Lake Thunderbird Water Quality

2022 Final Report

Submitted to

Central Oklahoma Master Conservancy District

Submitted by

Oklahoma Water Resources Board

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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 but rapidly developing 245 square mile watershed. Construction of the reservoir began in 1962 by the Bureau of Reclamation and Lake Thunderbird began operation in 1965. The lake boasts a large state park with many recreational opportunities including two marinas, multiple campgrounds with recreational vehicle sites, two swim beaches, multi-use trail systems, and a nature center. The lake itself is also a source of recreational activities including a large boating presence, swimming, kayaking, jet skiing, and fishing. 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 for over two decades. In 2022, monitoring was conducted to continue identification of any water quality concerns and assess against water quality standards.

2022 monitoring documented a typical thermal stratification pattern in the lake with the onset of stratification occurring in May and mixing in late October. The hypolimnion experienced anoxic conditions throughout the summer sampling season; the metalimnion also experienced anoxia from July through September. Nutrient concentrations were high throughout the sampling season and reached peak levels in late summer. Hypolimnetically stored nutrients accumulated throughout the monitoring season due to internal release from anoxic sediment and organic material buildup, which is sequestered below a density gradient in this thermally stratified system.

A summary of 2022 results are as follows:

- Chlorophyll *a* values increased to their highest annual average in the previous 10 years.
    - Fails to meet beneficial use for Public and Private Water Supply.
- Taste and odor complaints collected by the City of Norman drinking water facility experienced a slight decrease.
- Phosphorous species seem to maintain at previous year’s levels.
- Nitrogen levels increasing.
- Turbidity
    - Slight impairment in lake-wide average.
    - Fails to meet beneficial use for Fish and Wildlife Propagation based on 10-year average.
- Dissolved Oxygen
    - Fails to meet beneficial use for Fish and Wildlife Propagation.

A modernized comprehensive plan emphasizing both active in-lake and watershed best management practices would help Lake Thunderbird meet water quality standards for turbidity, dissolved oxygen, and chlorophyll *a* and meet TMDL targets. Continued exploration of a holistic approach improving water quality in Lake Thunderbird including both in-lake and watershed mitigation of water quality pollutants are critical to the success of improving water quality at Lake Thunderbird.

Introduction

Lake Thunderbird is a multi-purpose reservoir in the Cross Timbers Ecoregion of south-central Oklahoma in Cleveland County and has extensive history with water quality issues, documented in the long-term dataset from 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 exceedance of chlorophyll *a* criterion, and the Fish and Wildlife Propagation beneficial use due to low dissolved oxygen conditions and increased turbidity (ODEQ, 2022). Lake Thunderbird is also designated as a Sensitive Water Supply (SWS) and is subject to stringent Oklahoma Water Quality Standards (OWQS) for chlorophyll *a* of 10 µg/L. In response to these long-term water quality impairments, OWRB has provided water quality based environmental services for COMCD since 2000 and continues to conduct water quality monitoring at the lake and provide analysis on lake condition. This report presents data and analysis from the 2022 sample year.

In 2010, the COMCD gained funding to implement an in-lake mitigation infrastructure to address various aspects of impairment. A supersaturated dissolved oxygenation (SDOX) system was selected and began adding oxygen to the deepest portion of the lake's anoxic hypolimnion near the dam while maintaining thermal stratification. This added oxygen was thought to limit the transfer of nutrients from the hypolimnion to surface waters and decrease the internal load of phosphorus, among other ancillary benefits. After years of operation, the system failed catastrophically in June of 2020 and is no longer operational. As such, assessment of the SDOX system is not included in this report. For additional information on the SDOX system, please refer to previous Thunderbird Water Quality Reports at www.owrb.ok.gov/reports and click on "Lake Restoration."

Sampling Regime

Water quality sampling for 2022 occurred between April 26 and October 26. Monitoring was conducted for the parameters in **Table 1** at sites indicated in **Figure 1.**

Table 2. 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 are represented to allow for whole lake analysis, beneficial use assessment, and comparison between riverine and lacustrine zones.

Table 1. 2022 water quality sampling parameters.

General Water Quality		
Chlorophyll *a* (µg/L)	Nephelometric Turbidity (NTU)	Secchi Disk Depth (cm)
Nutrients		
Total Kjeldahl Nitrogen (TKN)	Dissolved Orthophosphate (ortho-p)	Total Phosphorus (TP)
Nitrate as Nitrogen (NO_3)	Nitrite as Nitrogen (NO_2)	Ammonia as Nitrogen (NH_3)
Total Nitrogen (TN)	Total Organic Carbon (TOC)	
Profile Parameters		
Dissolved Oxygen Concentration (mg/L)	Dissolved Oxygen Percent Saturation	Water Temperature (°C)
Specific Conductance (µS/cm)	Oxidation Reduction Potential (ORP)	pH
Environmental Observations		
Air Temperature (°C)	Wind (Direction/Speed)	Cloud Cover
Precipitation	Wave Classification	Barometric Pressure
Site Depth (m)	Surface Specific Conductance (µS/cm)	Sample Collection Time

Table 2. 2022 Lake Thunderbird sample dates. Only profiles recorded on 11/9/2022 to bookend stratification.

Sample Date	Site 1 Final Depth (m)	Lake Elevation (1039.00 ft)
4/26/2022	16.4	1039.04
5/18/2022	16.3	1039.53
6/15/2022	16.8	1040.31
7/13/2022	16.3	1038.91
7/27/2022	16.2	1038.41
8/10/2022	16.0	1038.00
8/24/2022	15.8	1037.58
9/7/2022	15.8	1037.64
9/21/2022	15.9	1037.22
10/5/2022	15.7	1036.77
10/26/2022	15.2	1036.51
11/9/2022	14.7	1036.43

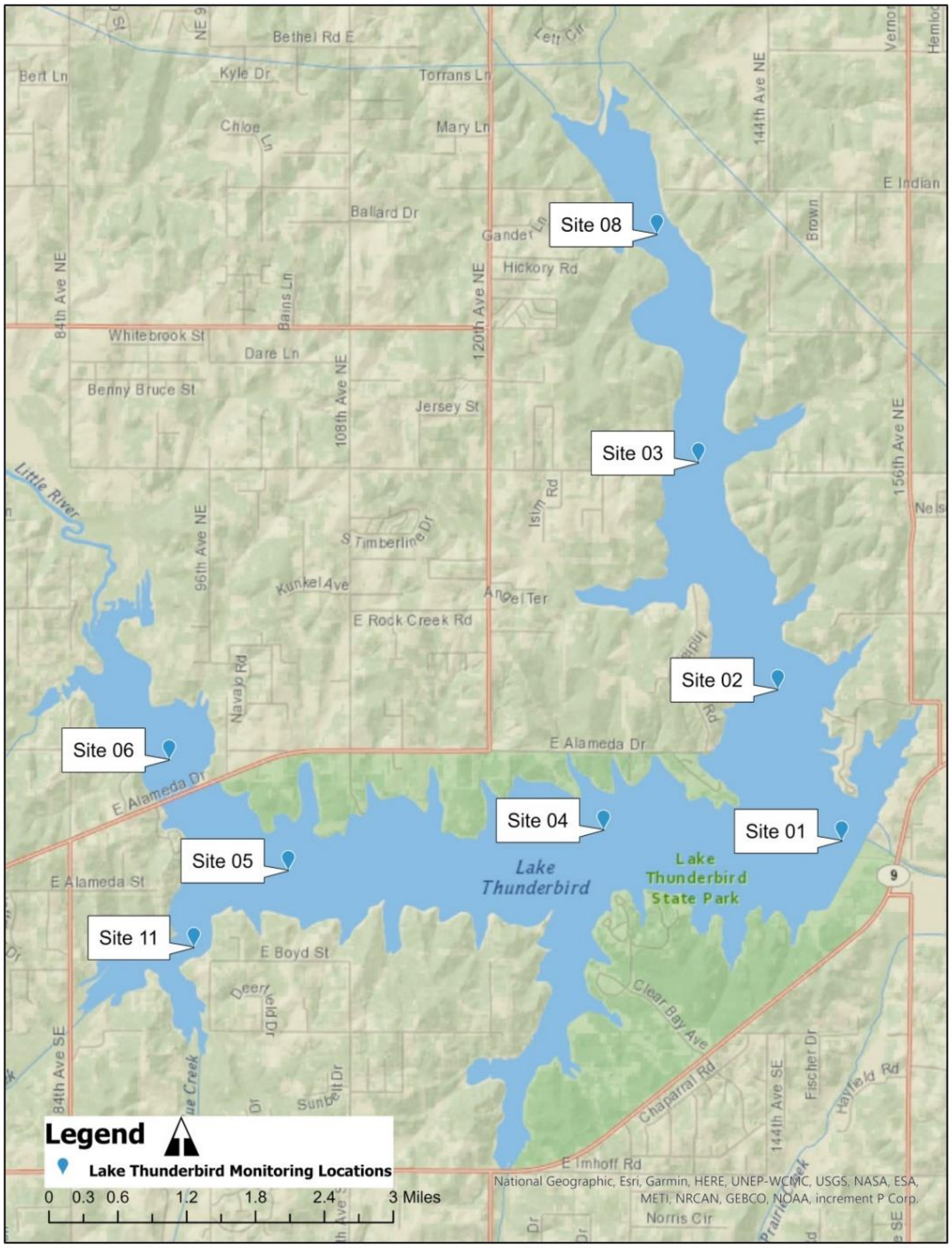


Figure 1. 2022 Lake Thunderbird sampling sites. The lacustrine zone is comprised of Sites 1, 2, and 4. Riverine zones are represented at Sites 6, 8, and 11. Sites 3 and 5 represent the transitional zone from riverine to lacustrine.

Data for water quality indicators were collected following OWRB's standard operating procedures (SOPs) for water quality samples (OWRB, 2019). Variables such as pH, Dissolved Oxygen (DO), water temperature Specific Conductance (SpC), and Oxidation-Reduction Potential (ORP) were monitored in situ using a YSI® multi-parameter sonde. In accordance with manufacturer's specifications and published SOPs, all parameters were calibrated weekly and verified daily with appropriate standards. Measurements were recorded at each sampling station on the lake in the form of a vertical profile. Readings began 0.5 m below the surface of the water and continued in whole-meter intervals (1.0 m, 2.0 m, 3.0 m etc.) to 0.2 m above lake bottom. During periods with anoxic conditions (DO < 2.0

mg/L), an additional reading was taken 0.5 m above the first depth with measured anoxia to narrow down the point of transition.

Water quality samples were collected using a depth-integrated sampler (DIS) and churn splitter. A DIS is designed to collect a representative sample of the water column to a targeted depth, which is calculated by first measuring the Secchi disc depth (cm) at each site. The Secchi disc depth is doubled to represent the photic, or light penetrating zone of the water column and is the targeted sample depth. For instance, if a Secchi disc depth is 80 cm, the targeted depth for collecting a DIS is 160cm. The DIS is marked every 10cm from 50cm to 200cm. If the doubled Secchi disc depth is less than 50cm, a surface water grab is collected 0.5m below surface. More information on DIS procedures can be found in OWRB's Standard Operating Procedure for the Collection of Water Quality Samples in Lakes (2019).

Other field observations such as Secchi disk depth, surface chlorophyll *a*, and turbidity samples were collected at all sites. Nutrient samples were also collected at all sample locations. Additional sampling occurred at Site 1, including surface Total Organic Carbon (TOC) and at-depth nutrient samples collected with a Van Dorn sampler at 4.0m, 8.0m, 12.0m, and 0.2m above the bottom sediment-water interface. Information on Van Dorn sampling can be found in the SOP listed above. Sediment cores were also collected pre, during, and post stratification to estimate phosphorous release. Environmental conditions were also recorded for each site and can be found in **Table 1** above. Specific nutrients collected can be found in **Table 1**.

Watershed

Lakes do not exist in isolation but 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 is often a reservoir. **Figure 2** presents Lake Thunderbird's modified Hydrologic Unit Code 8 (HUC 8) watershed, encompassing 245 square miles in the Cross Timbers Ecoregion of central Oklahoma. Lake Stanley Draper lies within the same HUC 8 watershed, but the hydrologic connection between the two lakes is negligible as Lake Stanley Draper is highly managed for Oklahoma City's water supply and does not release downstream. As such, the immediate watershed draining into Lake Stanley Draper has been removed from watershed calculations.

In 2015, the Bureau of Reclamation (BOR) conducted a bathymetric survey of the reservoir and calculated the top of the conservation pool at 1039.0 feet above sea level (BOR, 2020). At this elevation, the lake surface area extends to 5,505 acres with a volumetric capacity of 103,840 acre-feet (BOR, 2020). The BOR concluded that total capacity of the lake has declined by 12% since construction in 1965, with an average 50-year annual sedimentation rate of approximately 470 acre-feet per year (BOR, 2020).

Lake Thunderbird is a Bureau of Reclamation multi-use reservoir. Major tributaries to the lake are the Little River to the west, Dave Blue Creek to the southwest, and Hog Creek to the north. The Little River serves as the longest flow path through the watershed, starting in the northwestern portion of the watershed and draining substantial amounts of the City of Moore before entering Lake Thunderbird near Site 6 (U.S. Geological Survey, 2022). Water is released below the dam into the Little River, which has a confluence with the Canadian River roughly 137 km downstream.

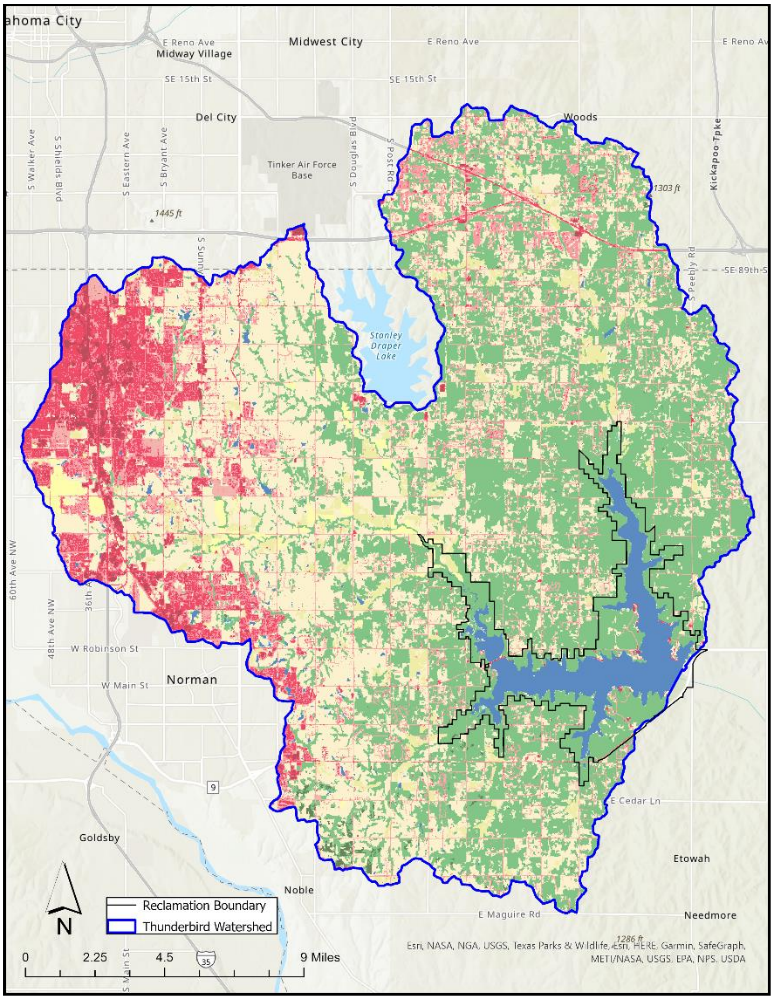


Figure 2. Updated 2019 National Land Cover Data for Lake Thunderbird's watershed.

Land uses in the watershed are important for determining potential sources of nutrients, sediment, or other forms of pollution. During 2021, new National Land Cover Data (NLCD) was released from the Multi-Resolution Land Characteristics Consortium corresponding to remotely sensed data collected in 2019. **Table 3** presents updated land use changes in the Lake Thunderbird watershed between 2016 and 2019. Bolded changes indicate increases in coverage while negative values correspond to losses. Grasslands and deciduous forest make up nearly 70% of land use and are the dominant categories. However, developed land has increased to 21.65% (vs 17.7% in 2016) as development continues in the northwest portion of the watershed. This nearly four percent change in three years highlights continuing development in the watershed and underscores the need for best management practices (BMPs) and opportunities for low impact development (LID) that would support greater long-term watershed health.

Table 3. 2019 NLCD acreage totals for the Lake Thunderbird watershed. MRLC, 2021.

Category	Acres	Watershed % 2016	Watershed % 2019	Percent Change
Open Water	6,165	5.08%	3.93%	-1.15%
Developed Open Space	11,885	7.58%	7.57%	-0.01%
Developed Low Intensity	8,964	5.58%	5.71%	**0.13%**
Developed Medium Intensity	9,544	3.70%	6.08%	**2.38%**
Developed High Intensity	2,007	0.84%	1.28%	**0.44%**
Barren Land	26	0.14%	0.02%	-0.12%
Deciduous Forest	58,947	37.45%	37.56%	**0.11%**
Evergreen Forest	398	0.20%	0.25%	**0.05%**
Mixed Forest	151	0.10%	0.10%	**-**
Shrub or Scrub	2,751	1.73%	1.75%	**0.02%**
Grassland or Herbaceous	49,635	33.58%	31.63%	-1.95%
Pasture or Hay	4,803	2.99%	3.06%	**0.07%**
Cultivated Crops	1,511	0.93%	0.96%	**0.03%**
Woody Wetlands	24	0.00%	0.02%	**0.02%**
Emergent Herbaceous Wetlands	111	0.01%	0.07%	**0.06%**
Total Watershed	156,922	100%	100%	-

Climate

Knowledge of potential climatological influences is critical 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, stormwater 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 2022. Annual precipitation at Lake Thunderbird dam in 2022 totaled 27.47 inches, as reported by the United States Army Corps of Engineers (USACE) (USACE, 2022), substantially less than the lake's long-term average of 38 inches (U.S. Geological Survey, 2022). Rainfall events correspond to increases in lake elevation.

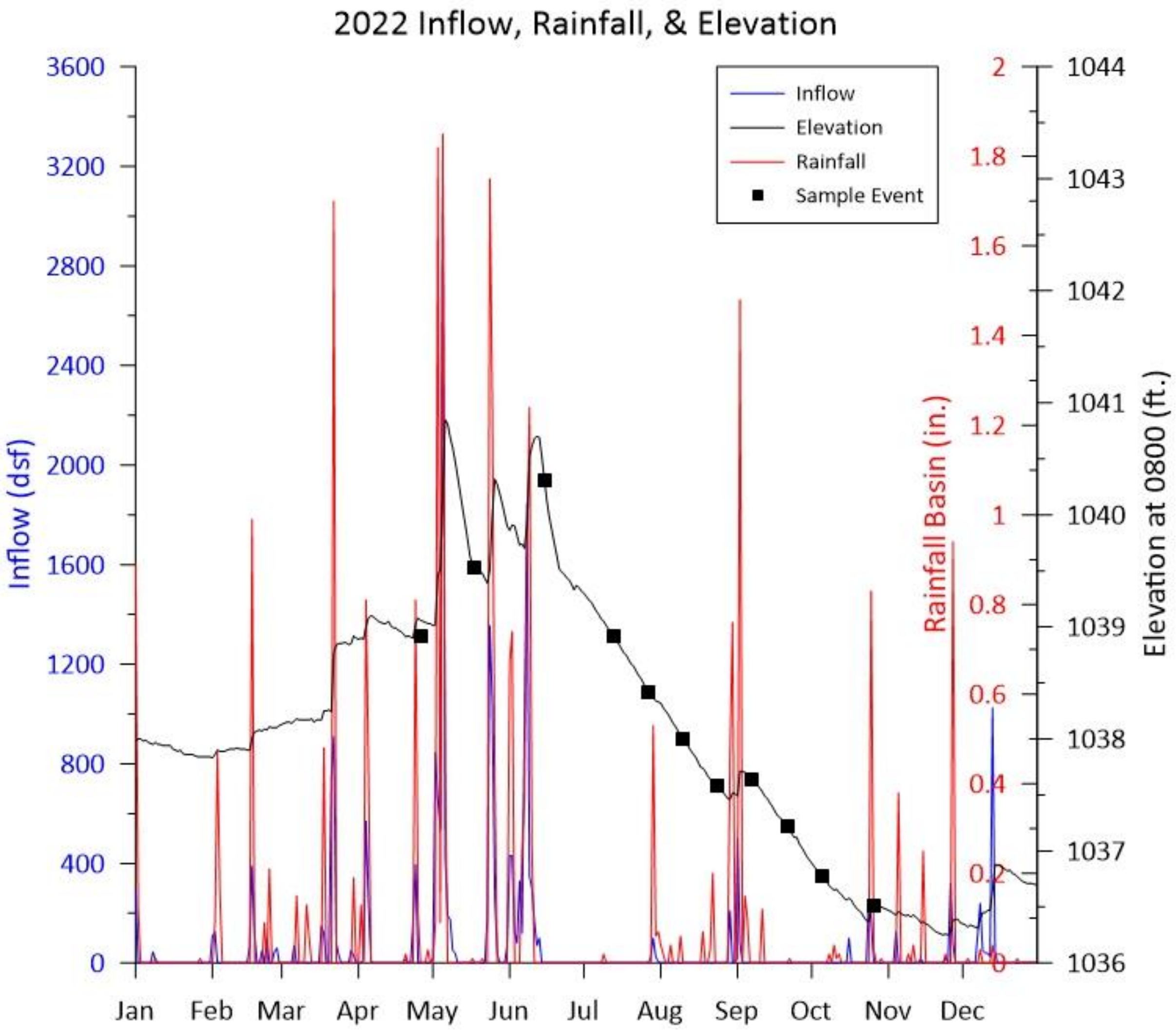


Figure 3. 2022 Inflow, Rainfall, and Elevation Data for Lake Thunderbird, with Sample Dates Indicated. Inflow as dsf (daily-second-foot) indicates daily volume passing through a single location.

