

Lake Thunderbird Water Quality

2021 Final Report

Submitted to

Central Oklahoma Master Conservancy District



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Submitted by

Oklahoma Water Resources Board



OKLAHOMA
Water Resources Board

Table of Contents

Table of Figures	6
List of Tables	7
Executive Summary	5
Introduction.....	6
Sampling Regime	6
Watershed	9
Climate.....	11
Hydrologic Budget	13
Water Quality Evaluation	16
Thermal Stratification, Temperature, and Dissolved Oxygen	16
pH and Oxidation-Reduction Potential	21
Nutrients	23
Phosphorus – P	23
Nitrogen – N.....	26
Algae	31
Algal Biomass	31
Algal Limitation	34
Nutrients	35
Light.....	36
Trophic State Index – TSI.....	36
Total Organic Carbon – TOC	38
Taste and Odor Complaints	39
Water Quality Standards	41
Dissolved Oxygen – DO.....	42
Chlorophyll <i>a</i>	42
Water Clarity.....	43
Discussion	45
Recommendations.....	48
References	50
Appendix A.....	53
Quality Assurance and Quality Control Data	53
Appendix B.....	55
Temperature and Dissolved Oxygen with Depth	55
Appendix C.....	65
Relative Thermal Resistance Plots	65

Table of Figures

Figure 1. 2021 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.....	8
Figure 2. Updated 2019 National Land Cover Data for Lake Thunderbird’s watershed.	10
Figure 3. 2021 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.	12
Figure 4. 2021 and Long-Term Average Monthly Temperature as recorded at the Norman Mesonet Station. (Mesonet, 2021).....	13
Figure 5. 2021 Lake Thunderbird Water Input and Output sources by month, expressed as the percent of total.	15
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.....	17
Figure 7. RTRM graphic for Site 1 on July 21, 2021.	18
Figure 8. 2021 Isopleths of Temperature (°C) and Dissolved Oxygen (mg/L) versus Depth (m) at Site 1.	19
Figure 9. A Temperature and Dissolved Oxygen vertical profile with the highest temperature recorded at Site 1. ..	20
Figure 10. Temperature and Dissolved Oxygen profile at Site 1 on October 11, 2021, showing a near isothermal water column.	21
Figure 11. 2021 Isopleth of pH (S.U.) Versus Depth (m) at Site 1.	22
Figure 12. 2021 Isopleth of Oxidation-Reduction Potential (mV) versus Depth (m) at Site 1 from April to October.	23
Figure 13. 2021 Surface Phosphorus variables as TP and Ortho-P (mg/L) at Site 1. Ortho-P values on the green dotted line indicate its presents below reporting limit and are graphed at half that value.	24
Figure 14. 2020 Site 1 Orthophosphate at surface and bottom depths.	25
Figure 15. Surface Phosphorus (mg/L) from the three riverine sites, 2019-2021.	26
Figure 16. 2021 Surface Total Nitrogen and Ammonia over time at Site 1. Of note, 2019-present Ammonia samples are present below the detection limit and are graphed at half the reporting limit (0.05).	27
Figure 17. Surface Nitrogen species at Site 1 for 2021. Blue dashed line indicates presence below detection limit and are graphed at half the reporting limit (0.05 mg/L).	28
Figure 18. Site 1 Hypolimnetic Nitrogen species in 2021.	29
Figure 19. 2021 Surface Total Nitrogen (mg/L) from the three riverine sites and Site 1.	30

Figure 20. 2019-2021 chlorophyll <i>a</i> values at Site 1, highlighting annual increase. Dashed line represents OWQS for SWS reservoirs of 10 µg/L.	32
Figure 21. Lacustrine chlorophyll <i>a</i> values for 2021. Dashed line represents OWQS for SWS reservoirs of 10 µg/L.	33
Figure 22. 2021 Lake Thunderbird surface chlorophyll (µg/L) at riverine sites. Dashed line represents OWQS for SWS reservoirs of 10 µg/L.	34
Figure 23. 2021 Lake Thunderbird TN:TP by sample event.	35
Figure 24. Site 1 Chlorophyll TSI in 2020. Dashed lines represent the divisions of trophic states.	37
Figure 25. 2021 Carlson's Chlorophyll <i>a</i> TSI values for riverine sites. Dashed line delineates ranges for trophic state.	38
Figure 26. Taste and Odor complaints by month. Data is from personal communication with G. Wellborn, City of Norman, January 31, 2022.	40
Figure 27. 2021 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.	41
Figure 28. 2021 Lake Thunderbird chlorophyll <i>a</i> (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.	43
Figure 29. 2021 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.	44
Figure 30. 2021 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.	45

List of Tables

Table 1. 2021 Water quality sampling parameters.	7
Table 2. 2021 Lake Thunderbird sample dates.	7
Table 3. 2019 NLCD acreage totals for the Lake Thunderbird watershed. MRLC, 2021.	11
Table 4. 2021 Lake Thunderbird Water Budget Calculations expressed in Acre-feet. Parentheses indicate a negative value. Values taken from USACE, 2022.	15
Table 5. Summary of Carlson's Trophic State Categories. Carlson, 1977.	37
Table 6. 2021 Lake Thunderbird Total Organic Carbon (mg/L).....	39

Table 7. Summary of 2021 Replicate Sample Results Designated as 1 (12) & 1 (22)	53
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.	54

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. Lake Thunderbird began operation in 1965 after construction by the Bureau of Reclamation starting in 1962. 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 2021, monitoring was conducted to continue identification of any water quality concerns and an assessment against water quality standards.

2021 monitoring documented a typical thermal stratification pattern in the lake with the onset of stratification occurring in June 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 2021 results are as follow:

- 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 improvement 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 could help Lake Thunderbird meet water quality standards for turbidity, dissolved oxygen, and chlorophyll *a*. Continued exploration of technologies for in-lake 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, 2018). 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 2021 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 2021 occurred between April 14 and October 11. Monitoring was conducted for the parameters in **Table 1** at sites indicated in **Figure 1**. Additional information about sample dates is provided in

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. 2021 water quality sampling parameters.

General Water Quality		
Chlorophyll <i>a</i> (mg/L)	Nepthelometric Turbidity (NTU)	Secci Disk Depth (cm)
Nutrients		
Total Kjeldahl Nitrogen (TKN)	Orthophosphate (ortho-p)	Total Phosphorus (TP)
Nitrate as Nitrogen (NO ₃)	Nitrite as Nitrogen (NO ₂)	Ammonia as Nitrogen (NH ₃)
Total Nitrogen		Total Organic Carbon (TOC)
Profile Parameters		
Dissolved Oxygen Concentration (mg/L)	Dissolved Oxygen Percent Saturation	Water Temperature
Specific Conductance (SpC)	Oxidation Reduction Potential (ORP)	pH
Environmental Observations		
Air Temperature	Wind (Direction/Speed)	Cloud Cover
Precipitation	Wave Classification	Barometric Pressure
Site Depth	Surface SpC	Sample Collection Time

Table 2. 2021 Lake Thunderbird sample dates.

Sample Date	Site 01 Final Depth (m)	Lake Elevation (1039.00)
4/14/2021	16.3	1038.12
5/19/2020	16.4	1039.95
6/16/2021	16.3	1039.26
7/7/2021	17.4	1043.65
7/21/2021	16.7	1041.24
8/4/2021	16.2	1039.32
8/18/2021	16.2	1039.09
9/1/2021	16.2	1038.79
9/15/2021	16.1	1038.46
10/11/2021	16.1	1038.02

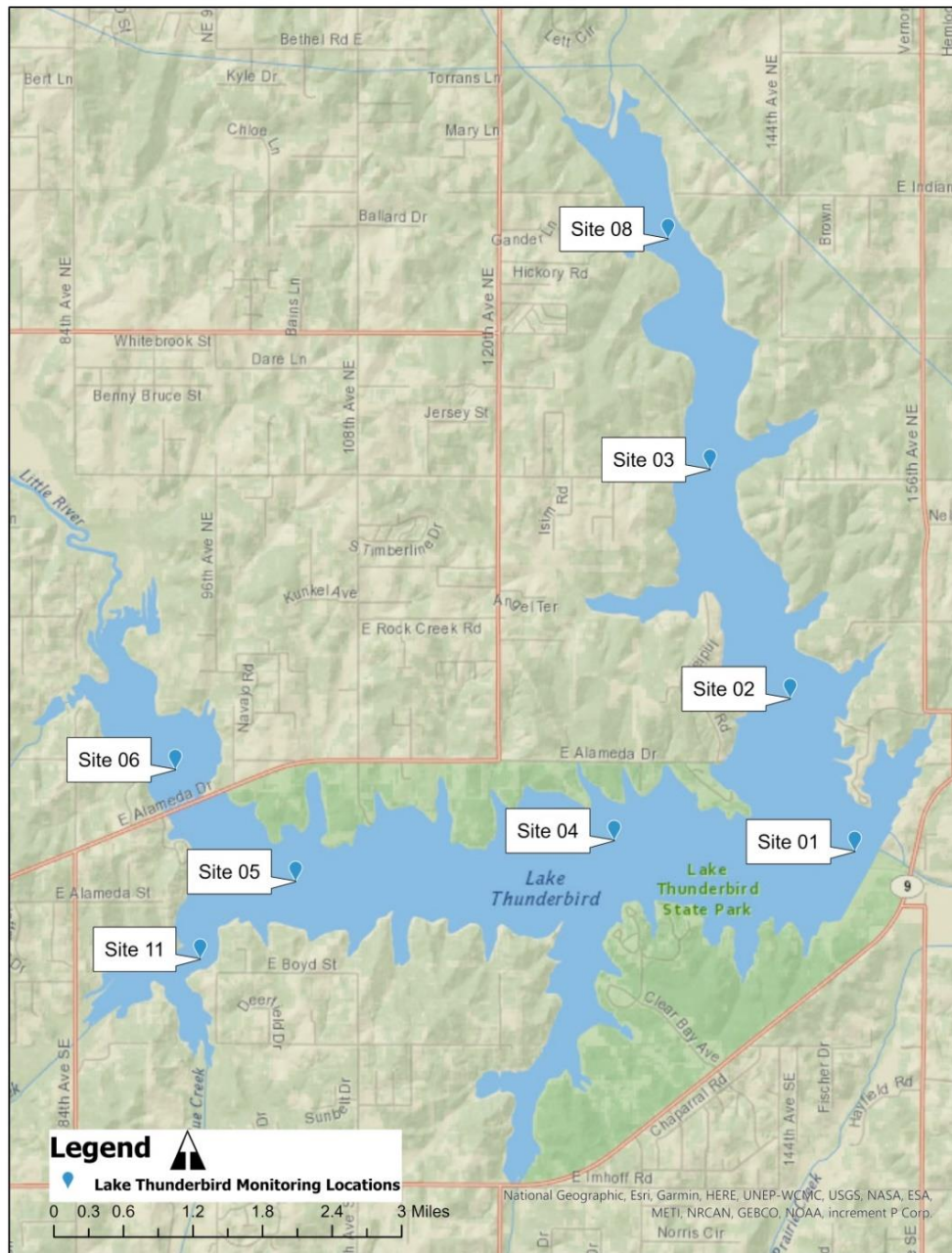


Figure 1. 2021 Lake Thunderbird sampling sites. The lacustrine zone is comprised of Sites 1, 2, and 4. Riverine zones are represented at Sites 6, 8, and 11. Sites 3 and 5 represent the transitional zone from riverine to lacustrine.

