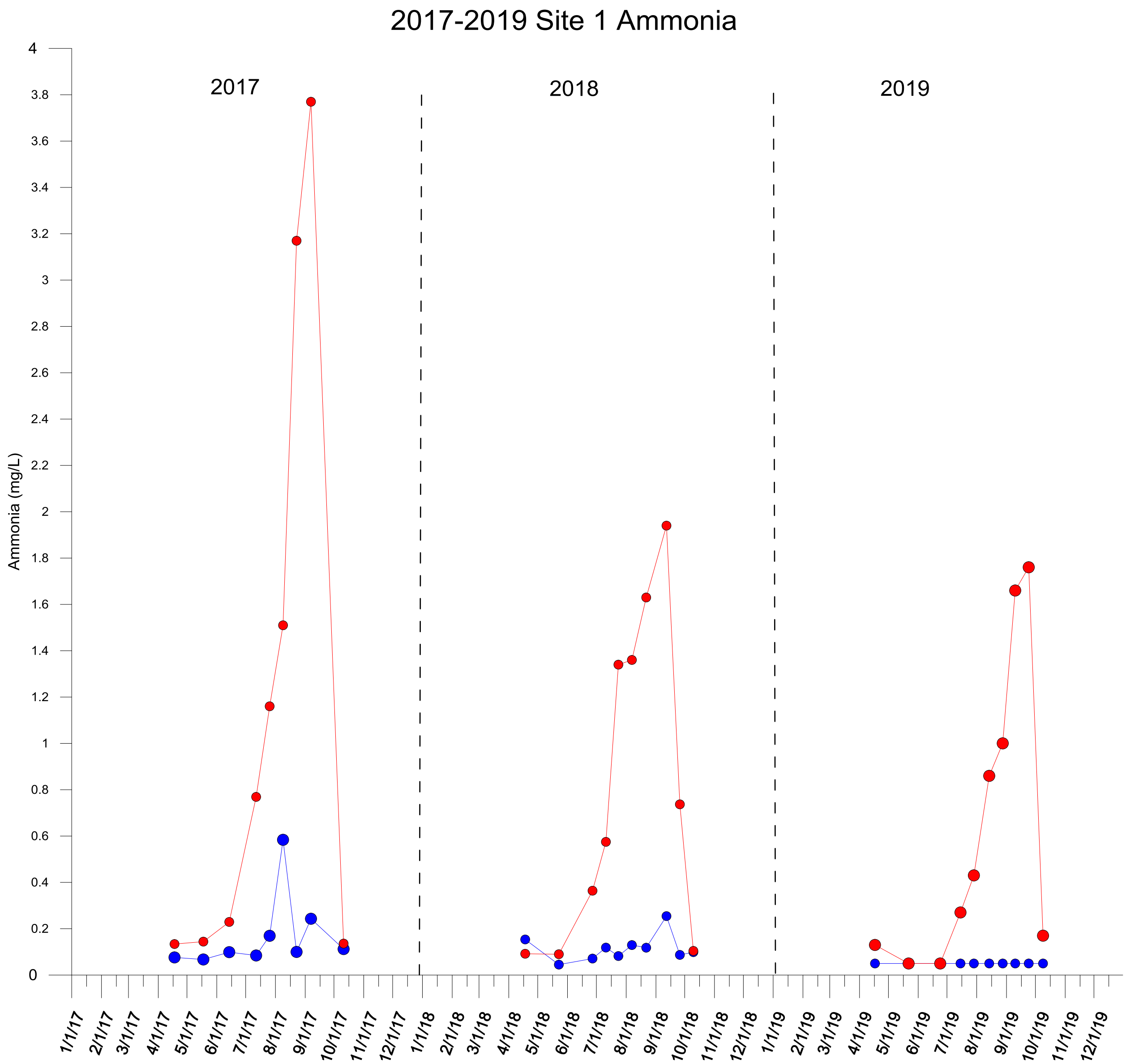

Figure 17 2018 Site 1 Ammonia at Surface and Bottom Depth

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 higher values observed in April and May at site 6.

Lacustrine and riverine sites' nutrient concentrations are often disparate from each other; riverine values are consistently higher than in open water sites. In 2019, site 8 and 11 behaved very similarly and exhibited TN values slightly higher than the lacustrine sites. All sites' nitrogen concentrations followed a similar peak and fall pattern. Site 6 had the highest TN values lake wide, peaking in October at 1.35 mg/L.

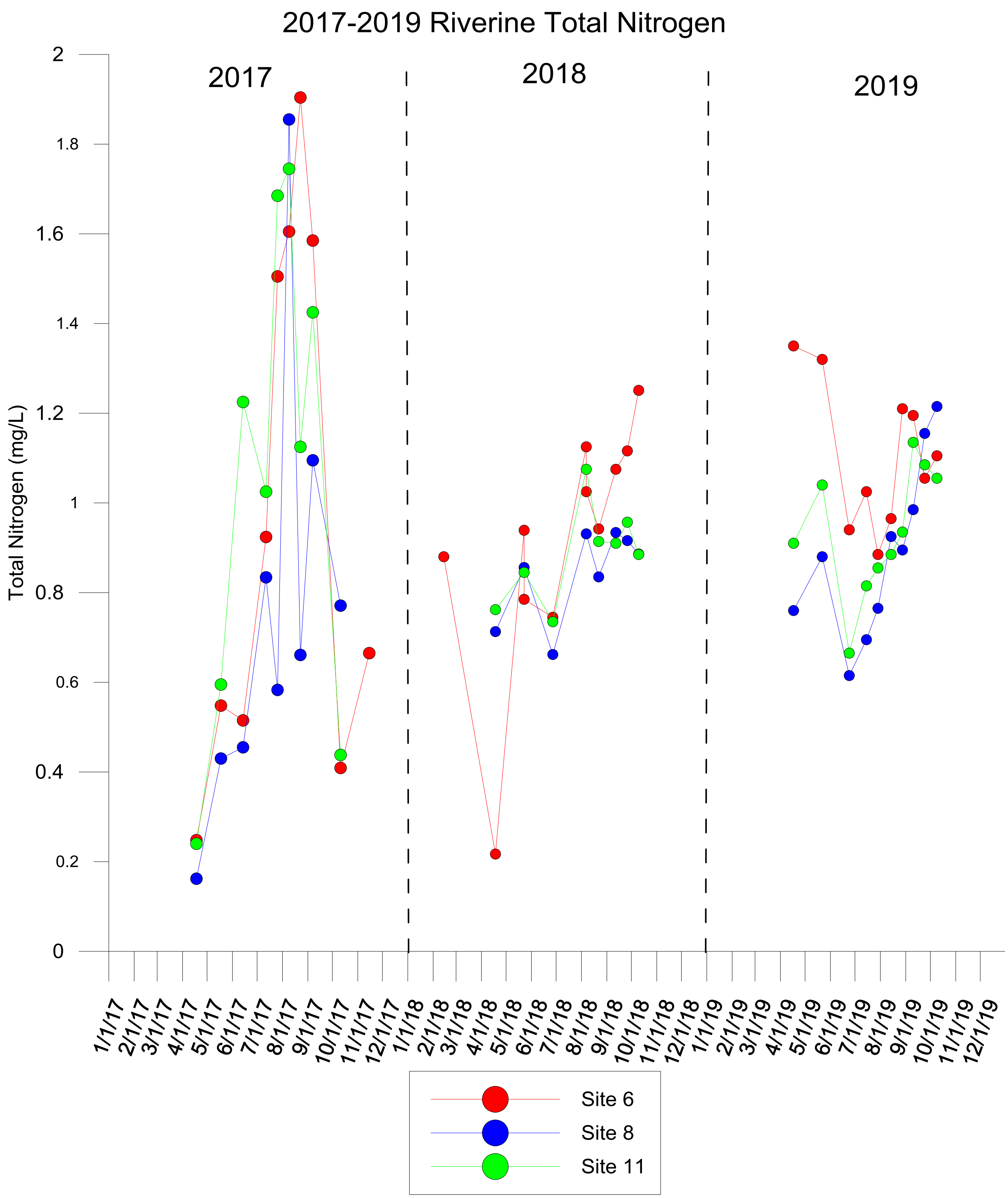

Figure 18. 2018 Surface Total Nitrogen Variables as N (mg/L) from the three riverine sites.

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 not detected throughout the monitoring season, contrary to previous years. This falls in line with biological principles, 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, and this was observed in 2019 (**Figure 16**).

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 as 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**). 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 22nd event, the majority of 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. Interestingly, chlorophyll decreased at site one in the late summer; historically this is the time when the values peak. The other lacustrine sites, only just upstream from site 1, continued to increase until the end of the season.

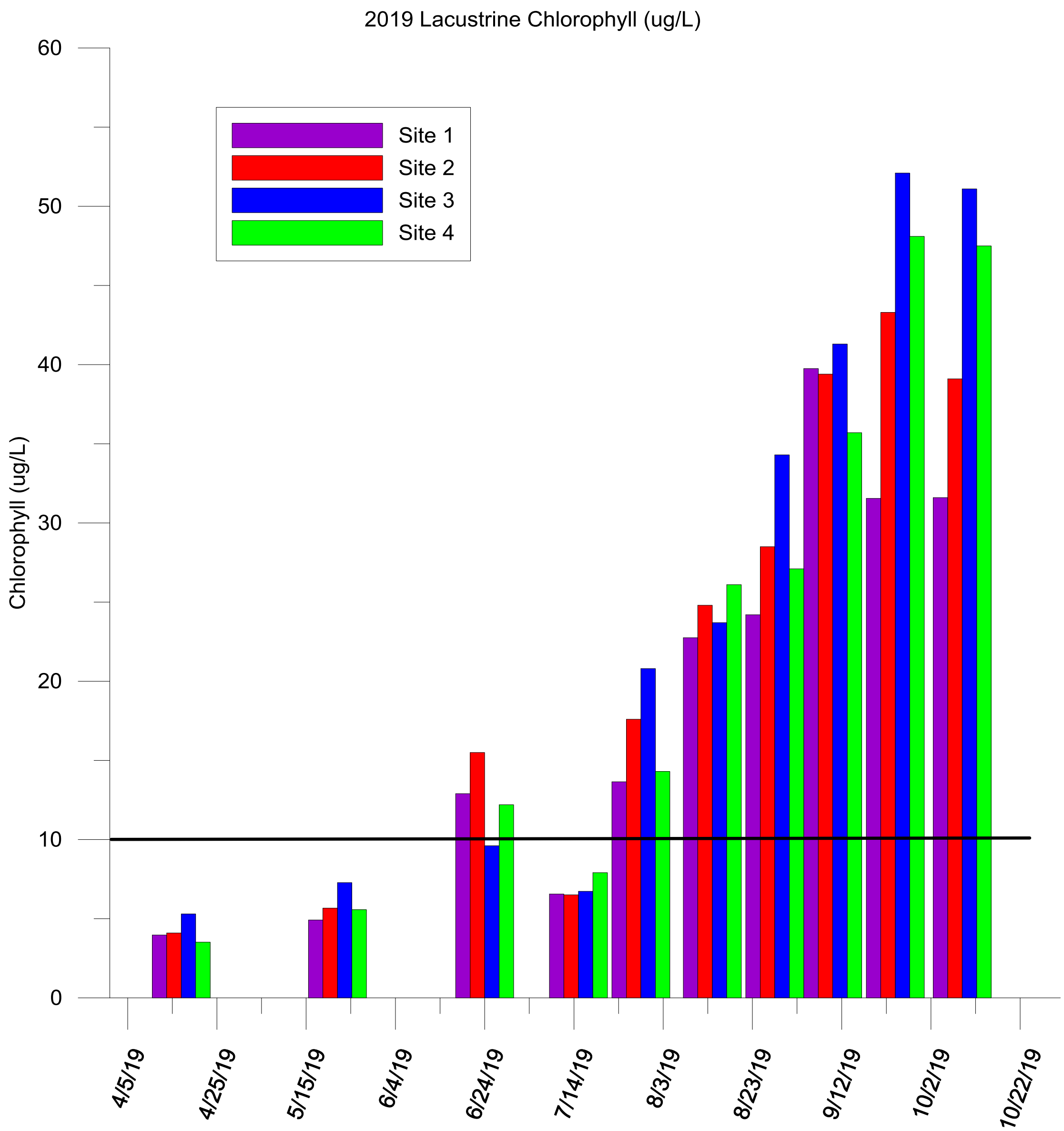

Figure 19. 2019 Lake Thunderbird surface chlorophyll (µg/L) at lacustrine sites. Black line denotes SWS criteria of 10 µg/L

Chlorophyll in riverine sites followed somewhat similar patterns as chlorophyll in lacustrine sites, although at a higher magnitude (**Figure 20**). All site started out the season already close to the 10 µg/L criterion. Site 8 and site 11 gradually increased over early summer while site 6 increased sharply, likely due to storm events in late May. 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.

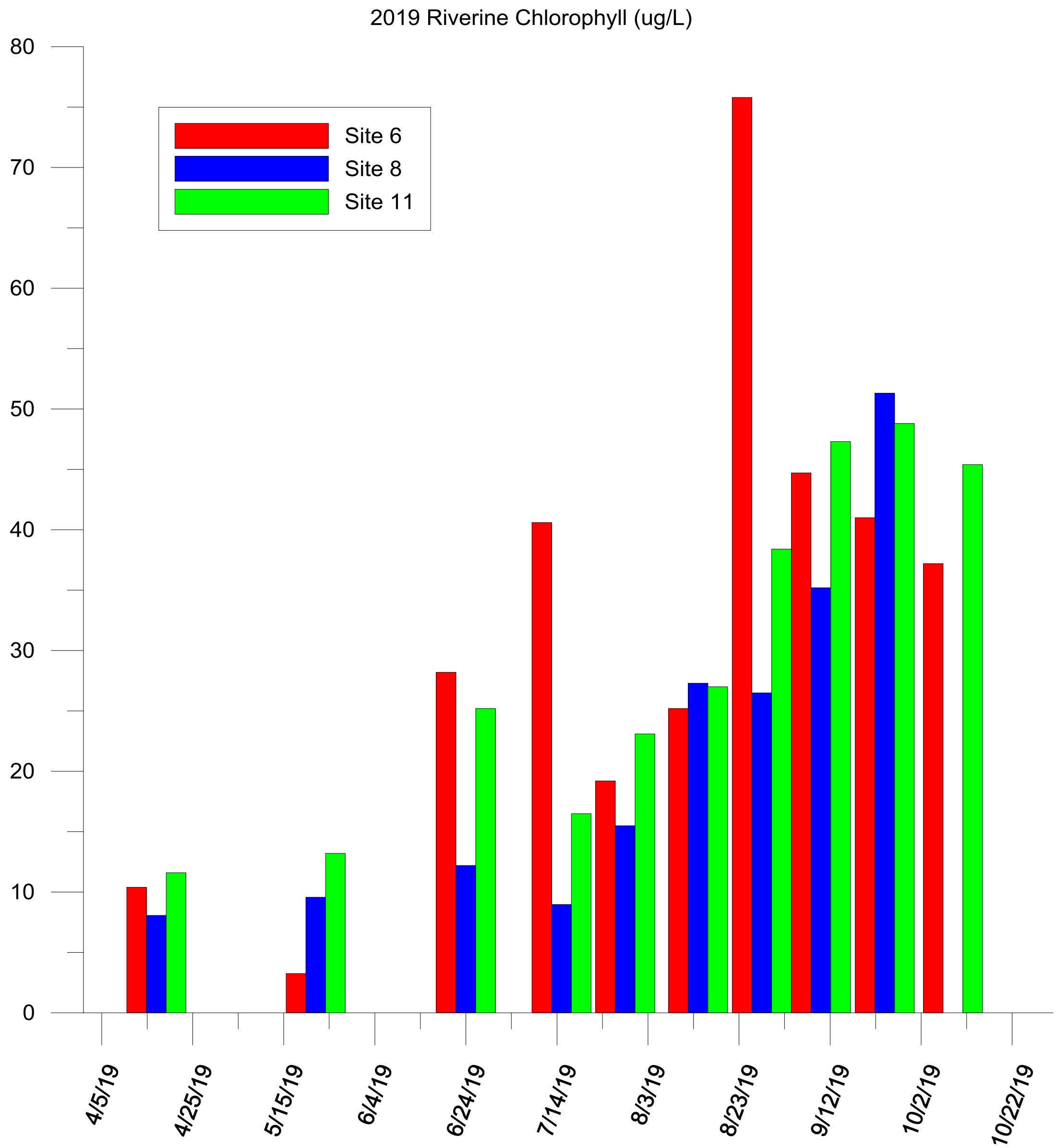

Figure 20. 2019 Lake Thunderbird surface chlorophyll (µg/L) at riverine sites. Black line denotes SWS criteria of 10 µg/L

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.

Historically, Lake Thunderbird has been in the co-limitation range, as both nutrients were readily available for algal growth. Data collected in 2019 exhibited similar co-limitation tendencies although several calculated ratios were in the indeterminate zone (**Figure 21**).