In addition to hydrology, air temperature can influence lake characteristics such as thermal stratification and nutrient availability, which subsequently influences primary productivity, which serves as proxy for algal growth or biomass.

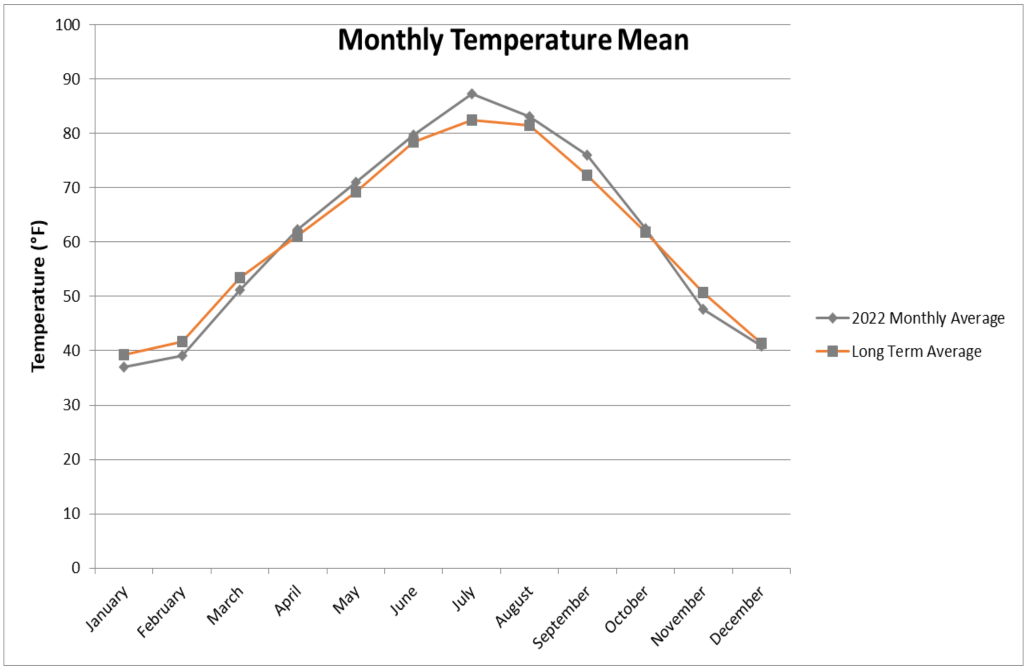


Figure 4 compares monthly mean temperatures in 2022 to the long-term monthly mean using 2002-2022 data from the Oklahoma Mesonet's Norman station, which is approximately 27 kilometers west of Site 1 at Max Westheimer Airport (Mesonet, 2022). 2022 was a typical year for temperature. The months January through April started off slightly below the 20-year average, while average temperatures in May through October exceeded their monthly averages. Peak Mesonet-recorded air temperature occurred in late July at 110.2°F, while peak water temperature during a sampling event (Site 1) occurred in mid-July.

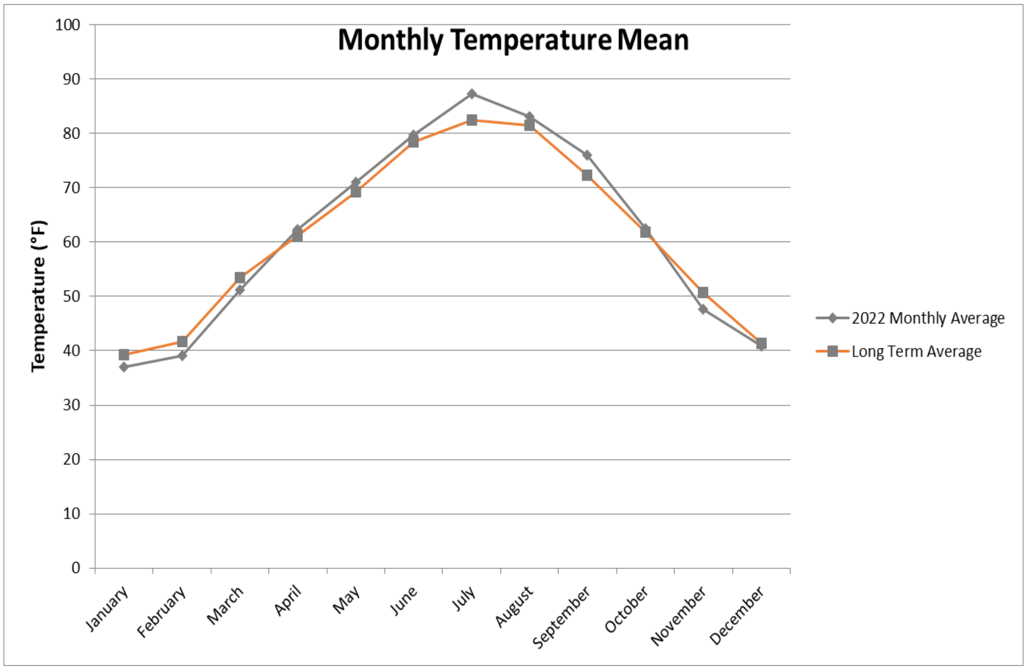


Figure 4. 2022 and Long-Term Average Monthly Temperature as recorded at the Norman Mesonet Station. (Mesonet, 2022)

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. 1.

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

Where **V** is lake volume (acre-feet),

t is time (month),

$\boldsymbol{A_s}$ is lake surface area (acres),

$\boldsymbol{Q_{in}}$ and $\boldsymbol{Q_{out}}$ are net flows into and out of the lake due to tributary inflows and gated releases,

$\boldsymbol{P}$ is the rainfall directly on the lake (feet),

$\boldsymbol{E_v}$ is the lake evaporation (feet),

$\boldsymbol{W_s}$ is the water exported for water supply use (acre-feet)

In layperson terms, 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 subsurface outputs and water released downstream or exported as water supply. For Lake Thunderbird, subsurface and groundwater flow is assumed insignificant, based on the relatively impermeable lake substrate.

Because the USACE reported inflow term includes direct rainfall, their reported inflow minus calculated direct rainfall volume was used as the runoff term for the budget. Precipitation was calculated from the direct rainfall measurement data provided by the USACE. The precipitation contribution to the total inflows is derived by multiplying the daily rainfall amounts by the surface area of the lake on each date, as shown by:

Eq. 2. $$Q_p = P * A_s$$

Where Q_p is precipitation,

P is rainfall amount,

and 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. 3. $$Q_e = E_v * A_s$$

Where Q_e is evaporation,

E_v is the evaporation rate,

and 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. To estimate reservoir volume more accurately, the 2021 water budget used results generated by BOR's 2015 bathymetric survey elevation-capacity tables (BOR, 2020).

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 4**). 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. Examining the 2022 water budget reveals the lake received most inputs and released the largest volumes in May and June. The remainder of the year followed similar patterns to previous years, with a late input spike in December. **Figure 5** provides a visual summary of water gains and losses. Water releases only occurred in May and June and water supply was the sole withdraw from July through the end of the year while evaporation accounted for the greatest loss from the lake.

Table 4. 2022 Lake Thunderbird Water Budget Calculations expressed in acre-feet. Parentheses indicate a negative value and were taken from USACE, 2022.

Month	INPUTS			OUTPUTS				ERROR TERM		
	Inflow (ac-ft)	Rainfall (ac-ft)	Total Inputs	Evaporation (ac-ft)	Water Supply (ac-ft)	Releases (ac-ft)	Total Outputs	I-O	ΔV	Error
Jan	265	428.60	694	1,604	1,129	-	2,733	(2,039)	(1,057)	982
Feb	1,210	902.02	2,112	1,797	1,009	-	2,806	(694)	1,589	(895)
Mar	3,179	1,164.12	4,343	2,952	1,291	-	4,243	99	4,326	(4,227)
Apr	1,695	1,101.18	2,796	3,845	1,171	-	5,016	(2,220)	549	1,671
May	15,297	2,807.42	18,105	4,235	1,576	11,107	16,918	1,187	5,019	(3,832)
Jun	8,795	1,715.30	10,510	5,055	1,654	10,078	16,787	(6,277)	(3,359)	2,918
Jul	231	76.29	307	6,068	1,768	-	7,836	(7,528)	(5,465)	2,063
Aug	(77)	513.04	436	4,350	1,866	-	6,216	(5,780)	(4,229)	1,551
Sep	119	1,030.97	1,150	3,761	1,906	-	5,667	(4,517)	(3,081)	1,436
Oct	34	1,017.41	1,051	2,544	1,619	-	4,163	(3,112)	(2,005)	1,107
Nov	411	709.64	1,120	1,073	1,330	-	2,403	(1,283)	(495)	788
Dec	2,277	866.14	3,143	1,166	1,329	-	2,495	648	1,985	(1,337)
Total	**33,436**	**12,332**	**45,768**	**38,450**	**17,648**	**21,185**	**77,284**	**(31,516)**	**(6,223)**	**2,224**

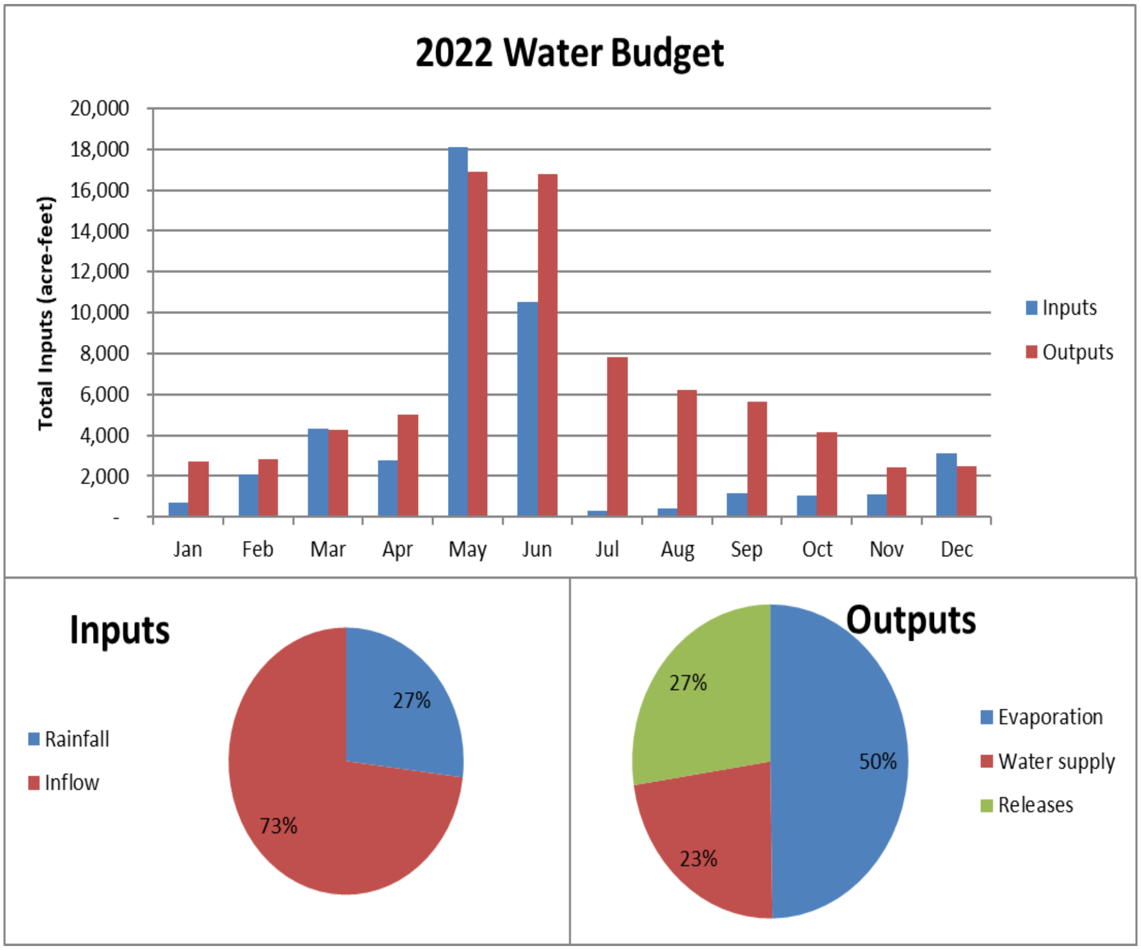


Figure 5. 2022 Lake Thunderbird Water Input and Output sources by month, expressed as the percent of total.

Once a hydrologic budget is constructed, hydrologic retention time can be estimated. Tau (T) represents hydrologic retention time and is the ratio of lake capacity at normal elevation to the annual exiting flow. This represents the theoretical time it takes a given molecule of water to flow through the reservoir. Lake Thunderbird had a T value of 2.67 years in 2022, which is lower than the average T (1995 to 2022) of 3.35 years and could be attributed to the largest volume of gated release since 2019 and partially flushing the system.

Total monthly error is the difference between the change in elevation-based lake volume and change in lake volume based on inputs-outputs. Using 2015 BOR survey data, the 2022 cumulative annual error is 2,224 acre-feet, averaging to a monthly error of 185.37 acre-feet. While seemingly negligible compared to the reservoir's overall volume, this demonstrates an increase in accuracy by reducing the number of unknowns.

According to the bathymetric survey completed by BOR in 2015, the average sedimentation rate below the spillway crest is approximately 428 acre-feet per year since impoundment in 1965 (BOR, 2020). This amount equates to roughly 11% of lost storage as originally designed. The potential distribution of deposited sediment is considered high and has consequences for in-lake processes such as sediment suspension and nutrient flux (BOR, 2006).

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

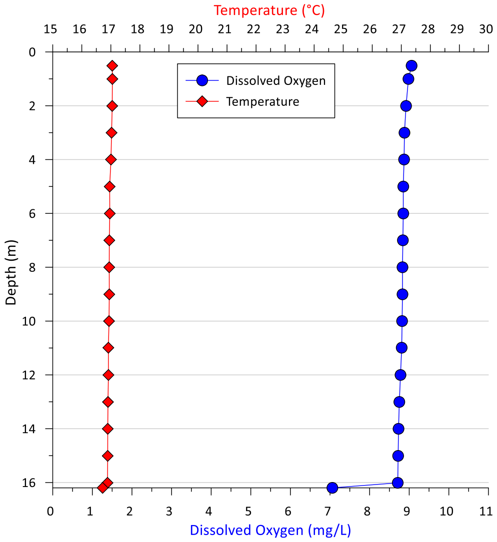
Thermal Stratification, Temperature, and Dissolved Oxygen

Warming of the lake surface throughout spring marks the outset of thermal stratification, which occurs when an upper, less dense layer of water known as the epilimnion forms over a cooler, denser layer of water called the hypolimnion. The area between the epilimnion and hypolimnion is the region with the greatest temperature and density gradient and is known as the metalimnion (**Figure 6**). Additional examples of temperature and DO profiles from Site 1 are available in