Data for water quality indicators were collected following OWRB’s standard operating procedures (SOPs) for water quality samples (OWRB, 2018a). Variables such as pH, Dissolved Oxygen (DO), water temperature (°C), Specific Conductance (SpC), and Oxidation-Reduction Potential (ORP) were monitored in-situ utilizing a YSI® multi-parameter sonde. In accordance with manufacturer’s specifications and published SOP’s, 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 begin 0.5 m below the surface of the water and continue 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 is 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 80cm, the targeted depth for collecting a DIS is 160cm. The DIS is marked every 10cm from 50cm until 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, and turbidity samples are collected at all sites. Nutrient samples are only collected at the surface of Sites 1, 6, 8, and 11. 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. Specifics for nutrients, where collected, is 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 their hydrologic connection to each other is negligible as it 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 for 2021.

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 (Bureau of Reclamation, 2020). At this elevation, the lake surface area extends to 5,505 acres with a volumetric capacity of 103,840 acre-feet (Bureau of Reclamation, 2020). The BOR concluded that total volume of the lake has declined by 12% since construction in 1965, with an annual 50-year sedimentation rate of approximately 470 acre-feet per year (Bureau of Reclamation, 2020). Equating to an annual sediment yield, or amount of sediment entering the reservoir from the watershed, at around 1.93 ace-feet per square mile per year, which the Bureau considers high (Reclamation, 2006).

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, 2021). Water is released below the dam into the Little River, which has a confluence with the Canadian River roughly 85 miles downstream.

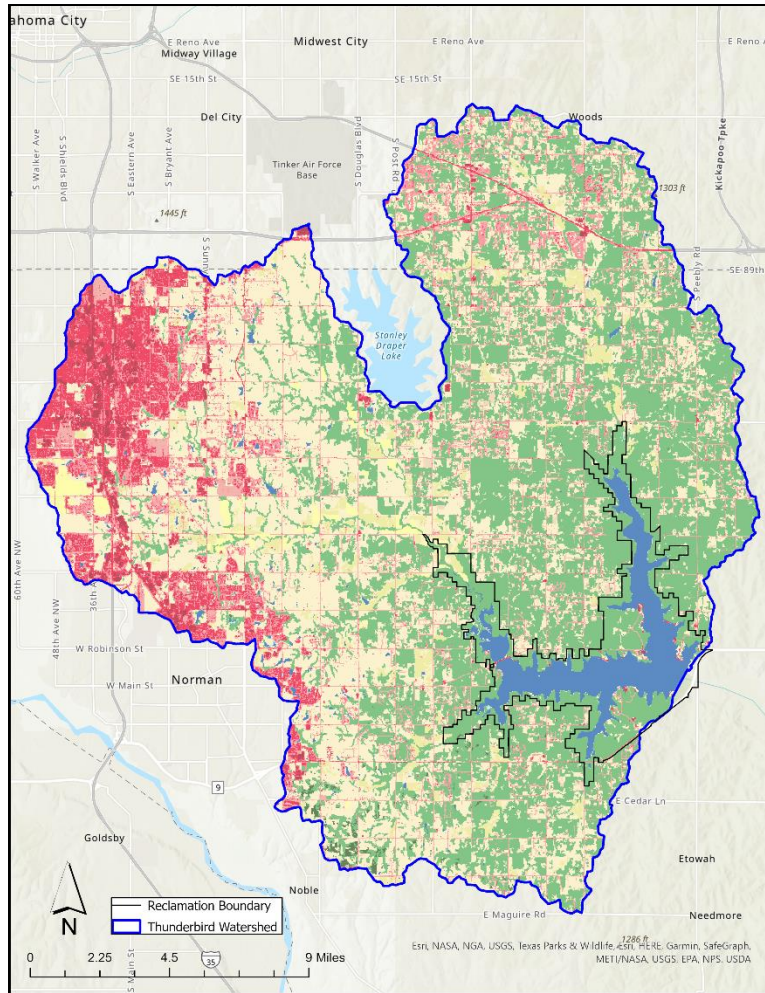


Figure 2. Updated 2019 National Land Cover Data for Lake Thunderbird's watershed.

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 still make up nearly 70 percent 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 2021. Annual precipitation at Lake Thunderbird dam in 2021 totaled 25.25 inches, as reported at the dam by the United States Army Corps of Engineers (USACE) (USACE, 2021), substantially less than the lake's long-term average of 38 inches (U.S. Geological Survey, 2021). Peak rainfall events correspond to increases in lake elevation, while inflow volumes were significantly lower in 2021 compared to 2020 and followed rain events. 2021 sampling season also captured the lowest and highest lake elevations at 1037.89ft and 1043.87ft, a variation of nearly six feet. This contrasts with the more stable elevations experienced in 2020 where sample season elevations fluctuated 2.1 feet. Such variation in elevation observed in 2021 could signify flushing events and is important to keep in mind when examining nutrient levels and non-algal turbidity throughout the reservoir.

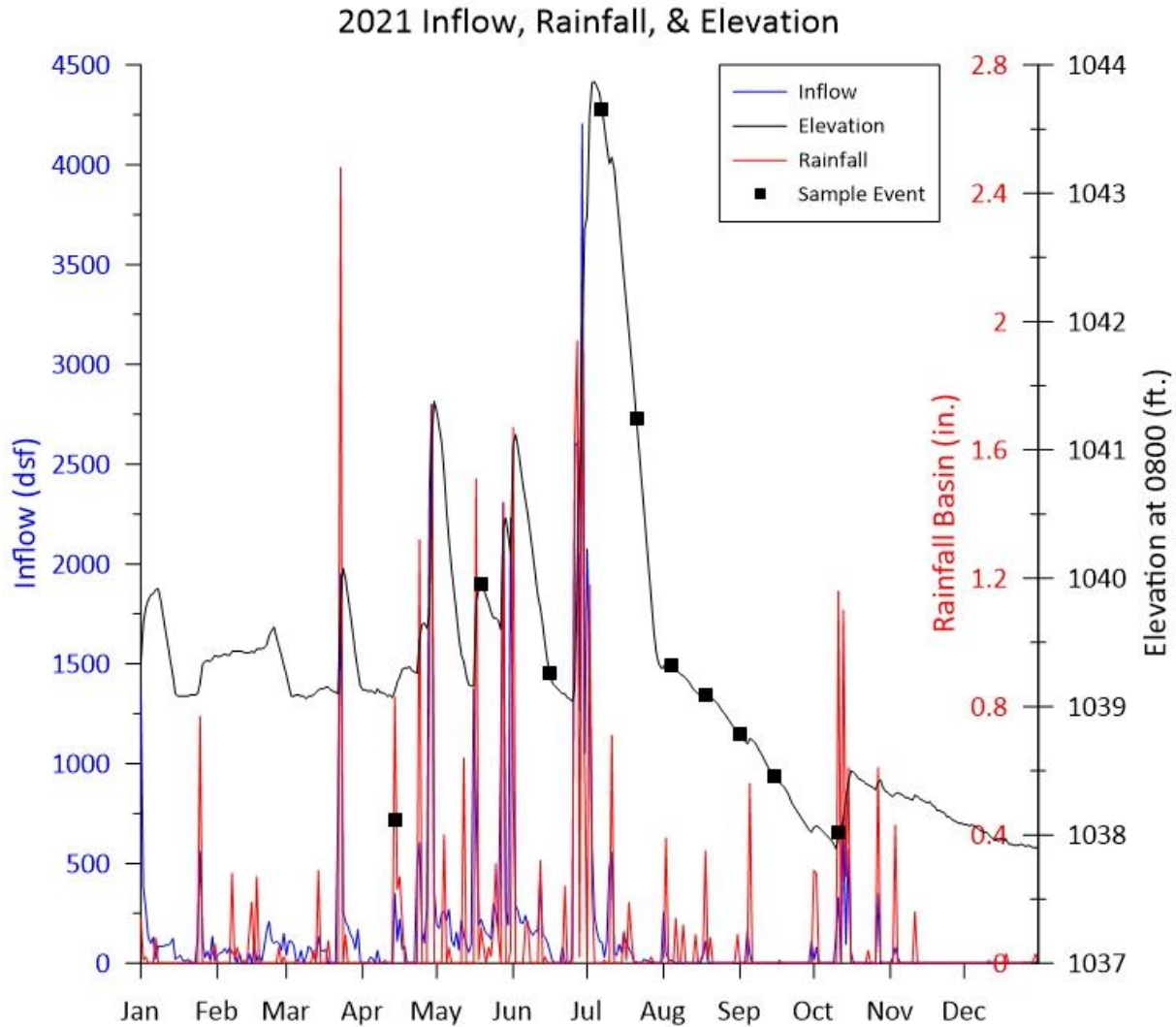


Figure 3. 2021 Inflow, Rainfall, and Elevation Data for Lake Thunderbird, with Sample Dates Indicated. Inflow as dsf (daily-second-foot) indicates daily volume passing through a single location.

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 44** compares monthly mean temperatures in 2021 to the long-term monthly mean using 2002-2021 data from the Oklahoma Mesonet's Norman station, which is approximately 27 kilometers west of Site 1 at Max Westheimer Airport (Mesonet, 2021). 2021 was an interesting year for temperature. January started off slightly above average, but quickly fell to the lowest average for February in Mesonet's history for the station, thanks to a historic cold spell that affected much of the United States. However, March rebounded with above average temperatures. April through August again dipped below the monthly mean before jumping above average from September through December. Peak Mesonet recorded air temperature occurred in late July, while peak water temperature (Site 1) occurred at the first sampling event in September, much later in the sampling season than previous years. Despite climatological variances from the mean observed in 2021, the lake's annual pattern and duration of thermal stratification remained.