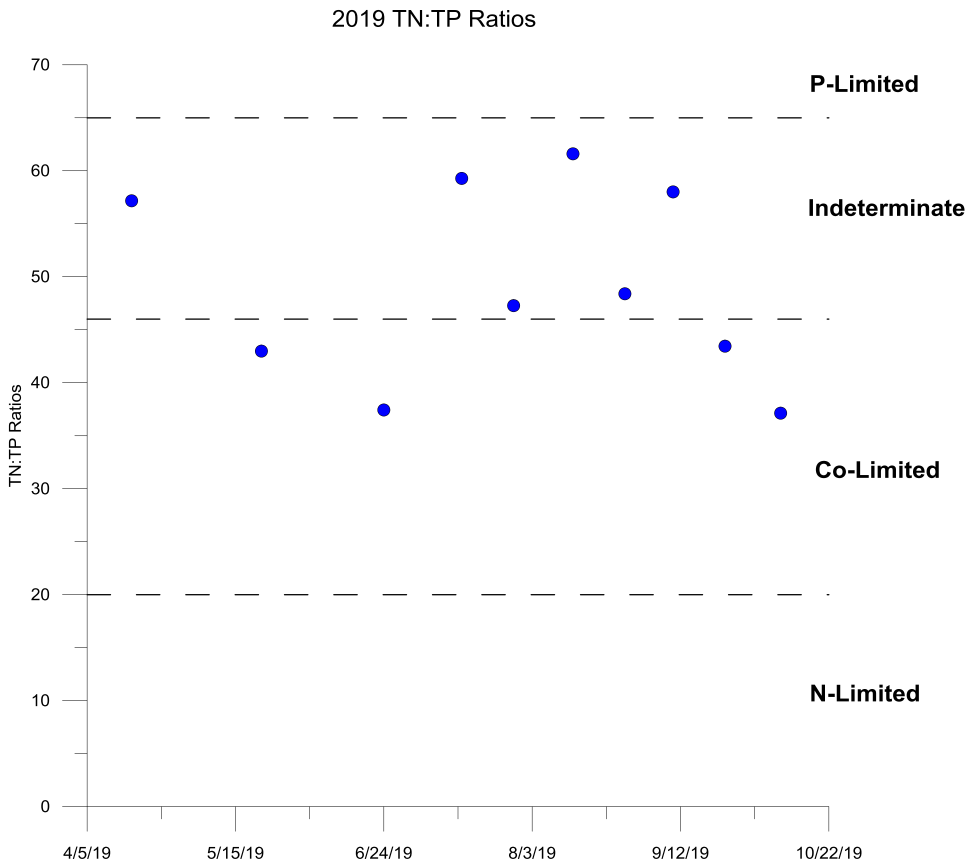

Figure 21 2019 Lake Thunderbird TN:TP ratios by sample event

Light

In 2019, 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, 66.7% 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.

Data collected in 2019, was also examined with respect to Canfield and Bachmann's model predicting chlorophyll from nutrient concentrations (1981). This model is not well calibrated to predict chlorophyll in Oklahoma reservoirs. Most of the model results under-predicted measured chlorophyll. According to Canfield and Bachmann, *"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"*(1981). These insights could help explain why chlorophyll values were lower than would be expected by the high amount of nutrients present in the system.

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 and are depicted as dashed lines in **Figure 22**. Lake Thunderbird's TSI(CHL) levels at site one began the season as mesotrophic, increased to eutrophic in July and August, then increased to hypereutrophic where it remained for the rest of the season and represented half of the total number of sample events.

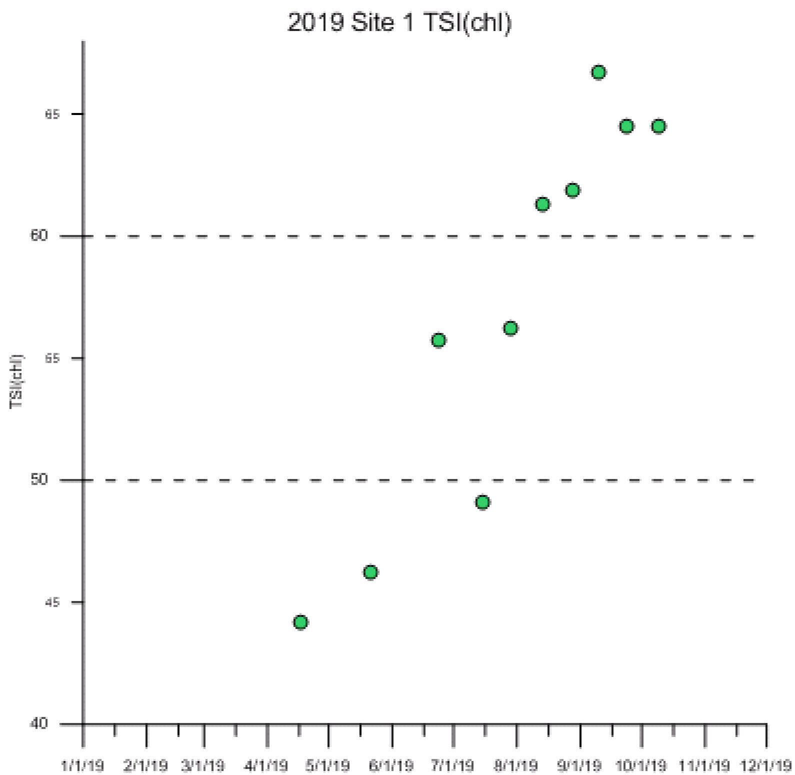

Figure 22 Site 1 TSI(Chl) in 2019. Dashed lines represent the divisions of trophic state

Lake Thunderbird's TSI for each of the three parameters are displayed in **Figure 23**. TSI(CHL), a reflection of actual or realized algae growth, showed site 1 to have been mesotrophic in April and May steadily increasing to the eutrophic range in July and in the hypereutrophic range for the remainder of the season. 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) 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 most of the monitoring period, corresponding to a eutrophic state.

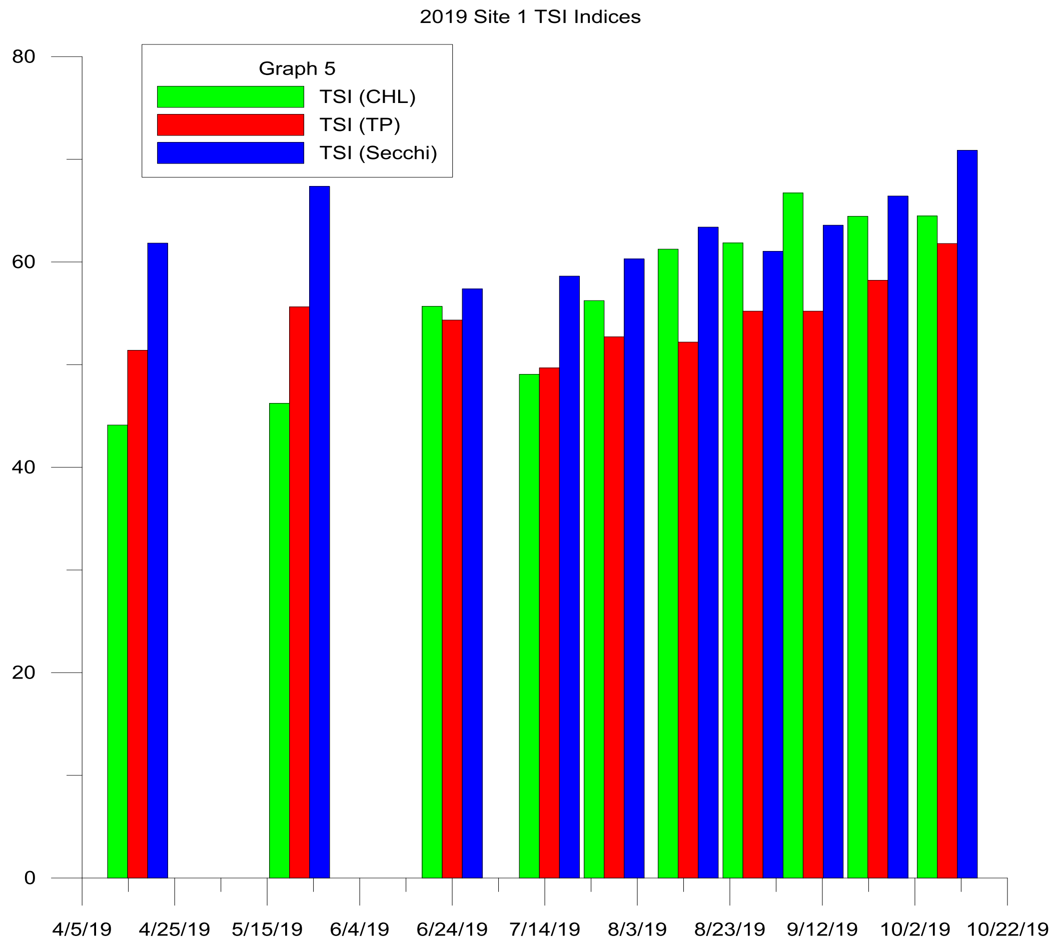

Figure 23. 2019 Carlson's Trophic State Index values for Lake Thunderbird at Site 1.

In a similar pattern as site 1, TSI(CHL) at the riverine sites increased from through the season and were mostly in the eutrophic and hypereutrophic ranges. TSI(CHL) varied between sites and were consistent with realized chlorophyll in the system (**Figure 24**).

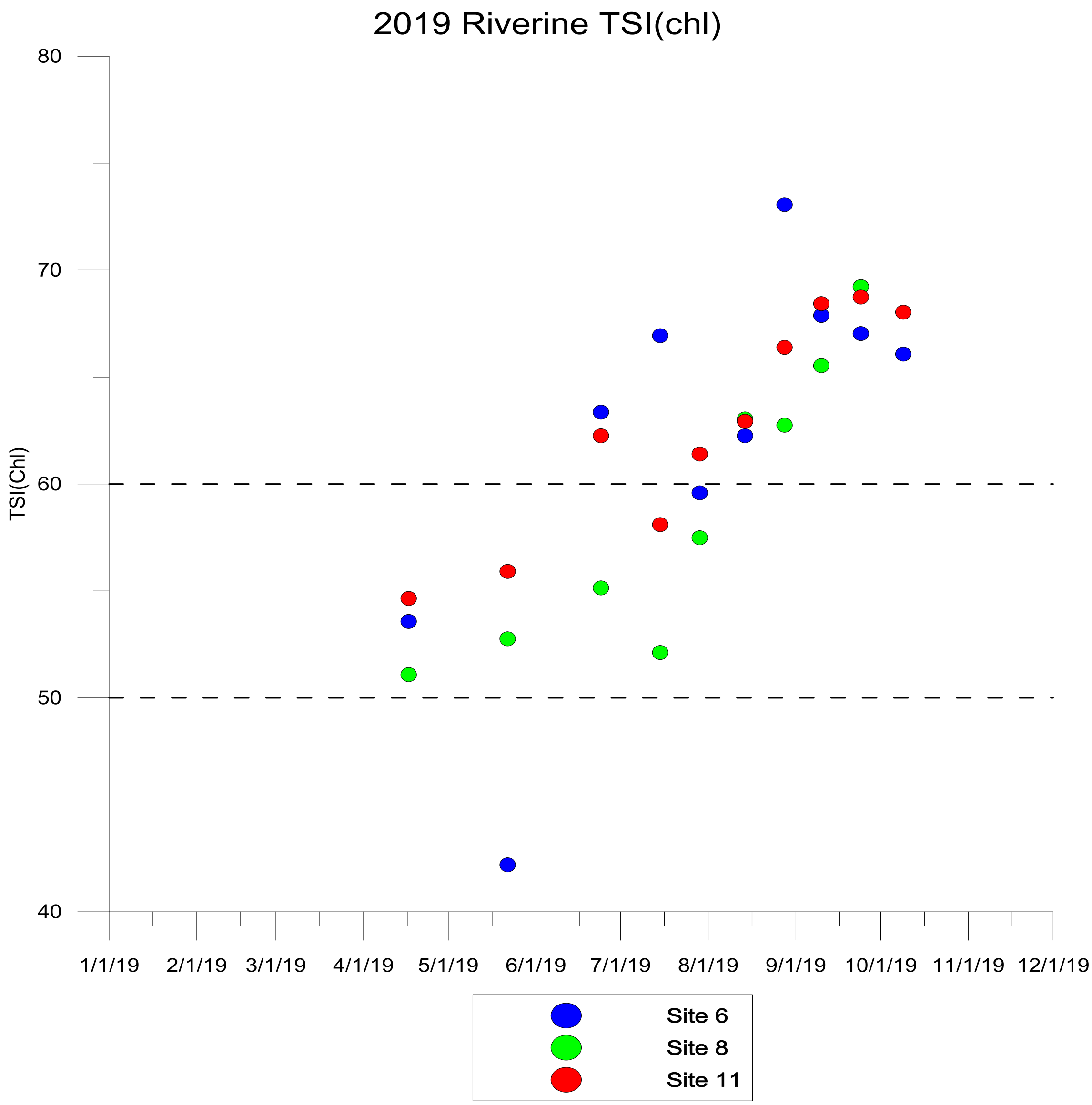

Figure 24. 2019 Carlson's Trophic State Index values for riverine sites (sites 6, 8, and 11) for Lake Thunderbird. Dashed lines delineate ranges for trophic states.

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 2019, Lake Thunderbird TOC values ranged from 4.79 to 5.95 mg/L with a mean value of 5.415 mg/L (**Table 4**). In 2019, 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 2019 Lake Thunderbird Total Organic Carbon (mg/L)

Total Organic Carbon (mg/L)	
04-17-2019	4.79
05-22-2019	4.93
06-24-2019	5.49
07-15-2019	5.48
07-29-2019	5.54
08-14-2019	5.88
08-28-2019	5.55
09-10-2019	5.95
09-24-2019	5.3
10-09-2019	5.24

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 – 2019) 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 2019, exhibited a different pattern from previous years, with no months soliciting more than three complaints (**Figure 25**). In past years, taste and odor complaints coincided with lake mixing events cycling hypolimnetic chemicals into the water column. Interestingly, Geosmin peaked in January of 2019 and MIB spiked in October (**Figure 26**). It is clear that various algae processes are active throughout the fall winter months; however, it is impossible to evaluate the winter season nutrient dynamics and algal processes because monitoring is not conducted in the winter month. In 2020, chlorophyll will be measured during the formerly missing months and more analysis will be reported on in the final report.

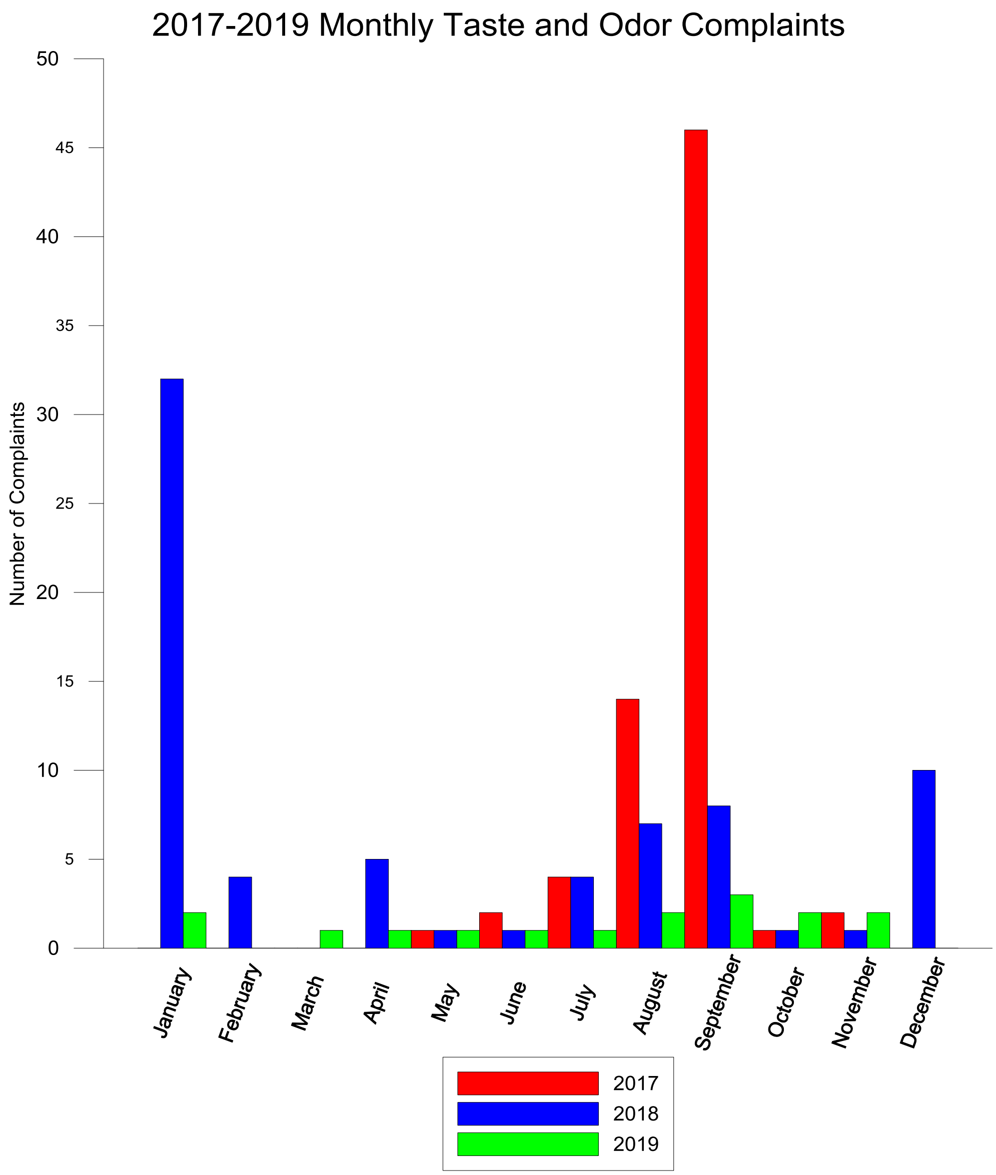

Figure 25. 2017-2019 City of Norman compiled monthly Taste and Odor complaints. March complaints in 2018 not recorded.