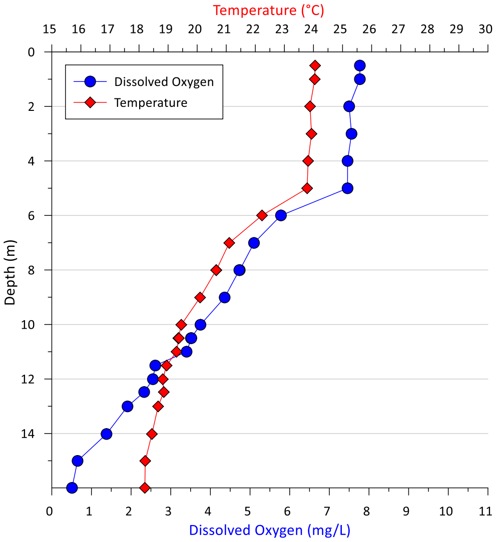
Appendix B

Temperature and Dissolved Oxygen Profiles

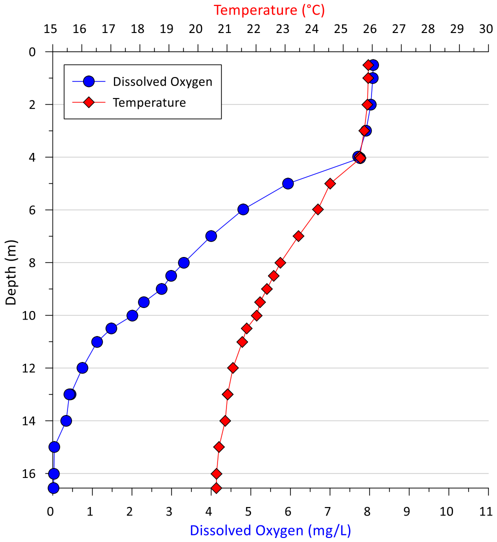
Site 1 - April, 26 2022



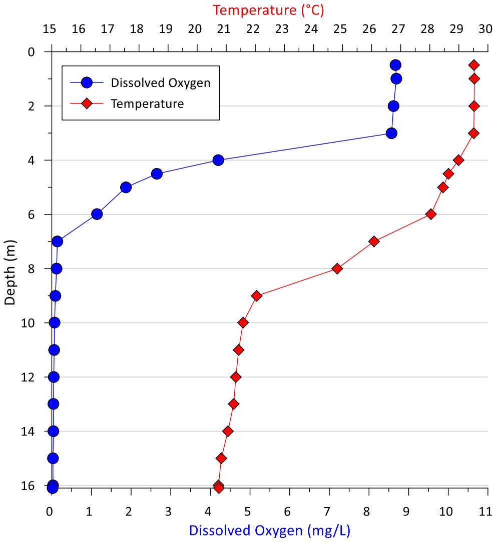
Site 1 - May 18, 2022



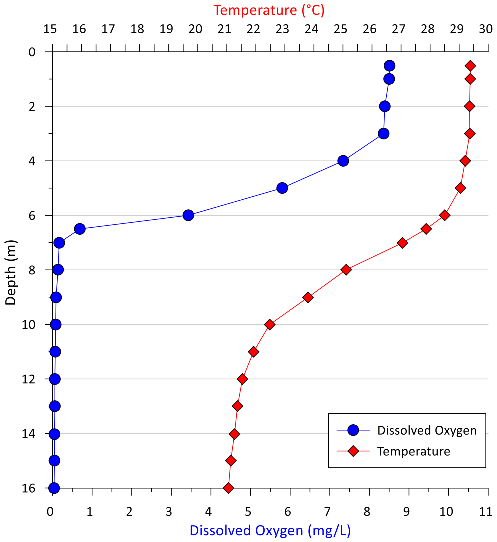
Site 1 - June 15, 2022



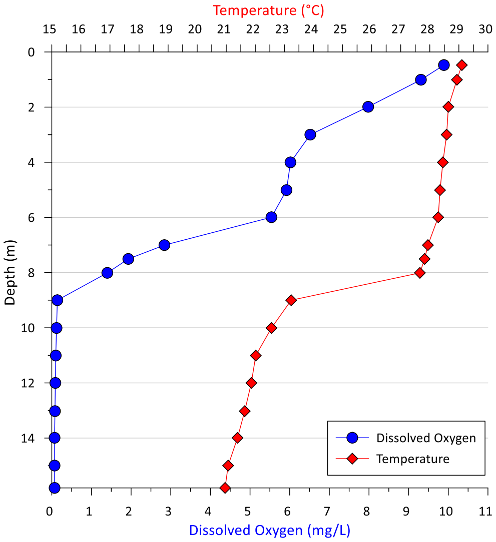
Site 1 - July 13, 2022



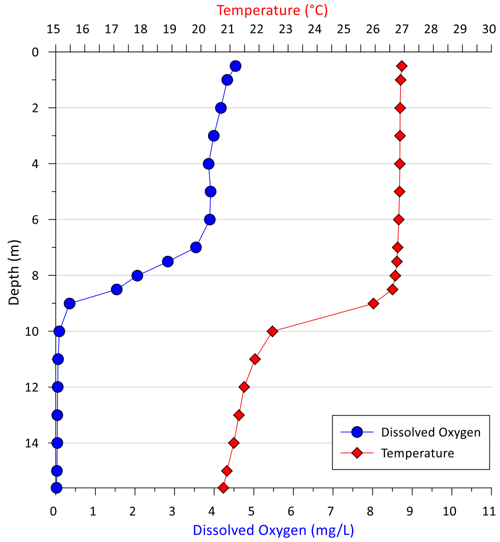
Site 1 - July 27, 2022



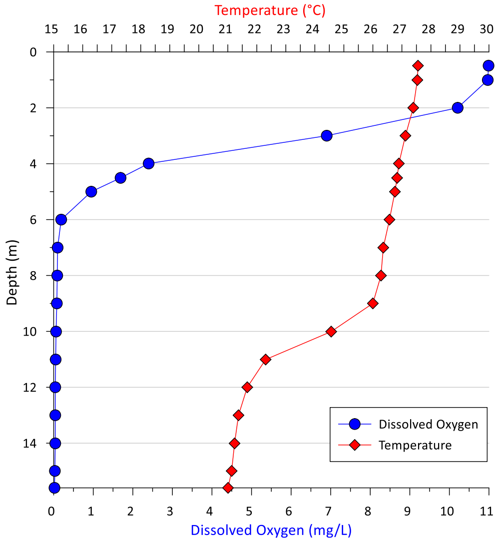
Site 1 - August 10, 2022



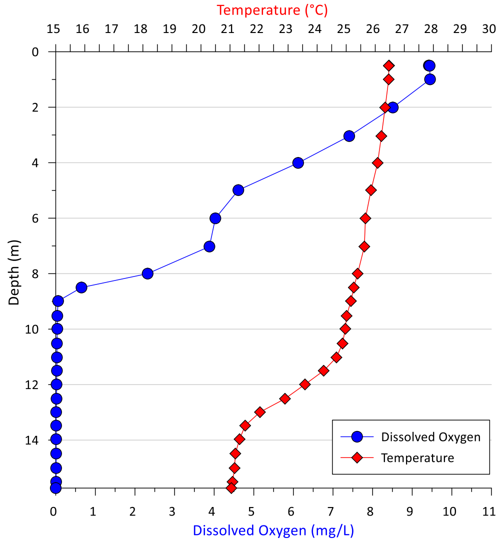
Site 1 - August 24, 2022



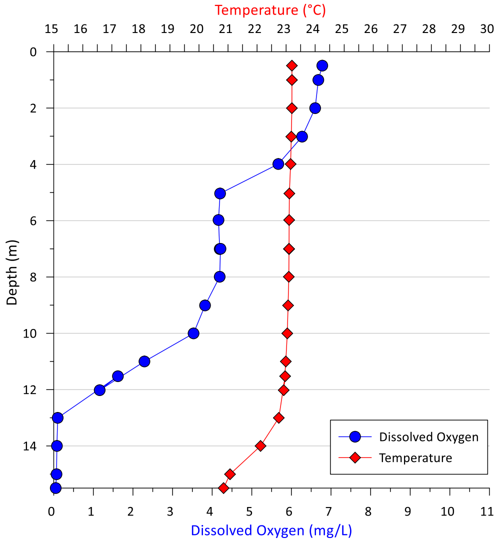
Site 1 - September 7, 2022



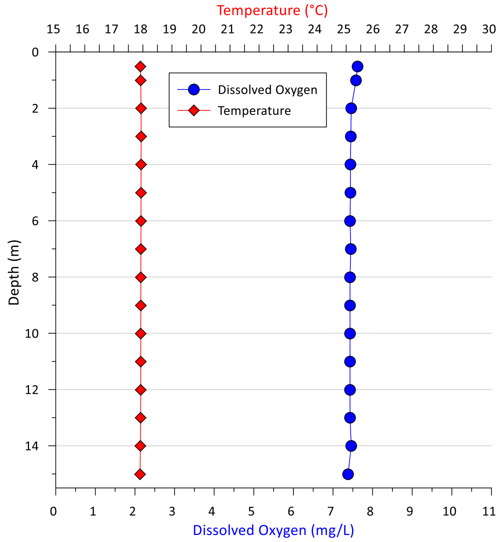
Site 1 - September 21, 2022



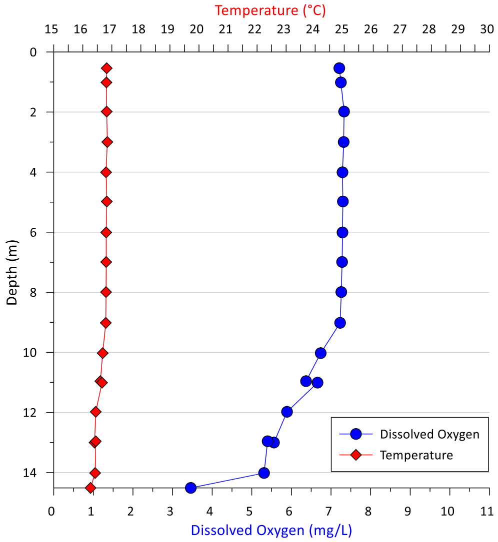
Site 1 - October 5, 2022



Site 1 - October 26, 2022



Site 1 - November 9, 2022



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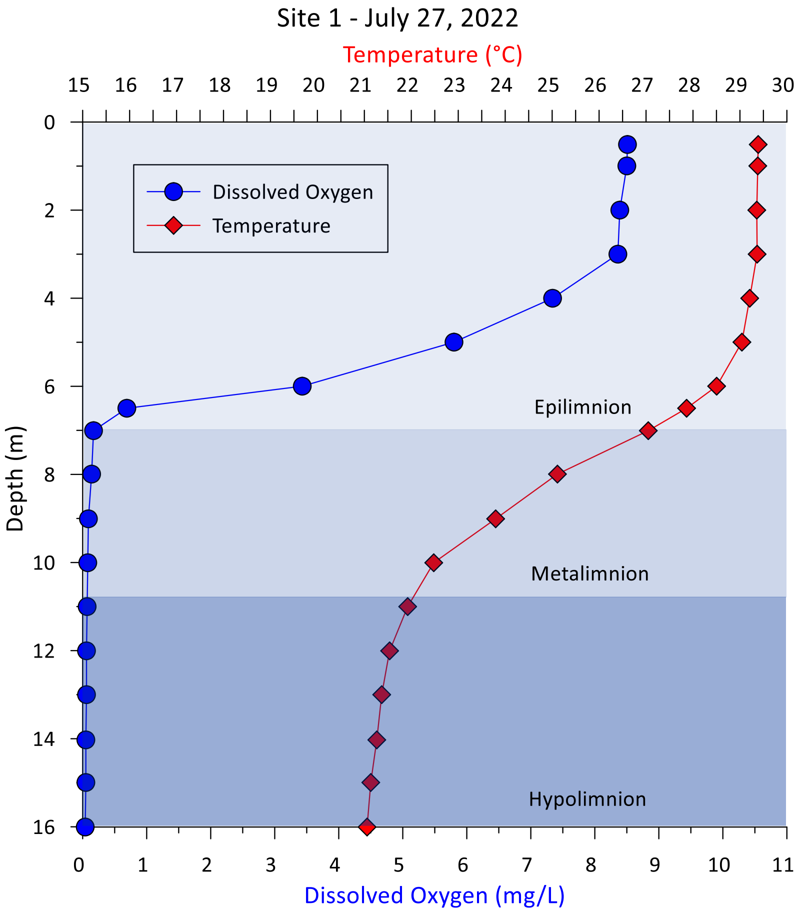

Figure 6. A typical Temperature and Dissolved Oxygen vertical profile for Lake Thunderbird during stratification. Boundaries between the Epilimnion, Metalimnion and Hypolimnion are approximated for illustrative purposes.

Relative thermal resistance to mixing (RTRM) calculations inform on the strength or intensity of stratification and is a unitless measure of temperature-based density differences, indicating how likely or unlikely layers are to mix. RTRM figures for each sample date aid in determining the size of the epi-, meta- and hypolimnion layers and can be found in **Appendix C**. **Figure 7** displays RTRM for sampling at Site 1 on July 27, 2022. During stratification, decomposition processes occurring in the hypolimnion deplete dissolved oxygen that cannot be replenished by more oxygenated water from above. The OWRB has documented this process at Lake Thunderbird each monitoring year since 2000. Stratification and anoxia in the hypolimnion are common and regular processes across Oklahoma reservoirs.

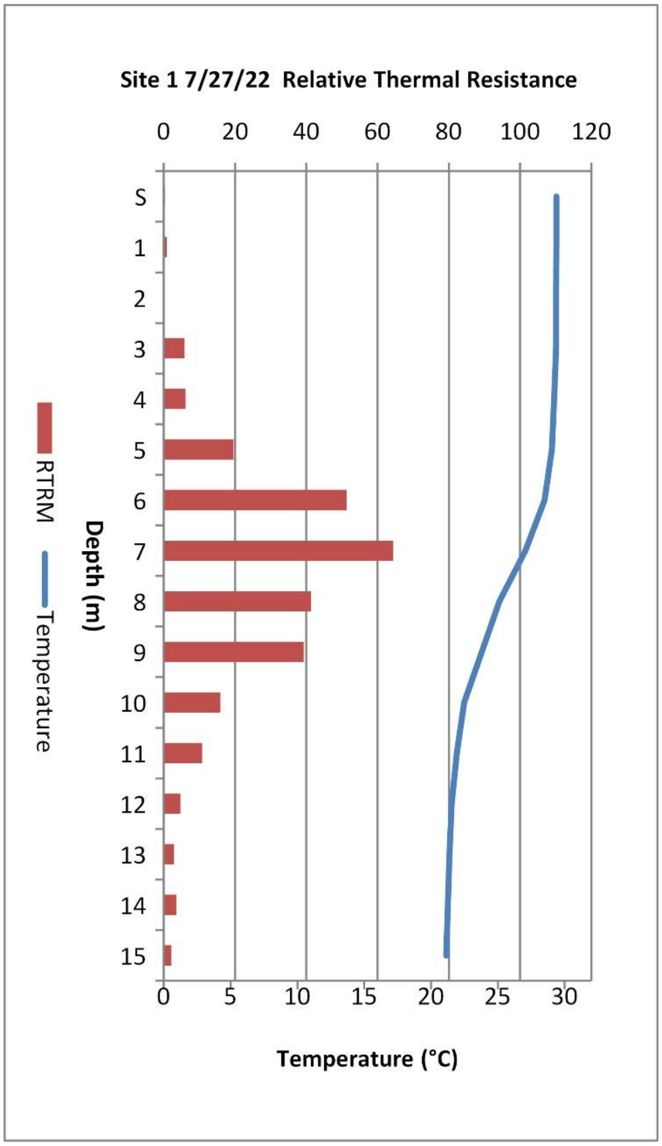

Figure 7. RTRM graphic for Site 1 on July 27, 2022.

Isopleths are a graphical method to illustrate lake dynamics as they interpolate hundreds of data points into one figure to show variation in measured parameters over depth and time. While not exact, isopleths illustrate the process of thermal stratification and the impact it has on DO. **Figure 8** displays temperature and DO data from Site 1 over the monitoring period. Each line represents a specific temperature or DO value. More vertical lines indicate a completely mixed water column. As lines begin running horizontal, some degree of stratification is present. On the temperature plot, warmest temperatures are red, graduating to cooler temperatures in green. The DO plot presents lower values in red with higher concentration readings in shades of blue. When DO values are below 4.0 mg/L, the water is termed hypoxic, or having low enough oxygen content that induce some amount of stress for organisms. Once DO concentrations fall below 2.0 mg/L, the water is anoxic or lacking sufficient oxygen for most organisms to survive.

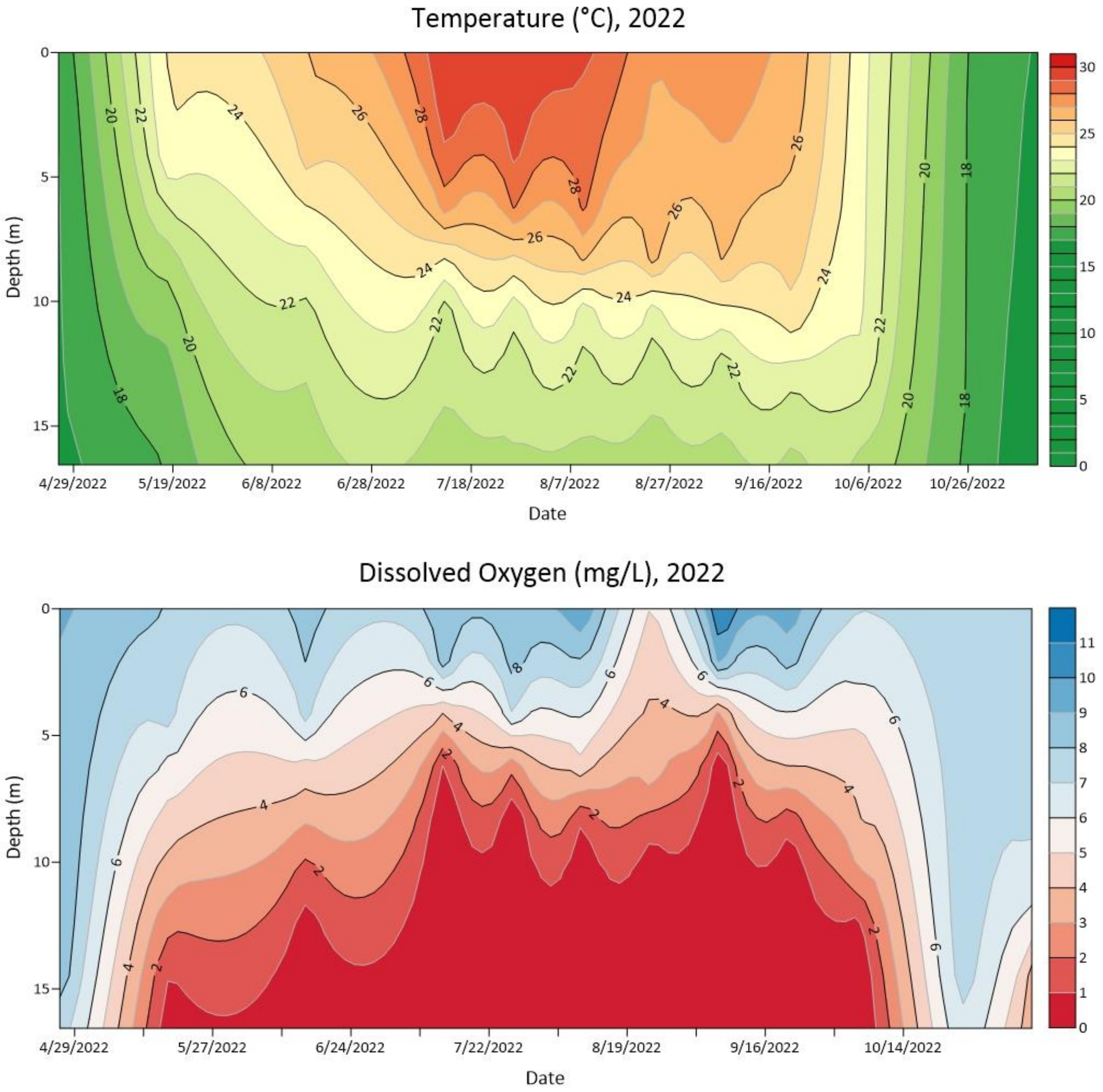

Figure 8. 2022 Isopleths of Temperature (°C) and Dissolved Oxygen (mg/L) versus Depth (m) at Site 1.

Little thermal difference with depth was observed on the first sample event in April, indicating a well-mixed water column (see also Appendix B). At the next event on May 18, 2022, thermal stratification had begun to develop, with a 5.86°C temperature gradient from surface to bottom, and DO dynamics began setting up for the season with hypoxic water developing in the hypolimnion of lacustrine and transition sites. Epilimnetic warming continued until July 13th when Site 1 reached a peak temperature of 29.53°C (**Figure 9**). Anoxia started at a depth of about 6 m and was sustained at this depth until late August by the increased organic loading and high oxygen demand from both the sediment and hypolimnetic water. Anoxic water in the metalimnion was observed throughout lacustrine and transition sites as early as May and continued through early October.

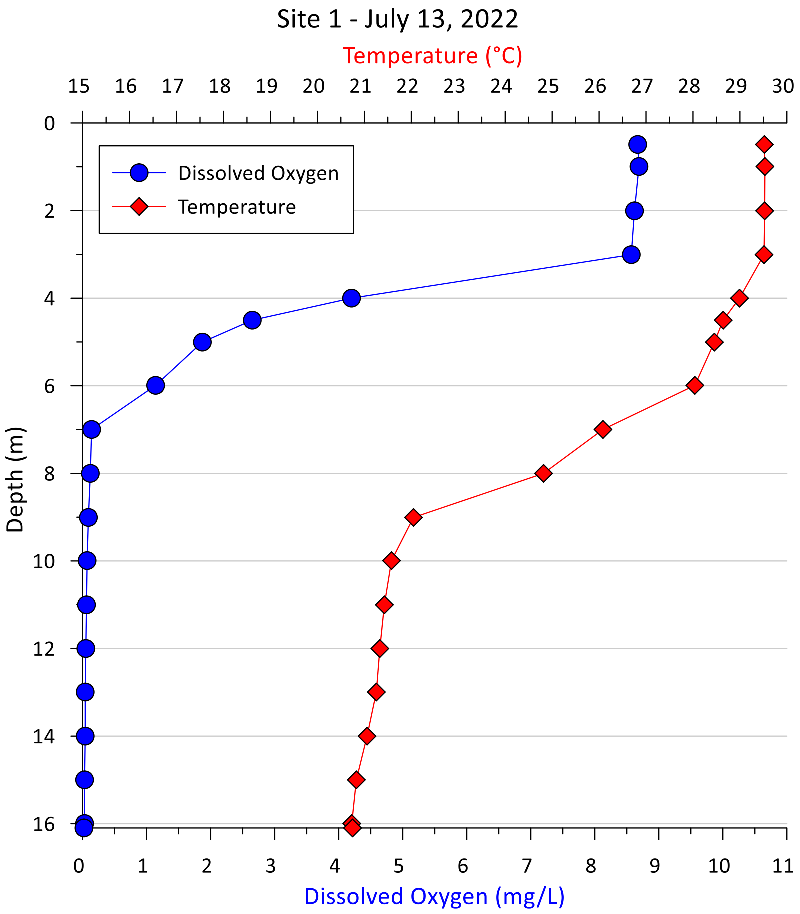

Figure 9. A Temperature and Dissolved Oxygen vertical profile with the highest temperature recorded at Site 1.

After the second sampling event in September (9/21/2022), water began to cool as the epilimnion began to deepen with slight stratification in the hypolimnion. This marks the outset of lake mixing, with the water column being almost completely mixed by the first October event (10/5/2022) and confirmed to be completely isothermal by the second October event (10/26/2022) (**Figure 10**).

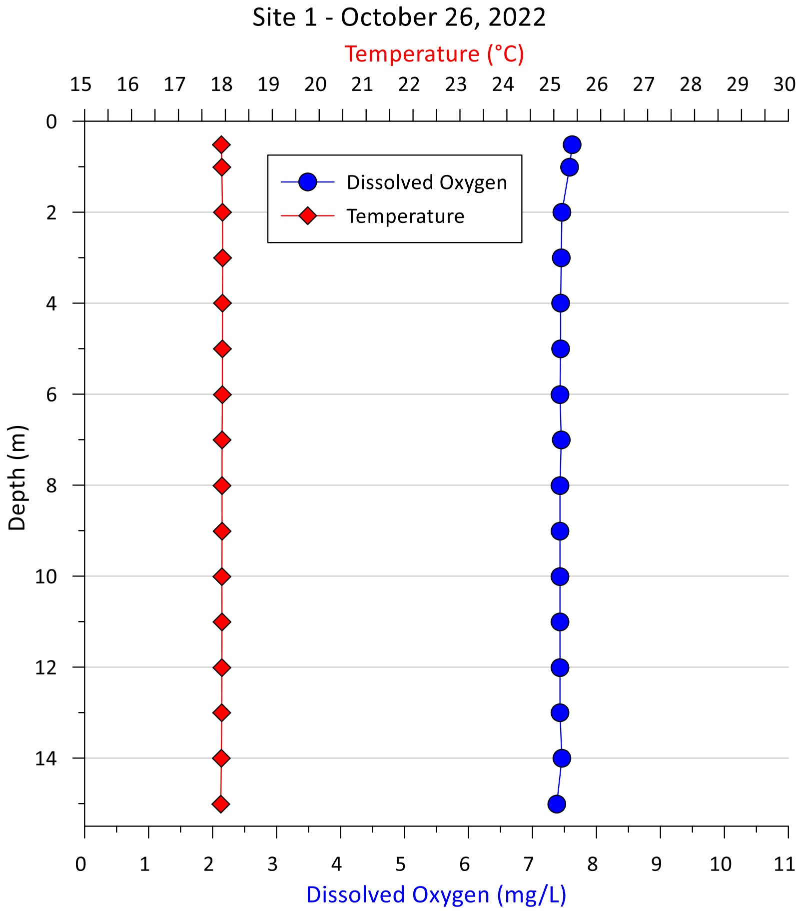

Figure 10. Temperature and Dissolved Oxygen profile at Site 1 on October 26, 2022, showing a near isothermal water column.

Metalimnetic anoxia evident throughout the lacustrine and transition zones on Lake Thunderbird in 2022 is indicative of a eutrophic system, driven by a high organic load created largely by algal growth and die-off. As algal cells lyse and settle out, hypolimnetic bacteria require an electron acceptor for survival and feed on the dead algae. When strong anaerobic conditions are present, elements other than oxygen function as terminal electron acceptors in the decomposition process. This process results in the release of nutrients and other constituents from the sediment. When mixing events occur, such as fall turnover, released nutrients are brought to the surface and can stimulate further algal growth.

pH and Oxidation-Reduction Potential

While not documented by our sampling regime, it is commonly accepted that epilimnetic pH values experience diurnal fluctuations of increasing during daylight hours and decreasing at night. These shifts follow carbon dioxide conversion to oxygen by algae through daytime photosynthesis and production by all *in situ* organisms during nighttime ecosystem respiration. Lake Thunderbird exhibited elevated pH in surface water over the summer, indicating high rates of photosynthesis, while decomposition of the settling algae and sinking organic matter decreased pH in the hypolimnion, especially during the summer months (**Figure 11**). As seen in 2022 data, peaks of high epilimnetic and low hypolimnetic pH correspond with peaks in algal productivity, particularly late July through October. This process can be exacerbated by increased algal production in eutrophic systems or influx of organic material from the watershed.