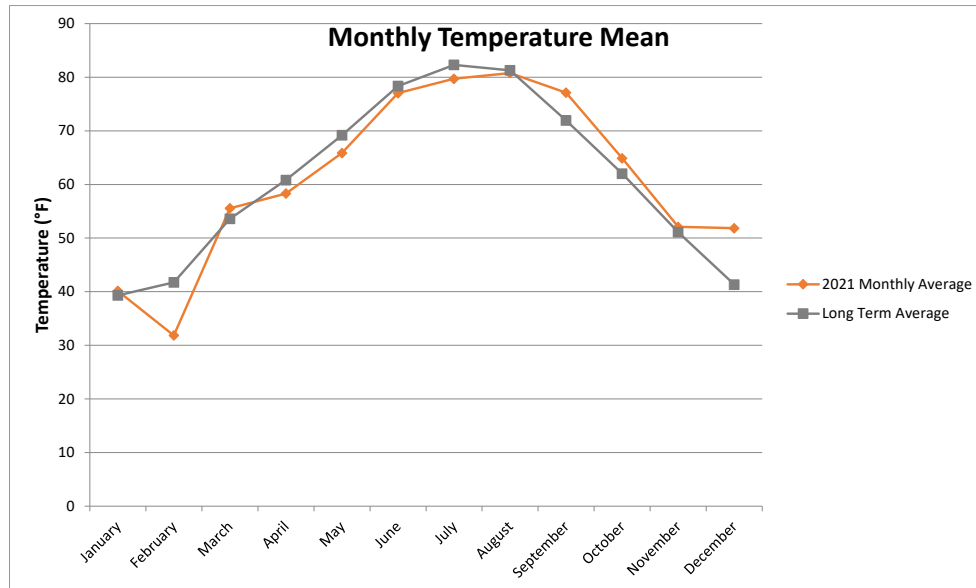


Figure 4. 2021 and Long-Term Average Monthly Temperature as recorded at the Norman Mesonet Station. (Mesonet, 2021)

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:

$$\text{Eq. 1.} \quad \frac{\Delta V}{\Delta t} = Q_{in} - Q_{out} + PA_s - E_v A_s - W_s$$

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

A_s is lake surface area (acres),

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

P is the rainfall directly on the lake (feet),

E_v is the lake evaporation (feet),

W_s is the water exported for water supply use (acre-feet)

In 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 close to calculated error and insignificant, based on the relatively impermeable lake substrate.

Because the USACE reported inflow term includes direct rainfall, we use their reported inflow minus calculated direct rainfall volume 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:

$$\text{Eq. 2.} \quad Q_p = P * A_s$$

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.

$$\text{Eq. 3.} \quad Q_e = E_v * A_s$$

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 (Bureau of Reclamation, 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 44**). 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 2021 water budget reveals the lake received most inputs in the earlier portions of the year and released a large volume in July. The remainder of the year followed similar patterns to previous years, with an input spike in October. Total inputs were highest through June and early July, corresponding to when the lake received most of the inflow. **Figure 5** provides a visual summary of water gains and losses. Overall, inputs peaked early in the year with outputs controlling the three consecutive months of May, June, and July. Water supply was the sole withdraw or release from July through the end of the year.

Table 4. 2021 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	7,451	1,006.21	8,457	1,113	1,129	5,498	7,740	718	557	(161)
Feb	3,388	171.86	3,559	1,094	1,009	2,440	4,542	(983)	(557)	426
Mar	8,608	1,188.24	9,796	3,030	1,291	7,660	11,981	(2,185)	(1,108)	1,077
Apr	15,354	708.32	16,062	3,147	1,171	1,359	5,676	10,386	12,576	(2,190)
May	23,075	1,087.94	24,163	2,959	1,576	23,445	27,980	(3,817)	(1,785)	2,032
Jun	27,971	2,944.41	30,915	3,873	1,654	15,142	20,669	10,246	10,948	(702)
Jul	11,128	2,108.22	13,237	4,664	1,768	30,230	36,662	(23,426)	(20,631)	2,795
Aug	512	499.53	1,011	4,253	1,866	-	6,119	(5,108)	(2,757)	2,351
Sep	380	245.08	625	4,070	1,906	-	5,976	(5,351)	(3,778)	1,573
Oct	2,940	1,759.54	4,700	2,792	1,619	-	4,411	289	1,070	(781)
Nov	(98)	375.77	278	1,784	1,330	-	3,114	(2,837)	(1,070)	1,767
Dec	32	17.62	50	1,956	1,329	-	3,285	(3,236)	(529)	2,707
Total	100,740	12,113	112,853	34,735	17,648	85,773	138,156	(25,304)	(7,064)	10,893

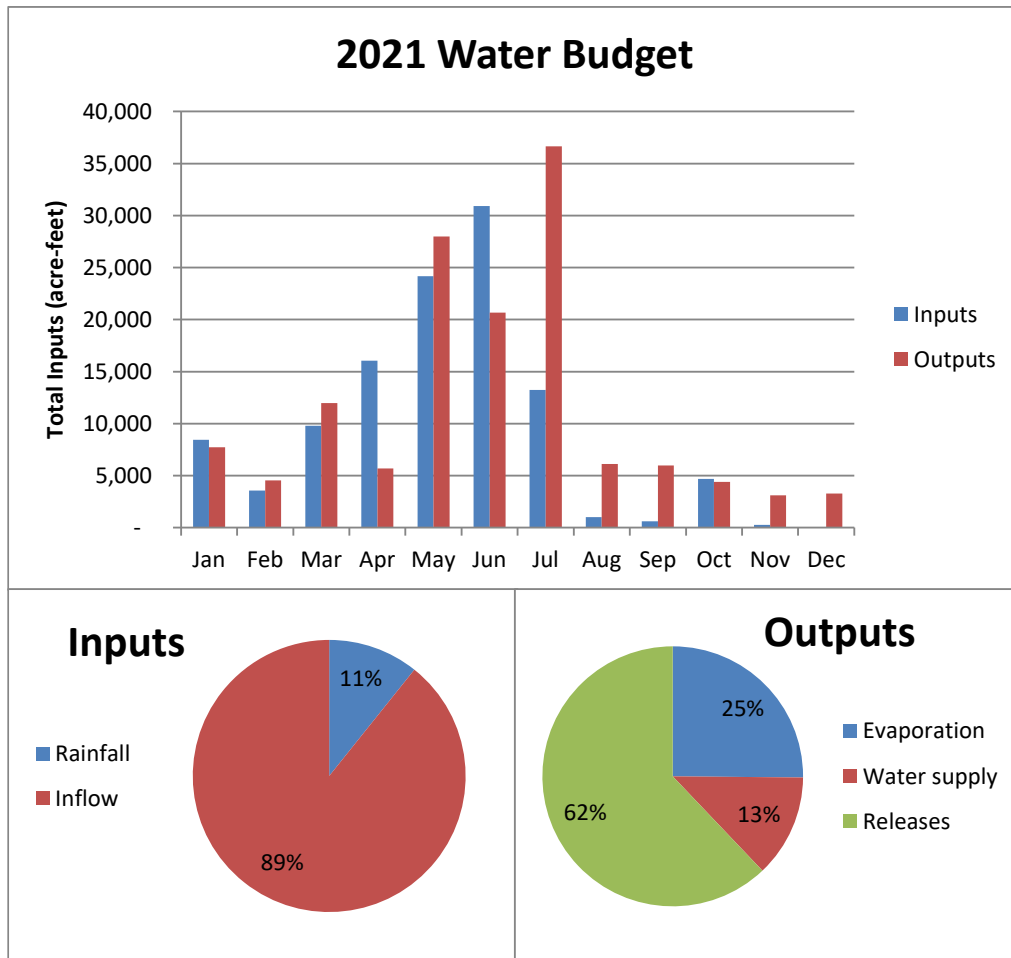


Figure 5. 2021 Lake Thunderbird Water Input and Output sources by month, expressed as the percent of total.

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 1.00 years in 2021, which is considerably lower than the average T (1995 to 2021) of 3.38 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. Utilizing 2015 BOR survey data, the 2021 cumulative annual error is 10,893 acre-feet, averaging to a monthly error of 907.77 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 1965 (Bureau of Reclamation, 2020). This amount equates to roughly 11% of lost storage as original designed. The potential distribution of deposited sediment has consequences for in-lake processes such as sediment suspension and nutrient flux and is considered high (Reclamation, 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 onset 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**.

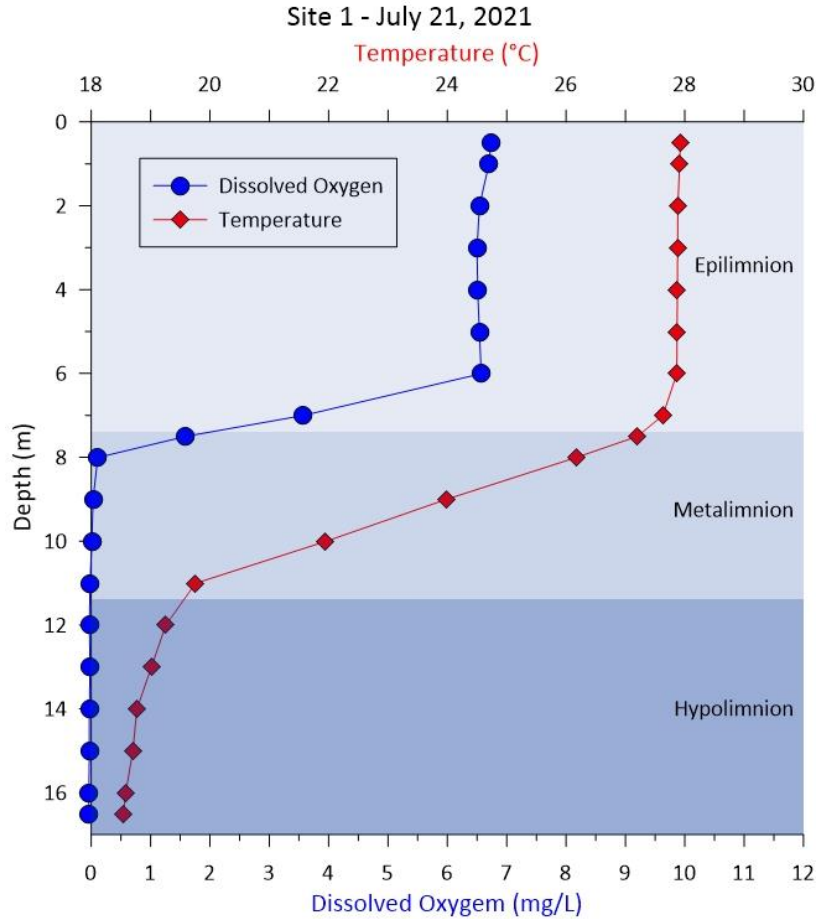


Figure 6. A typical Temperature and Dissolved Oxygen vertical profile for Lake Thunderbird during stratification. Boundaries between the Epilimnion, Metalimnion and Hypolimnion are approximated for illustrative purposes.

Relative thermal resistance to mixing (RTRM) calculations inform on the strength or intensity of stratification and is a unit-less measure of temperature-based density differences, indicating how likely or unlikely layers are to mix. RTR 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 RTR for sampling at Site 1 on July 21, 2021. 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.