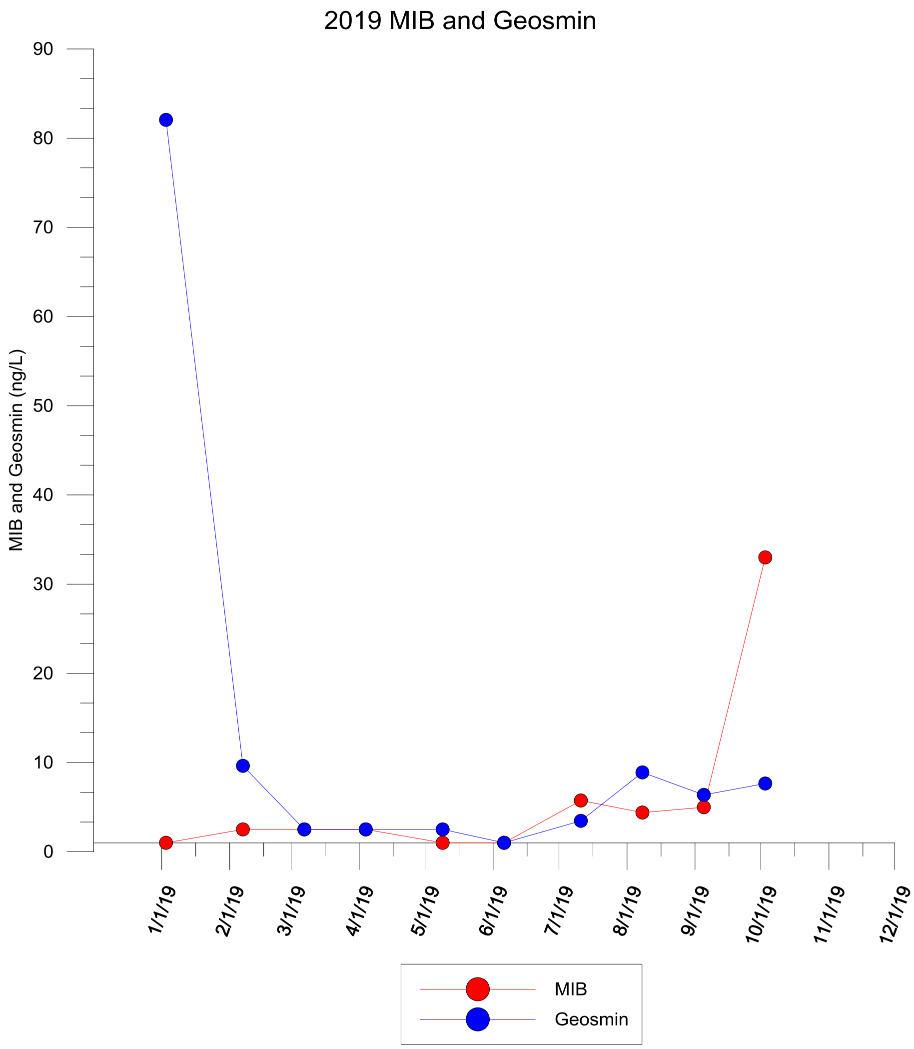

Figure 26. 2019 City of Norman raw water laboratory analysis.

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 2019 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 volumetric DO violation occurred in 2019, as the volume of anoxic water was 52% of the lake's total volume on September 10th.

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. In 2019, the lake wide chlorophyll average in Lake Thunderbird was 24.3 µg/L, with 75% of the samples exceeding 10 µg/L, whereas samples collected in 2018 had a lake wide average of 22.5 µg/L with 84% of samples exceeding **(Figure 27)**. The long-term ten-year lake-wide average is 26.0 µg/L, with 82% 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.

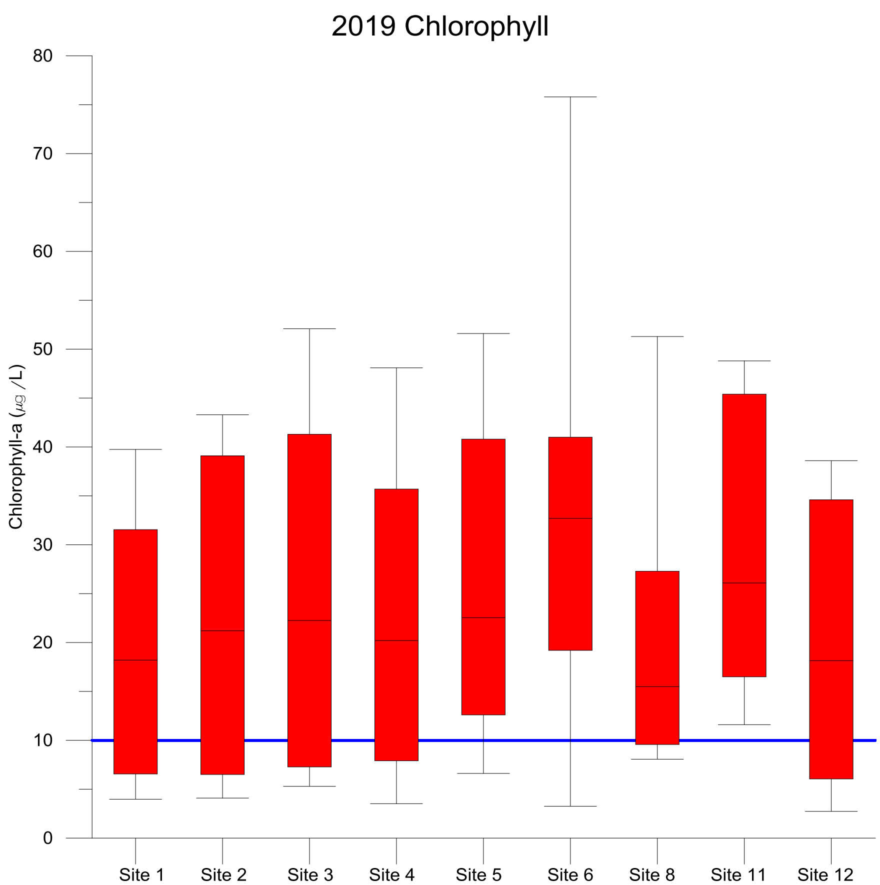

Figure 27. 2019 Lake Thunderbird chlorophyll-a (µg/L) by Site, where boxes represent 25% of the data distribution both above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Blue line represents 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 2019 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 28**).

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 2019 sampling season, the lake wide turbidity average in Lake Thunderbird was 27.4 NTU, with 26.1% of the samples exceeding 25 NTU **(Figure 29**). The long-term, ten-year, lake-wide average is 24.8 NTU, with 26.4% 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.

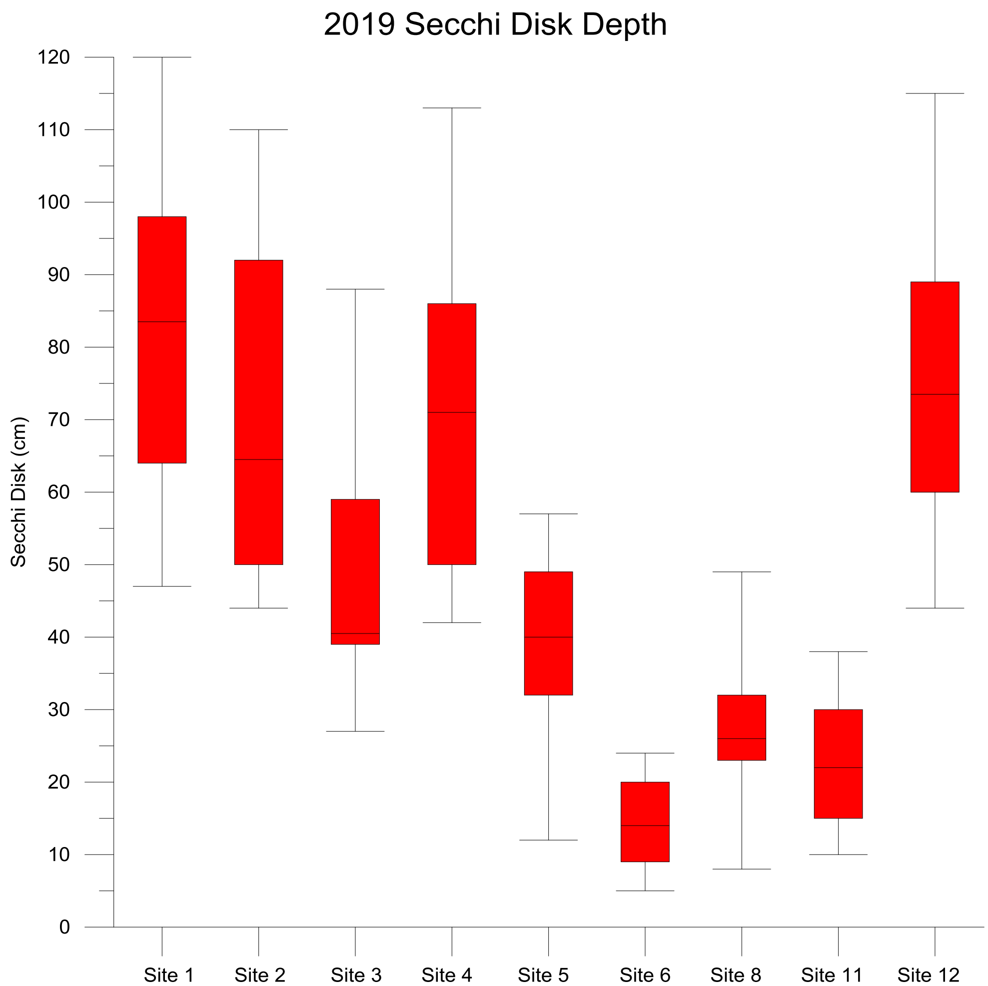

Figure 28. 2019 Lake Thunderbird Secchi Disk Depth (in centimeters) by Site, where boxes represent 25% of the data distribution both above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values.

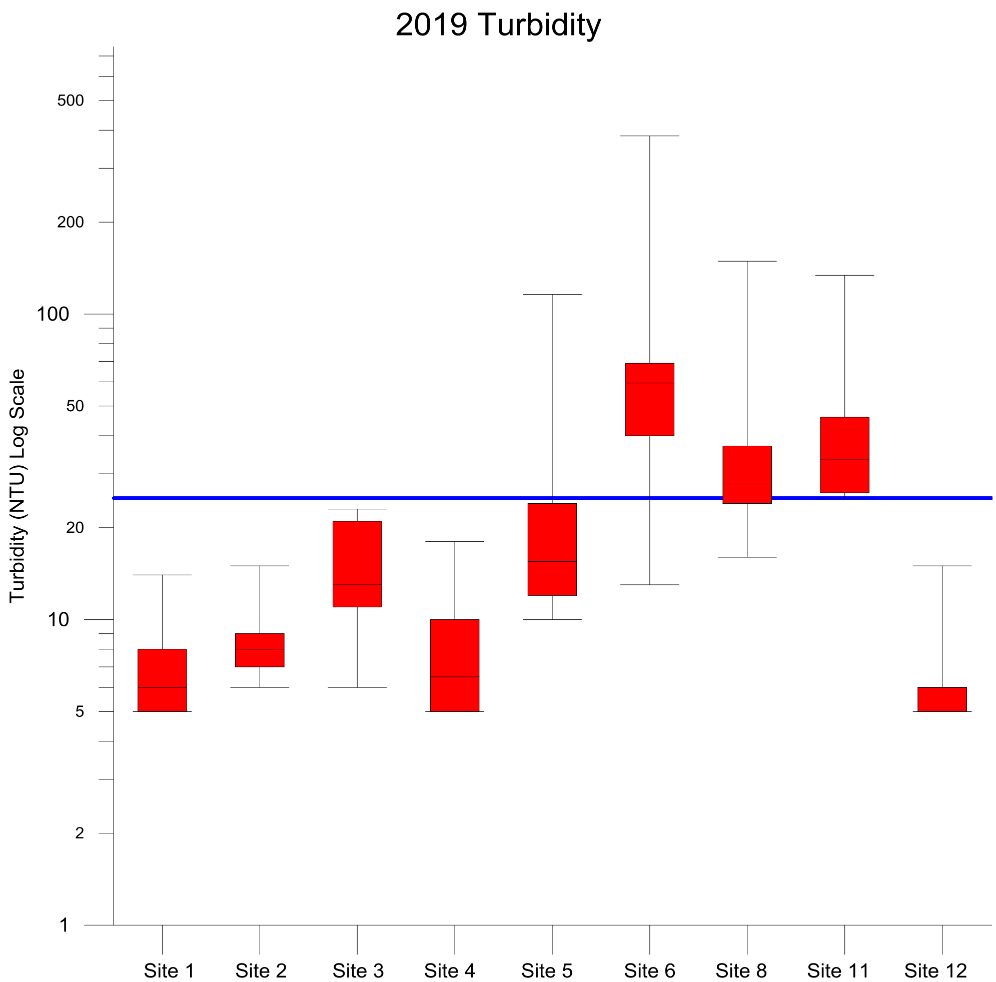

Figure 29. 2019 Lake Thunderbird Turbidity (NTU), by Site, where boxes represent 25% of the data distribution both above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Solid blue line indicates the 25 NTU water quality standard.

Supersaturated Dissolved Oxygen Injection System (SDOX)

The SDOX system is an important water quality management tool at Lake Thunderbird and over the last two reporting cycles, COMCD has been increasingly curious about the background and original capacities and intent of the SDOX project. This section provides a summary review of the history, original and current design, implementation decisions, key points on modifications, and a historical to contemporary review of performance. Opportunities to better capture SDOX efficacy in the future will also be discussed.

The fundamental purpose of the SDOX system is to provide sufficient oxygen to the lake hypolimnion. When oxygen is present it acts as 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 was working optimally, by providing 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, reducing phosphorus sediment load, and providing oxidant for breakdown of organic molecules including taste and odor compounds.

Sample year 2019 marked the ninth season of operation for the SDOX installed in Lake Thunderbird. It is designed to operate throughout the entire stratification period, May-September 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 at site 12 (Error! Reference ource not found.)

In the first few years after the SDOX was installed, considerable modifications occurred in both the system's components and operation; therefore, this monitoring season marked the seventh year of operation at optimal design. The SDOX delivered 435,675 lbs. of oxygen at an average rate of 4,356.75 pounds per day in 2019. However, there were periodic interruptions in operation in 2019, which complicated analysis of effectiveness.