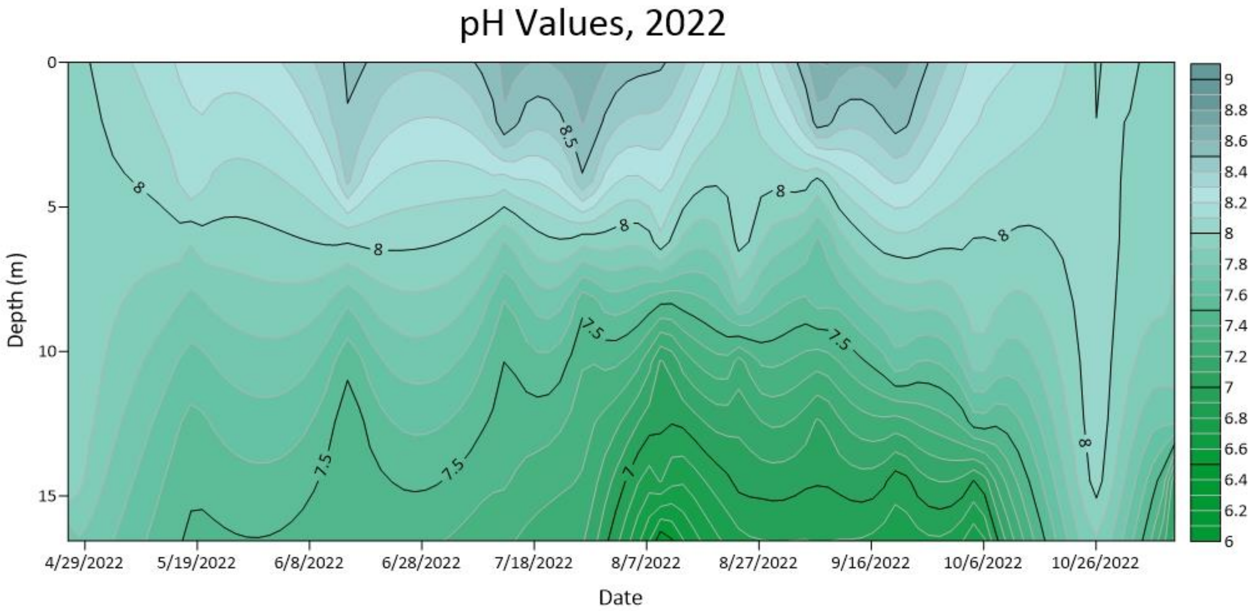

Figure 11. 2022 Isopleth of pH Versus Depth (m) at Site 1.

Oxidation-Reduction Potential, or ORP, is a measure of the equilibrium potential of water as an oxidizing or reducing agent, as measured in millivolts (mV). Typical ORP values can range from positive 500 to negative 400. A general rule of thumb is that positive ORP values indicate water as an oxidizing agent, but as values get closer to zero and negative, water acts as a reducing agent (Kremer, n.d.). Under well oxygenated conditions, ORP remains highly positive (300-500 mV) as oxygen is readily available as an electron acceptor during bacterial respiration. However, aerobic bacterial communities can consume oxygen to the point of anoxia in the hypolimnion when the bacterial community will shift to anaerobic, using other ions or compounds as the final electron acceptor for respiration. Prior to this bacterial shift, the water maintains a relatively positive ORP. However, as the ORP drops towards -100mV or lower (indicating strongly reducing conditions), sediment-bound phosphorus dissolves into the water column and nitrification (the process by which ammonia is converted to nitrate+nitrite) does not occur. The duration and extent of strong hypolimnetic reducing conditions are related to the accumulation of these compounds in the hypolimnion. By June, ORP dropped below -200 mV in anoxic conditions in the hypolimnion and remained until the lake was no longer stratified (**Figure 12**).

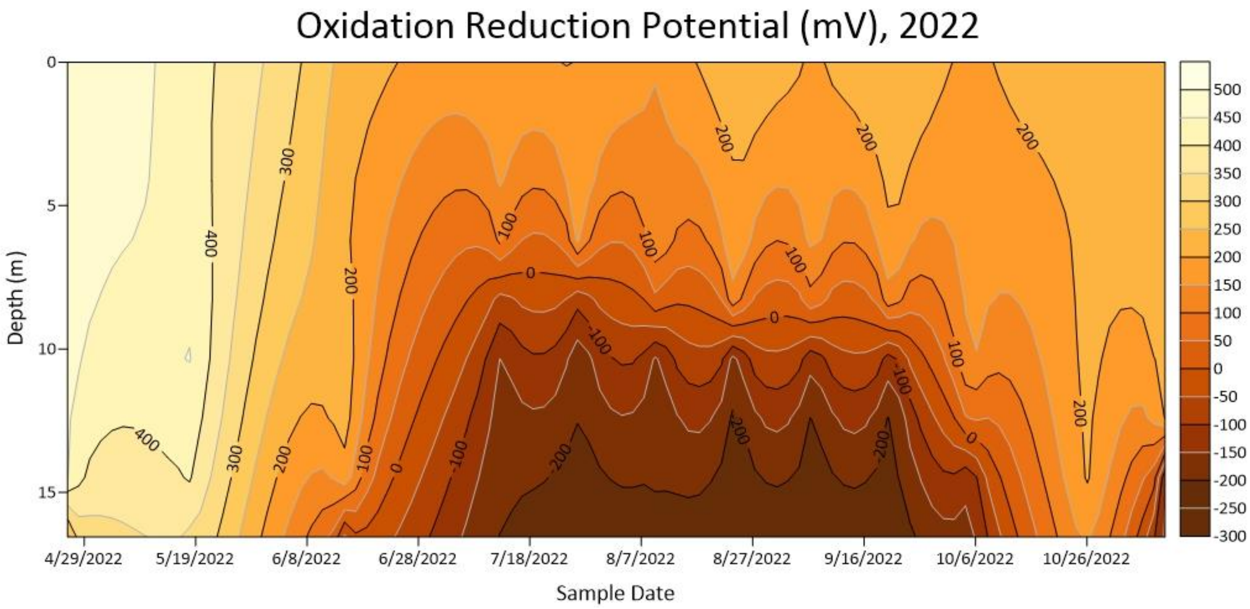

Figure 12. 2022 Isopleth of Oxidation-Reduction Potential (mV) versus Depth (m) at Site 1 from April to October.

Nutrients

Nutrient pollution through high nitrogen and phosphorus loading has consistently ranked as one of the top causes of degradation in U.S. waters. Lakes with excess nutrients are roughly 2.5 times more likely to have poor biological health (EPA, 2009). Excess nitrogen and phosphorus lead to significant water quality problems including reduced spawning grounds and nursery habitats for fish species, hypoxic and anoxic conditions, fish kills, harmful algal blooms (HABs), 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 orthophosphate, 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. Generally, when 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 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 as nutrient levels vary spatially and seasonally and riverine areas may represent sources to the system. Some nutrient graphs are presented here as a time series across one year to show changes within the sampling year or three years to provide context across recent years.

Phosphorus – P

Total phosphorus (TP) is a measure comprised of particulate phosphorus and ortho-phosphate and represents all phosphorus in the water sample. Dissolved orthophosphate (ortho-P) is the bioavailable, dissolved form of phosphorus, used by algal communities for photosynthesis. Site 1 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 0.027 mg/L to a high of 0.065 mg/L in October. Unsurprisingly, epilimnetic ortho-P was below the laboratory reporting limit the entire sample year and is the first form of phosphorous algae will consume (**Figure**

13). The interesting crash of TP in July corresponds with a high volume of gated releases and subsequent re-accumulation the remainder of the sample year.

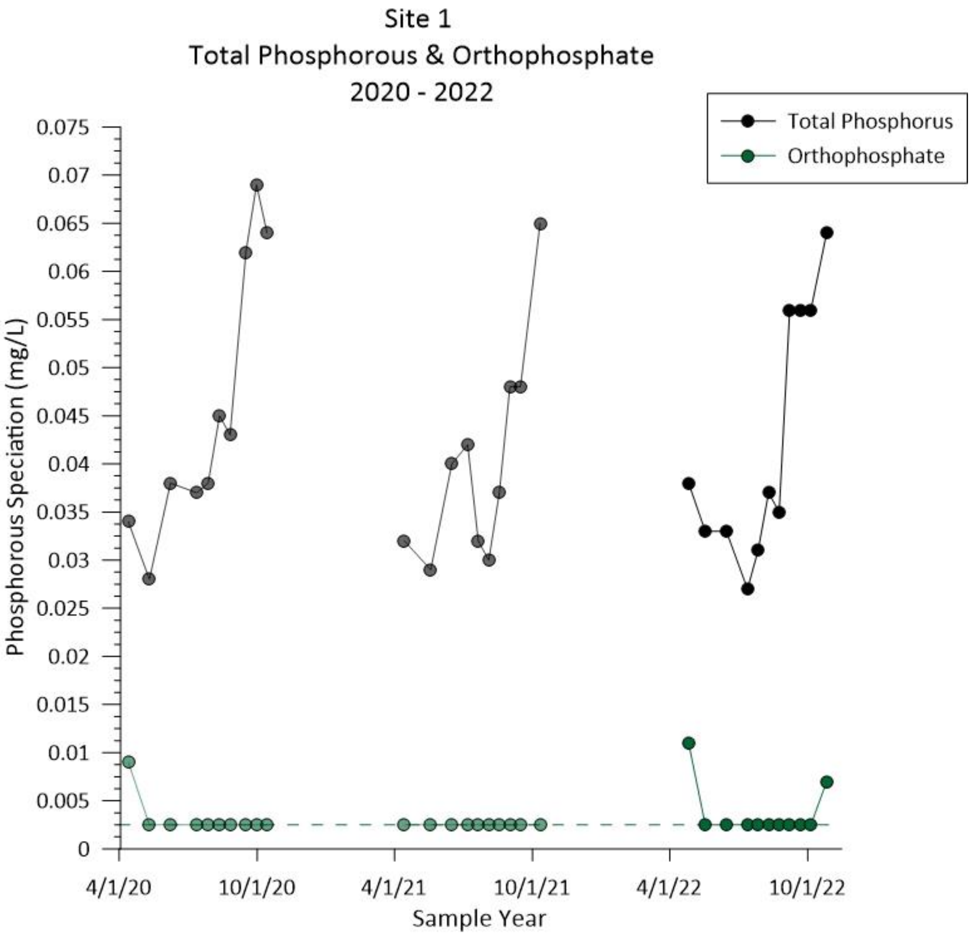

Figure 13. 2020-2022 Surface Phosphorus variables as TP and Ortho-P (mg/L) at Site 1. Ortho-P values on the green dotted line indicate its presence below the reporting limit and are graphed at half that value.

Physical characteristics, such as stratification driven by thermal dynamics and DO depletion influence numerous 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 14).**

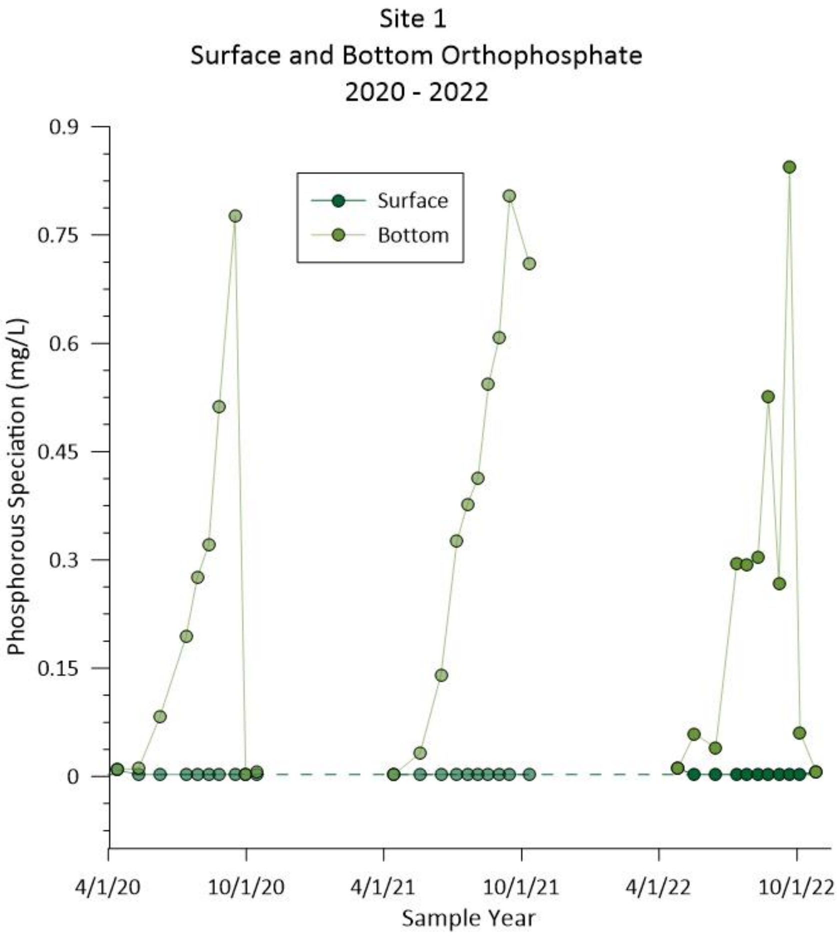

Figure 14. 2020-2022 Site 1 Dissolved orthophosphate (mg/L) at surface and bottom depths.

Riverine sites are much shallower than lacustrine sites and therefore do not stratify as readily, allowing nutrients to continuously cycle through the water column for algal uptake. Wind mixing drives nutrient and sediment resuspension throughout these shallow and turbid zones. Lacustrine and riverine sites' nutrient concentrations are often distinct from each other with riverine values are consistently higher than in open water lacustrine sites (**Figure 13** and **Figure 15**). As was the case in 2021, Sites 8 and 11 behaved similarly and exhibited TP values slightly higher than the lacustrine sites in 2022. Riverine TP values ranged from 0.037-0.133 mg/L in 2022. Site 6 on the Little River arm varied the greatest and had the highest TP value in May (0.133 mg/L) and Site 8 had the lowest in June (0.037 mg/L). There were often notable differences in TP values across all riverine sites. However, this is particularly interesting when looking at Sites 6 and 11 given that they are so spatially proximate to one another, yet their characteristics can still differ wildly.

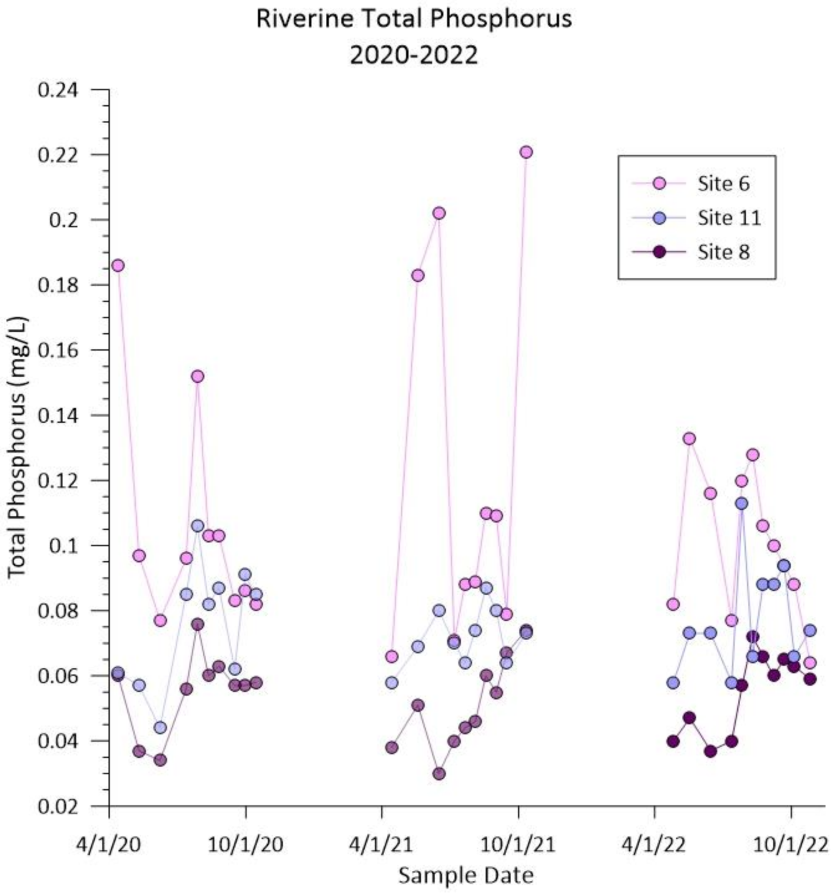

Figure 15. Surface Phosphorus (mg/L) from the three riverine sites, 2020-2022.

Site 1 surface TP and ortho-P values are consistent with those seen in eutrophic and hypereutrophic lakes and shows a slow increase over previous years, as indicated in **Figure 13**. 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 14**). Riverine areas (**Figure 15**) are susceptible to wind mixing and resuspension of sediment and nutrients as they display greater impact from storm and high-flow events. These higher levels of phosphorus year-over-year represent a greater risk for elevated phosphorus in the main lake body, potentially leading to increased algal growth.

Nitrogen – N

Total nitrogen (TN) is the summation of total Kjeldahl nitrogen (TKN), nitrate (NO_3), and nitrite (NO_2), representing all organic and inorganic nitrogen compounds of each sample. Values for TN at the surface of Site 1 ranged from 0.68 mg/L to 1.35 mg/L in 2022 and generally increased throughout the sampling year (**Figure 16)**, primarily driven by organic nitrogen present in algae. It is important to note the gradual increase of TN over previous years, as shown. Additionally, ammonia at the surface has been present below reporting limits in this sampling year and in the previous two years, likely due to it being preferentially consumed by algae and follows quick depletion in productive reservoirs.

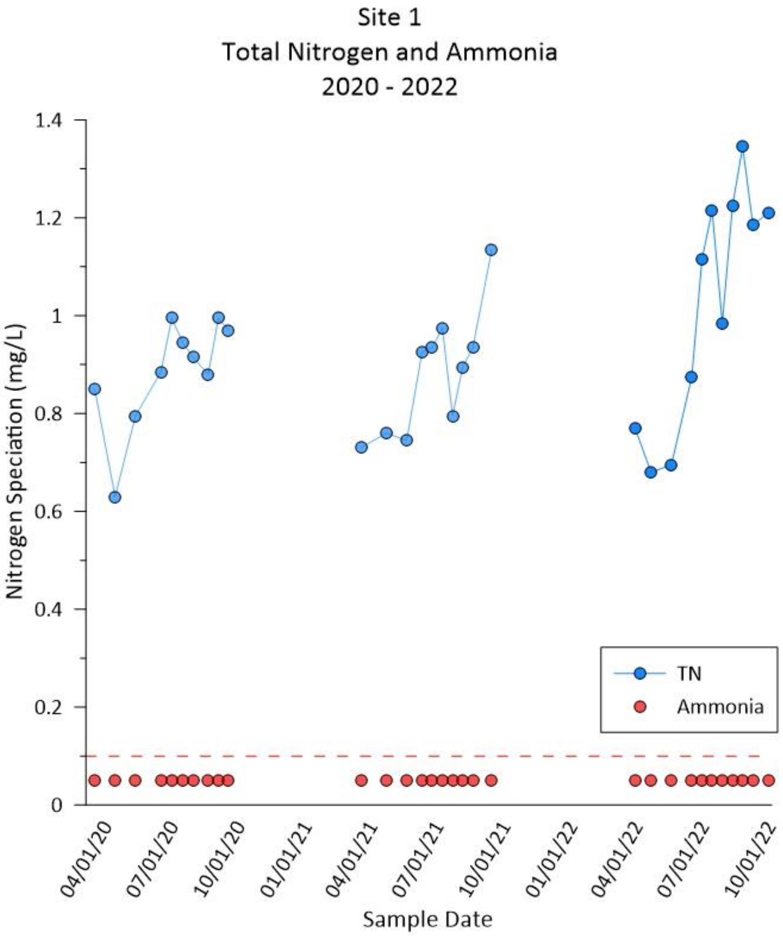

Figure 16. 2020-2022 Surface Total Nitrogen and Ammonia over time at Site 1. The dashed line represents the reporting limit and all ammonia levels were less then the reporting limit and graphed at half that value.

Lake Thunderbird's typical pattern at the surface has been temporal increases of Total Kjeldahl nitrogen while nitrate+nitrite fall below reporting limit. In 2022, surface and 4-m water samples showed nitrate+nitrite fall below reporting limit in June and remained below reporting limit throughout the sampling year (**Figure 17**). After nitrate+nitrite falls below the reporting limit, Total Nitrogen is largely comprised of Total Kjeldahl nitrogen, which is a measure of organic forms of nitrogen and inorganic forms of ammonia and ammonium.