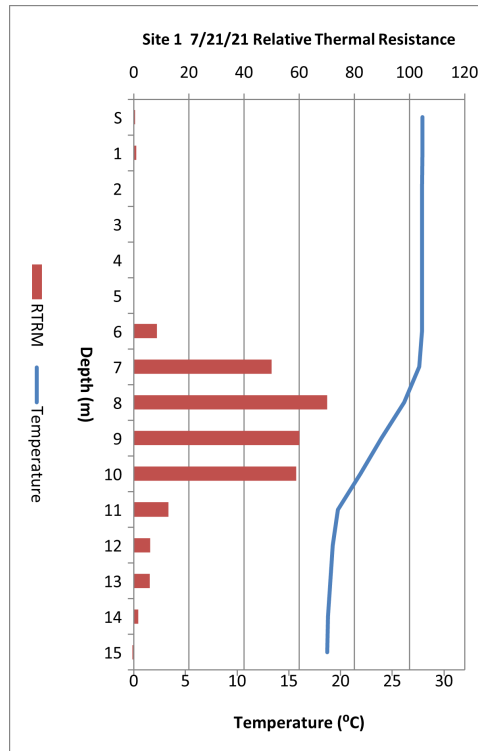


Figure 7. RTRM graphic for Site 1 on July 21, 2021.

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 green as temperature cools.

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 to induce some amount of stress for organisms. Once DO content falls below 2.0 mg/L, the water is anoxic or lacking sufficient oxygen for most organisms to survive.

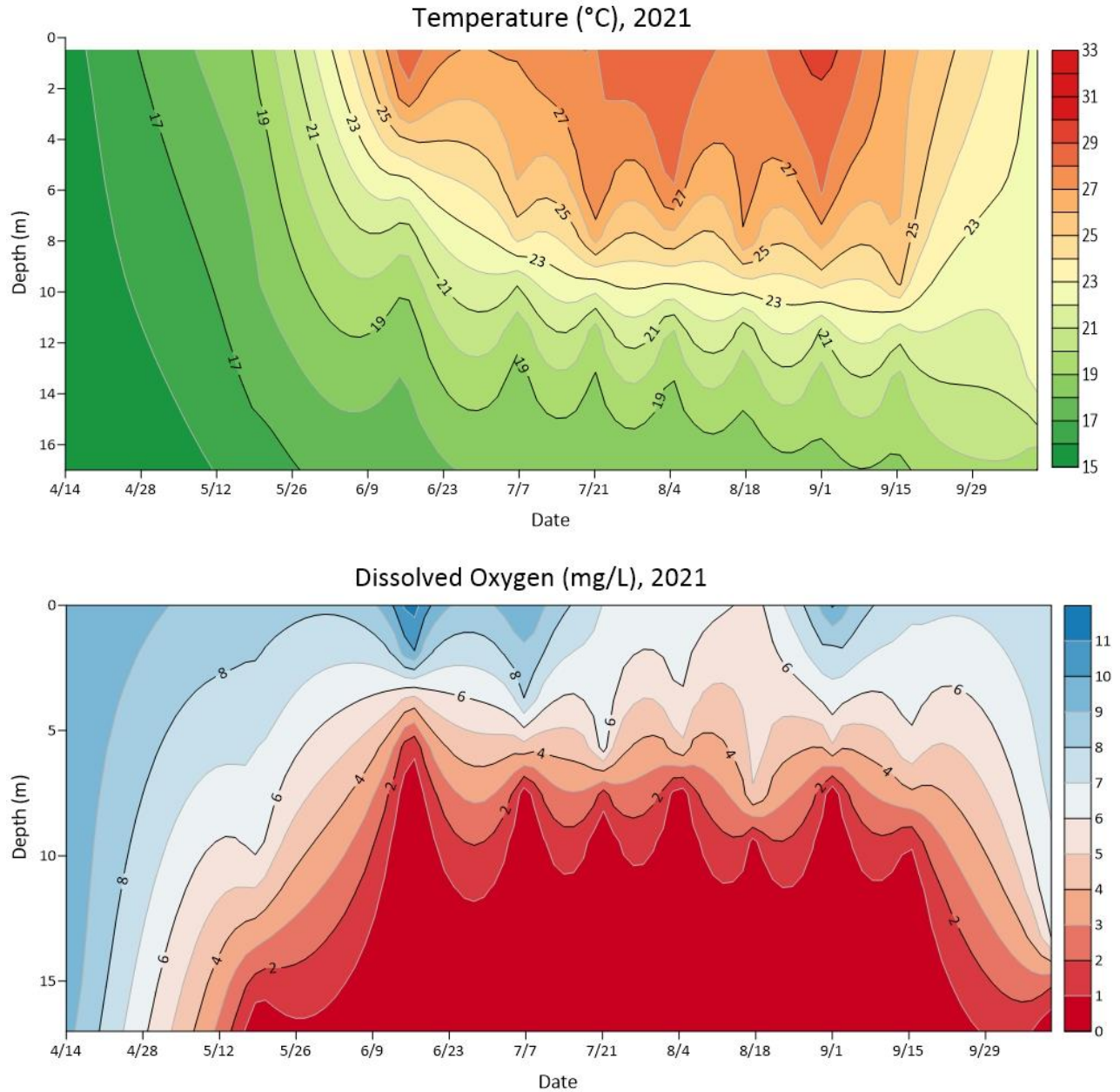


Figure 8. 2021 Isoleths of Temperature (°C) and Dissolved Oxygen (mg/L) versus Depth (m) at Site 1.

Little thermal difference with depth was observed on the first sample event in April, indicating a well-mixed water column. At the next event on May 19, 2021, thermal stratification had increased, with a 2.58°C temperature gradient from surface to bottom. By June of 2021, DO dynamics began setting up for the season with mostly anoxic water in the hypolimnion of lacustrine and transition sites. Epilimnetic warming continued until September 1st when Site 1 reached a peak temperature of 29.63°C (**Figure 9**). Evident at this sampling event is the push of anoxic water upwards, breaking into and weakening the metalimnion and dominating the hypolimnion. This is evidence of 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 June and continued through September.

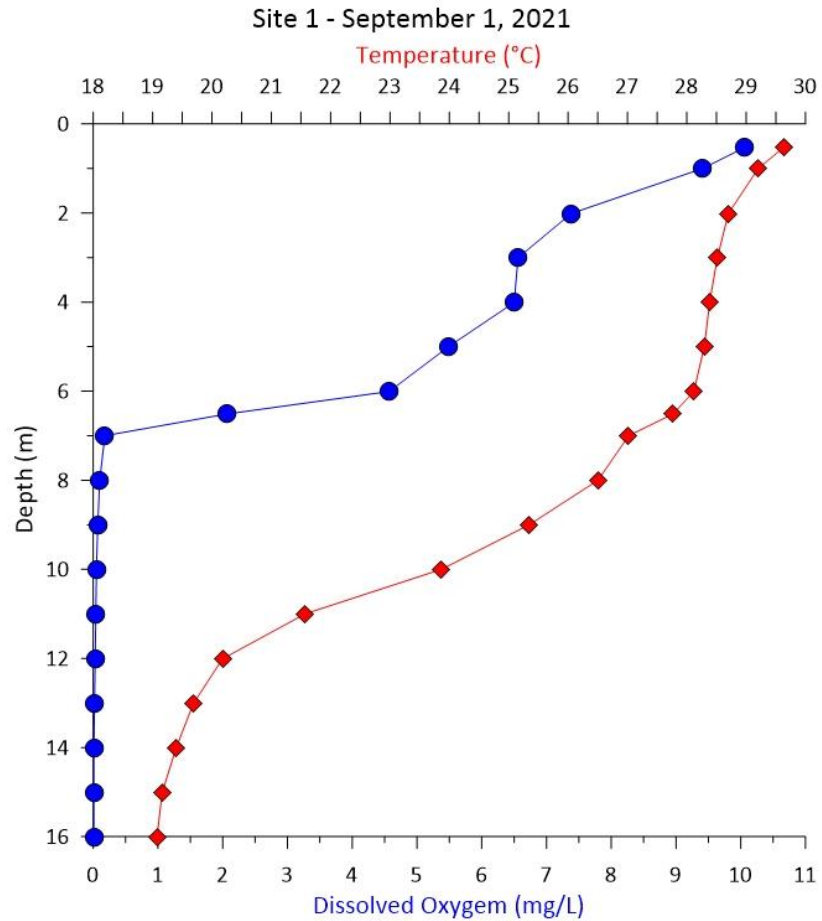


Figure 9. A Temperature and Dissolved Oxygen vertical profile with the highest temperature recorded at Site 1.

After the second sampling event in September (9/15), water began to cool as the epilimnion began to deepen with slight stratification in the hypolimnion. This marks the onset of lake mixing and by the October event, the water column was days away from being isothermal, or completely mixed (**Figure 10**).

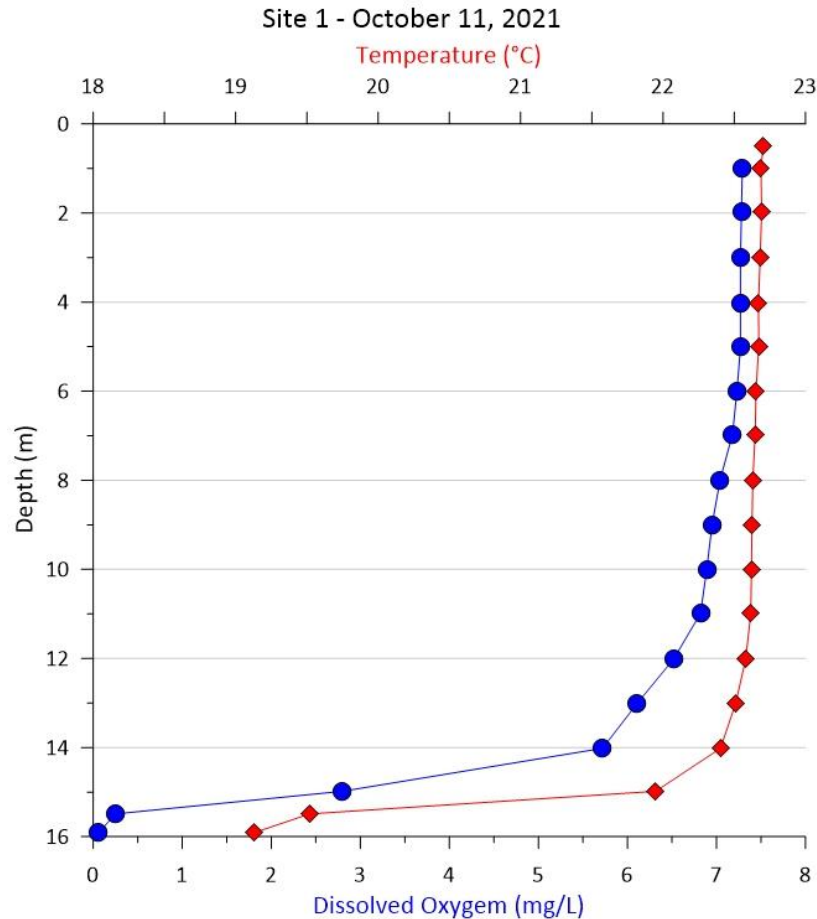


Figure 10. Temperature and Dissolved Oxygen profile at Site 1 on October 11, 2021, showing a near isothermal water column.