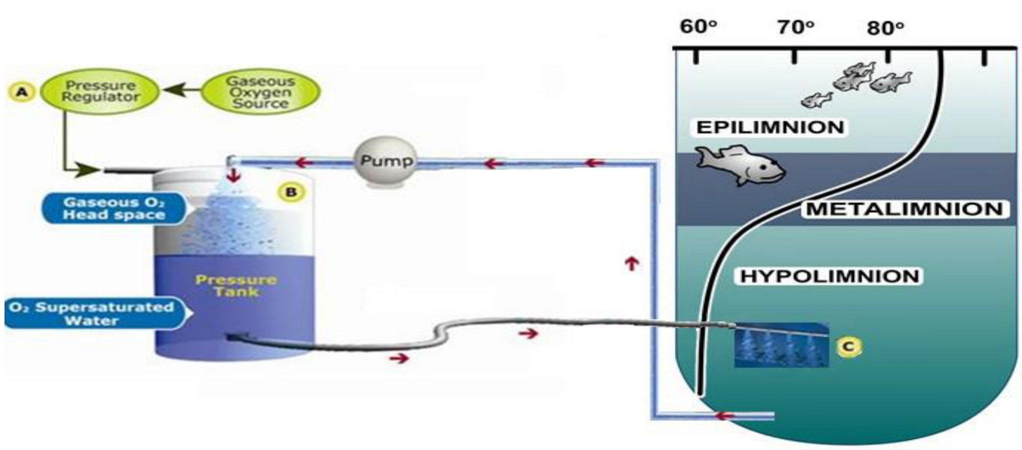

Figure 30. Conceptual illustration of the SDOX System at Lake Thunderbird

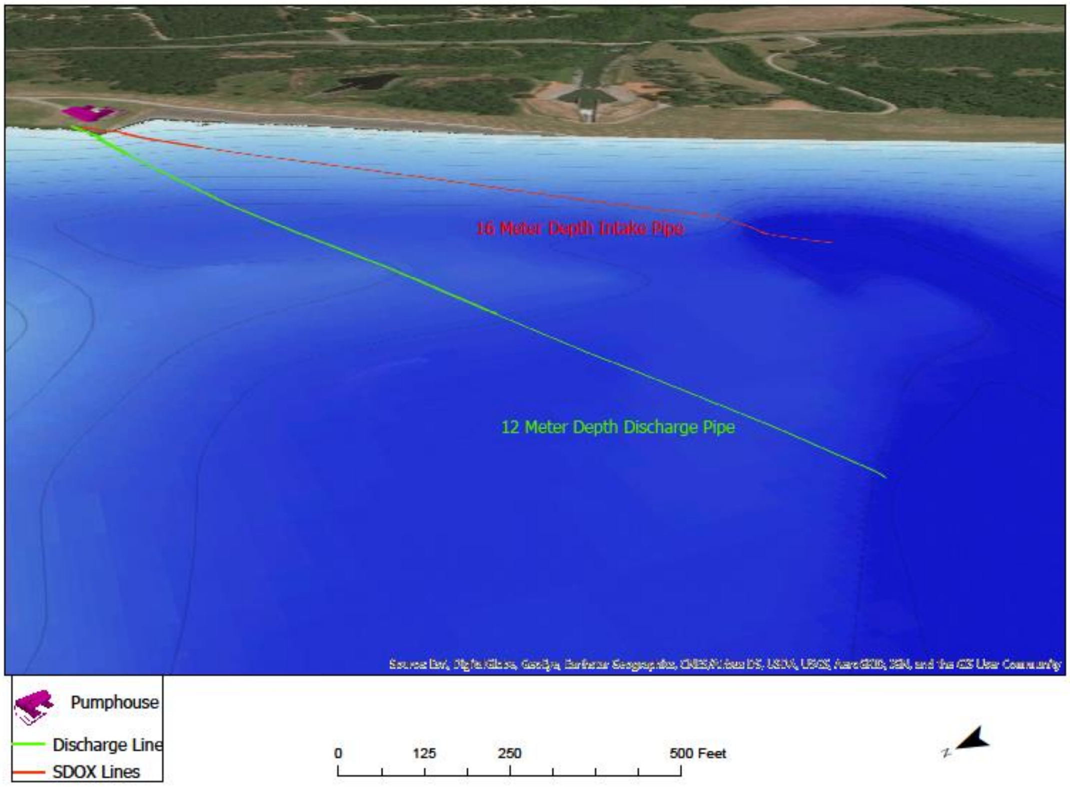

Figure 31. Map highlighting SDOX location and current configuration.

Literature Review

Several hypolimnetic oxygenation systems have been implemented in the past few decades around the world with varying levels of success. Most systems reported positive results with regard to providing oxygen to the hypolimnion and mitigating some internal phosphorus load. In Prepas's study Amisk Lake began hypolimnetic oxygenation in 1988 and has experienced a drop of over 50% in hypolimnetic TP resulting in a 13% and 55% reduction in whole lake epilimnetic TP and chlorophyll concentrations respectively. Arguably, this is a substantial improvement to the water quality, which also had impacts to the algal community structure and changed the entire trophic status of the lake from eutrophic to mesotrophic (Beutel, 1999).

In Newman Lake, hypolimnetic oxygenation was employed and was able to oxygenate the hypolimnion in several studied years, except when the system was only partially operational for repairs. Lower hypolimnetic TP was observed even when the system was partially operational although this result is complicated by the addition of external load controls and alum injection. Biologically, peak phytoplankton biovolumes as well as cyanobacteria presence and blooms decreased (Beutel, 1999).

In Lake Serraia, Italy which has similar maximum and mean depths as Lake Thunderbird, implementation of a hypolimnetic oxygenation system decreased nutrient release from the sediments which in turn decreased algal communities and shifted the dominance of those communities from cyanobacteria to chlorophyte (Preece, 2019).

These studies and more provide results that indicate a hypolimnetic oxygenation system can be successful when sized appropriately and operated at full capacity. These examples provide hope that an SDOX system can be effective in mitigating some of Lake Thunderbird's issues. However, the system needs to be inspected for operational issues, further monitoring completed, and the size limitations need to be recognized to meet expectations.

History of the SDOX

In 2009, OWRB initiated a project focused on investigating in-lake best management practices (BMP) for two Oklahoma reservoirs (OWRB, 2009). Lake Thunderbird has long been identified as a reservoir with significant nutrient loading from the watershed and has been presumed to have a large internal nutrient load. Nutrient loading both from the watershed and internally from the lake are important drivers for algal growth. Lake Thunderbird was chosen for the 2009 investigation because of the lake's water quality impairments and its designation as a Sensitive Water Supply (SWS). The lake was also known to have a history of taste and odor compounds and increasing drinking water treatment costs that have the potential to be mitigated through in-lake BMPs. OWRB produced a SWAT watershed model and a BATHTUB model for Lake Thunderbird to investigate the relationship between nutrient input and algal growth and recommend a strategy to decrease the nutrient loading to the lake.

Several mitigation strategies were examined as a part of this project, including fine-bubble diffusion, depth-selective flow routing, and an SDOX. Ultimately, OWRB recommended the SDOX as an effective strategy for mitigating internal phosphorus loading and to promote corresponding reductions in algal biomass. In 2010, the SDOX was funded as a "Green Project" under the American Recovery and Reinvestment Act (ARRA) of 2009 and BlueInGreen was contracted to produce design, cost, and implementation information.

The original scope of the SDOX implementation project was to provide an oxygenated hypolimnion for part of the lake through much of the summer and thereby increase redox potential. Redox potential governs chemical reactions such as release of phosphorus, iron, and manganese from sediments. BlueInGreen submitted many proposals with varying sizes and capacities to accomplish these goals. The original recommended proposal designed for Lake Thunderbird was to employ two SDOX systems with 16-inch oxygen delivery pipes to oxygenate a hypolimnetic volume of 49.4 million m^3. Ultimately, the cost of this system exceeded available ARRA funds and was not installed, as recommended. BlueInGreen made revisions and submitted additional proposals designed to oxygenate a lesser volume of the hypolimnion and consequently were less expensive. Ultimately, in order to align with available funding, the SDOX proposal was scaled back to only one SDOX system and two 6 inch pipes, one for water uptake and one for oxygen deliver, estimated to provide oxygen to a hypolimnetic volume of 2.5 million m^3. This represents nearly a 95% reduction to volume of water intended to be treated with the current SDOX.

Because the capacity of the SDOX project was so dramatically reduced the intent, or spirit, of this installation became that of a "pilot project." With the installed SDOX capacity reduced by 95% it was not reasonable to expect this system to fully mitigate water chemistry conditions as originally conceived. Yet, it seems that over the years, the pilot project concept was lost and the SDOX was believed to be a "silver bullet" to remedy Lake Thunderbird's water quality impairments. Recalling this original spirit, allows board members and stakeholders to more clearly interpret the performance of the SDOX and inform decision-making in the future.

The current system is designed to operate throughout the entire stratification period and provide oxygen to a portion of the lake's hypolimnion. The system withdraws water from the deepest area of the hypolimnion approximately 16 meters in depth near the dam, supersaturates this water with oxygen under pressurized conditions, and then re-injects it at a separate location approximately 12 meters deep, referred to here as the nozzle site or site 12.

The 2011 data showed some thermal mixing due to the SDOX, which is not preferable (OWRB, 2012). BlueInGreen recommended that modifications to the nozzle be made to better direct flow of oxygen. While investigating and implementing these new modifications, a decision was made to shut down the originally installed northern pipeline due to a large leak and the southern pipeline was moved to deeper water to better facilitate oxygenation. All oxygen is now only delivered from the southern pipeline.

Summary of Past SDOX Performance

Some positive indicators were observed in the early years of optimal design operation. In 2012, lateral transects performed near the nozzle, showed supersaturated oxic conditions directly at the nozzle and hypoxic conditions (~3.0-4.0 mg/L DO) in the hypolimnion up to 300 meters from the nozzle. In 2013, another transect was done and hypoxic conditions were experienced only up to only 90 feet away from the nozzle, a decrease of approximately 2/3 it's radius of influence. Interestingly, at the dam site in 2013, a slight "bump" in dissolved oxygen concentrations occurred around 12 meters – the depth of the nozzle. This occurred at two events in mid-summer, but unfortunately was not of the magnitude to elevate DO to hypoxic conditions in the hypolimnion. These slight hypolimnetic DO increases have not been seen in years since. These DO measurements demonstrate that the SDOX pilot project did slightly raise oxygen concentrations in the hypolimnion but did not have the capacity to wholly oxygenate the hypolimnion as the full-scale installation was anticipated to achieve.

Other indicators were also examined with respect to the SDOX, throughout the years, such as oxidation reduction potential (ORP) increases and Anoxic Factor (AF) (Nürnberg, 1994). In 2011-2014, strong reducing conditions (lower ORP values) were more limited in extent and duration. While this is not the primary indicator of SDOX success, a shorter period of low ORP values does provide indication that bacteria may have had more opportunity to break down organic matter in the hypolimnion in times of higher ORP.

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. It has been shown to decrease from 2011-2014 relative to a calculated baseline followed by an increase from 2015-2017. It again decreased relative to the baseline in 2018 and 2019. The AF however, is not well suited to evaluating SDOX performance, especially given that the installed SDOX only has the potential capacity to oxygenate a small volume of water and this metric has been applied to evaluate the entire lake.

These measures are proxy indicators of SDOX performance rather than direct measures of its efficacy. Direct measures are often cost-prohibitive or difficult to monitor frequently, so proxy indicators are often utilized and are acceptable tools to make decisions. The nutrient samples added in the 2019 monitoring season are also proxy indicators, but are informative as they are directly at the nozzle site so we can better understand SDOX efficacy.

Evaluation of the 2019 SDOX Performance

Sample year 2019 marked the ninth season of operation for the SDOX installed in Lake Thunderbird. As discussed in previous sections, thermal stratification is a natural process occurring at Lake Thunderbird and can be presented as isopleths to gain insight on thermal and DO dynamics across the study period. Dissolved oxygen dynamics are often dictated by thermal stratification; when the cool, dense water sinks to the bottom, respiring bacteria utilize the oxygen present to decompose organic matter. Due to the density gradient, no more oxygen may dissolve into the hypolimnion, leading to prolonged periods of anoxia.

In 2019, profiles were taken every event at every site; presented here is an examination of the differences between site 1 (the dam) and site 12 (oxygen injection site). Site 1 is roughly 1,200 feet from the nozzle injection location and has historically been presented as a proxy for studying dissolved oxygen and nutrients at the nozzle site. Dependent on lake level, site 1 is usually 15-17 meters in depth whereas site 12 is usually 14-16 meters in depth. These two sites exhibited similar patterns related to thermal stratification in 2019. At the first sample event, April 17th, the lake was relatively isothermal; by the second event, May 22nd, the cooler, more dense waters started to stratify at both sites (**Figure 32**Figure 32).

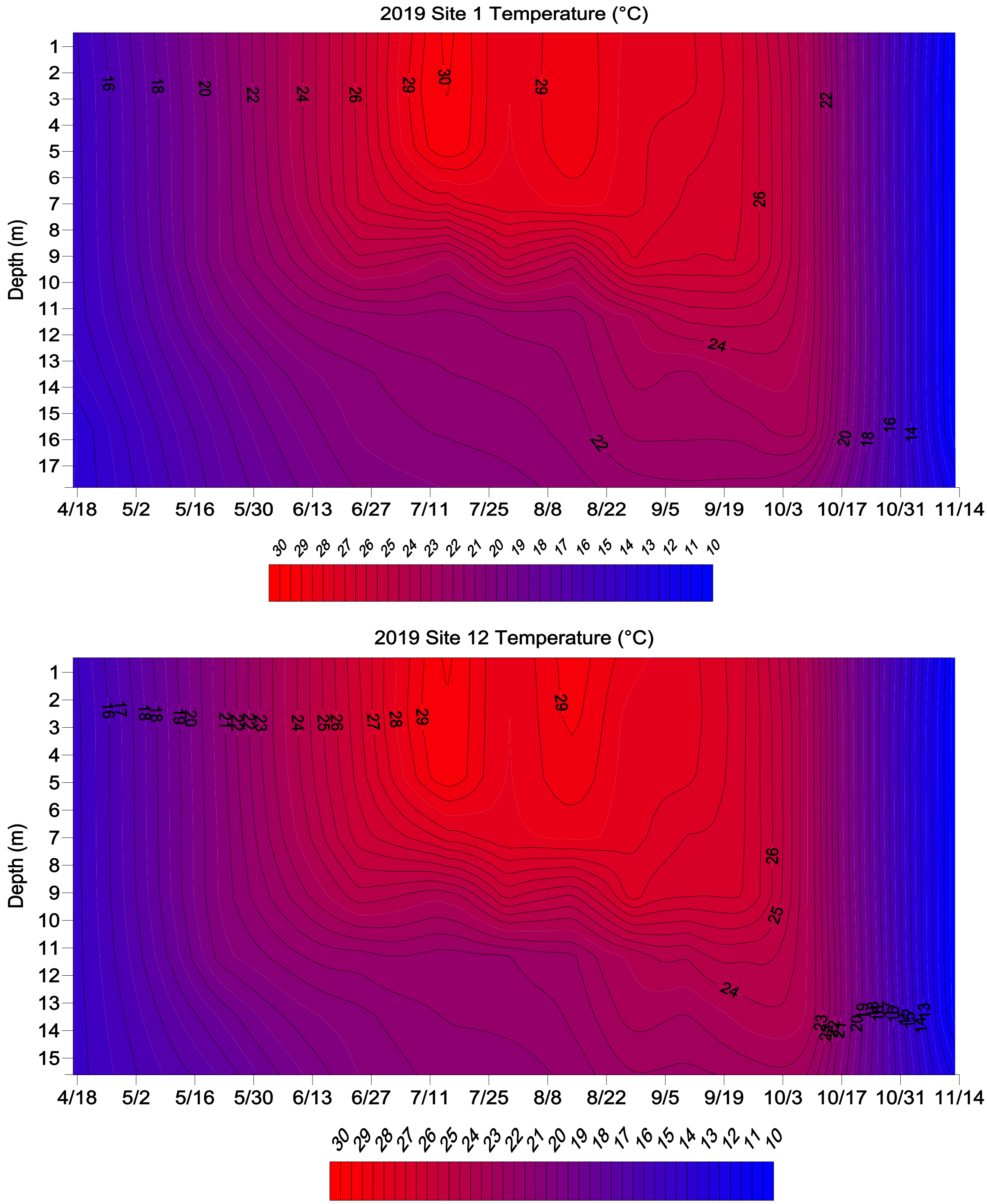

Figure 32 Thermal Stratification at Sites 1 and 12

By June 24th, site 1 was completely stratified with a defined epilimnion, metalimnion and hypolimnion (**Figure 33**). Deeper waters tend to stratify more strongly earlier in the year, evidenced here by site 12, shallower water, was not as stratified quite yet, documentation of the strength of stratification can be found in **Appendix B**. However, by early July both sites were thermally setup for the season. Even though it was witnessed in the first years of operation, it appears that the SDOX did not induce any thermal mixing in 2019, nor in the past few years.