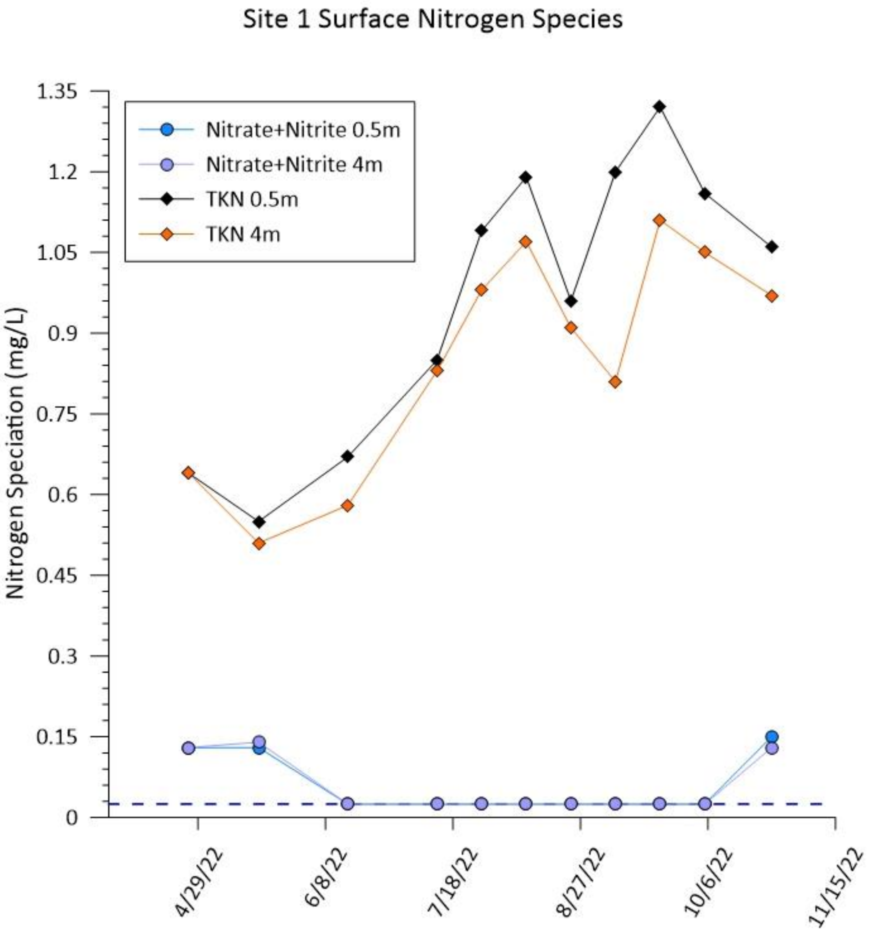

Figure 17. Surface Nitrogen species at Site 1 for 2022. Blue dashed line indicates presence below the reporting limit and are graphed at half the detection limit (0.05 mg/L).

Hypolimnetic TN peaked in September, coinciding with hypolimnetic ammonia accumulation due to sequestration by the density gradient and release from lake-bottom sediments. The stepwise breakdown of thermal stratification in the fall mixed the nutrient rich hypolimnetic waters to the surface, decreasing hypolimnetic concentration (**Figure 18**).

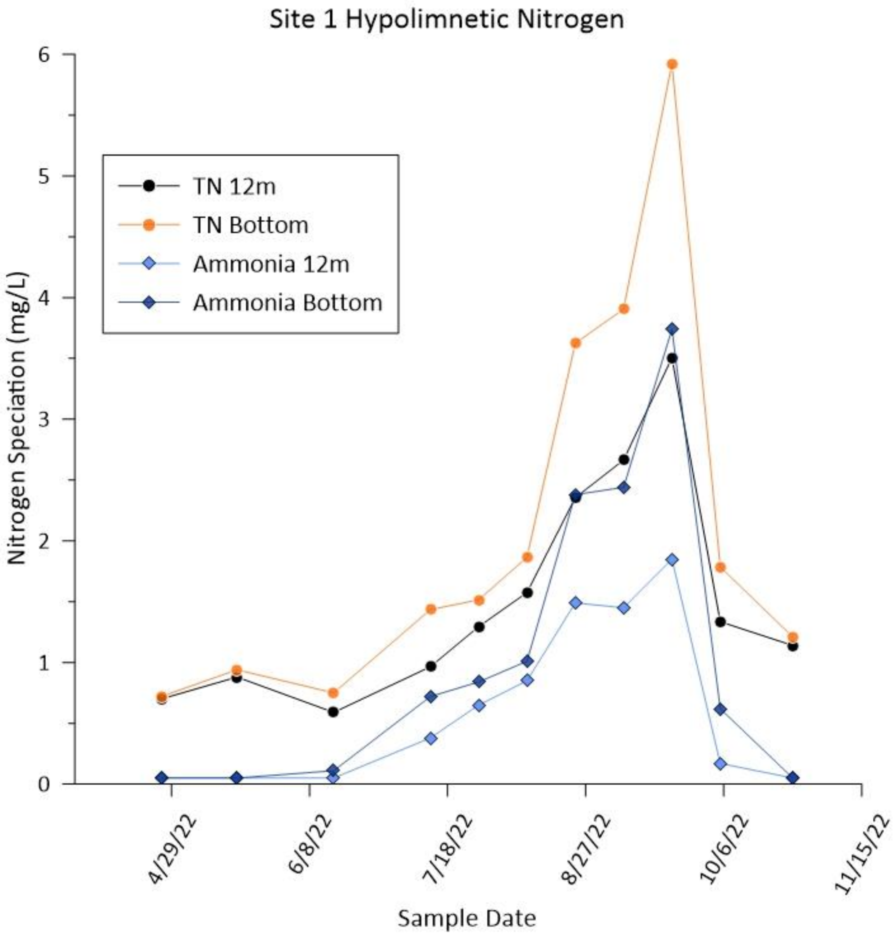

Figure 18. Site 1 Hypolimnetic Nitrogen species in 2022.

Compared to the lacustrine sites, riverine TN concentrations were usually higher and suggest that tributaries may be a source of nitrogen to the reservoir (**Figure 19**). Other than a general increase in riverine TN levels throughout the sampling period, there were no consistent temporal patterns evident among the three sites. Additionally, similar to Site 1, total nitrogen levels at the riverine sites tended to show an increase in 2022 from the previous years (data not shown).

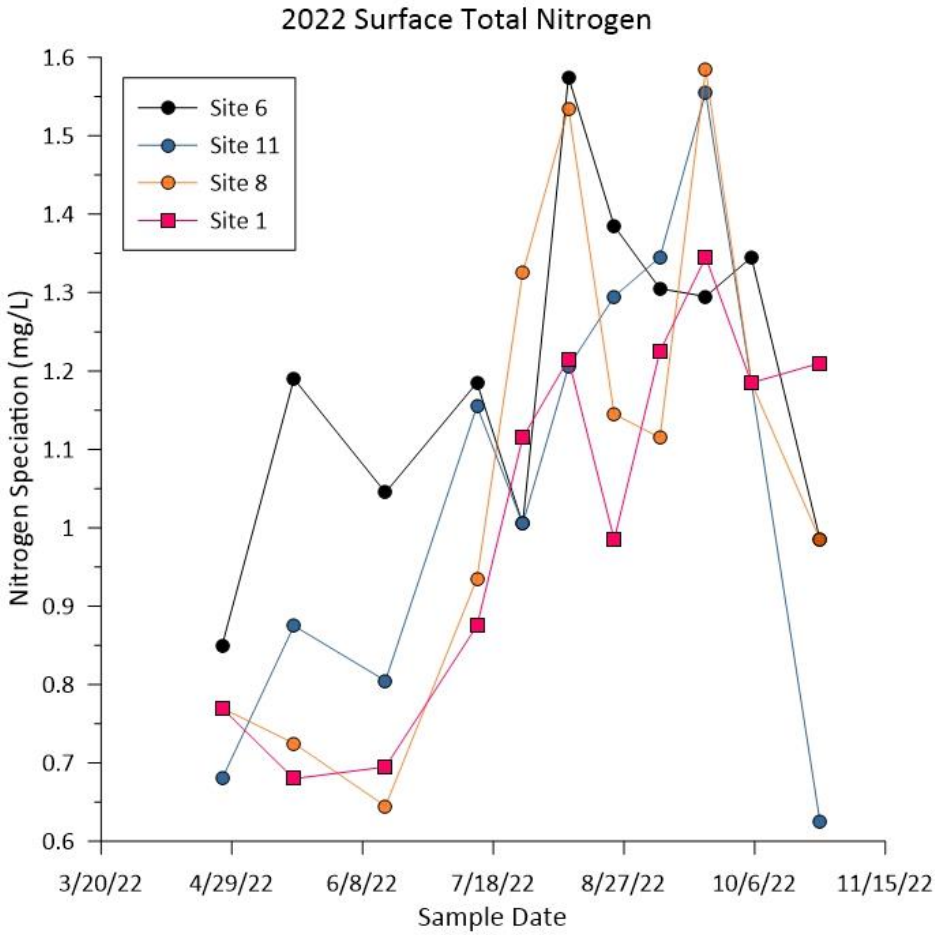

Figure 19. 2022 Surface Total Nitrogen (mg/L) from the three riverine sites and Site 1.

Algae

Chlorophyll *a* is a pigment common to all photosynthetic plants and is used as a proxy for measuring algal biomass in aquatic ecosystems. Primary production is a term often associated with photosynthesizing organisms, including algae. Algal biomass and subsequent primary production can have several impacts to overall water quality, including ecosystem stability, drinking water suitability, and recreational affects related to water transparency. Increasing eutrophication in Oklahoma reservoirs has amplified the frequency and severity of blue-green algae blooms, which result in measurable amounts of cyanotoxins in affected waterbodies and can often lead to health concerns for humans, pets, and local wildlife as well as loss of recreational opportunities. Monitoring for blue-green algal blooms was not included in the scope of this project; however, the continuous detection of the taste and odor compounds, Geosmin and Methyl-Isoborneol (MIB), confirms presence of nuisance blue-green populations in Lake Thunderbird.

Algal Biomass

Chlorophyll *a* concentrations vary spatially and seasonally throughout the year. Lacustrine sites (1, 2, & 4) generally have lower values than riverine sites (6, 8, & 11), partially due to constant influx and resuspension of nutrients from tributaries. Transitional sites (3 & 5) bridge between deeper, calmer, open water lacustrine sites and shallower, more turbulent riverine sites.

Looking at chlorophyll *a* values for the previous three years indicates a year-over-year increase at Site 1 (**Figure 20**), with only two sampling events falling below the SWS criteria of 10 µg/L for chlorophyll *a* in 2022. When looking at the rest of the lacustrine zone, we see a similar pattern emerge where values begin the monitoring season below the OWQS criteria and as the sampling year progresses these values increase until July and August before decreasing in October (**Figure 21)**. Chlorophyll *a* concentrations at Site 1 remained high throughout the summer into early fall. Measurements in the latter half of July reached 52.7 µg/L and peaked at the September 21st sampling event reaching 64.9 µg/L.

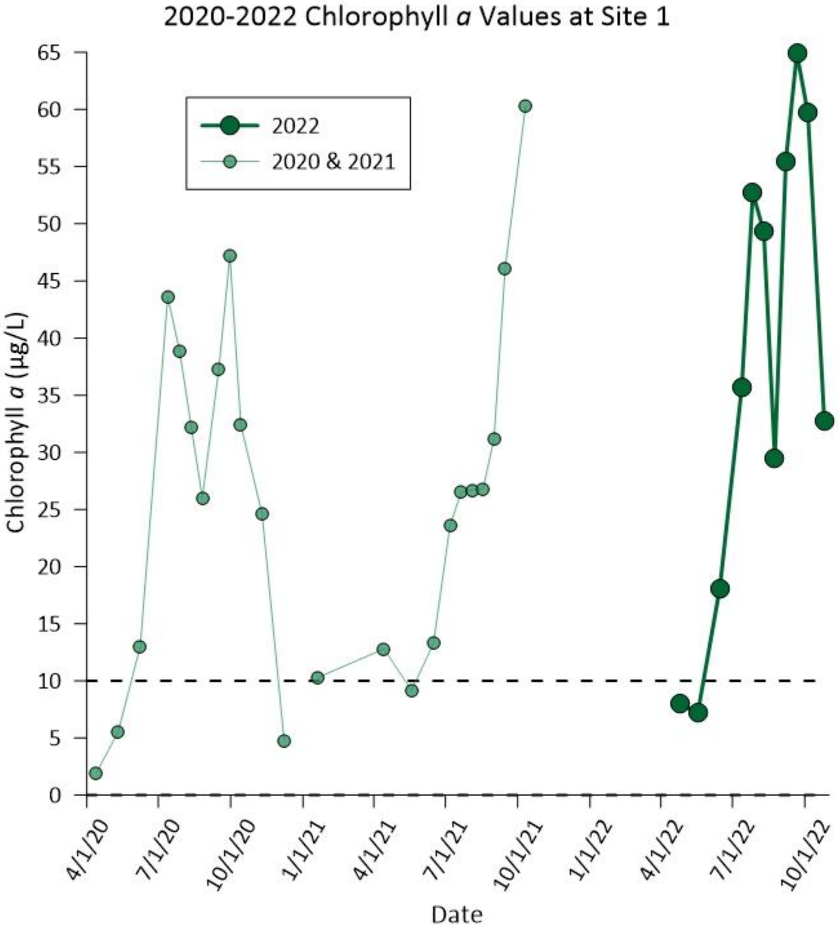

Figure 20. 2020-2022 chlorophyll *a* values at Site 1, highlighting annual increase. Dashed line represents OWQS for SWS reservoirs of 10 µg/L.

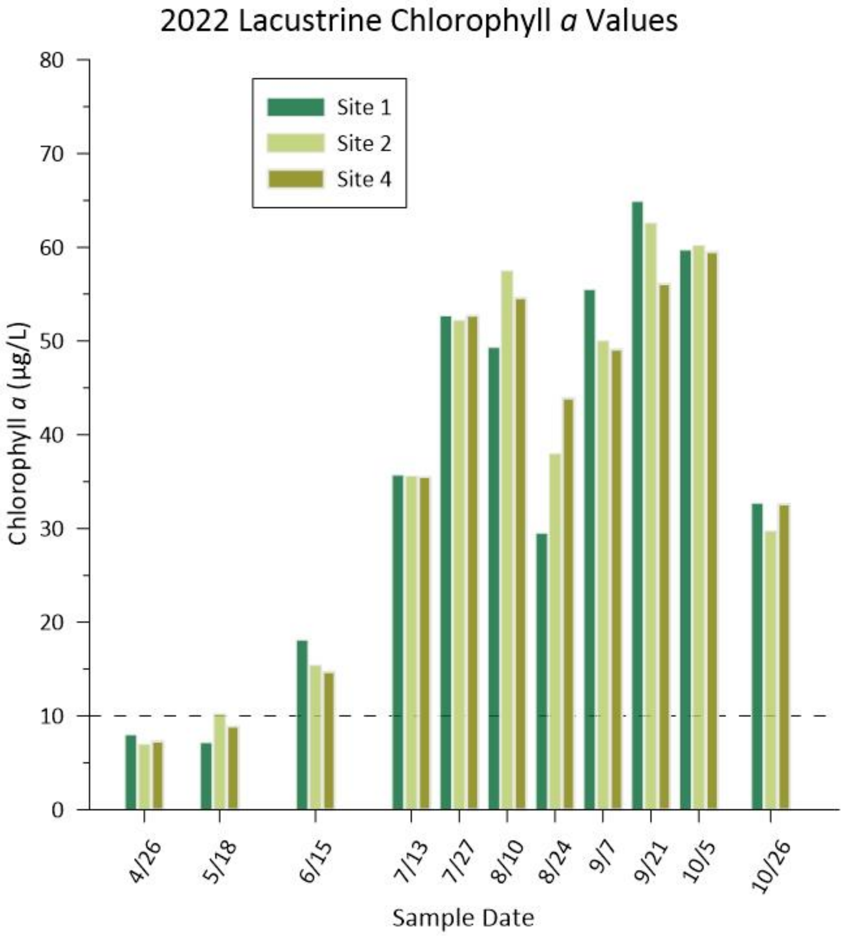

Figure 21. Lacustrine chlorophyll *a* values for 2022. Dashed line represents OWQS for SWS reservoirs of 10 µg/L.

Chlorophyll *a* in riverine sites followed a similar pattern as lacustrine sites, but at a slightly greater magnitude. Most sites started the season well above the SWS criteria with only a single sample at Site 8 slightly above the threshold in May, but quickly jumped to at least three-times the standard by July (**Figure 22**). Site 6 received stormwater from the largest and most urbanized portion of the watershed which may account for higher overall observed values, as seen with a peak riverine value of 74.3 µg/L in August. 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 watersheds, which likely suppresses algae from blooming to higher levels. Overall, lake-wide chlorophyll *a* values ranged from 6.97 µg/L to 74.3 µg/L, with an annual average of 39.99 µg/L, which is nearly four times higher the SWS criteria. The 2022 average was also the highest annual average in the last 10 years.

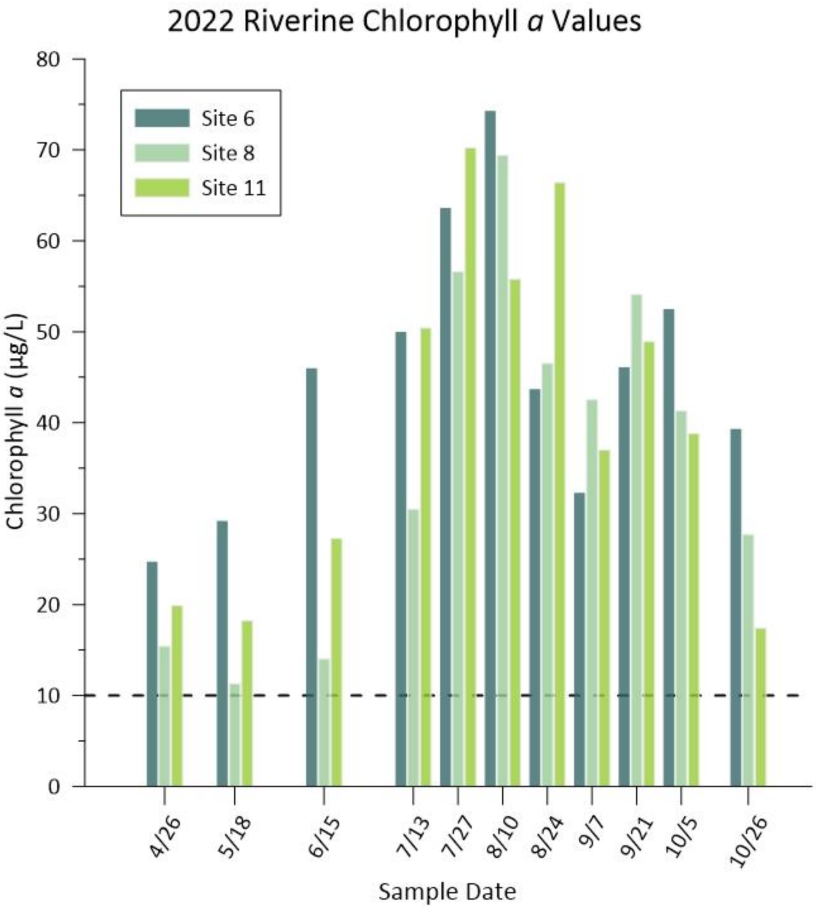

Figure 22. 2022 Lake Thunderbird surface chlorophyll (µg/L) at riverine sites. Dashed line represents OWQS for SWS reservoirs of 10 µg/L.

Algal Limitation

Understanding causal factors of excessive algae growth is critical in developing effective mitigation measures. To this end, the OWRB has employed a variety of diagnostic tools to examine the relationship between algal macronutrients (light, phosphorus, and nitrogen) and measures of algal biomass.

Nutrients

A common tool for examining the limiting nutrient relationship is the ratio of Total Nitrogen to Total Phosphorus (TN:TP). 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. Lake Thunderbird has historically occupied the co-limitation range, where both nutrients are readily available for algal growth. However, in 2022, Lake Thunderbird was occupying the indeterminate and phosphorous-limited zone for much of the sample year (**Figure 23**).

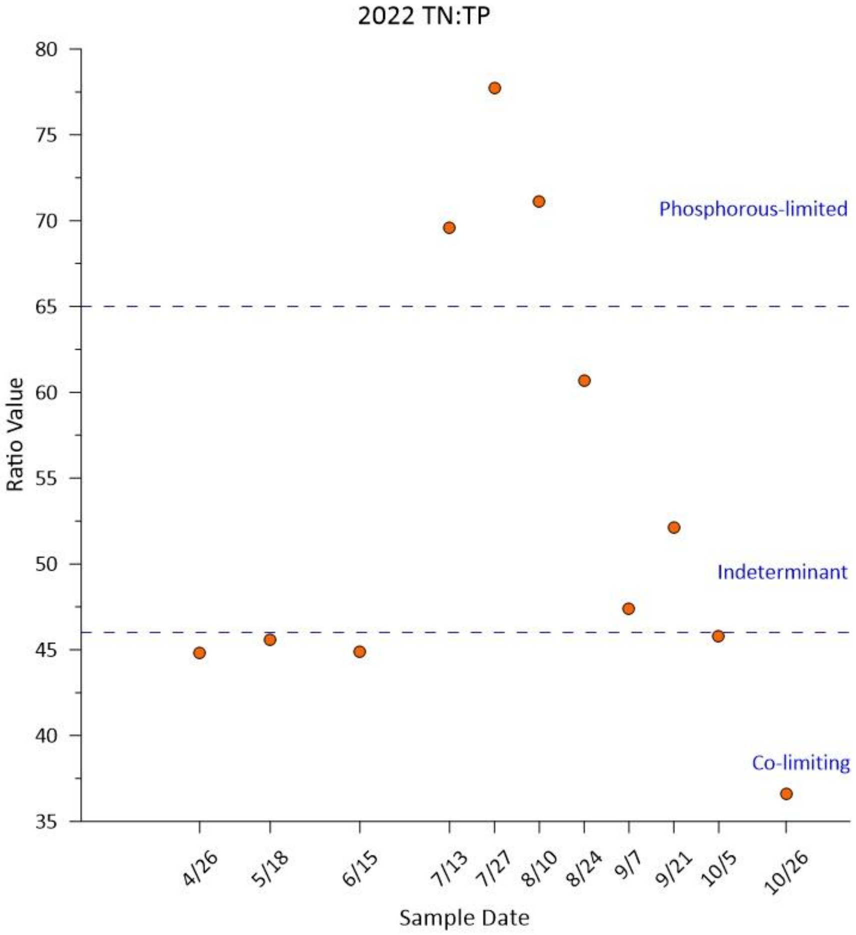

Figure 23. 2022 Lake Thunderbird TN:TP by sample event.