Metalimnetic anoxia experienced throughout the lacustrine and transition zones on Lake Thunderbird in 2021 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 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 oxygen concentration driven by algae through daytime photosynthesis and nighttime ecosystem respiration. Lake Thunderbird exhibited elevated pH in surface water over the summer, indicating high rates of photosynthesis. Photosynthesis converts carbon dioxide into energy and temporarily elevate pH, while catabolism of the settling algae depresses pH in the hypolimnion (**Figure 11**). In contrast, carbon dioxide is either produced through respiration or consumed during photosynthesis faster than can be replenished by atmospheric diffusion. Sinking organic matter in summer months, due to high algal production or influx of organic material from the watershed, stimulates decomposition processes in the hypolimnion, driving pH and ORP values down. As seen in 2021 data,

peaks of high epilimnetic and low hypolimnetic pH correspond with peaks in algal productivity, particularly July through October.

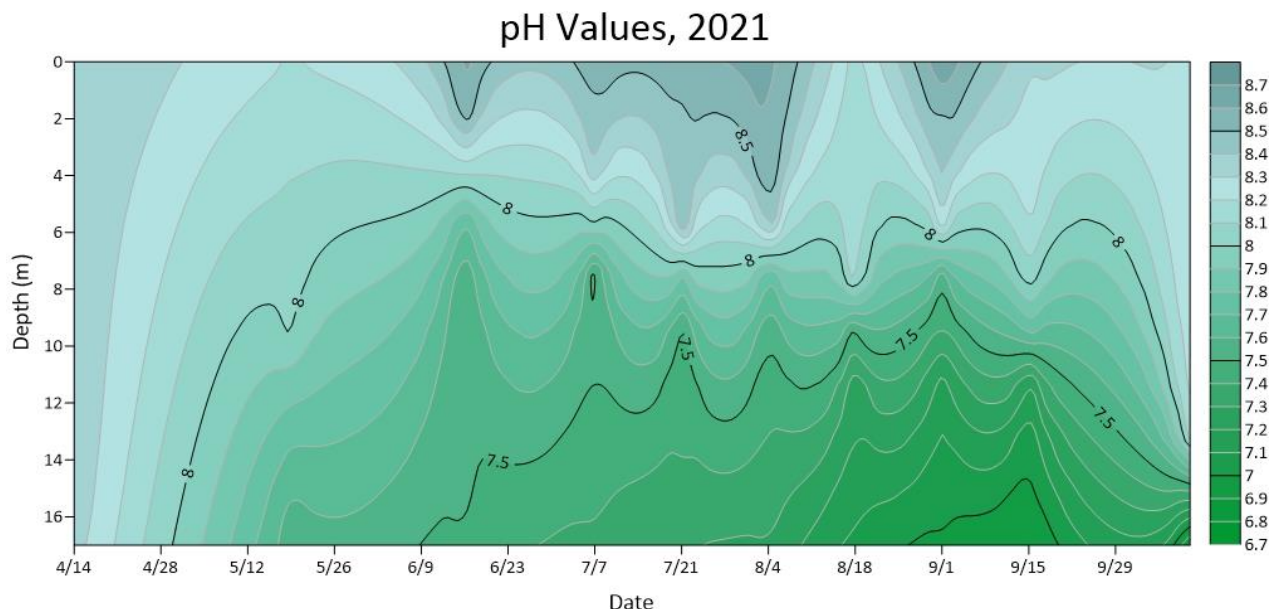


Figure 11. 2021 Isopleth of pH (S.U.) Versus Depth (m) at Site 1.

Oxidation-Reduction Potential, or ORP, is a measure of water's ability to function 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. At that point, the bacterial community will shift to anaerobic, using other ions or compounds as the final electron acceptor for respiration. During this bacterial shift, the water maintains a relatively positive ORP. Generally, as the ORP drops towards 100mV or lower (indicating strongly reducing conditions), sediment-bound phosphorus dissolves into the water column. The duration and extent of strong hypolimnetic reducing conditions are related to the accumulation of these compounds in the hypolimnion. Finally, low ORP conditions slow the oxidation (breakdown) of organic materials such as the contents of dead and dying algal cells providing another source of nutrients to accumulate in the hypolimnion.

In 2021, anoxia in the hypolimnion was observed at Site 1, but only within two meters of the bottom. By June, however, until the June sampling event, and by July, oxidation-reduction potential (ORP) dropped below 200 mV in anoxic conditions (**Figure 12**).

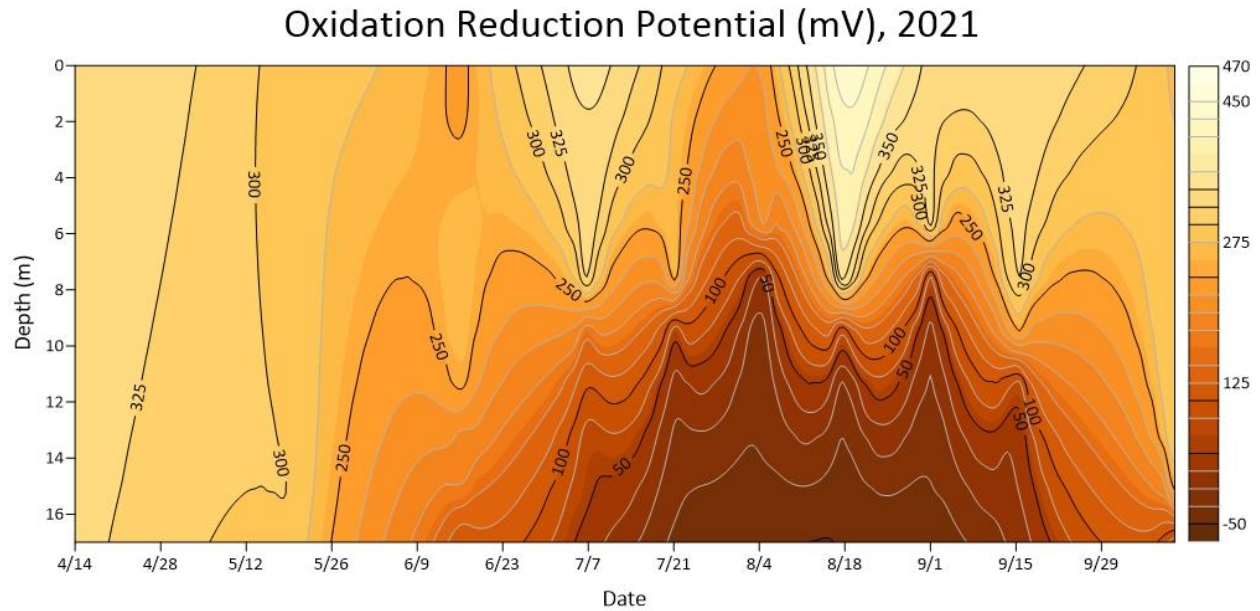


Figure 12. 2021 Isopleth of Oxidation-Reduction Potential (mV) versus Depth (m) at Site 1 from April to October.

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 ortho-phosphate, 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. Nutrient graphs are presented here as a time series across three years to provide context across recent years.

Phosphorus – P

Total phosphorus (TP) is a measure comprised of particulate phosphorus and ortho-phosphorus and represents all phosphorus in the water sample. 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 0.029 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.

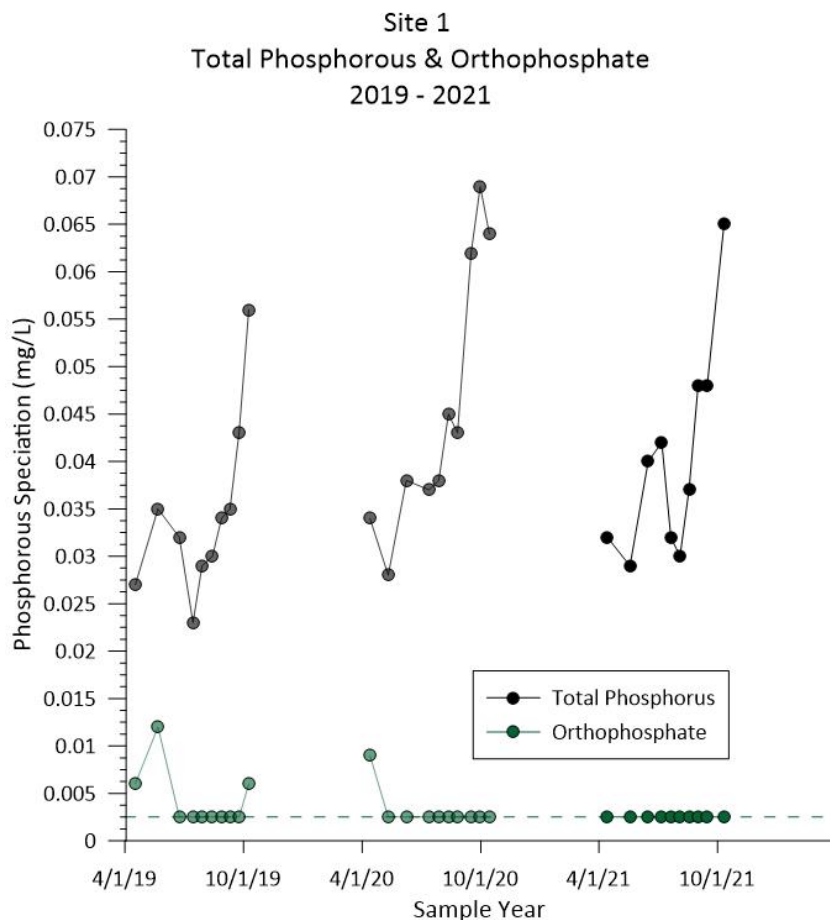


Figure 13. 2021 Surface Phosphorus variables as TP and Ortho-P (mg/L) at Site 1. Ortho-P values on the green dotted line indicate its presents below reporting limit and are graphed at half that value.

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**).