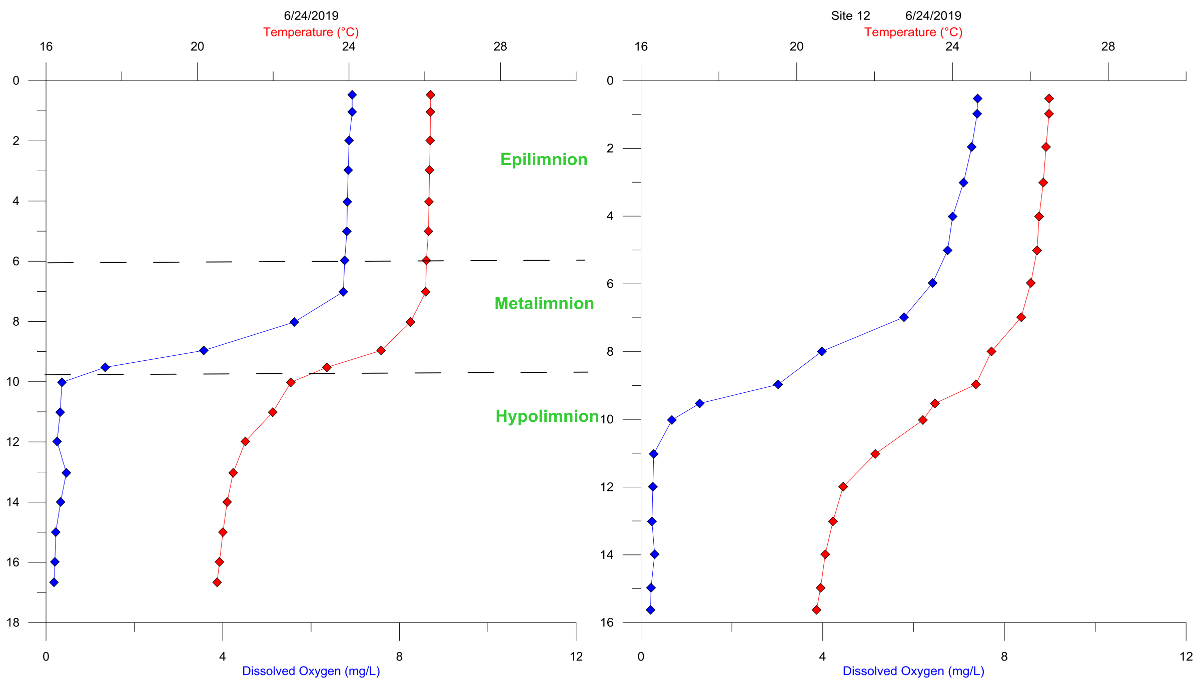

Figure 33 Thermal Stratification Setup at Sites 1 and 12

Hypolimnetic dissolved oxygen exhibited similar characteristics as in previous years as well, with anoxia beginning in early May and extending through most of the season before mixing in October. As was the case for thermal stratification, site 1 and site 12 demonstrated similar patterns in dissolved oxygen in 2019. Site 12 is slightly shallower than site 1, and as expected, experienced less anoxic volume and duration, while still remaining anoxic for much of the season (**Figure 34**). Peaks in anoxic depth occurred at both sites in July and September, corresponding to high epilimnetic temperatures. These peaks are an increasingly common effect in Lake Thunderbird and are worrisome because the anoxic volume of water completely dominates the metalimnion during these events. This is evidence of increased organic load and hypolimnetic water and sediment oxygen demand resulting from the eutrophication occurring in the lake. Anoxic water maintained a constant presence at both sites throughout the summer into September when thermal resistance to mixing began to decrease.

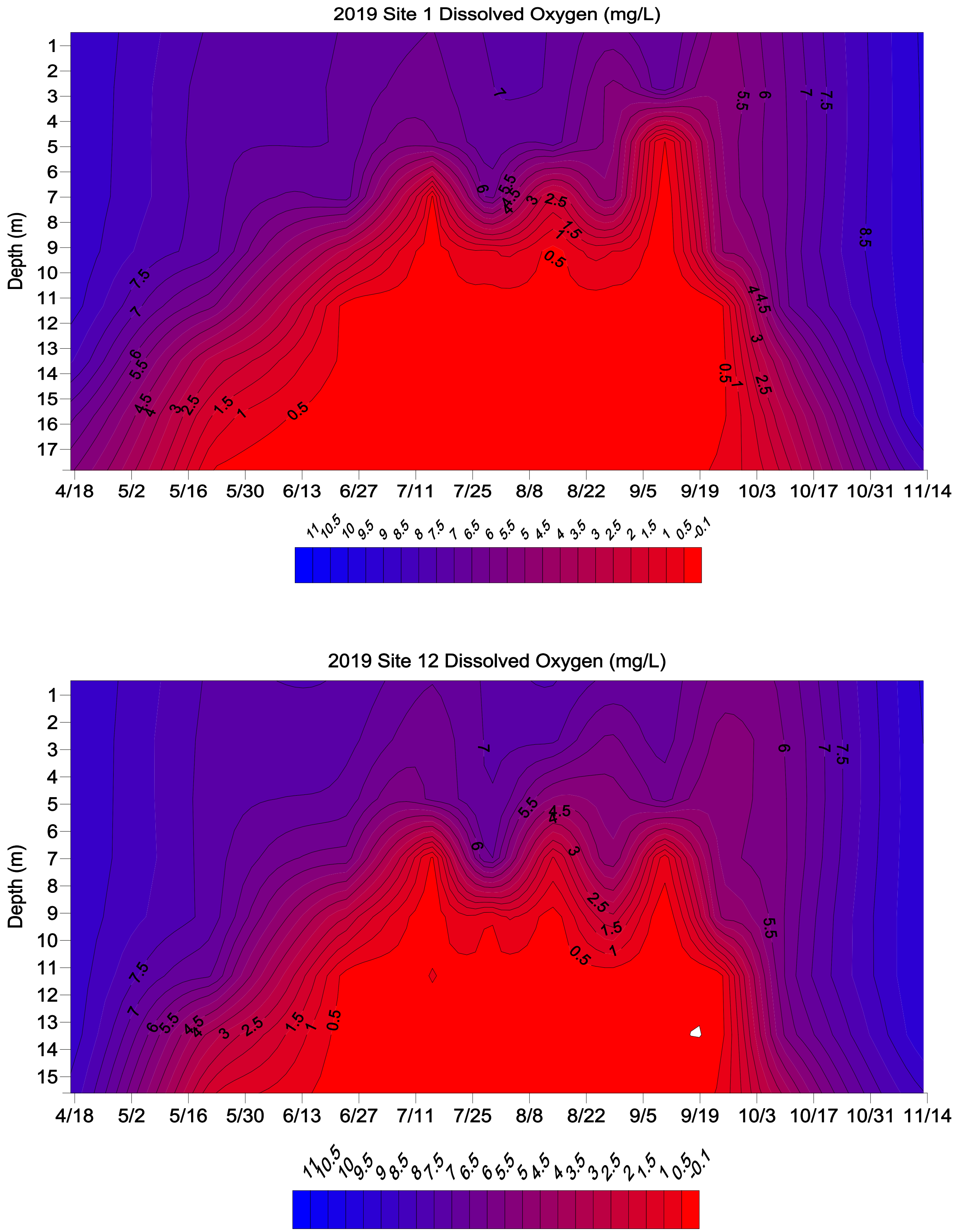

Figure 34 Dissolved Oxygen at Sites 1 and 12

It is clear from the profiles collected at the nozzle throughout the season, the SDOX is not adding any measurable DO to the hypolimnion. When comparing to site 1, another deep water site near the nozzle, site 12 is mimicking normal thermal and DO stratification regardless of the SDOX. Additionally, the interruptions in SDOX operation are not evidenced in the monitoring data; one would expect that if the SDOX was successful in oxygenating the hypolimnion, the breaks in interruption could be seen in the isopleth.

Interruptions in SDOX Operation
July 6th – July 8th
July 30th – August 5th
September 1st – September 19th

Table 5 Interruptions in SDOX Operation

In addition to the vertical examination of dissolved oxygen dynamics related to SDOX performance, OWRB implemented a lateral examination in 2019. The sampling design was to take continuous vertical profiles, measured every second, at four locations roughly fifty feet from the nozzle in a circular pattern (**Figure 35**). This DO transect monitoring was completed at the same sites both pre-stratification in May and peak stratification in July to allow for a comparison of before and during SDOX operation.

Figure 35 Lateral DO Monitoring around nozzle site in July

During pre-SDOX operation in May, the lake was just beginning to thermally stratify and hypoxic conditions were witnessed in the hypolimnion at all DO transect sites. During SDOX operation in July, no discernable oxygen was measured in the hypolimnion at any of the DO transect sites (**Figure 36**).

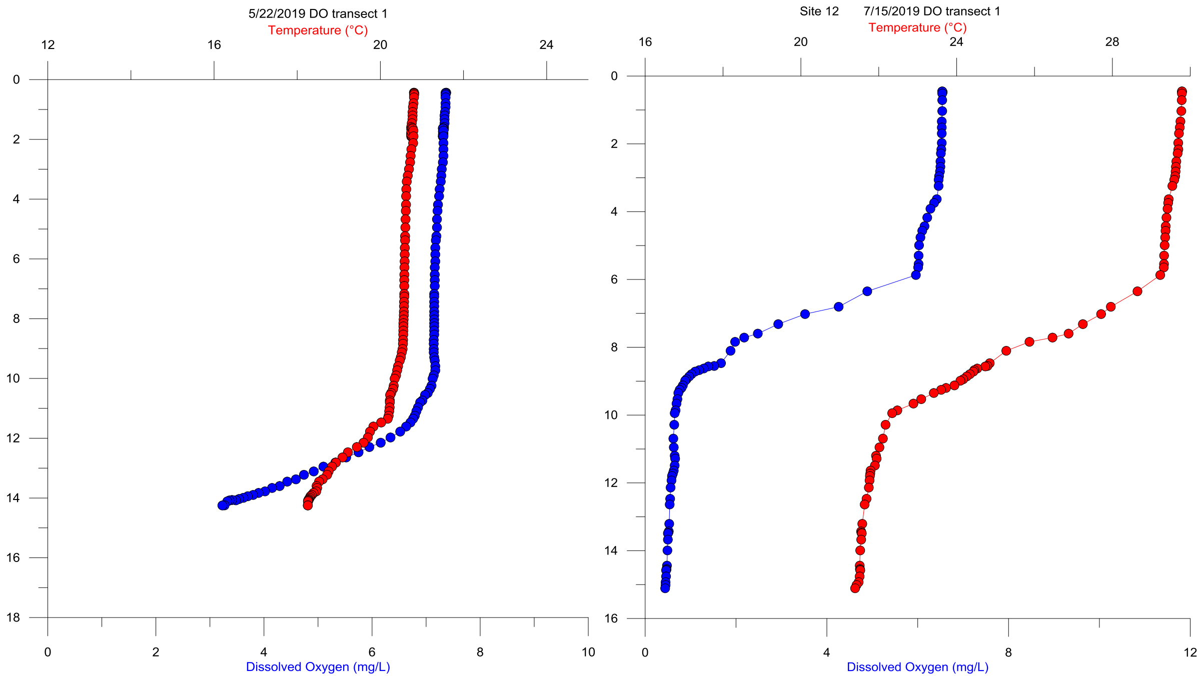

Figure 36 May and July DO transect 1 Temperature and Depth Profiles

Therefore, oxygenation of the hypolimnion was not observed in a vertical profile directly above the nozzle site and was not observed at peak stratification in any direction 50 feet away from the nozzle site. This indicates there was no lateral effect on dissolved oxygen concentration in the hypolimnion at or near the nozzle site.

Sediment oxygen demand (SOD) is another important consideration to evaluating the dissolved oxygen dynamics in Lake Thunderbird. SOD is the rate at which oxygen is removed from the system due to organic load decomposition. The SOD must be overcome before any real oxygenation is realized. This has never been measured in Lake Thunderbird; therefore, it is difficult to understand the effect this has on SDOX efficacy.

SDOX Effect on Nutrient Dynamics

In an effort to better characterize SDOX effect, additional water chemistry samples were collected in 2019. These included nutrient samples collected in the epilimnion and hypolimnion at the nozzle site. The nutrient panel collected at site 12 was the same as for site 1 and riverine sites and included total phosphorus, ortho-phosphorus, Kjeldahl nitrogen, nitrates and nitrites, ammonia. Chlorophyll samples were also collected in the epilimnion at the nozzle site to examine possible SDOX effects on algal biomass. The additional data acquired through this increased monitoring allows for a comparison between these parameters at site 1 and site 12 to further understand the SDOX effect on water chemistry.

During stratification, phosphorus can accumulate in the hypolimnion as a result of external load, sediment nutrient release, and decomposition of organic matter. 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. In **Figure 37**, the total and ortho phosphorus at sites 1 and 12 at surface and bottom are compared. The pattern in both the surface and bottom are very similar; the surface samples at both sites differ by miniscule amounts. At both sites, hypolimnetic total and ortho-phosphorus accumulated throughout the stratification period and then decrease following lake mixing. In the hypolimnion, site 1 exhibits a greater accumulation of total and ortho phosphorus; since site 1 is deeper, there is a larger anoxic volume of water overlying the sediment creating more opportunity for sediment phosphorus release. Stronger thermal stratification at site 1 also contributes to the higher accumulation of phosphorus as there is a stronger density gradient to keep it sequestered in the hypolimnion.

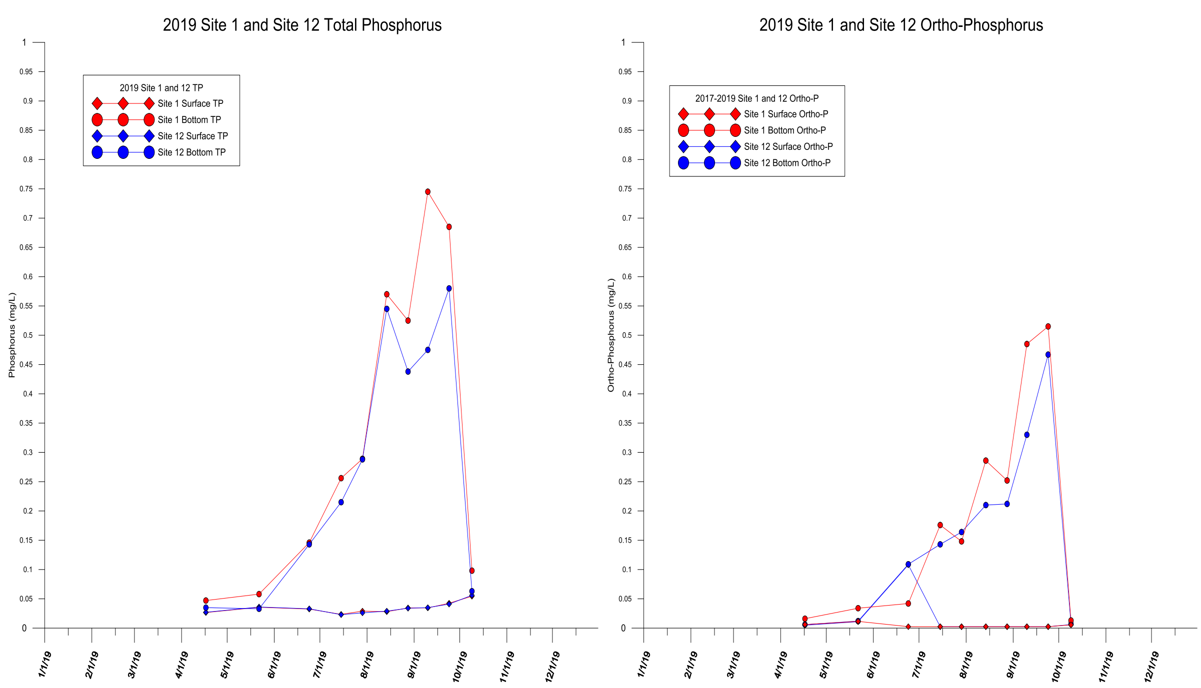

Figure 37 Total Phosphorus and Ortho Phosphorus at Surface and Bottom Comparison between Site 1 and Site 12

With these considerations in mind, it appears that the SDOX has not had a measurable effect of mitigating sediment phosphorus release as intended.

Nitrogen species were also examined between the two sites. Sites 1 and 12 exhibited similar patterns in both total nitrogen and ammonia in 2019 (**Figure 38**). Similar to the patterns seen in phosphorus, nitrogen and ammonia accumulate in the hypolimnion throughout the stratification period and then decrease during lake mixing. Ammonia at the surface is minimal, due to it being the preferable nutrient for algal uptake and ammonia readily undergoes nitrification to become nitrate in the presence of oxygen. Ammonia is present in large amounts in the hypolimnion where there is an absence of growing algae and oxygen. Ammonia is the reduced form of nitrogen and is often measured in large quantities particularly in anoxic environments, as it is a byproduct produced by bacteria that are decomposing organic matter.