Light

Turbidity and Secchi disk depth (SDD) are ways of measuring water clarity and suspended particles present in a lake. In pristine and natural lakes, SDD can be measured in meters. However, in most Oklahoma lakes it is common for SDD to be less than one meter and is reported in centimeters (cm). Secchi disk depth can provide information on light's ability to penetrate the water column and influence the water's productivity.

In 2022, non-algal turbidity was calculated to examine its effect on algal limitation using the equation below, derived from the BATHTUB model (Walker, 1999). Non-algal turbidity generally describes turbidity associated with parent material originating elsewhere and brought in or introduced to the system, often referred to as allochthonous.

Eq. 4. $$T = 1/ Z_{SD} - 0.025 \text{ Chl } a$$

Where ***SD*** is Secchi Depth in meters

and **Chl *a*** is extracted chlorophyll *a* result value in mg/L

Overall, 45 of the 95 samples collected during the 2022 sampling year had a non-algal turbidity (T) value >1 indicating allochthonous particulates are generally important to Lake Thunderbird algal dynamics. Thus, turbidity from particles brought into the system is potentially more important in limiting light's ability to drive excessive algal growth, regardless of excessive nutrients in the system. However, T had differing results at different zones within the reservoir. At the lacustrine sites, only 3 of 31 samples were >1 and 13 samples had a T of <0.4 indicating turbidity from allochthonous particles has less of an impact at the lacustrine sites of Lake Thunderbird and that a higher potential algal response to nutrients is expected. In contrast, all 33 of the riverine sites sampled were >1 suggesting that these areas of the lake tend to have more influence from allochthonous sources than lacustrine sections. Although these regions have higher turbidity values, light limitation does not seem to be an issue in Lake Thunderbird. Due to the shallow nature of these areas and re-suspension of nutrients from wind mixing, chlorophyll *a* values tended to be higher than would be expected due to turbidity levels and contributions from non-native particles.

Trophic State Index – TSI

A common method of classifying lakes based on biological response to nutrients is trophic state, which indicates the amount of biological activity present in a waterbody at a particular time. Lakes that have high nutrient concentrations and productive plant growth are described as eutrophic, whereas low nutrient concentrations and low plant growth lakes are characterized as oligotrophic (Water on the Web, 2004). Lakes that exhibit moderate levels of nutrients and plant growth are termed mesotrophic. Carlson (1977) developed the most widely used biomass-based Trophic Status Index (TSI) to classify and describe lakes. The Carlson chlorophyll *a* TSI equation has long been used by OWRB to determine lake trophic status. **Table 5** below presents the various trophic states and associated descriptions.

Eq. 5. Carlson's TSI calculation based on chlorophyll *a* biomass.

$$\boldsymbol{TSI = 9.81\, x\, ln(\text{chlorophyll } a) + 30.6}$$

Where **chlorophyll *a*** is the value of extracted chlorophyll *a* mg/L

Table 5. Summary of Carlson's Trophic State Categories. (Carlson, 1977).

Trophic State	TSI Value	Description
Oligotrophic	< 40	Low primary productivity and/or low nutrient levels
Mesotrophic	41-50	Moderate primary productivity with moderate nutrient levels
Eutrophic	51-60	High primary productivity and nutrient rich
Hypereutrophic	> 60	Excessive primary productivity and excessive nutrients

This concept has been expanded over time to classify lakes 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. Chlorophyll *a* is the most relatable TSI metric, as it is the most direct measure of algal biomass, which is the measure of primary productivity that the trophic state seeks to classify. **Figure 24** displays Lake Thunderbird's TSI levels at Site 1. Lake Thunderbird began the season eutrophic and accelerated to hypereutrophic by July, where it remained the rest of the sample year.

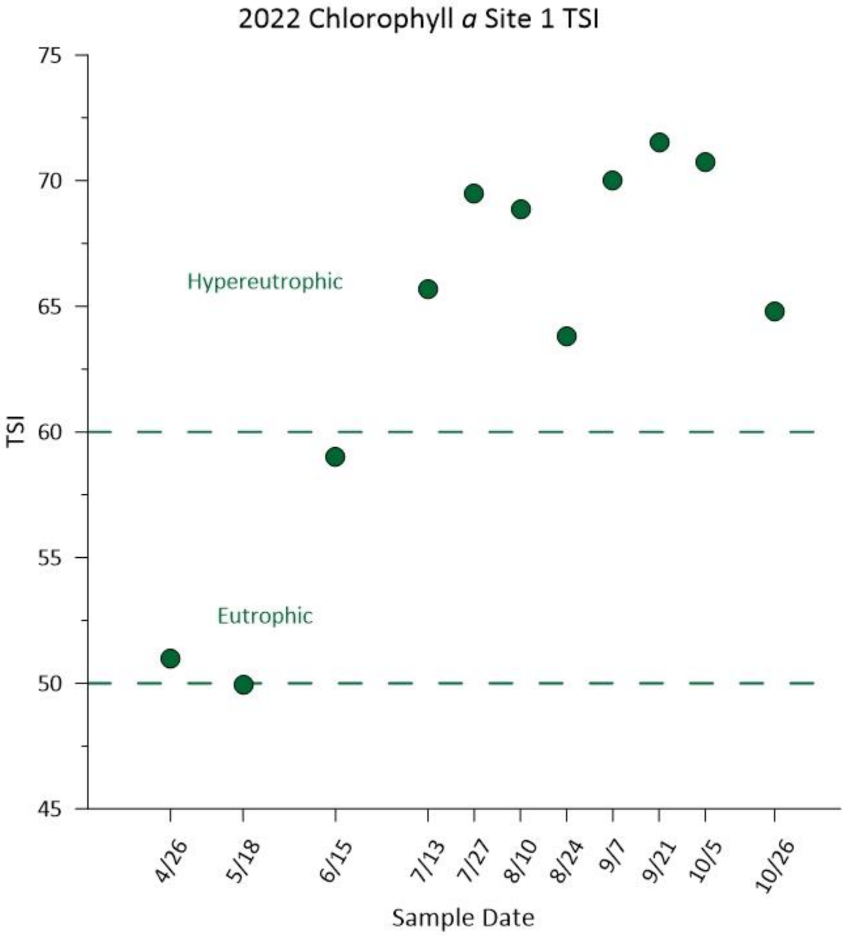

Figure 24. Site 1 Chlorophyll TSI in 2022. Dashed lines represent the divisions of trophic states.

The advancement of lakes toward a eutrophic or hypereutrophic condition is often accelerated by anthropogenic activities that introduce excess nitrogen and phosphorus into lakes. This is commonly referred to as cultural eutrophication. In a pattern similar to Site 1, TSI at the riverine sites increased throughout the season and were mostly within the hypereutrophic range. Chlorophyll TSI varied between individual sites and were consistent with measured chlorophyll in the system. **Figure 25** shows riverine TSI throughout the 2022 sample year.

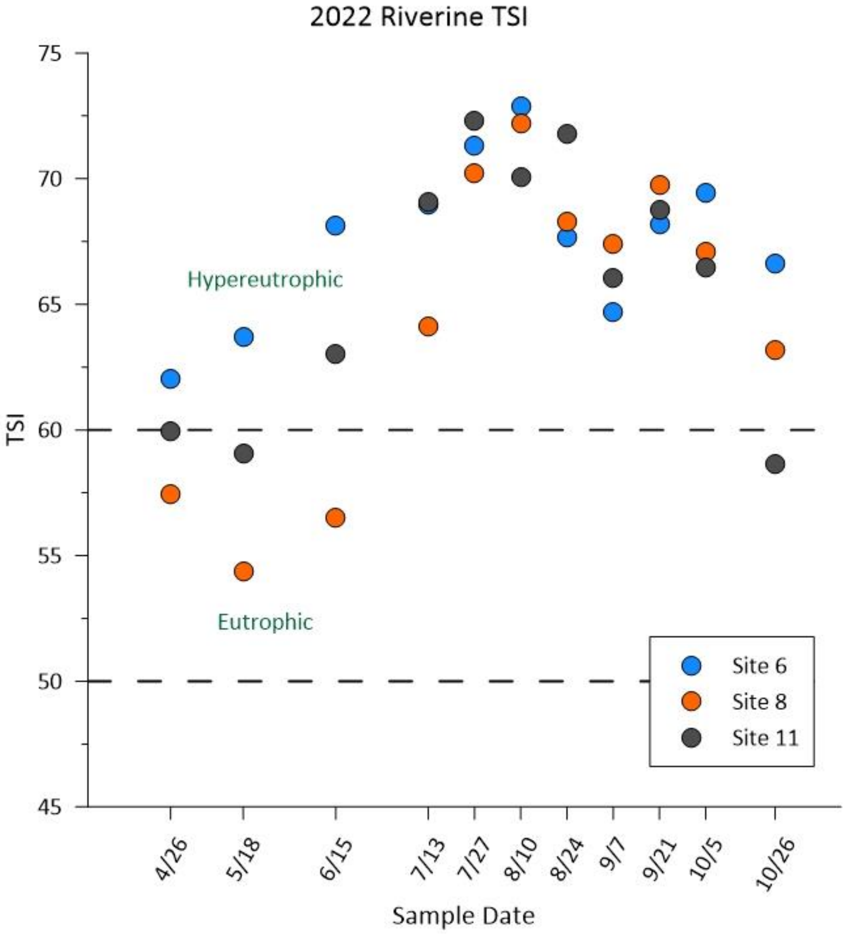

Figure 25. 2022 Carlson's Chlorophyll *a* TSI values for riverine sites. Dashed line delineates ranges for trophic state.

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 – 2022) and more recently has included taste and odor compound analysis. Annual data indicates that changes in lake water quality correlates with customer complaints in the final finished drinking water. Consumers at the tap can detect taste and odor causing compounds in extremely low concentrations (~ 5 ηg/L) (Graham et al 2008). Algae are responsible for producing the majority of taste and odor compounds (T&O) found in Oklahoma reservoirs. Primarily, Geosmin and 2-methylisoborneol (MIB). Both of which are produced primarily by Cyanobacteria.

2022 T&O complaints revealed a different pattern from previous years, with only a handful logged for the entire year. **Figure 26** displays the previous three years of T&O complaints the City of Norman has recorded.

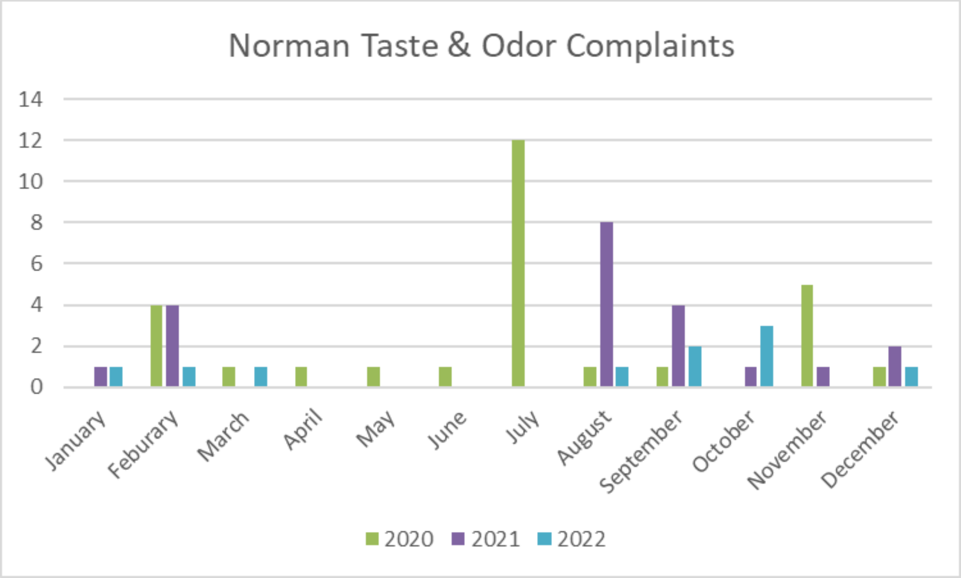

Figure 26. Taste and Odor complaints by month. Data is from personal communication with G. Wellborn, City of Norman (January 2022).

In past years T&O complaints coincided with lake mixing events, when hypolimnetic chemicals cycle into the water column. However, in 2022, Geosmin from raw water prior to chlorination did not peak until November, while MIB at the same source spiked in early August (**Figure 27**). The overall average for both Geosmin and MIB were lower than reported in 2021.

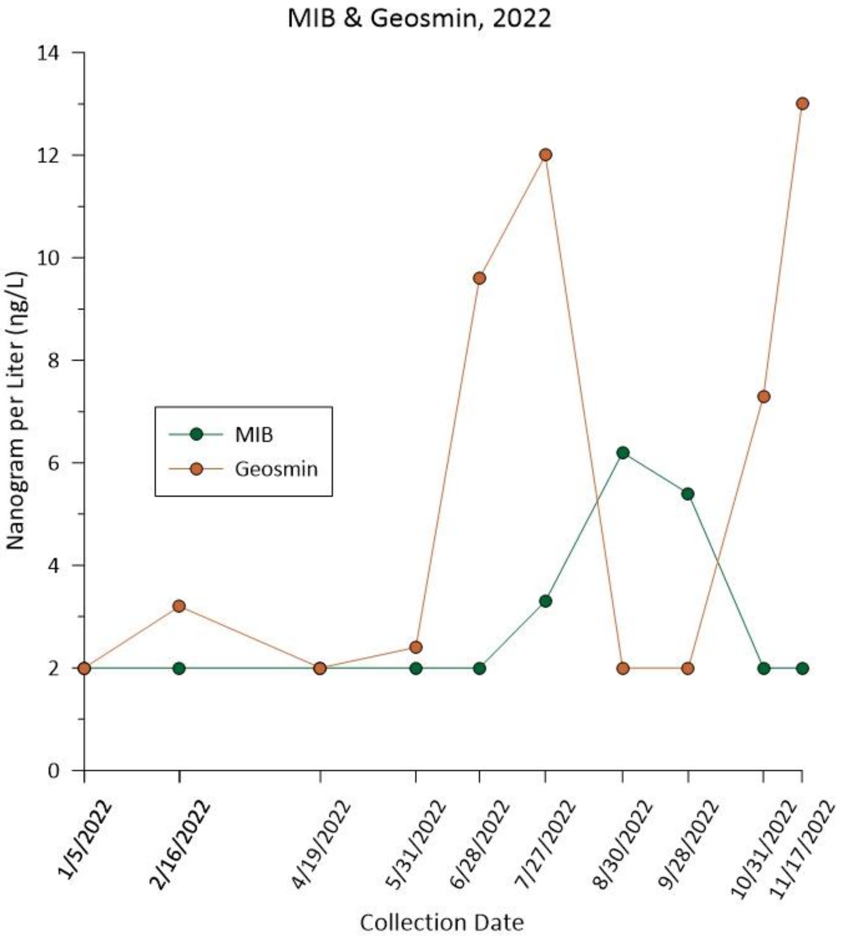

Figure 27. 2022 City of Norman monthly raw water laboratory analysis for Geosmin and MIB. Points graphed at 2.00 are considered non-detect. Data is from personal communication with G. Wellborn, City of Norman, January 12, 2022.

Total Organic Carbon – TOC

Total organic carbon (TOC) is a measure of carbon containing compounds present in a water sample, providing insight to the amount of organic material present. Sources of these organic compounds include soil and plant detritus and to a lesser degree, 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 2022, Lake Thunderbird surface TOC values at Site 1 ranged from 5.37 to 7.99 mg/L with a mean value of 6.49 mg/L (**Table 6**). 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 create by-products that could be carcinogenic (TCEQ, 2002). Reducing TOC in the source water could lead to a reduction in treatment cost for finished drinking water.

Table 6. 2022 Total Organic Carbon (mg/L), Site 1.

Total Organic Carbon (mg/L)	
04-20-2022	5.37
04-26-2022	5.56
05-18-2022	5.43
06-15-2022	5.94
07-13-2022	6.35
07-27-2022	7.81
08-10-2022	7.99
08-24-2022	6.31
09-07-2022	7.35
09-21-2022	7.41
10-05-2022	6.35
10-26-2022	6.11

Water Quality Standards

All Oklahoma surface waters are subject to Oklahoma's Water Quality Standards (OAC 252:730) and Implementation Rules (OAC 252:740), designed to maintain and protect the quality of waters of the state. Oklahoma Water Quality Standards 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, 2022). In order to address these impairments, Lake Thunderbird has undergone Total Maximum Daily Load (TMDL) development by the Oklahoma Department of Environmental Quality (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 water quality assessments (i.e., 305(b) and 303(d) reports). 2022 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 criteria (OAC 785:46-15-5). Surface water DO criteria for a designation of not supporting is a seasonal threshold of 4.0 mg/L during the summer months and 5.0 mg/L in spring and fall. Accordingly, no surface DO readings fell below either threshold in 2022.

Volumetric criteria for the fully supporting designation of the Fish and Wildlife Propagation beneficial use have a threshold of less than 50% of the cumulative lake volume measuring anoxic (< 2.0 mg/L DO). No events during 2022 recorded the oxygenated volume below the 50% criteria. Two events, the first sampling in July, as well as the first in September, recorded DO oxygenated volumes close to 60%. However, July of 2021 failed to meet criteria based on volumetric data with 49.13% oxygenated volume. That, and reports for the 2018 and 2019 sample years also with highlighted occurrences of the lake failing to meet the volumetric criteria, still shows the lake not supporting this beneficial use due to the 10-year assessment window.

Chlorophyll *a*

Oklahoma surface water drinking supplies are vulnerable to eutrophication and communities can experience substantial hardship and excessive costs to treat water affected by eutrophication. Specifically, blue-green algae (cyanobacteria) blooms are considered a principal source of compounds that cause T&O complaints. Blue-green algae can also produce several toxic and carcinogenic compounds such as microcystin – a known hepatotoxin that can cause liver damage. The 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 2022, the lake-wide chlorophyll average in Lake Thunderbird was 39.09 µg/L, with over 93% of samples exceeding 10 µg/L. Samples collected in 2021 averaged 32.07 µg/L and the 2020 average was 29.65 µg/L. The ten-year (2012-2022) lake-wide average is 28.09 µg/L, with 86% of samples exceeding 10 µg/L. (**Figure 28)**.Figure 28. 2022 Lake Thunderbird chlorophyll a (*µg*/L) by site. Boxes represent 25% of the data distribution both above and below the median (horizontal line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Based on these calculations, Lake Thunderbird's beneficial use of Public and Private Water Supply is considered non-supporting and impaired with respect to chlorophyll *a*.

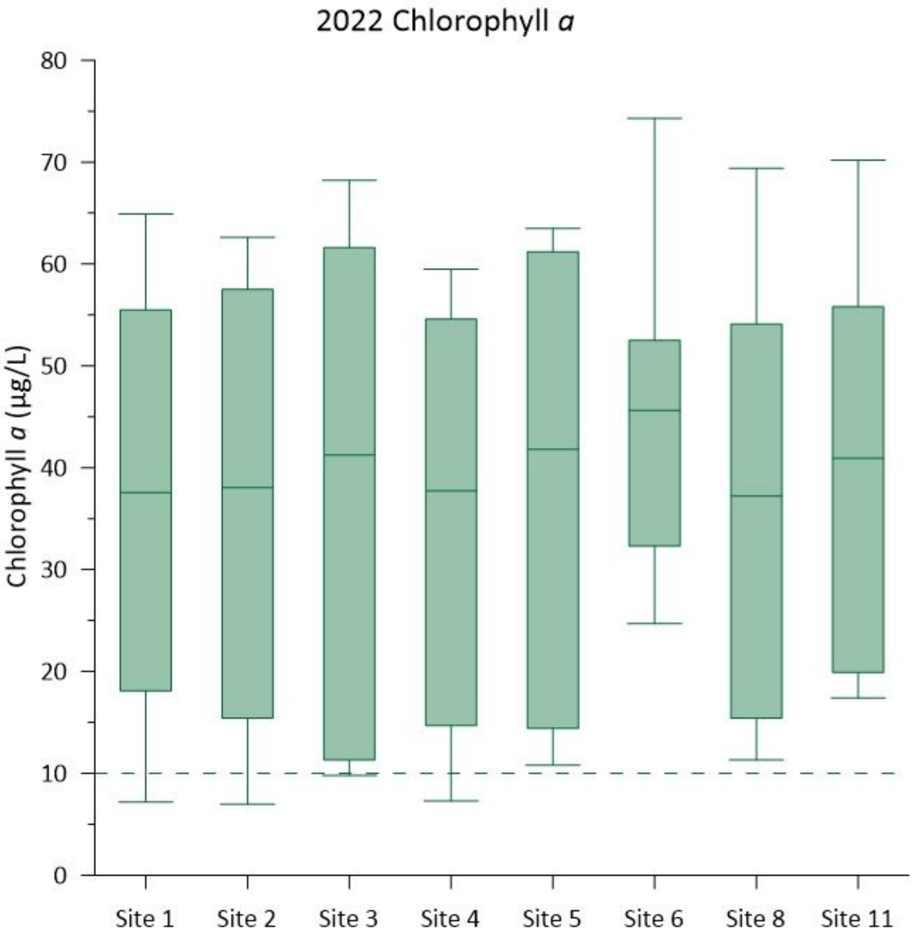

Figure 28. 2022 Lake Thunderbird chlorophyll *a* (µg/L) by site. Boxes represent 25% of the data distribution both above and below the median (horizontal line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Dashed line indicates SWS criteria of 10 µg/L.