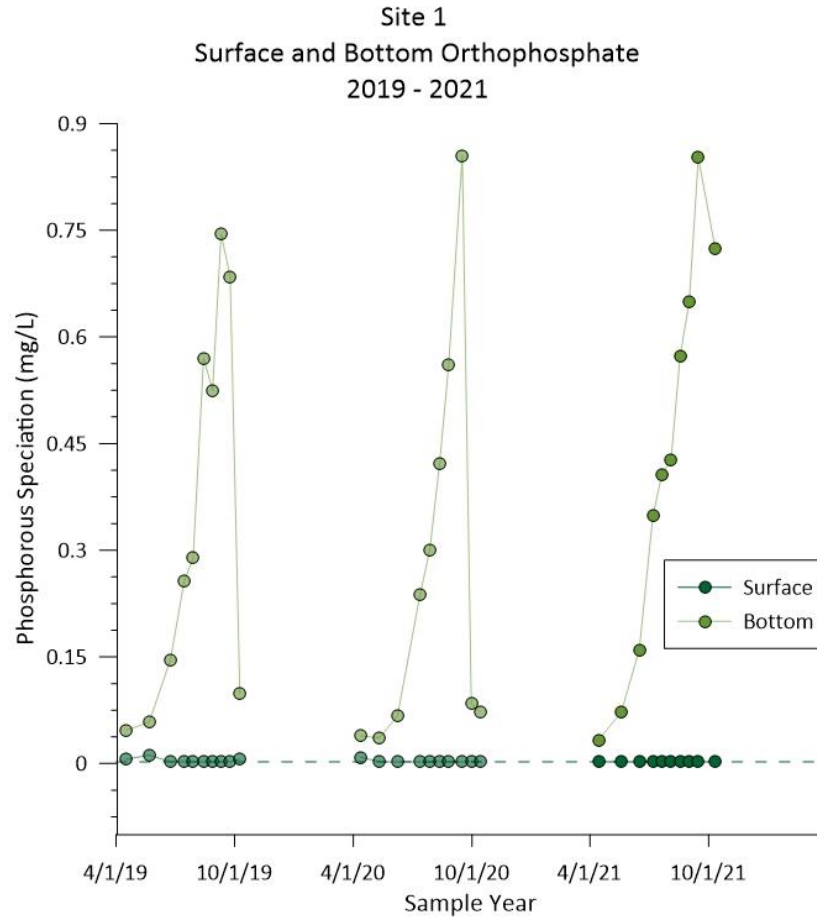


Figure 14. 2020 Site 1 Orthophosphate at surface and bottom depths.

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; riverine values are consistently higher than in open water lacustrine sites (**Figure 13** and **Figure 15**). As was the case in 2020, Site 8 and 11 behaved similarly and exhibited TP values slightly higher than the lacustrine sites in 2021. Site 6 on the Little River arm varied the greatest and had the highest TP value at 0.221 mg/L in September. Riverine TP values ranged from 0.03-0.221 mg/L in 2021. At the June 16th sampling event, the second highest Riverine value (0.202 mg/L) was recorded at Site 6 while directly the lowest riverine value of 0.03 mg/L was recorded at Site 11. This is particularly interesting because Sites 6 and 11 are spatially the most proximate to one another, yet their characteristics can differ wildly.

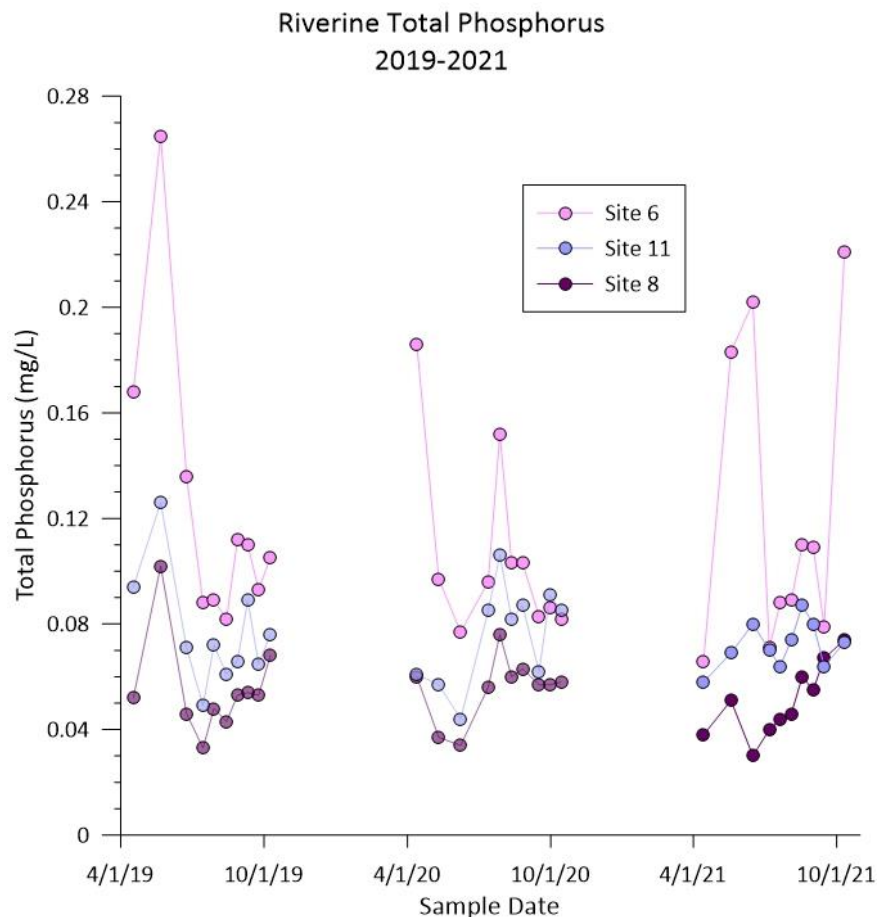


Figure 15. Surface Phosphorus (mg/L) from the three riverine sites, 2019-2021.

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 0.55 mg/L to 1.11 mg/L and increased throughout the season, primarily driven by organic nitrogen present in algae (**Figure 16**). 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 the previous three years, likely due to it being preferentially consumed by algae and follows quick depletion in productive reservoirs.

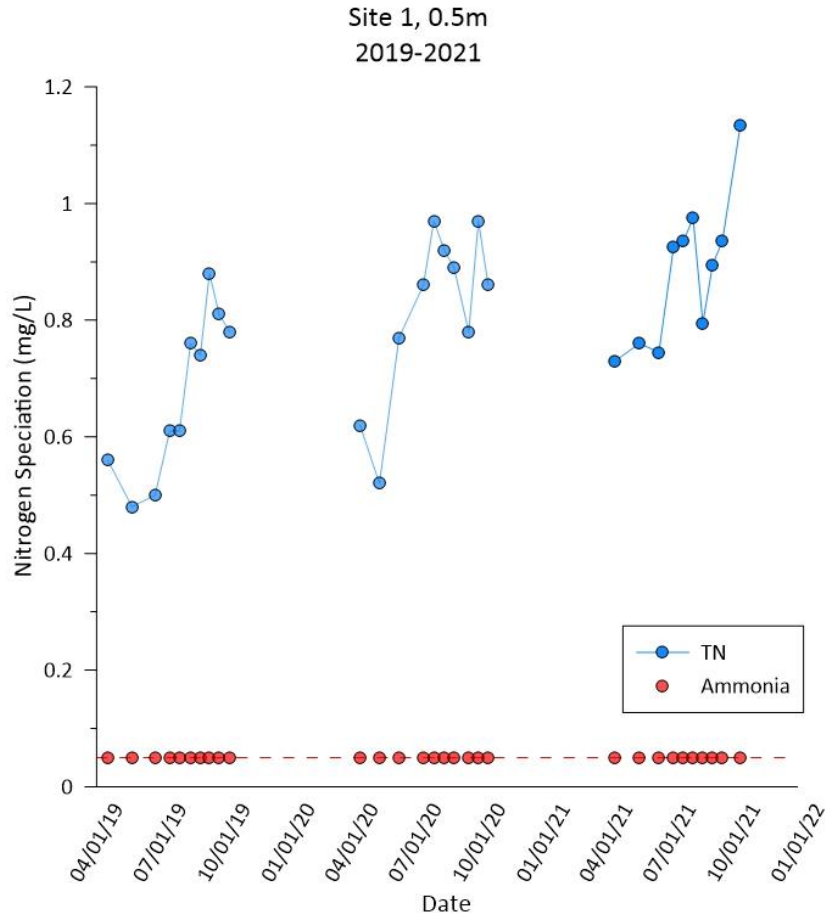


Figure 16. 2021 Surface Total Nitrogen and Ammonia over time at Site 1. Of note, 2019-present Ammonia samples are present below the reporting limit and are graphed at half the detection limit (0.05).

Thunderbird's typical pattern at the surface has been seasonal increases of Kjeldahl nitrogen while nitrate+nitrite fall below reporting limit. In 2021, surface nitrate+nitrite fell 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.

Site 1 Surface Nitrogen Species

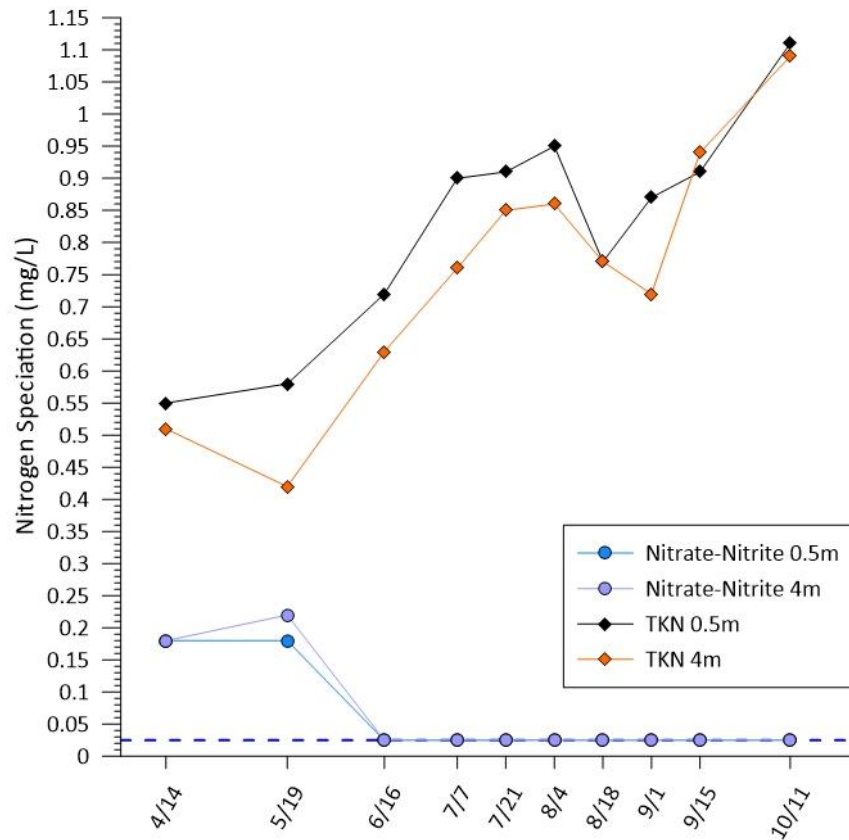


Figure 17. Surface Nitrogen species at Site 1 for 2021. Blue dashed line indicates presence below the reporting limit and are graphed at half the detection limit (0.05 mg/L).

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).