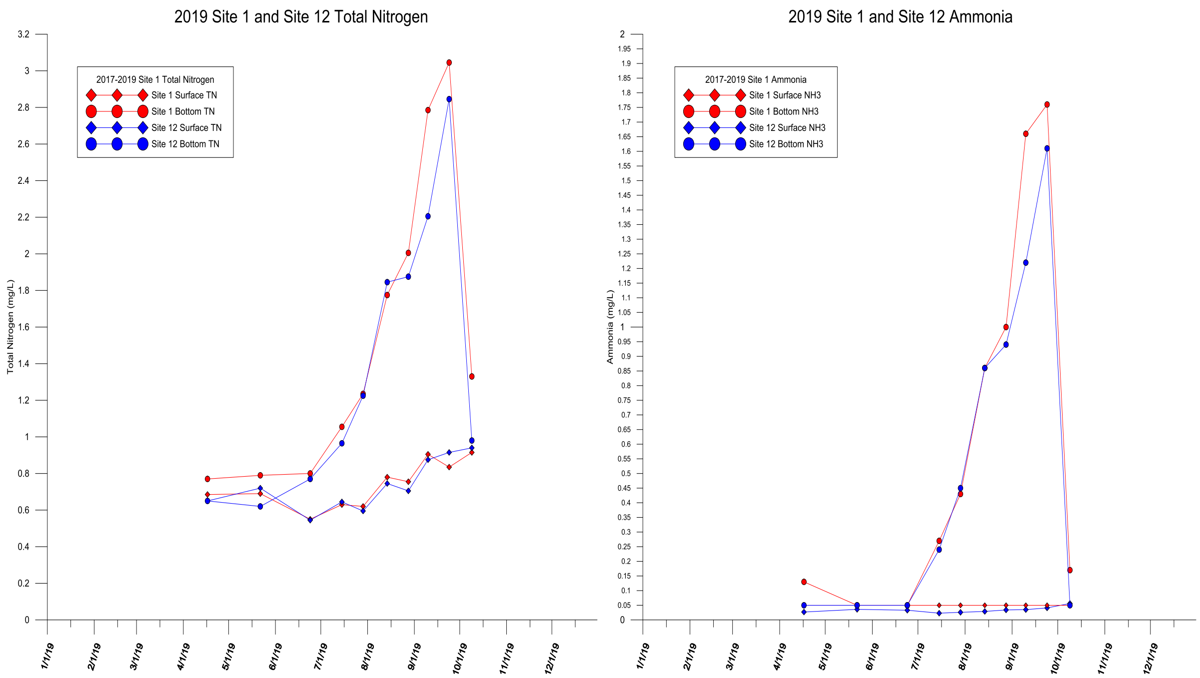

Figure 38 Total Nitrogen and Ammonia at Surface and Bottom Comparison between Site 1 and Site 12

With these considerations in mind, it appears that the SDOX has not had a measurable effect on altering nitrogen dynamics. As this is the first time nutrients were examined at the nozzle, more data is needed to better identify SDOX effect on nutrient accumulation and release.

Anoxic Factor and Release Rate of Phosphorus

Anoxic factor (AF) estimates sediment mediated phosphorus release in lakes and has historically been calculated in this report as a measure of SDOX efficacy (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 1.

Equation 1

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

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 present at a given sample event was determined using the dissolved oxygen profiles for site 1. 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 a rough estimate of sediment phosphorus load. Comparison of these calculations to the historical dataset can provide some insight to SDOX performance (**Table 6**).

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. 2018 and 2019 data showed a slight reversal of this increasing AF trend.

Table 6 Anoxic Factor and Relative Percent Difference (RPD) from Baseline

Year	AF (day^{-1})	RPD
05 — 09 Average	*34.94099*	0%
2010	46.22017	28%
2011	21.70	-47%
2012	25.61	-31%
2013	18.68	-61%
2014	30.67	-13%
2015	41.24	17%
2016	39.72	13%
2017	36.46	4%
2018	32.41	-8%
2019	32.03	-9%

Even though there was a decrease in the AF this year relative to the baseline, it is important to realize that this analysis provides estimates based on Nürnberg's nationwide model and the historical baseline was calculated from water column phosphorus, while the preferred method is to use sediment phosphorus content (1994). Therefore, it is not specific to Lake Thunderbird and baseline calculations would likely be different if there were available sediment phosphorus data. The internal phosphorus load should be empirically measured to accurately identify it.

SDOX Effect on Algal Biomass

Nutrients and chlorophyll are commonly known to have a stressor-response relationship. Increased nutrient concentration, phosphorus and nitrogen, will typically lead to increased chlorophyll concentration, a measure of algal biomass. Similar to the nutrient analysis of SDOX effect, it is important to also analyze chlorophyll in the same fashion. In **Figure 39**, it is apparent that chlorophyll concentrations at both sites 1 and 12 exhibited the same pattern for the season. This is understandable as there were no observed effects from the SDOX on nutrients, the stressor variable, so chlorophyll, the response variable, did not show any effect either.

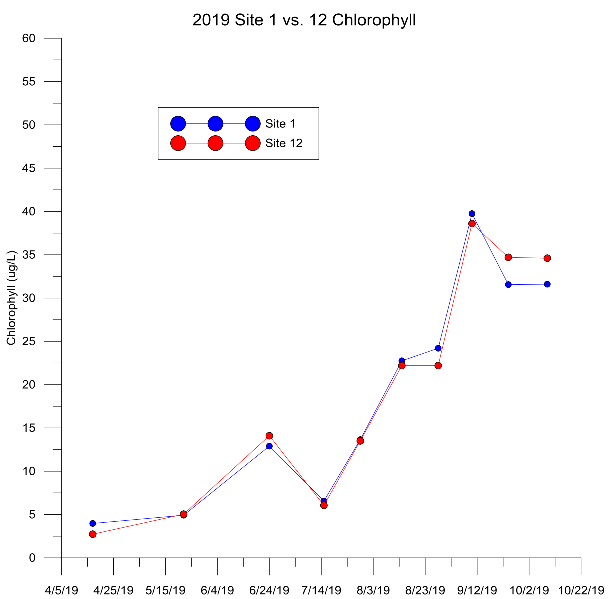

Figure 39 Chlorophyll Comparison between Site 1 and Site 12

Discussion of SDOX Performance

As a scientist with a vested interest in Lake Thunderbird's water quality, I have a lot of concerns regarding the SDOX, but ultimately would like to see it succeed in oxygenating the hypolimnion and mitigating sediment phosphorus release. Guided by the COMCD interest in SDOX performance, a considerable effort was made this year to further investigate the SDOX history, conduct a literature review, and analyze newly collected data. These measures discussed above create a weight of evidence that indicate the SDOX is not mitigating anoxia and therefore, not mitigating sediment nutrient release. This is not an unexpected conclusion given the volume of water requiring oxygenation (49.4 million m^3) compared to the volume of water the SDOX is able to provide oxygen to (*2.5 million m^3)*. At this time, OWRB would not recommend any sweeping decisions regarding SDOX operations be made until more information is gathered and more data collected.

It is important to keep in mind that the implemented design was limited in scope due to available funding, in accordance with this design we can only expect a limited response. Ideally, the SDOX would be able to provide oxygen to a much larger portion of the lake's hypolimnion. The performance results have this year not been well aligned with the stated performance potential. If COMCD works with BlueInGreen to reestablish what the expectations of the system are and investigate the potential mechanical limitations, then OWRB would recommend that the extra monitoring opportunities performed in 2019 be continued to better track performance. As seen in the literature, these systems can be successful when sized appropriately and operated constructively. Additional years of monitoring data are beneficial to analyzing effectiveness of hypolimnetic oxygenation as well as a study on the biological components, such as algae community structure and fish population.

BlueInGreen is working with COMCD to conduct a site visit to ensure mechanical aspects of the SDOX are functioning appropriately. Once this is complete, it should elucidate a lingering question regarding SDOX performance and provide an important check on operation.

In 2019, changes to the monitoring strategy were implemented to better capture SDOX performance measures, such as nutrient and chlorophyll analysis at the nozzle site as well as lateral DO investigation. OWRB believes that this is important monitoring and should continue in the future to establish longer-term trends in water quality affected by the SDOX. Other possible future analyses could be an investigation on the solubility of oxygen and an analysis on micronutrients, like iron, manganese and zinc, and their effect on algal growth and community structure. Further opportunities for studying Lake Thunderbird's internal nutrient load and a bathymetric mapping effort are located in **Appendix D** and **Appendix E**.

Discussion

For the past 20 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 March and a warmer than average September in 2019. Epilimnetic water temperature peaked in July. Water inputs to the lake remained relatively equal with total outputs, resulting in an relatively static water level through the monitoring season. The overall pattern of stratification remained similar to previous years. Thermal stratification was beginning to set up at May sample event coinciding with a small anoxic volume in the hypolimnion. Indicative of a hypereutrophic system, anoxia was creeping into the metalimnion by July, persisting through the summer until thermal mixing in early October. 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 July 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 2019. Ammonia and nitrate/nitrite are two forms of nitrogen available to algae; at the surface both remained near zero, below the detection limit, for most of the season. This indicates that a significant amount of algal production is occurring in the lake. 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 2019, as they were present in abundant amounts. Data collected in 2019 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 is 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 2019, average chlorophyll-a values increased from 2018 values, and 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. Walker's (1999) analysis on non-algal turbidity was employed this year to look at light's effect on algal growth. Results would indicate that allochthonous particles did have a negative effect on algal growth, but more analysis is needed. Trophic State Indices were also examined and the most stable index, TSI(CHL), determined that the lake would be classified as eutrophic in July, increasing to hypereutrophic in in August-October. 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 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. In 2019, taste and odor complaints were very low. Geosmin peaked in January and MIB peaked in October. This highlights that there is an interesting dynamic related to algal toxins occurring in winter months and additional chlorophyll monitoring efforts will be conducted in 2020 to gain understanding of algal growth. 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 2018 303(d) list of the Water Quality Integrated Report as impaired due to low dissolved oxygen, turbidity, and chlorophyll-a, with the driver of chlorophyll and dissolved oxygen impairments identified by the ODEQ TMDL as excess nitrogen and phosphorus. OWRB has thoroughly analyzed these impairments. Monitoring data, collected in 2019, 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 operation of a hypolimnetic oxidation system in 2011 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 thus enabling bacterial breakdown of organic detritus, and mitigating phosphorus release. As seen in the literature, these systems can be successful when sized appropriately and operated constructively. In 2019, OWRB monitored DO, nutrients, and chlorophyll at the site of discharge in an effort to measure effect of the SDOX. It is important to keep in mind that the implemented design was limited in scope due to available funding, in accordance with this design we can only expect a limited response. Analyzing these parameters created a weight of evidence indicating that the SDOX is not mitigating anoxia and therefore, not mitigating sediment nutrient release. The performance results have this year not been well aligned with the stated performance potential. However, BlueInGreen is working with COMCD to ensure an operational system. If it were to provide DO to the hypolimnion and mitigate some phosphorus release, it could improve 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 was improved in 2020, at no cost to COMCD. OWRB would recommend that those monitoring efforts be continued as they provided valuable information, particularly on the efficacy of the SDOX system.

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 should 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. **Appendix D** details the Scope of Work for the OWRB to complete an internal loading study.

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

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 2019 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 all sites
- 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

QA/QC samples were collected in 2019 and included replicates and analytical blanks. Replicate samples primarily control for the collection of a representative sample, but these results also include a measure of uncertainty from laboratory analysis. Analytical blanks control for cleaning the equipment, such as the dissolved integrated samplers and Van Dorns.

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 7**).

Table 7. Summary of 2019 Replicate Sample Results Designated as 1 (12) & 1 (22)

1(12)	TKN (mg/L)	Ammonia (mg/L)	NO2/NO3 (mg/L)	Total P (mg/L)	Ortho-P (mg/L)	Chlorophyll (µg/L)
04-17-2019	0.56	<0.1	0.15	0.027	0.006	NO DATA
05-22-2019	0.48	<0.1	0.23	0.035	0.012	4.71
06-24-2019	0.5	<0.1	<0.05	0.032	<0.005	11.9
07-15-2019	0.61	<0.1	<0.05	0.023	<0.005	6.51
07-29-2019	0.61	<0.1	<0.05	0.029	<0.005	13.5
08-14-2019	0.76	<0.1	<0.05	0.03	<0.005	21.1
08-28-2019	0.74	<0.1	<0.05	0.034	<0.005	24.9
09-10-2019	0.88	<0.1	<0.05	0.035	<0.005	39.1
09-24-2019	0.81	<0.1	<0.05	0.043	<0.005	28.9
10-09-2019	0.78	<0.1	0.13	0.056	0.006	29.8

1(22)	TKN	Ammonia	NO2/NO3	Total P	Ortho-	Chlorophyll

					P	
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(µg/L)
04-17-2019	0.52	<0.1	0.14	0.026	0.006	3.97
05-22-2019	0.44	<0.1	0.23	0.036	0.011	5.13
06-24-2019	0.55	<0.1	<0.05	0.033	<0.005	13.9
07-15-2019	0.6	<0.1	<0.05	0.024	<0.005	6.62
07-29-2019	0.58	<0.1	<0.05	0.029	<0.005	13.8
08-14-2019	0.75	<0.1	<0.05	0.026	<0.005	24.4
08-28-2019	0.72	<0.1	<0.05	0.035	<0.005	23.5
09-10-2019	0.88	<0.1	<0.05	0.034	<0.005	40.4
09-24-2019	0.81	<0.1	<0.05	0.042	<0.005	34.2
10-09-2019	0.79	<0.1	0.13	0.053	0.005	33.4

*NO DATA chlorophyll result was due to a lab accident

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

Equation 1 was applied to each replicate 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

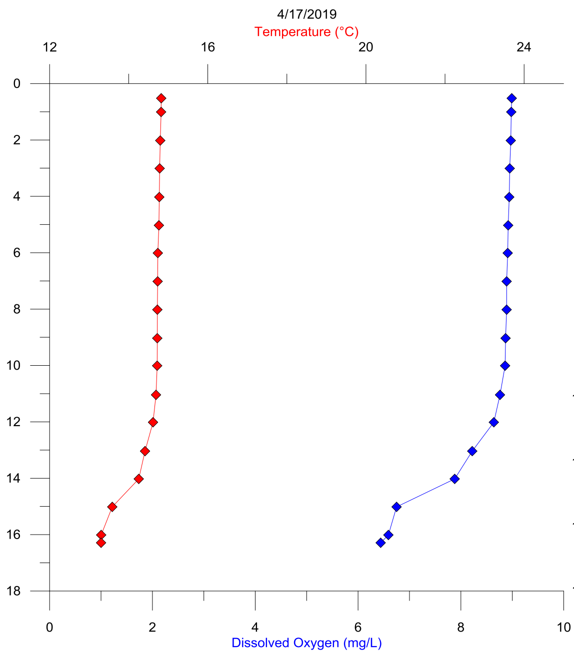
Parameter	Acceptable precision for laboratory replicates	Number of Sample Events Meeting RPD Threshold	Percent of Sample Events Meeting RPD Threshold
Total Kjeldahl Nitrogen	± 20%	10	100%
Nitrate/Nitrite	± 10%	10	100%
Ammonia	± 20%	10	100%
Total Phosphorus	± 10%	9	90%
Ortho-Phosphorus	± 20%	10	100%
Chlorophyll-*a*,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

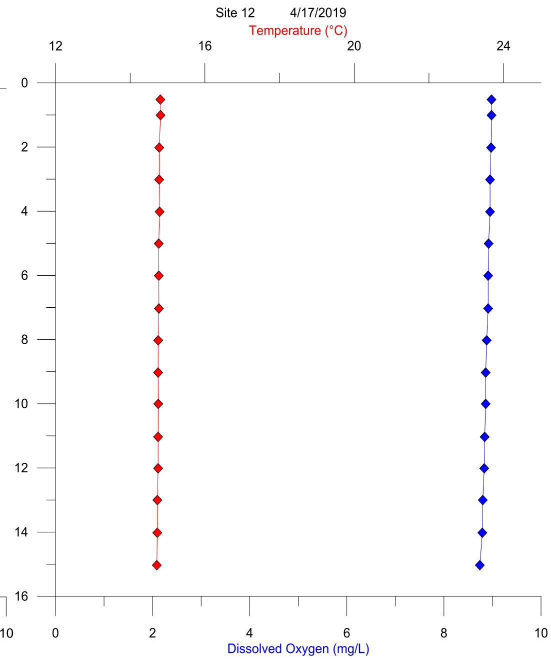
Chlorophyll replicates met precision limits for the majority of the time, but were still higher than other parameters. Chlorophyll is a biological parameter that is extracted under extreme care, however, a high degree of variability in the chlorophyll pigment and other pigments between various algal 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 (Error! Reference source not found.**8**).