Water Clarity

Turbidity and Secchi disk depth are methods of measuring water clarity and suspended particles in a lake and can vary spatially, seasonally, and with environmental conditions across a waterbody. Typical Secchi disk depths of eutrophic Oklahoma reservoirs measure one meter or less. In Lake Thunderbird, 2022 Secchi disk depths ranged 13 cm to 118 cm. The lake-wide average Secchi depth was 48.86 cm, with lacustrine sites having the deepest Secchi depths while the riverine sites had the shallowest, as is typical of Oklahoma reservoirs (**Figure 29**).

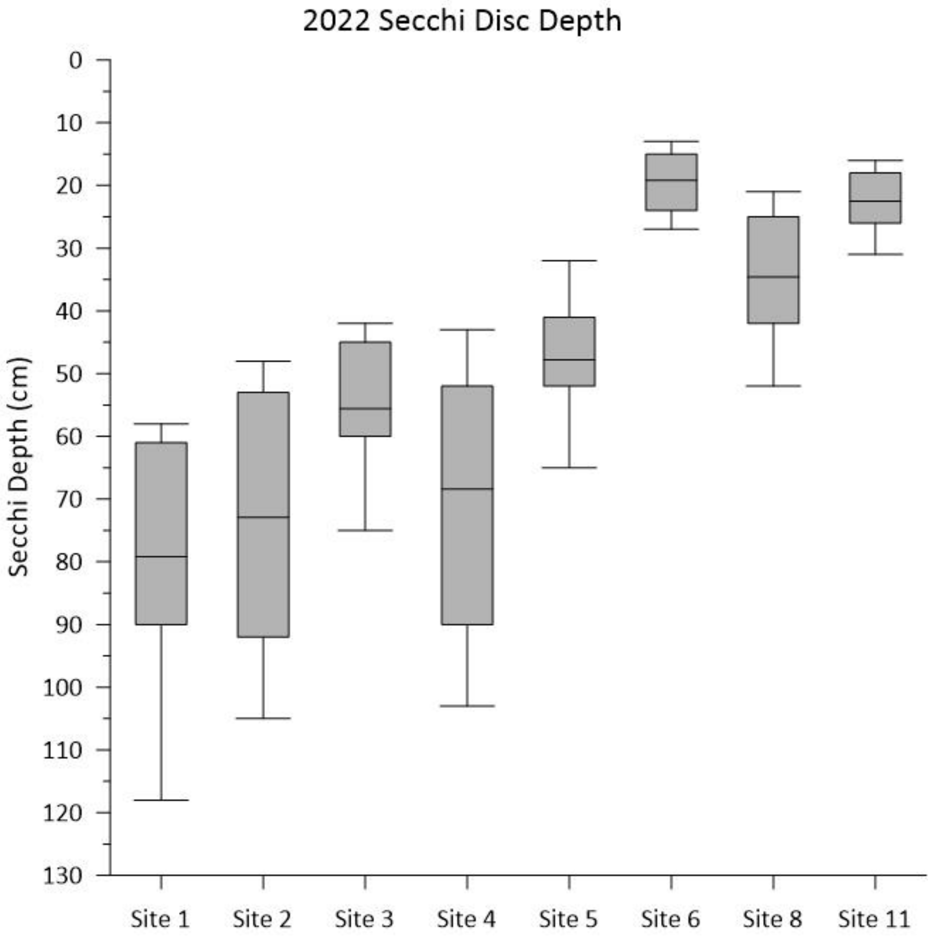

Figure 29. 2022 Lake Thunderbird Secchi Disk Depth (cm) by site. Boxes represent 25% of the data distribution both above and below the median (horizontal line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Depth starts at 0 to represent the surface of the water.

The OWQS criterion for turbidity for the protection of the of Fish and Wildlife Propagation beneficial use is 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 impaired for turbidity. Values in 2022 varied across the lake and ranged from 4.85 NTU to 89.1 NTU. For reference, the lower the NTU value, the clearer the water. The lake-wide turbidity average was 21.48 NTU, with 29.55% of the samples exceeding 25 NTU, all of which were in the riverine or transitional zones of the lake **(Figure 30**). The 10-year lake-wide average is 24.2 NTU, with 27.5% of those samples exceeding 25 NTU. Based on these calculations, Lake Thunderbird is not supporting the Fish and Wildlife Propagation beneficial use with respect to turbidity.

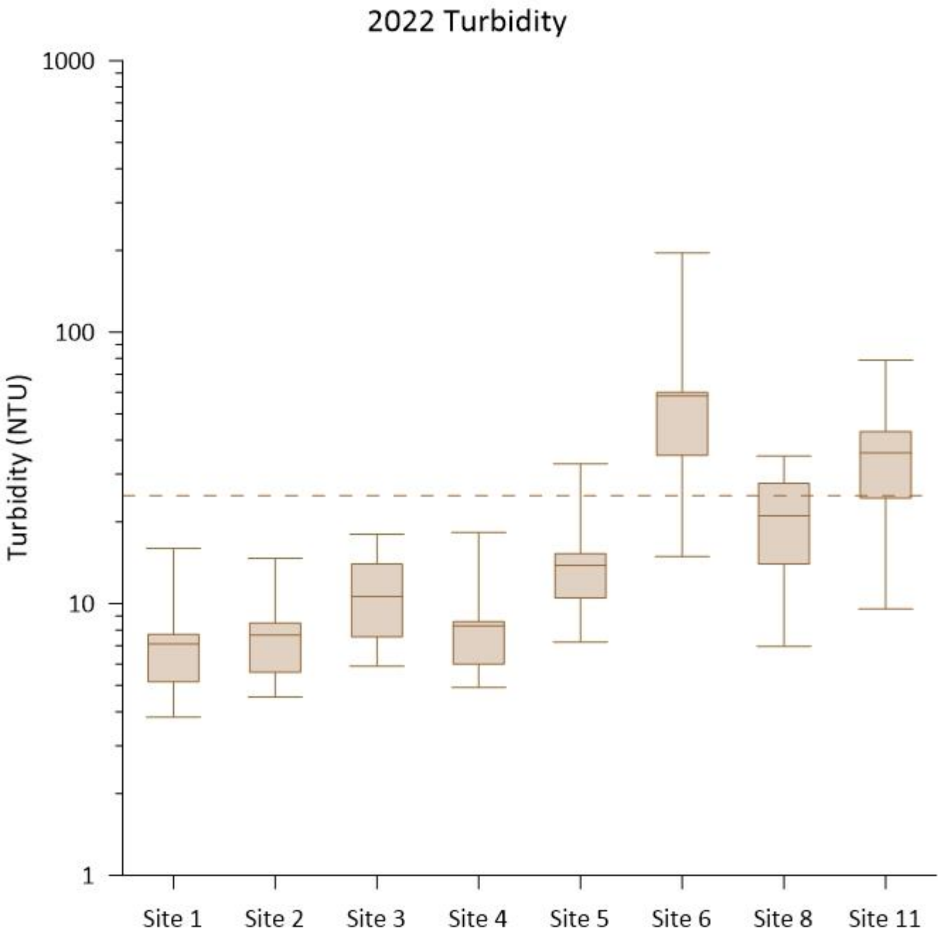

Figure 30. 2022 Lake Thunderbird Turbidity (NTU), by site, on a logarithmic scale. Boxes represent 25% of the data distribution above and below the median (horizontal line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Dashed line indicates the 25 NTU OWQS for turbidity.

Discussion

The OWRB has monitored the water quality of Lake Thunderbird since 2000 and has continued to document the degradation of water quality from cultural eutrophication. As time passes, impacts become increasingly severe. Rapid urban development in the watershed, excessive levels of nitrogen and phosphorus–especially in riverine areas, and progressively higher levels of measurable chlorophyll *a* contribute and culminate in the loss of beneficial uses in the lake.

The 2022 sampling season captured the highest lake elevation at 1040.85 ft in May. The lowest lake elevation of 1036.25 ft occurred in late November, outside of the sampling season. The difference between the highest and lowest elevation was about 4.6 ft. Variation in elevation is important in identifying flushing events and when examining nutrient levels and non-algal turbidity throughout the reservoir.

The overall pattern of stratification remained comparable to previous years. Thermal stratification began to set up by May sampling with a mostly anoxic volume in the hypolimnion of lacustrine and transition zone sites. Anoxia further crept into the metalimnion throughout the summer and into September indicating hypereutrophic conditions. This trend of metalimnetic anoxia underscores the excessive algal growth and high sediment oxygen demand and the need for addressing water quality impairments in the lake. Reducing conditions in the hypolimnion, indicated by low ORP values, occurred from late June through September, and encompassed a large volume of water, slowing the breakdown of organic materials. This provides a larger amount of material mixed into the surface water following the disruption of thermal stratification.

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 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 the fall, hypolimnetically stored nutrients mixed into the water column resulting in higher epilimnetic values. Ortho-P, the biologically available form of phosphorus, was not measured in any reportable amount in the epilimnion, likely due to uptake by algae. Hypolimnetic ortho-P accumulated throughout the season before mixing into the water column in the fall. Lacustrine phosphorus concentrations were generally lower than riverine surface phosphorus, suggesting substantial loading of phosphorous is entering the system as runoff from the watershed and dispersing throughout the lake. Riverine areas also allow constant cycling and resuspension of nutrients due to their shallow depths and susceptibility to wind mixing.

Nitrogen, another nutrient important for algal growth, was also readily available in 2022. Ammonia, nitrate, and nitrite are forms of nitrogen available to algae. Surface quantities of each quickly depleted below reporting limit for much of the season, indicating significant algal production was occurring in the lake. Average Site 1 epilimnetic total nitrogen values were similar to previous years and were in the range of eutrophic reservoirs in Oklahoma. Site 8 had the highest TN values lake-wide, with a peak in September of 1.59 mg/L. Lacustrine nitrogen measurements were generally lower than riverine nitrogen, suggesting tributaries were an important source of both nitrogen and phosphorus inputs. Hypolimnetic accumulation of ammonia was evident in summer and into early fall, stemming from the effect of thermal stratification over anoxic sediment. Anoxic conditions in the hypolimnion promoted and contributed to the release of ammonia from the sediments and decomposition of organic matter observed during the sample year. Without oxygen, nitrification reactions did not occur; thus, the increase of hypolimnetic ammonia concentrations was both typical and expected. As the lake turned over in the fall, oxygen was introduced, triggering nitrification, which created nitrite and could further oxidize to nitrate. This phenomenon was observed in September through October by a dramatic decrease in bottom depth ammonia and TN. Data collected in 2022 and documented relationships in scientific literature demonstrate the connection from excess nutrients to degraded raw water quality; therefore it remains imperative to meet nutrient reduction targets outlined in the TMDL. Nutrient and sediment load reduction targets were developed in the 2013 TMDL that, if met, would improve water quality in the lake such that designated beneficial uses could be attained by recommending a 35% load reduction rate for Total Nitrogen, Total Phosphorus, and Suspended Solids. This waste load allocation was divided amongst the three primary municipalities in the watershed: Moore, Norman, and Oklahoma City (ODEQ, 2013). In general, nutrients behaved similarly to previous years with riverine inorganic nutrients greater than lacustrine values, hypolimnetic accumulation of dissolved nutrients such as orthophosphate and ammonia, and seasonal buildup of epilimnetic TP and TN.

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 *a* to be less than 10 µg/L; however, lake wide chlorophyll concentrations in 2022 were more than three times the criteria.

2022 average chlorophyll *a* values increased from 2021 values and remained excessive, representing a need to mitigate conditions driving elevated algal biomass. Riverine sites experienced high chlorophyll *a* levels as did lacustrine areas, implying that productivity was not greatly limited by light penetration. However, it is possible that lower turbidity values, particularly in the riverine areas with a large number of T values >1, could have allowed for even higher chlorophyll *a* production. To control biological populations, it is important to understand what is driving their growth. Walker's (1999) analysis on non-algal turbidity was employed to look at light's effect on algal growth. Results indicate non-native particles did not have a limiting effect on algal growth by minimizing the ability of light to penetrate the water column to drive productivity. Re-suspension and availability of nutrients in these shallow areas continue to fuel productivity.

Thunderbird's TSI was examined using Chlorophyll *a* and classified the lake as eutrophic from April through July with hypereutrophic conditions occurring July through October. During this same time frame, TN:TP ratios indicate the lake as indeterminate or co-limiting, suggesting factors other than nitrogen or phosphorus may be driving productivity and algal growth.

Another consequence of cultural eutrophication that can lead to 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. The removal of elevated T&O compounds significantly increases the cost of producing palatable drinking water. The City of Norman has historically received T&O complaints in finished drinking water in September and October following significant lake mixing events. These mixing events contributed to T&O complaints through the process of hypolimnetically stored compounds mixing up and releasing into the epilimnion. While T&O complaints decreased from 21 in 2021 to 10 in 2022, Geosmin and MIB are still present in measurable quantities. Aside from 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 2022 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 *a* and dissolved oxygen impairments identified by the ODEQ TMDL as excess nitrogen and phosphorus. Monitoring data collected in 2022 was added to the data set and analyzed for beneficial use impairments in accordance with the USAP (OAC 252:730) 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 continues to exceed the 10 µg/L chlorophyll criterion for 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. 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 in Central Oklahoma.

Recommendations

To improve water quality, dynamic in-lake and watershed level activities must be implemented in tandem and designed to facilitate effective and measurable mitigation in the future. Hypolimnetic oxidation is worthwhile 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 hypolimnetic oxygenation alone will not provide the relief Lake Thunderbird needs to recover its attainment of beneficial uses.

In past years, the monitoring strategy has been modified several times for a multitude of reasons. Budgetary concerns have been at the forefront of that list which 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 sample year 2022. OWRB implemented the addition of nutrients collection across all sites, as they provide valuable information and minimize data gaps. Two additional sampling events were added for the year, one in October to collect data at all sites, and in November to collect vertical profiles at both Site 1 and Site 4 to bookend the breakdown of stratification and lake mixing.

In 2021, an internal loading study was initiated to document the lake's internal nutrient load through direct measurement. A series of sediment cores were collected during both the summer of 2021 and the winter of 2022 to determine the nutrient flux from the lake bottom sediments. Results from this analysis indicate that sediments are a clear source of nutrients in the water column contributing to both productivity and trophic state (Scott & Boedecker, 2023). This study provides valuable baseline information on existing conditions within the reservoir. Understanding the contribution from the lake's internal load coupled with external loads from the watershed aids decision makers in selecting appropriate in-lake BMPs and further monitoring strategies. This information will also help in identifying other in-lake technologies that are best suited to mitigate anoxic conditions in the hypolimnion.

It is important to also consider external loading, as watershed events continue delivering non-point source pollutants above numeric targets and load allocations prescribed in a TMDL. As a result, the efficacy of in-lake measures may be diminished. Vigorous watershed BMP implementation is necessary to reduce nutrient and solids movement to waterways and into Lake Thunderbird where in-lake measures can further reduce pollutant concentrations. Watershed level BMPs and in-lake mitigation strategies are not mutually exclusive but should be implemented in tandem. Elevated nutrients and low water transparency in riverine sites underscore this need to meet TMDL reduction targets.

Development of a mitigation plan for Lake Thunderbird should be unique and tailored to the reservoir. Any management plan should clearly state the current reservoir condition and desired state using measurable objectives. Finally, the plan should contain a toolbox of mitigation actions prioritized by cost and effectiveness. While not addressed in this brief, addressing watershed-based pollutant sources is an essential component of all reservoir mitigation plans. In the case of Lake Thunderbird, the plan should focus on two of the water quality impairments: excessive algae growth (chlorophyll) and suspended solids (turbidity). Developing this plan will require thoughtful consideration of methods and the potential for complimentary or synergistic effects.

Algal growth may also be addressed by focusing on nutrient reduction which in turn can also impact dissolved oxygen levels. Decreasing the amount of phosphorus, nitrogen, and solids washing into the lake from the watershed is critical. In-lake mitigation efforts focused on minimizing the suspension or re-suspension of solids from shallow areas and transfer of these suspended solids from the riverine zones to the main lake body would show the greatest positive impact to non-algal turbidity. Some methods will address both objectives, but to different levels. For this reason, cost effectiveness is a critical component to prioritize mitigation tools.

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Appendix A

Quality Assurance and Quality Control Data

Water quality sampling followed the agency-specific Standard Operating Procedures (SOPs) (OWRB, 2019). Several types of Quality Assurance/Quality Control (QA/QC) measures were employed to ensure quality data as part for the 2022 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 2022 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 depth integrated samplers and Van Dorns.

Replicate samples were collected at the surface of 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 2022 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)
4/26/2022	0.64	<0.1	0.13	0.038	0.011	7.98
5/18/2022	0.55	<0.1	0.13	0.033	<0.005	7.17
6/15/2022	0.67	<0.1	<0.05	0.033	<0.005	18.1
7/13/2022	0.85	<0.1	<0.05	0.027	<0.005	35.7
7/27/2022	1.09	<0.1	<0.05	0.031	<0.005	52.7
8/10/2022	1.19	<0.1	<0.05	0.037	<0.005	49.3
8/24/2022	0.96	<0.1	<0.05	0.035	<0.005	29.5
9/7/2022	1.2	<0.1	<0.05	0.056	<0.005	55.5
9/21/2022	1.32	<0.1	<0.05	0.056	<0.005	64.9
10/5/2022	1.16	<0.1	<0.05	0.056	<0.005	59.7
10/26/2022	1.06	<0.1	0.15	0.064	0.007	32.7

1(22)	TKN (mg/L)	Ammonia (mg/L)	NO2/NO3 (mg/L)	Total P (mg/L)	Ortho-P (mg/L)	Chlorophyll (µg/L)
4/26/2022	0.63	<0.1	0.12	0.041	0.011	7.4
5/18/2022	0.56	<0.1	0.13	0.029	<0.005	5.58
6/15/2022	0.63	<0.1	<0.05	0.032	<0.005	19.4
7/13/2022	0.78	<0.1	<0.05	0.026	<0.005	35.7
7/27/2022	1.29	<0.1	<0.05	0.029	<0.005	52.9
8/10/2022	1.08	<0.1	<0.05	0.032	<0.005	51.5
8/24/2022	0.97	<0.1	<0.05	0.037	<0.005	32
9/7/2022	1.17	<0.1	<0.05	0.051	<0.005	54.8
9/21/2022	1.33	<0.1	<0.05	0.057	<0.005	64.3
10/5/2022	1.1	<0.1	<0.05	0.056	<0.005	59.2
10/26/2022	0.98	<0.1	0.14	0.062	0.006	35.1

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. 5 $$\text{RPD} = |x_{S1(12)} - x_{S1(22)}| \;/\; \bar{x}\,(x_{S1(12)}, x_{S1(22)})\; x\; 100$$

Equation 6 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.

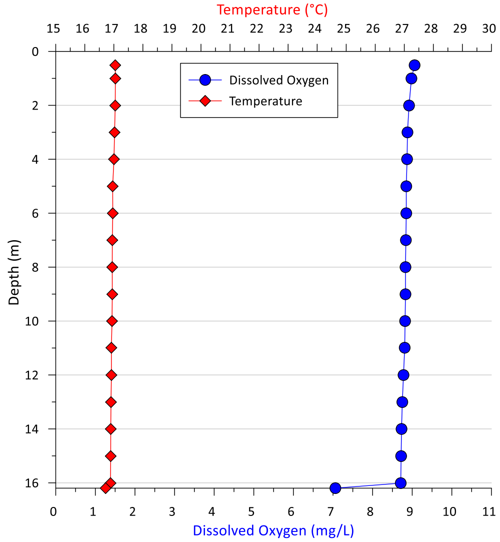
Table 8. Acceptable Limits for Laboratory Precision of Contract Laboratory Measured Parameters and Percent of Samples meeting those based on Relative Percent Differences of Replicate Samples at Site 1.

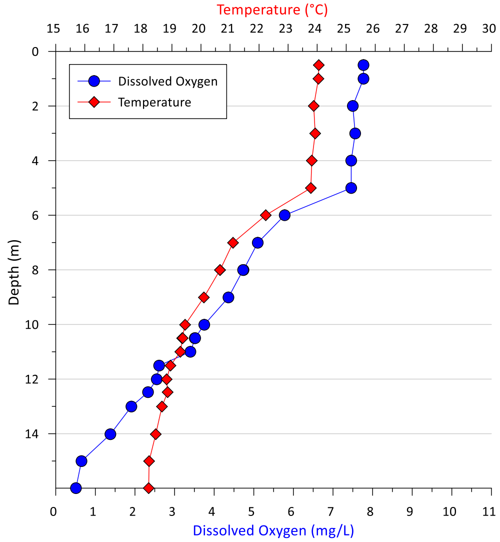
Parameter	Acceptable precision for laboratory replicates	Number of Sample Events Meeting RPD Threshold	Percent of Sample Events Meeting RPD Threshold
Total Kjeldahl Nitrogen	± 20%	11	100%
Nitrate/Nitrite	± 10%	11	100%
Ammonia	± 20%	11	100%
Total Phosphorus	± 10%	9	82%
Ortho-Phosphorus	± 20%	11	100%
Chlorophyll *a,* Sestonic Replicate	± 10%	11	100%

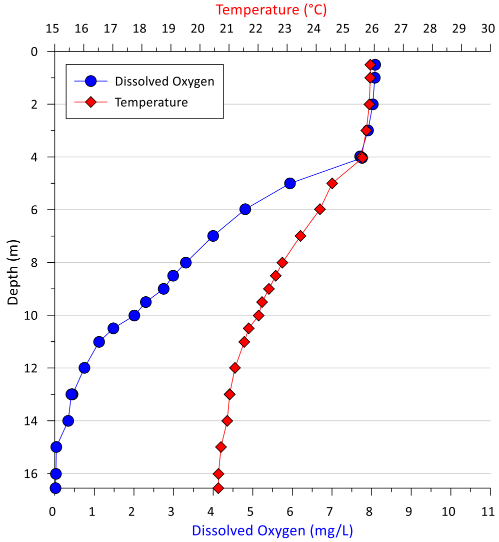
Chlorophyll *a* replicates met precision limits for the majority of the time but were still higher than other parameters. Chlorophyll *a* is a biological parameter that is extracted under extreme care, however, a high degree of variability in the chlorophyll pigment and other pigments between various 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.