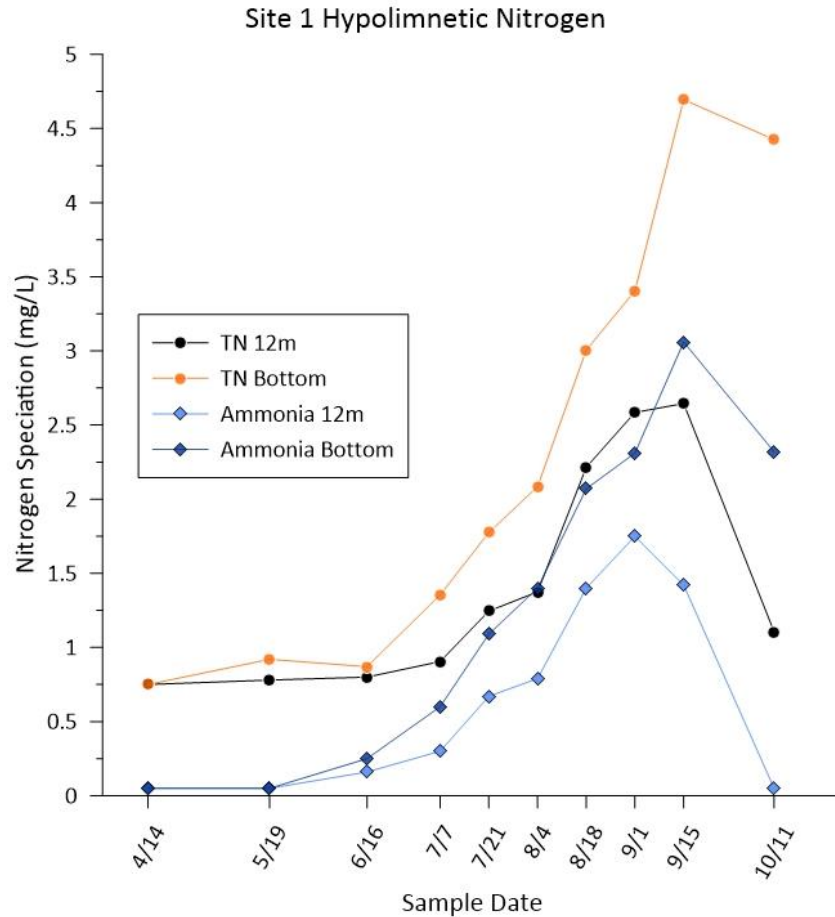


Figure 18. Site 1 Hypolimnetic Nitrogen species in 2021.

Compared to the lacustrine sites, riverine TN levels are higher and suggests tributaries are a key source of nitrogen (Figure 19). Overall, riverine TN increased throughout the season but not without anomaly. All sites started the sampling year in proximity for the first three events. However, several heavy storms washed across various parts of the watershed between sampling on June 16th and July 7th, causing lake elevation to rise nearly 4.4 feet. This dramatic rise and subsequent release to near normal pool elevation by August 4th may partially explain the substantial drop and recovery of TN at Site 8 in July. Climactic data from the Oklahoma Mesonet, USACE monthly summaries, and field notes were reviewed in this determination, however, such anomaly is perplexing to seasoned staff at OWRB.

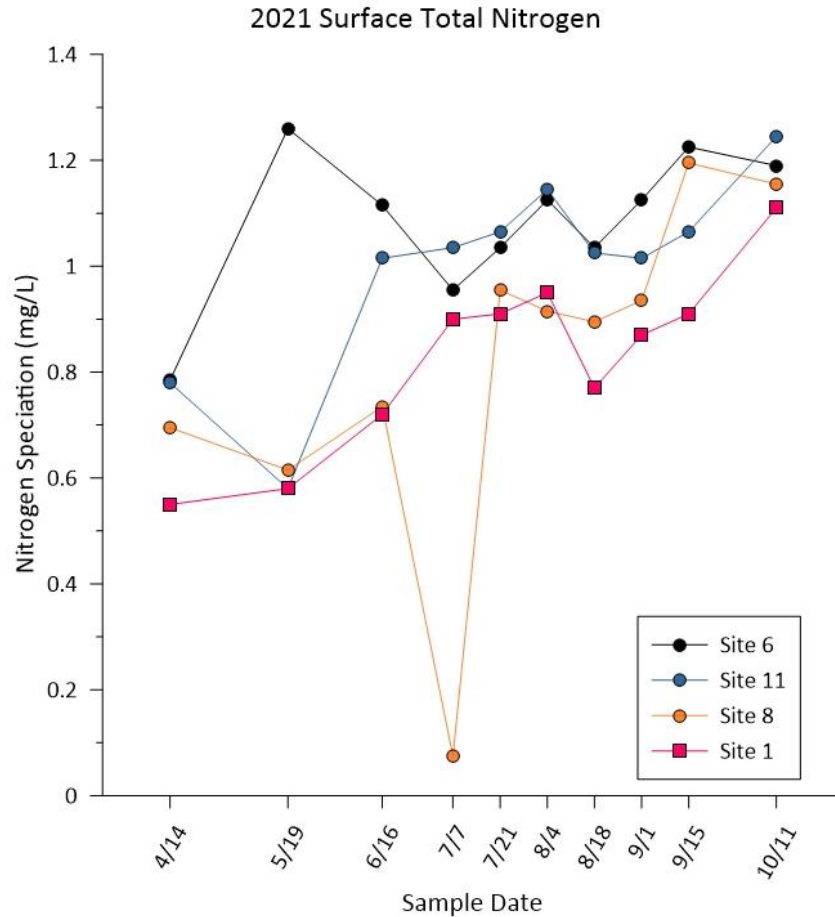


Figure 19. 2021 Surface Total Nitrogen (mg/L) from the three riverine sites and Site 1.

Lacustrine and riverine sites' nutrient concentrations are often dissimilar from each other, as riverine values are consistently higher than reported at Site 1, the only lacustrine site with nutrient data. In 2021, Sites 8 and 11 behaved similarly and exhibited TN values slightly higher than Site 1. Average Site 1 epilimnetic total nitrogen values were similar to previous years and are in the range of eutrophic reservoirs in Oklahoma. Site 6 had the highest TN values lake-wide, with an early peak in May of 1.26 mg/L.

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.

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 subsequently biological production can have several impacts to overall water quality, including ecosystem stability, drinking water suitability, and recreational impacts 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 human health concerns and loss of recreational opportunities. Monitoring for blue-green algal blooms was not included in the scope of this project; however, the continuous detection of taste and odor compounds, Geosmin and 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 a single sampling event falling below the SWS criteria of 10 µg/L for chlorophyll *a* in 2021. This minima may be attributed to heavy rains between April and May sampling events. When looking at the rest of the lacustrine zone, we see a similar pattern emerge. Values begin the monitoring season above the OWQS criteria and as the season progresses, values increase until a relative plateau in July and August before rapidly increasing in September (**Figure 21**). While Site 4 is nearest the freshwater intake, no taste or odor complaints were registered in April, possibly due to intake gates located well below the surface. Values at Site 1 alone nearly doubled to its peak, from 31.2 µg/L in September to 60.3 µg/L by October 11th.

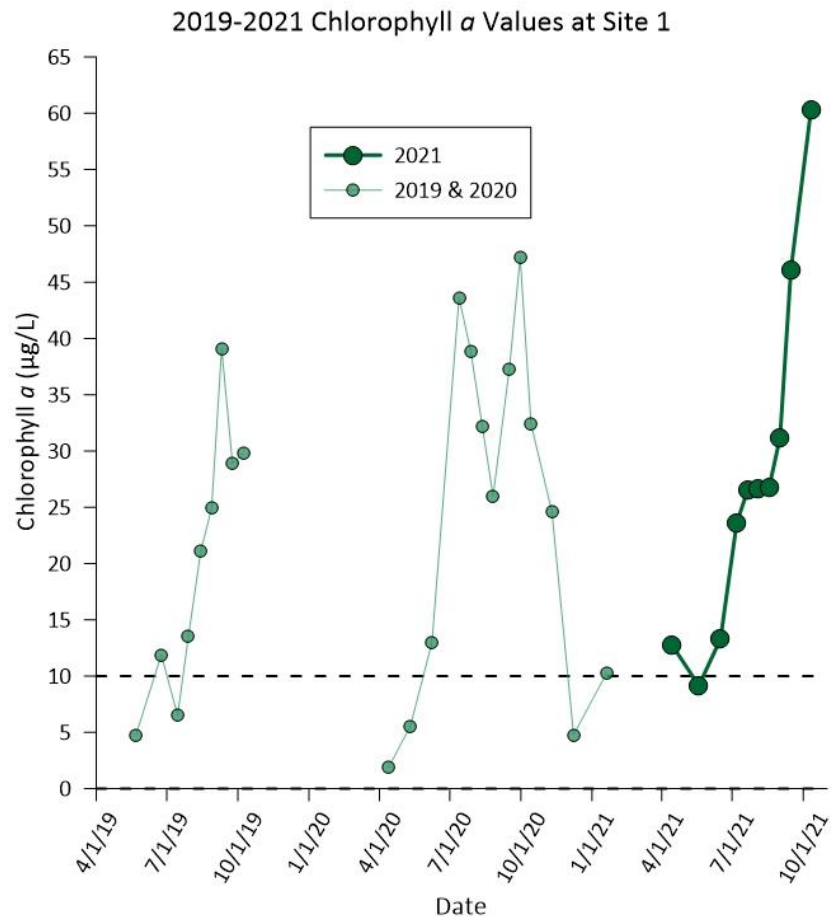


Figure 20. 2019-2021 chlorophyll *a* values at Site 1, highlighting annual increase. Dashed line represents OWQS for SWS reservoirs of 10 µg/L.

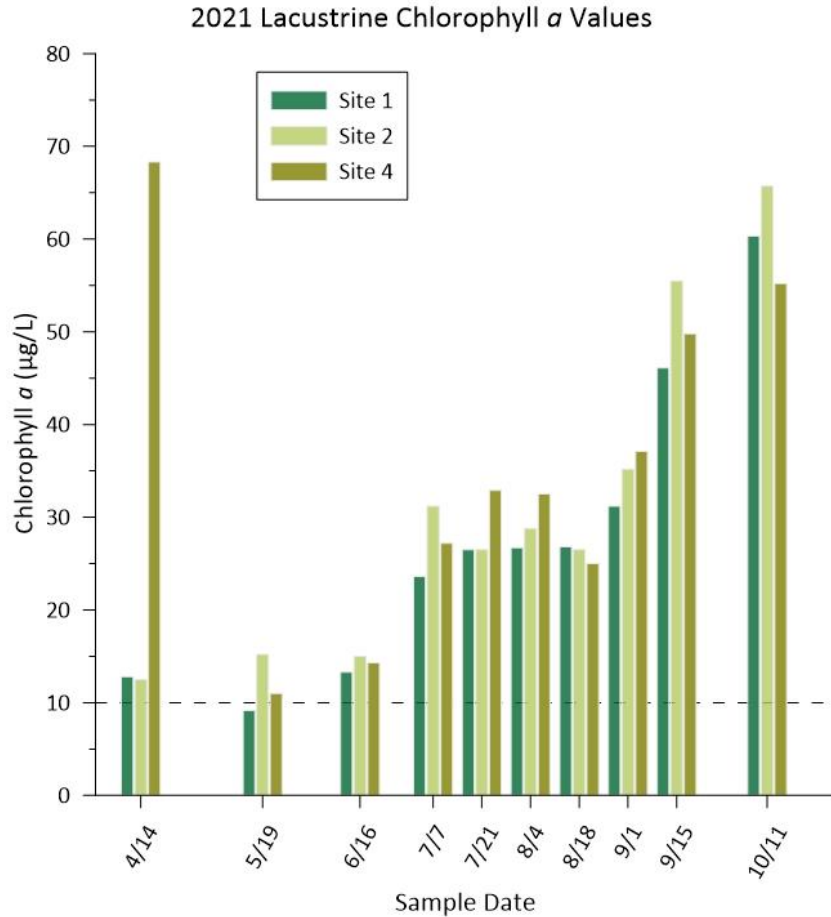


Figure 21. Lacustrine chlorophyll *a* values for 2021. Dashed line represents OWQS for SWS reservoirs of 10 µg/L.