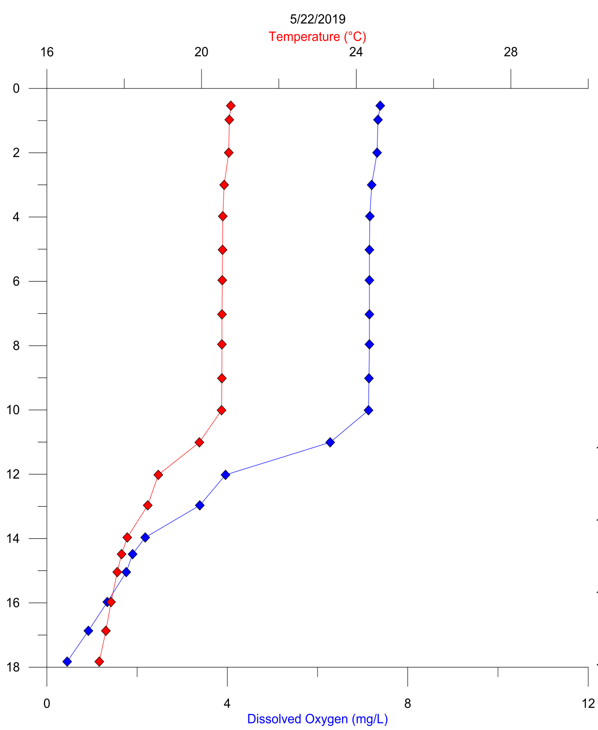
Appendix B

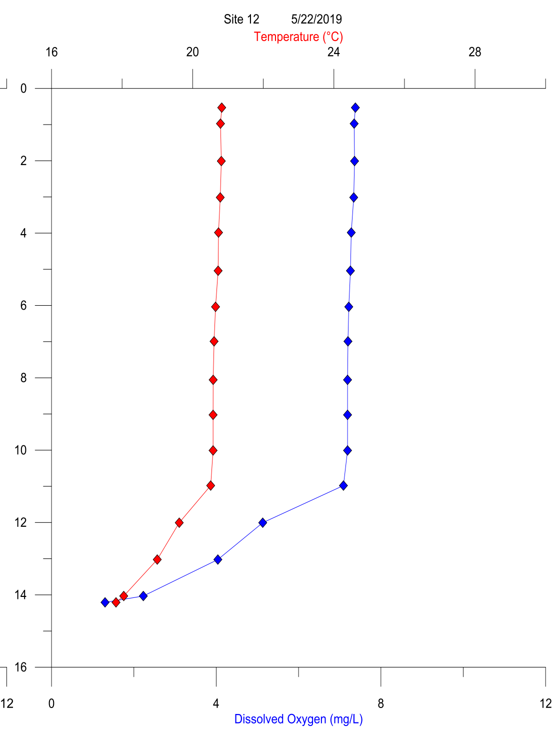
Temperature and Dissolved Oxygen versus Depth at Sites 1 and 12

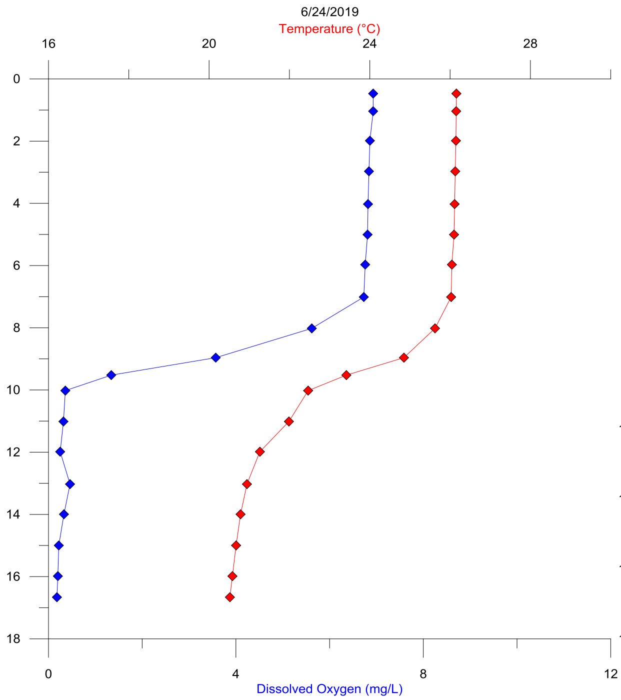
Temperature is denoted as Red Diamond Markers while Dissolved Oxygen is denoted as Blue Diamond Markers







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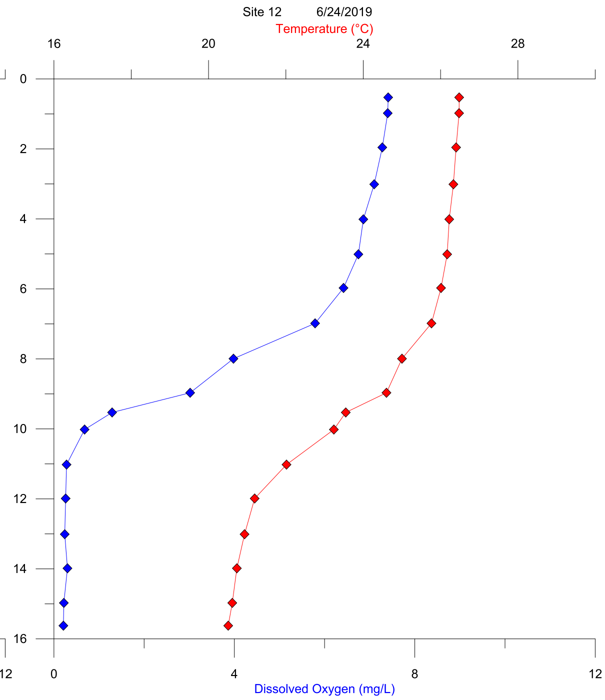
0 4 8 12
Dissolved Oxygen (mg/L)


Site 12 6/24/2019
Temperature (°C)
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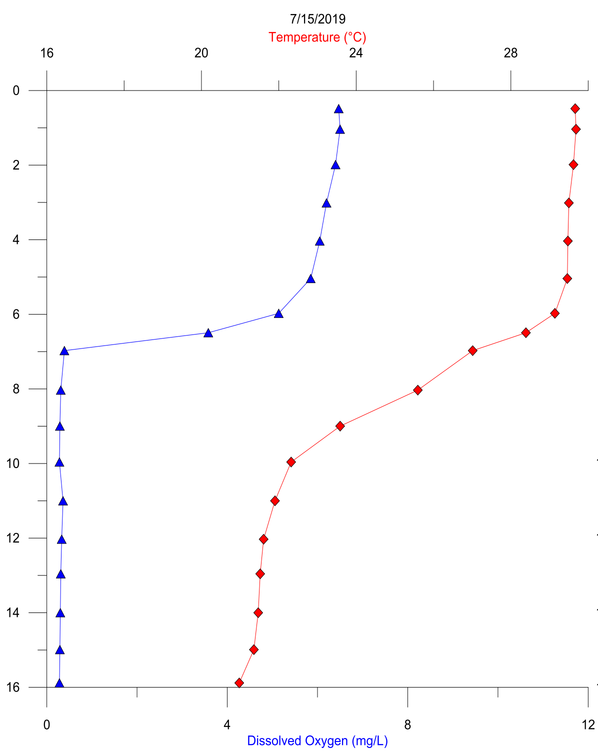
0 2 4 6 8 10 12 14 16
0 4 8 12
Dissolved Oxygen (mg/L)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Temperature (°C)
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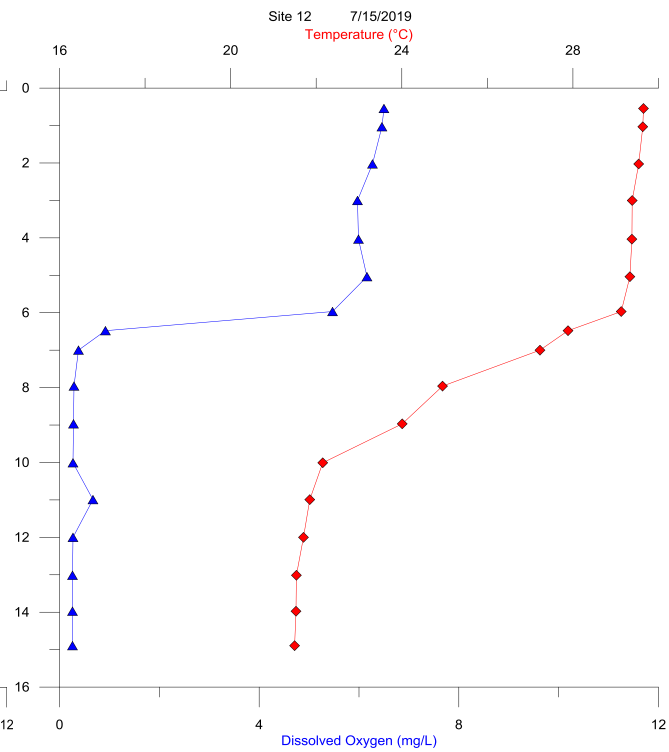
0 4 8 12
Dissolved Oxygen (mg/L)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Temperature (°C)
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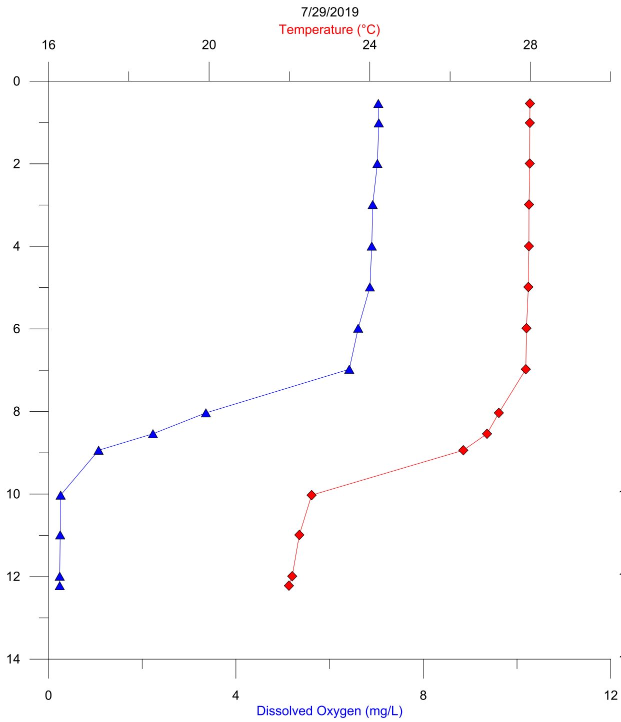
Dissolved Oxygen (mg/L)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Temperature (°C)
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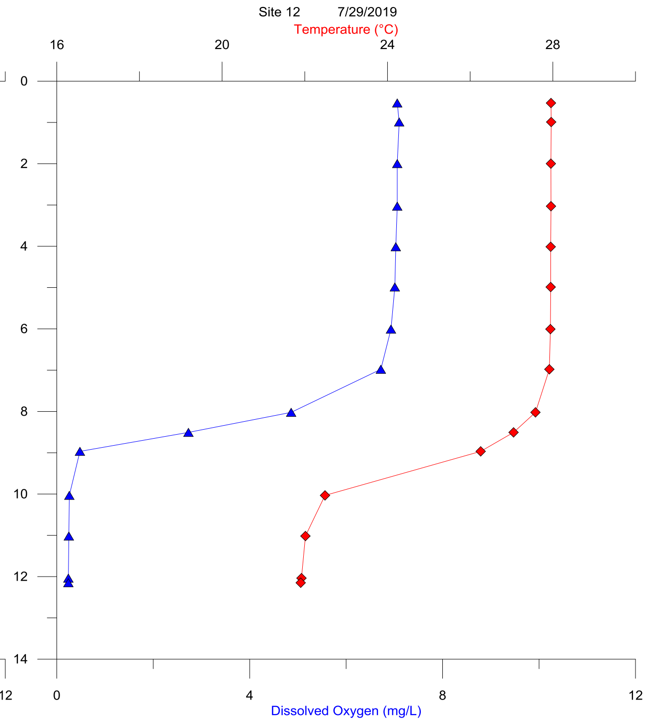
Dissolved Oxygen (mg/L)


Site 12 7/29/2019
Temperature (°C)
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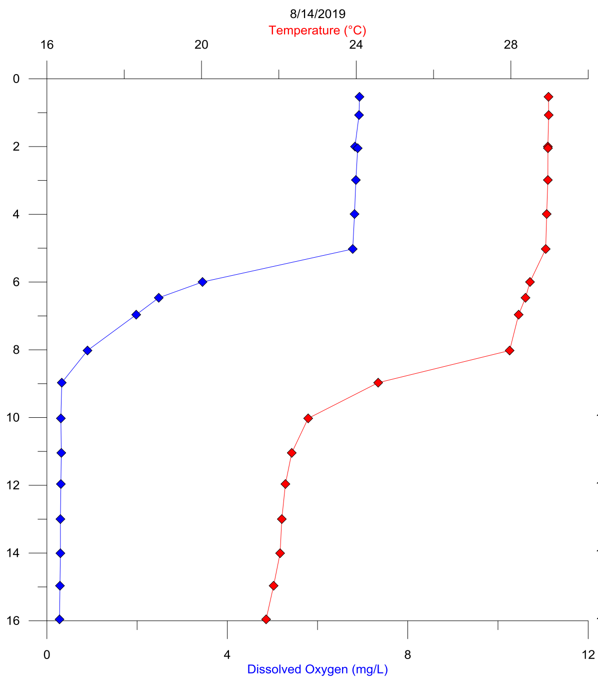
Dissolved Oxygen (mg/L)


8/14/2019
Temperature (°C)
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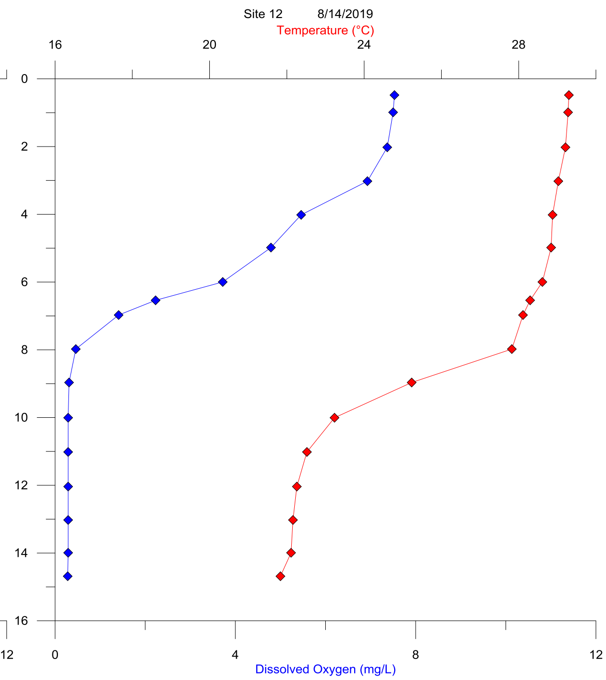
Dissolved Oxygen (mg/L)