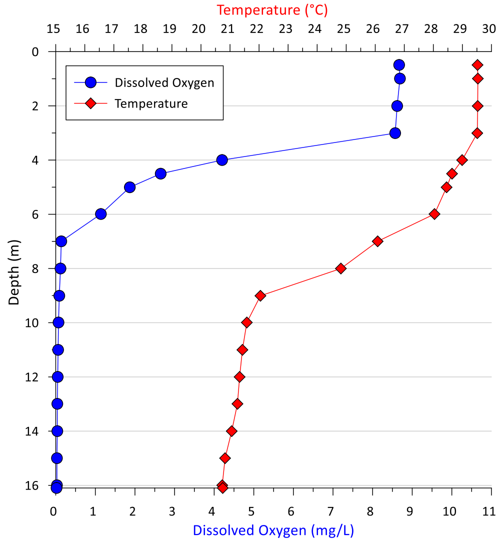
Appendix B

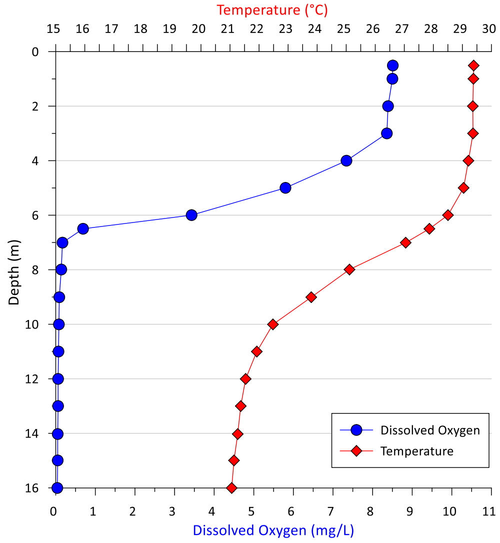
Temperature and Dissolved Oxygen Profiles

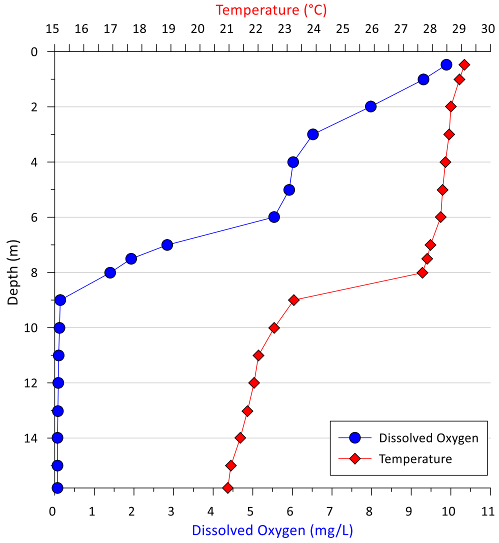

Site 1 - April, 26 2022

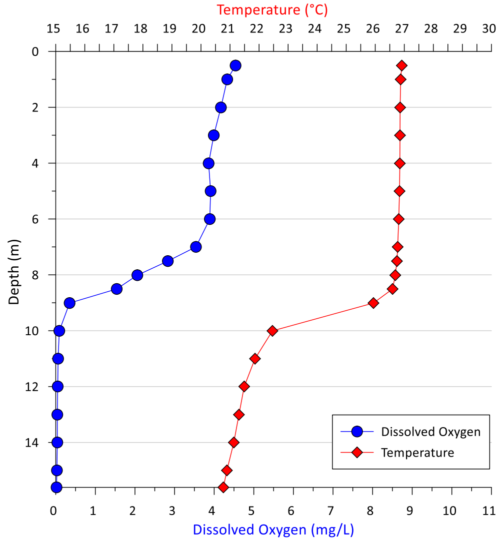

Site 1 - May 18, 2022

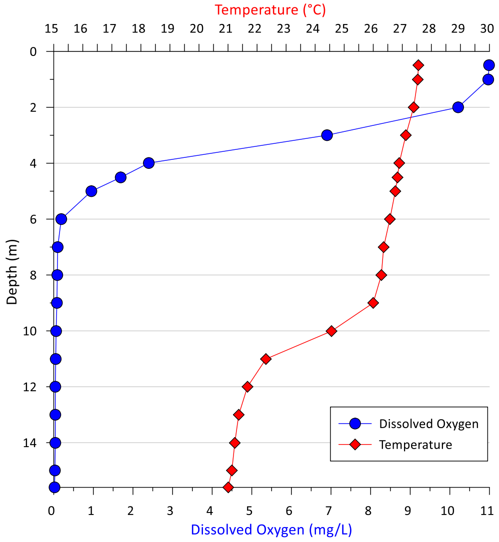

Site 1 - June 15, 2022

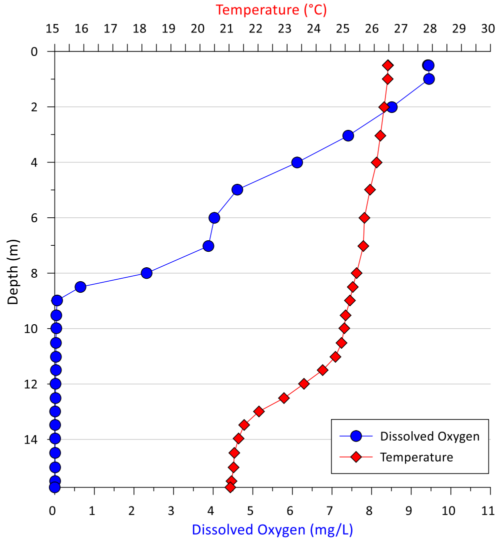

Site 1 - July 13, 2022

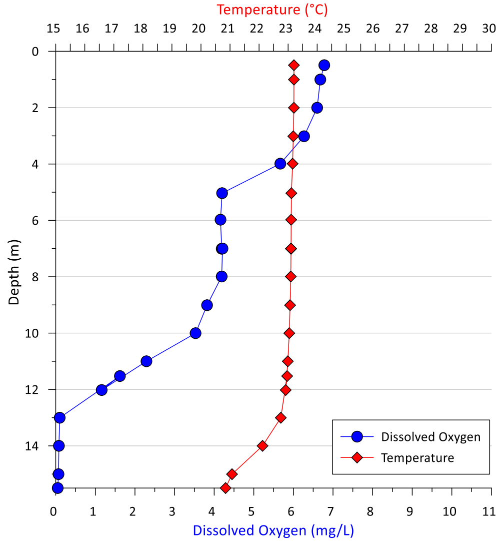

Site 1 - July 27, 2022

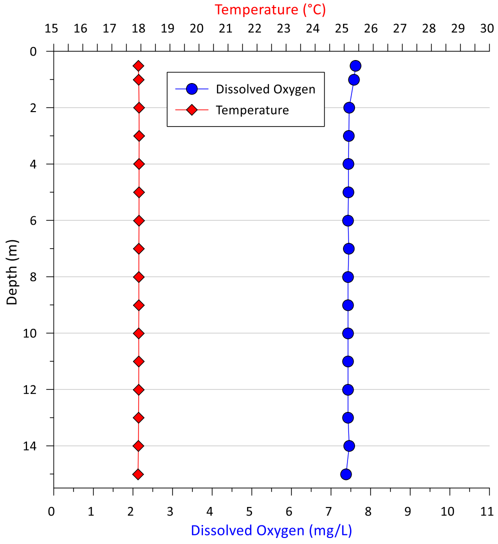

Site 1 - August 10, 2022

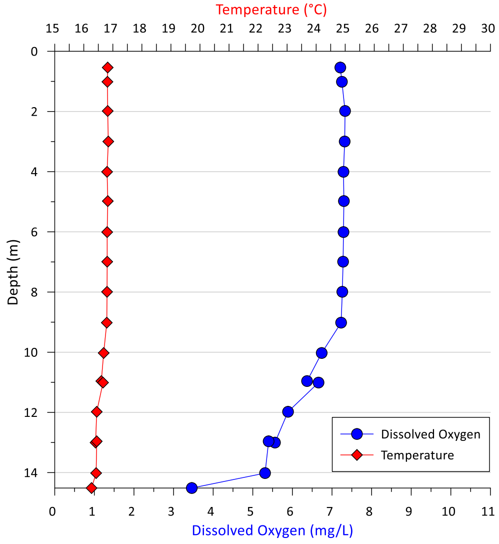

Site 1 - August 24, 2022


Site 1 - September 7, 2022


Site 1 - September 21, 2022

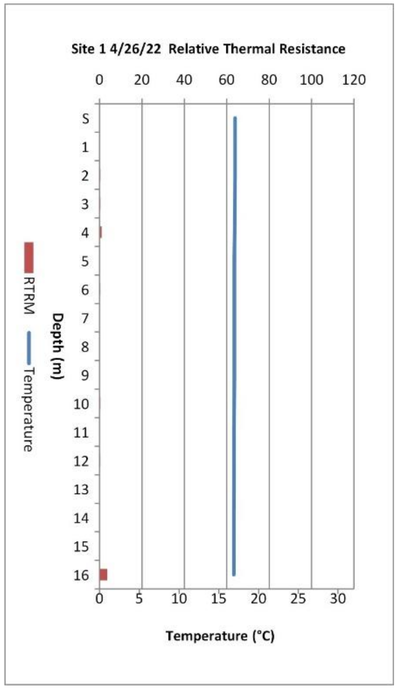

Site 1 - October 5, 2022


Site 1 - October 26, 2022

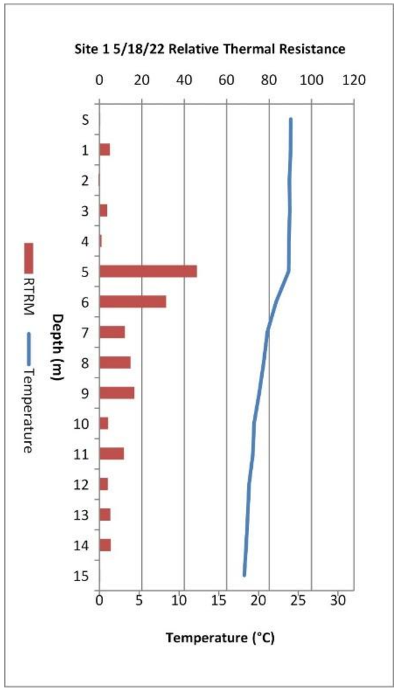

Site 1 - November 9, 2022

Appendix C

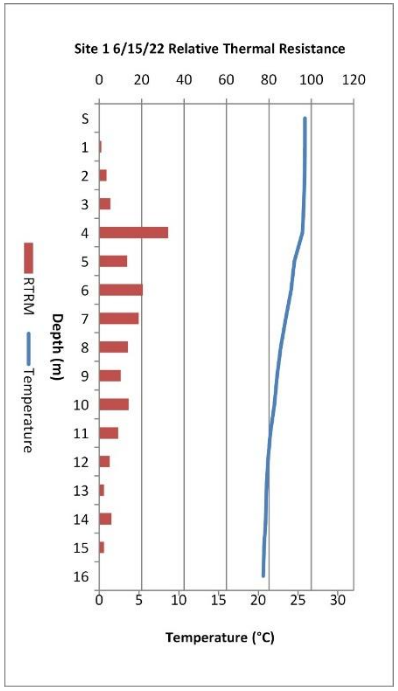
Relative Thermal Resistance Plots



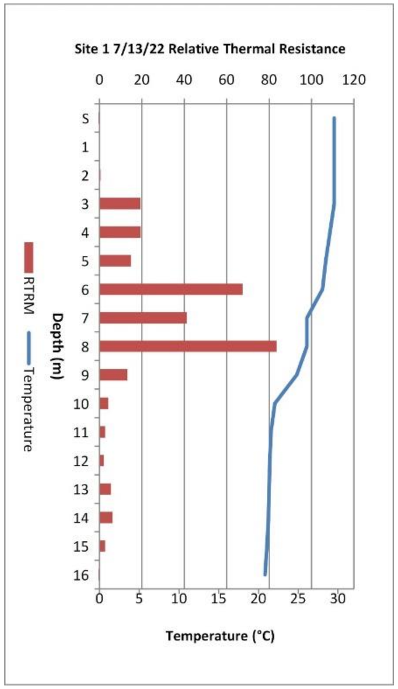
Site 1 4/26/22 Relative Thermal Resistance



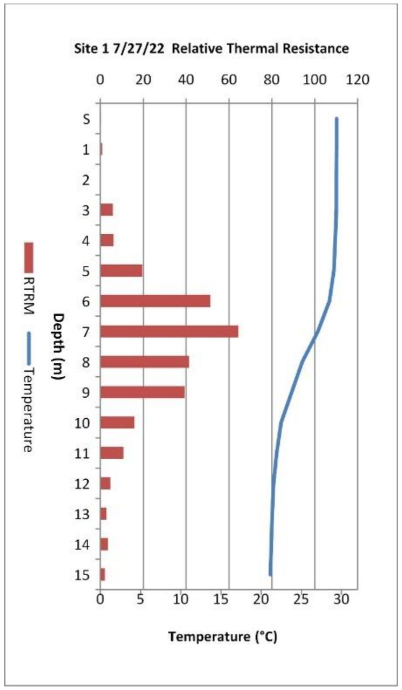
Site 1 5/18/22 Relative Thermal Resistance

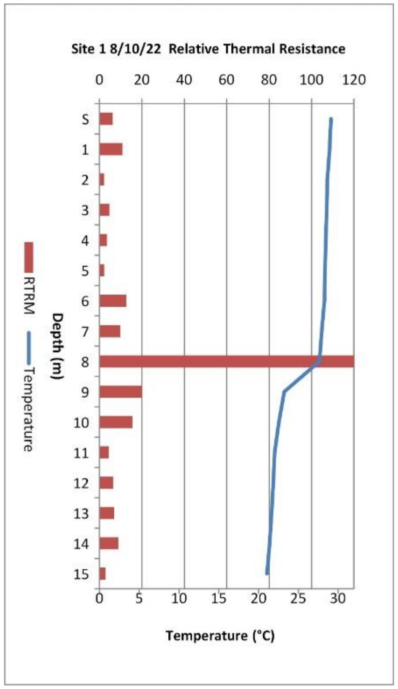


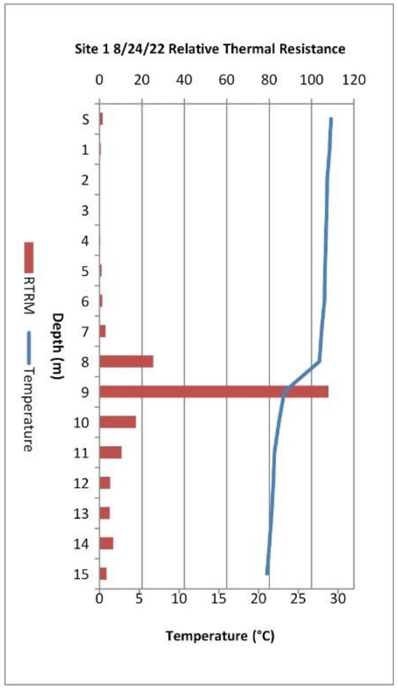
Site 1 6/15/22 Relative Thermal Resistance

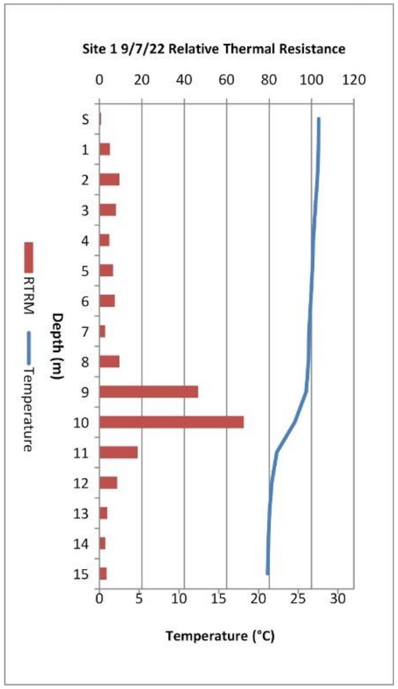


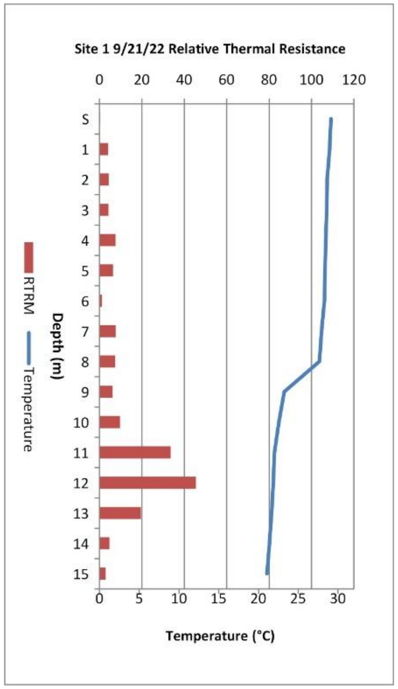
Site 1 7/13/22 Relative Thermal Resistance

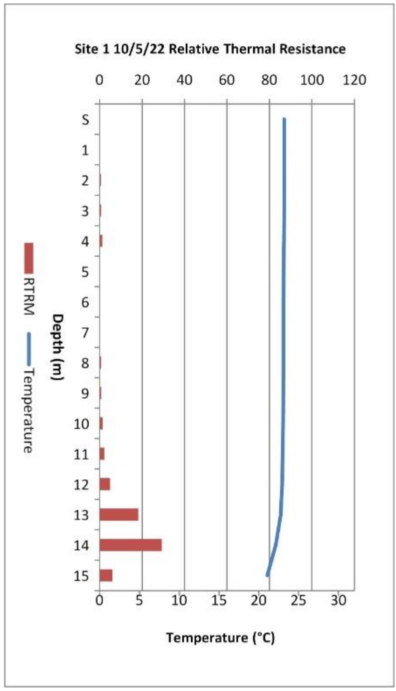

Site 1 7/27/22 Relative Thermal Resistance
0 20 40 60 80 100 120
S 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Depth (m)
RTRM
Temperature
0 5 10 15 20 25 30
Temperature (°C)

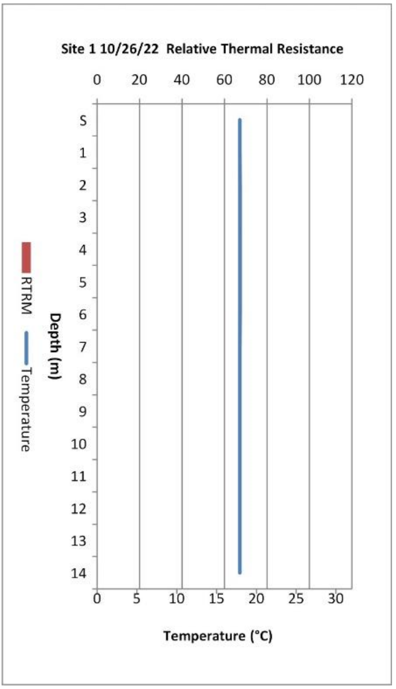

Site 1 8/10/22 Relative Thermal Resistance
0 20 40 60 80 100 120
S 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Depth (m)
RTRM
Temperature
0 5 10 15 20 25 30
Temperature (°C)

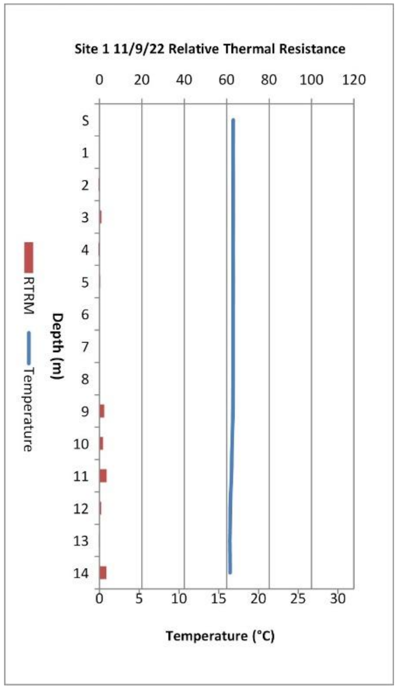

Site 1 8/24/22 Relative Thermal Resistance
0 20 40 60 80 100 120
S 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Depth (m)
RTRM
Temperature
0 5 10 15 20 25 30
Temperature (°C)


Site 1 9/7/22 Relative Thermal Resistance
0 20 40 60 80 100 120
S 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Depth (m)
RTRM
Temperature
0 5 10 15 20 25 30
Temperature (°C)


Site 1 9/21/22 Relative Thermal Resistance
0 20 40 60 80 100 120
S 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Depth (m)
RTRM
Temperature
0 5 10 15 20 25 30
Temperature (°C)


Site 1 10/5/22 Relative Thermal Resistance
0 20 40 60 80 100 120
S 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Depth (m)
RTRM
Temperature
0 5 10 15 20 25 30
Temperature (°C)


Site 1 10/26/22 Relative Thermal Resistance
0 20 40 60 80 100 120
S 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Depth (m)
RTRM
Temperature
0 5 10 15 20 25 30
Temperature (°C)


Site 1 11/9/22 Relative Thermal Resistance
0 20 40 60 80 100 120
S 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Depth (m)
RTRM
Temperature
0 5 10 15 20 25 30
Temperature (°C)