Site 12 8/14/2019
Temperature (°C)
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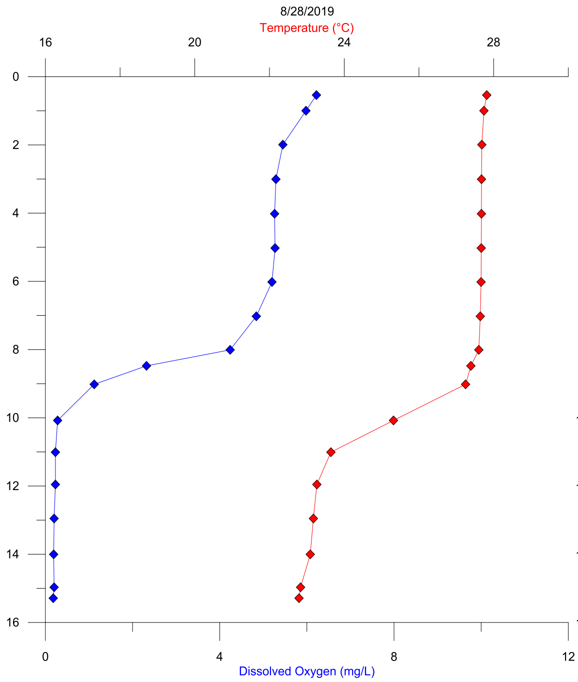
Dissolved Oxygen (mg/L)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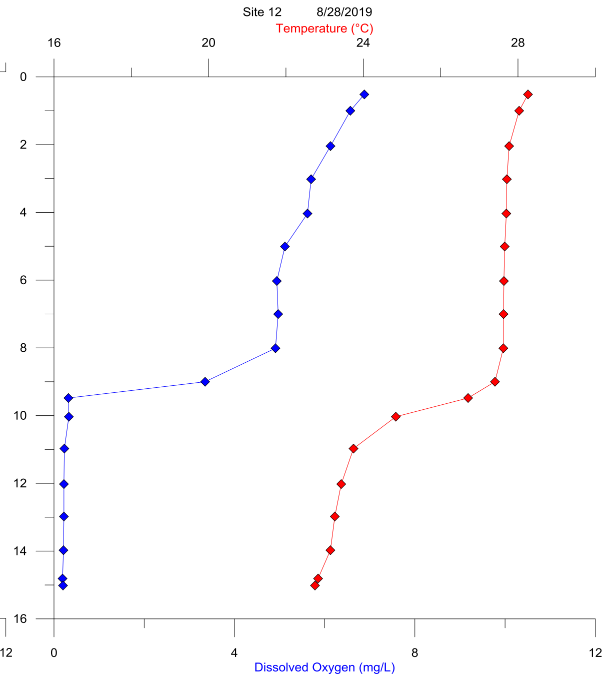
Temperature (°C)
Dissolved Oxygen (mg/L)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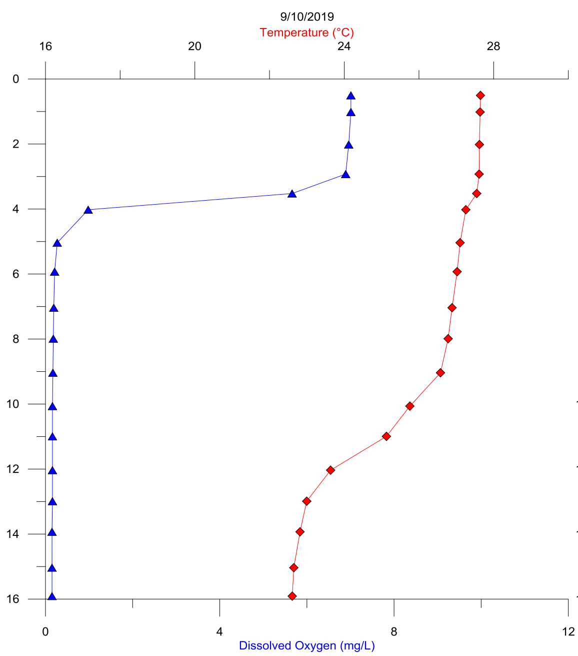
Temperature (°C)
Dissolved Oxygen (mg/L)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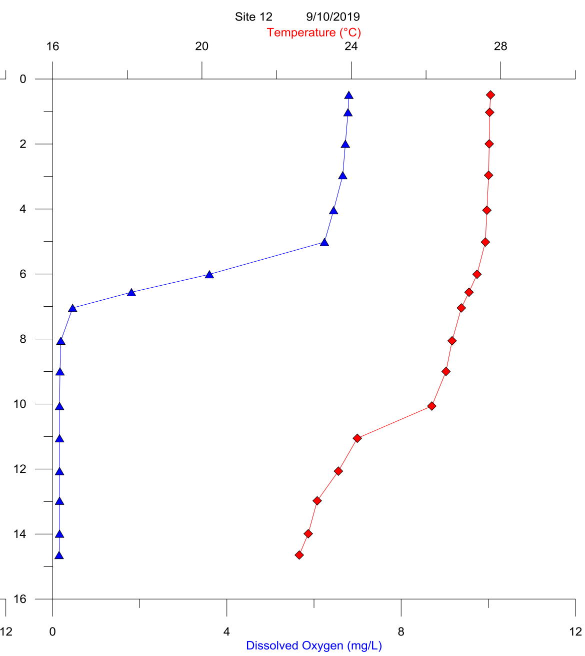
Temperature (°C)
Dissolved Oxygen (mg/L)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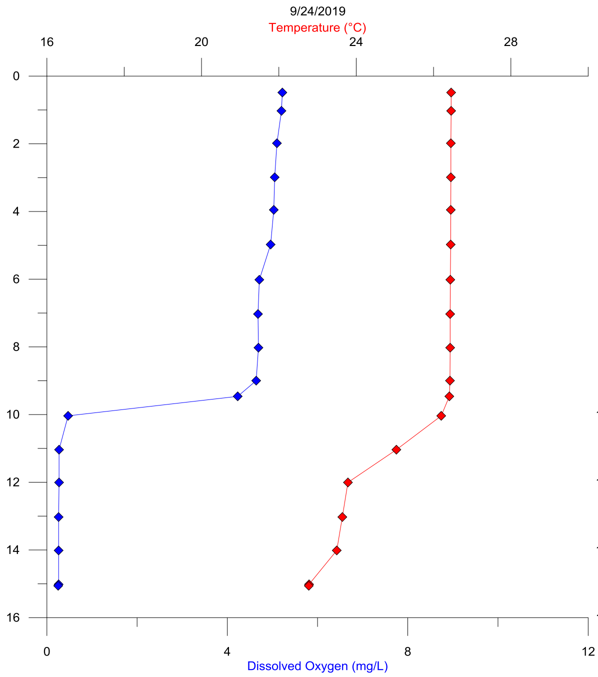
Temperature (°C)
Dissolved Oxygen (mg/L)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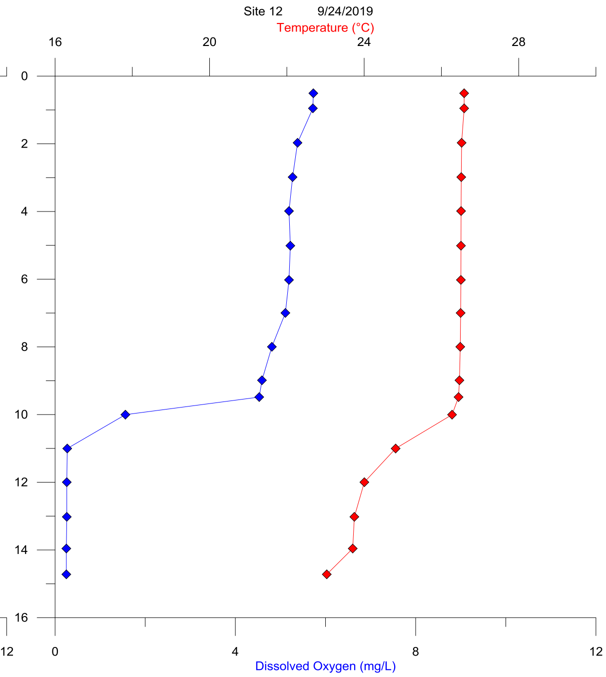
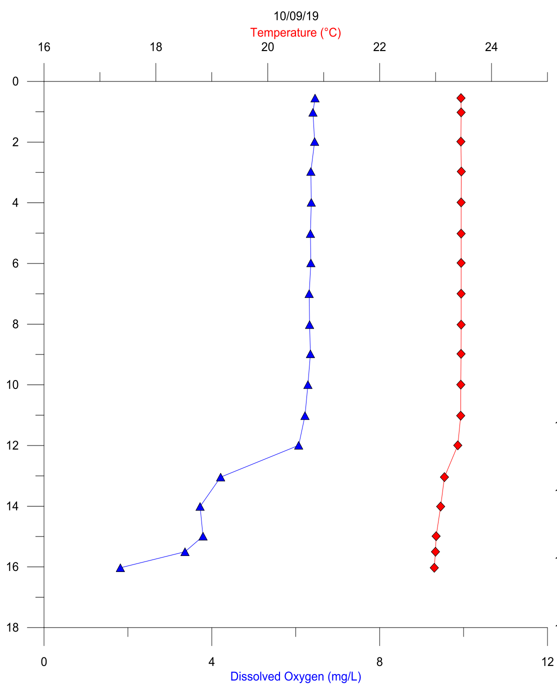
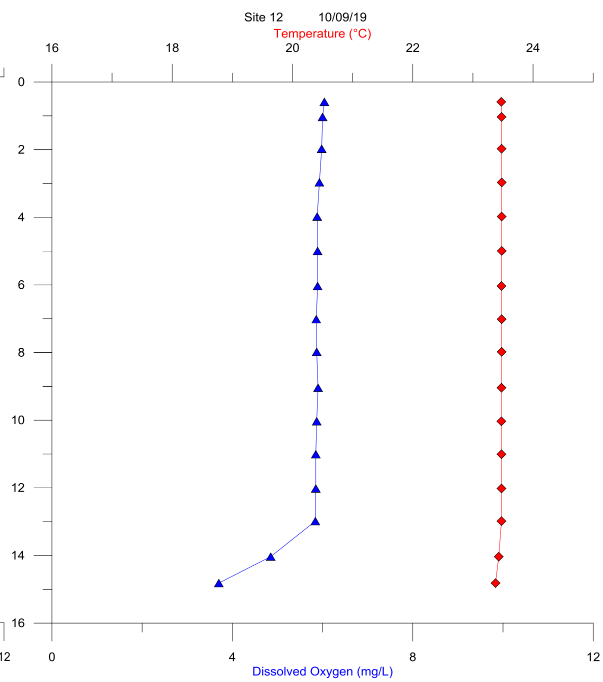
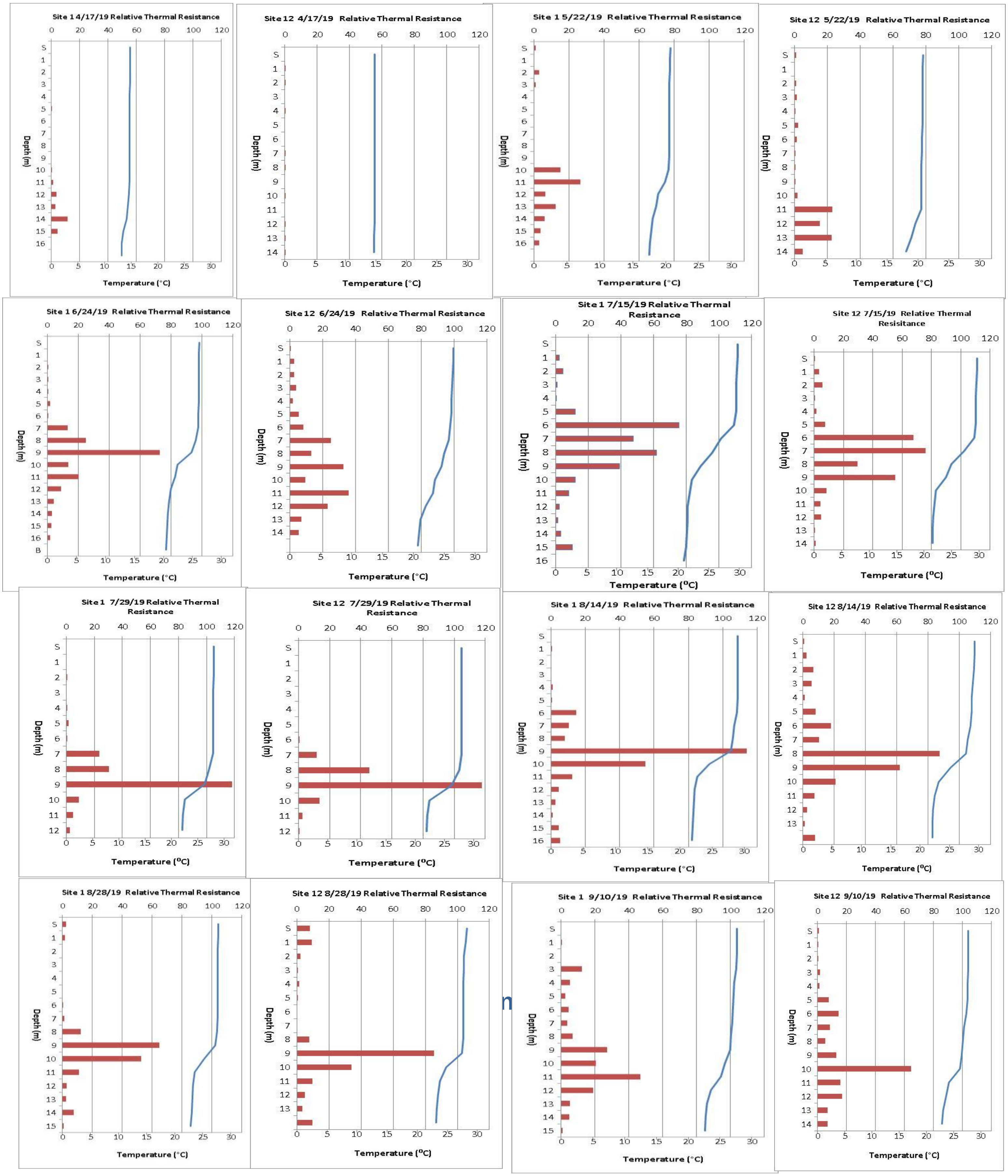
Temperature (°C)
Dissolved Oxygen (mg/L)


Site 12 9/24/2019
Temperature (°C)
Dissolved Oxygen (mg/L)


10/09/19
Temperature (°C)
Dissolved Oxygen (mg/L)


Site 12 10/09/19
Temperature (°C)
Dissolved Oxygen (mg/L)

Appendix C
Relative Thermal Resistance Plots



Appendix D

Internal Nutrient Loading in Lake Thunderbird

Introduction

Internal nutrient loading is an important process in Oklahoma reservoirs that often has a significant impact on the availability of nutrients for algal growth. When overlain by anoxic hypolimnetic waters, lake sediments will release nutrients, resulting in increased concentrations in lake water. Following mixis, these nutrients are then distributed through the water column, providing opportunity for further eutrophication. Internal loading is a natural process that is typically not accounted for in lake management or TMDL scenarios in a quantifiable way. This study aims to comprehend the internal load of nutrients to Lake Thunderbird to better account for nutrient dynamics in the future.

Method

Internal loading is often quantified through an approach referred to as the "core-flux" method. This method involves collecting intact cores in the field and then incubating the cores in the lab while measuring the change in concentration of nutrients in the overlying water. This change in concentration provides the nutrient flux rate.

The intent of this project is to collect nutrient flux data on Lake Thunderbird. The project will use the data to calculate internal nutrient loading for the lake to better understand nutrient availability for algal growth. The OWRB will provide the lead on all data collections activities, analyses, and reporting for the project.

A contractor will be employed to conduct the nutrient flux study; which will be performed during a summer and winter index period at a single location in the lacustrine zone of the lake. Nine core samples will be collected using either a sediment corer or Eckman dredge. Each set of cores will be grouped into three replicates of three different oxygen conditions, one oxic, one anoxic, and one hypoxic. In controlled laboratory conditions, reconstituted lake water will be added to the cores, and at most, eight samples will be collected over a 10 day period at days 1, 2, 3, 4, 5, 8, and 10. Each sample will be analyzed for a nutrient series consisting of total phosphorus, ortho-phosphorus, total Kjeldahl nitrogen, ammonia, and nitrate/nitrite. Additionally, all samples will be analyzed for alkalinity and hardness. Sediment samples will be analyzed for the same nutrient series after incubation period is complete. The budget for this project is presented below. OWRB staff will be responsible for project planning and reporting tasks under existing program funds.

Reporting

OWRB will analyze the internal load data provided by the contractor and deliver a technical addendum to the Annual Water Quality report discussing the findings.

Budget

Internal Loading Study	
TOTAL PROJECT COST	$ 22,000

Appendix E

Lake Thunderbird Hydrographic Survey Scope of Work

Introduction

The U.S. Army Corp of Engineers (USACE) recommends that reservoirs in Oklahoma be bathymetrically mapped every ten years. Lake Thunderbird has not been mapped since 2001, leading to uncertainty in actual lake volume, sedimentation rate, and future lake management. This survey seeks to reduce that uncertainty by collecting hydrographic data of Lake Thunderbird using the most up to date technology and increased bathymetric coverage.

This survey will benefit lake management and future planning in several ways. First, updated equipment, techniques, and increased coverage will result in more precise area/capacity figures and total volume calculations. The increased coverage will specifically aid in areas of interest such as the SDOX and the intake at the dam. Second, resurveying Thunderbird with current equipment and methods will allow for comparison of the updated area/capacity numbers with the previous 2001 survey to calculate a sedimentation rate. In addition, the survey would identify location of sediment accumulation, which would be especially important for Lake Thunderbird, as this lake experiences a considerable amount of shoreline erosion, so the areas of greatest sediment deposit could be pinpointed. The sedimentation rate would also provide estimates of volume lost in the future and be useful for determining life of the lake. Third, LiDAR data is now available which when combined with the updated hydrographic data could be used to calculate water volume into the flood pool, providing an accurate value for a variety of lake level conditions. Fourth, side scan imagery will be used to examine the SDOX to ensure that it is operating at the correct depth and has not silted over which would cause mixing of the sediment water interface. This side scan imagery could also be employed at any other areas of interest.

Method

The process of surveying a reservoir uses a combination of Geographic Positioning System (GPS) and acoustic depth sounding technologies that are incorporated into a hydrographic survey vessel. As the survey vessel travels across the lake's surface, the Echosounder gathers multiple readings every second from the lake bottom. The depth readings are stored on the survey vessel's on-board computer along with the positional data generated from the vessel's GPS receiver. The collected data files are downloaded daily and edited at the office after the survey is completed. During editing, data 'noise' is removed or corrected, and average depths are converted to elevation readings based on the elevation of the lake on the day that data was collected. Geographic Information System (GIS) software is used to process the edited XYZ data collected from the survey. Accurate estimates of area-capacity can then be determined for the lake by building a 3-D TIN surface model of the reservoir from the collected data.

Side scan imagery is used to detect debris items, intake structures, and material textures on the lake bottom. It uses a fan-type pulse to return a series of cross section slices, and when these slices are electronically stitched together, they form highly detailed images of the item of interest. By overlaying these images in ArcGIS or Google Earth, one can identify the items, details about them, and accurate location.

Reporting

A final report detailing methods, QA/QC procedures and updated contour maps will be provided. New area/capacity tables showing cumulative volume and surface area by 1/10 ft elevation increments will be generated and included in the final report. A map showing the approximate locations of survey lines used to collect the positioning and sounding data will also be provided. All data from the survey will be stored for future reference and can be made available upon request.

PROJECT BUDGET ESTIMATE			
Personnel			
	Sub-total =	**$**	**15,969**
Fringe and Indirect Costs			
	Sub-total =	**$**	**25,593**
Supplies and Maintenance			
	Sub-total =	**$**	**2,900**
	TOTAL PROJECT COST =	**$**	**44,462**