Chlorophyll *a* in riverine sites followed a similar pattern as lacustrine, but at a slightly higher magnitude. All sites started the season well above the SWS criteria with only a single sample at Site 8 falling below in June quickly jumped to nearly three-times the standard the following month (**Figure 22**). Site 6 receives stormwater from the largest and most urbanized portion of the watershed and may account for the dramatic spike in June, coinciding with the peak riverine value of 75 µg/L.

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 even higher levels.

Overall, lake-wide chlorophyll *a* values ranged from 6.25 µg/L to 75 µg/L, with an annual average of 33.45 µg/L, which is more than three times the SWS criteria. The 2021 average was also the highest annual average in the last 10 years.

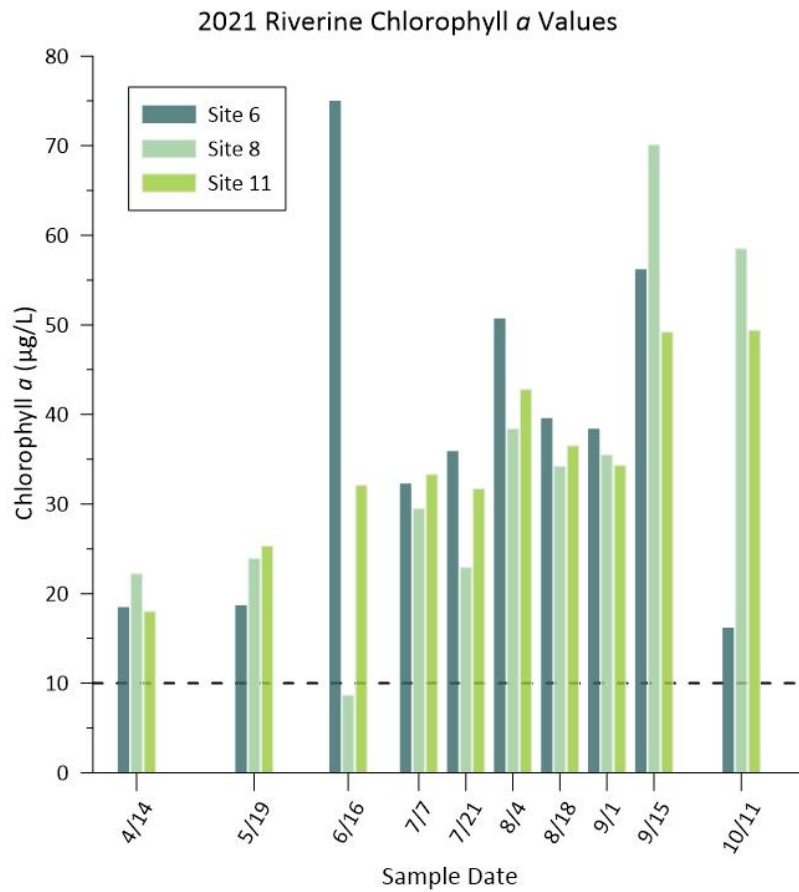


Figure 22. 2021 Lake Thunderbird surface chlorophyll ($\mu\text{g/L}$) at riverine sites. Dashed line represents OWQS for SWS reservoirs of $10 \mu\text{g/L}$.

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

Phosphorus is desirable as the limiting nutrient for most freshwater systems because under phosphorus limiting conditions, green algae will typically be the predominant algal community. This is opposed to a blue-green algae predominance, which, while less common, can cause a multitude of issues ranging from human health and recreation, to drinking water supply, and fish community structure. 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, since 2017 and in 2021, Thunderbird is occupying the indeterminate zone for the majority of the sample year. (**Figure 23**).

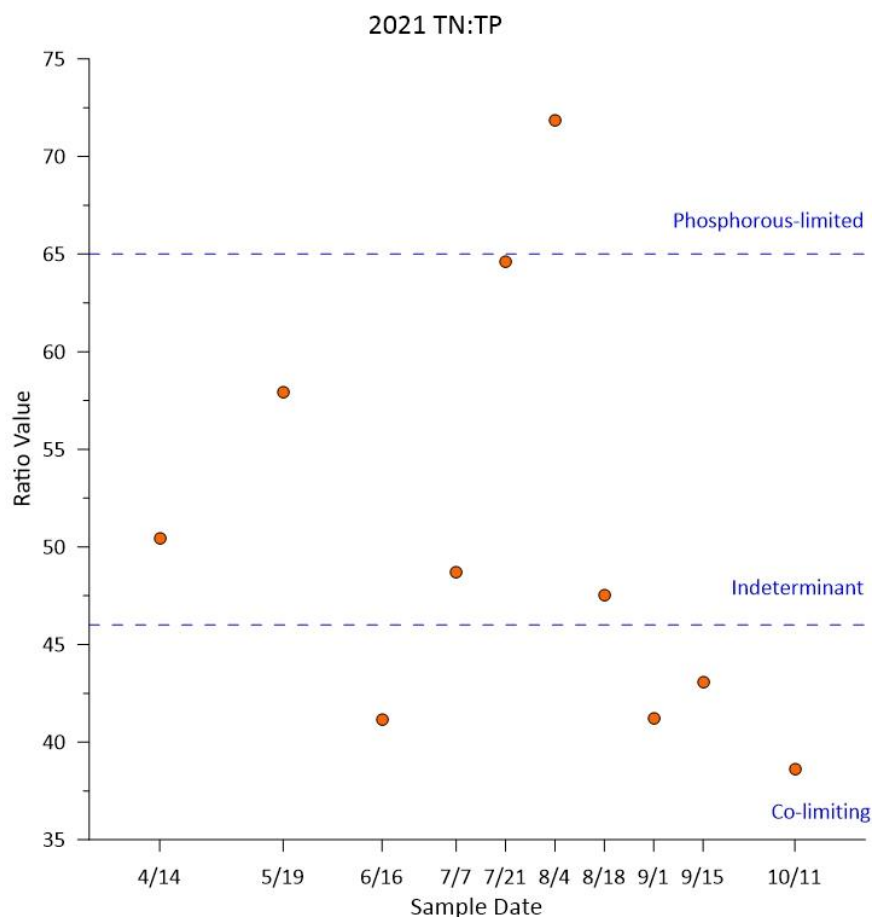


Figure 23. 2021 Lake Thunderbird TN:TP by sample event.

Light

Turbidity and Secchi disk depth (SDD) are ways of measuring water clarity and amount of suspended particles are in a lake. In pristine and natural lakes, SDD can measure 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.

2021 non-algal turbidity was calculated to examine its effect on algal limitation using the equation below, derived from BATHTUB model (Walker, 1999). Non-algal turbidity generally describes turbidity associated with parent material originating elsewhere and was brought in or introduced to the system, often referred to as allochthonous.

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

Where **SD** is Secchi Depth in meters

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

Of the samples analyzed for non-algal turbidity (T) influence on algal growth, 46 percent were found to have a T value greater than one, indicating allochthonous particulates are potentially important and the expected algal response to nutrients is likely low. 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.

Of the eight instances where T was less than 0.4, seven were in the lacustrine portion of the reservoir. These results are an indication turbidity from allochthonous particles are unimportant and a higher algal response to nutrients is expected as the lacustrine portion of Lake Thunderbird traditionally has greater SDDs than riverine portions. Riverine sections however, will tend to have more influence from allochthonous sources than lacustrine. Despite the presence of high nutrient concentrations, chlorophyll values were lower than would be expected due to turbidity 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 sustained 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 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.

$$TSI = 9.81 \times \ln(\text{chlorophyll } a) + 30.6$$

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. Thunderbird began the season eutrophic and accelerated to hypereutrophic by July, where it remained the rest of the sample year.

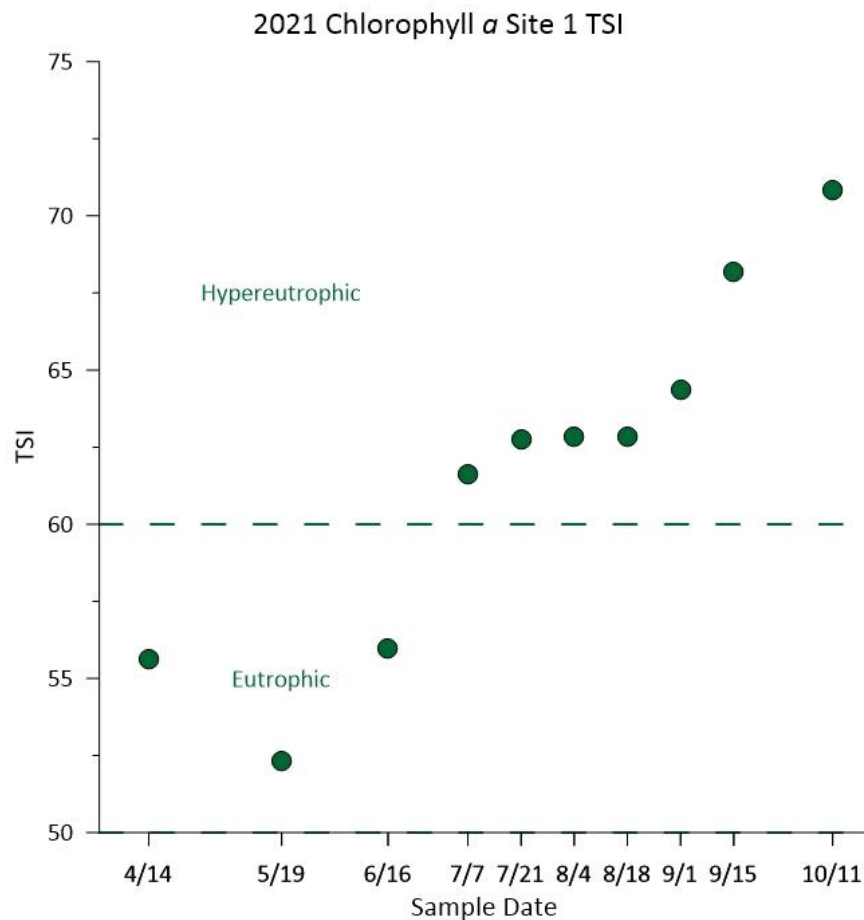


Figure 24. Site 1 Chlorophyll TSI in 2020. Dashed lines represent the divisions of trophic states.

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 similar pattern as Site 1, TSI at the riverine sites increased throughout the season and were mostly in 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 2021 sample year.

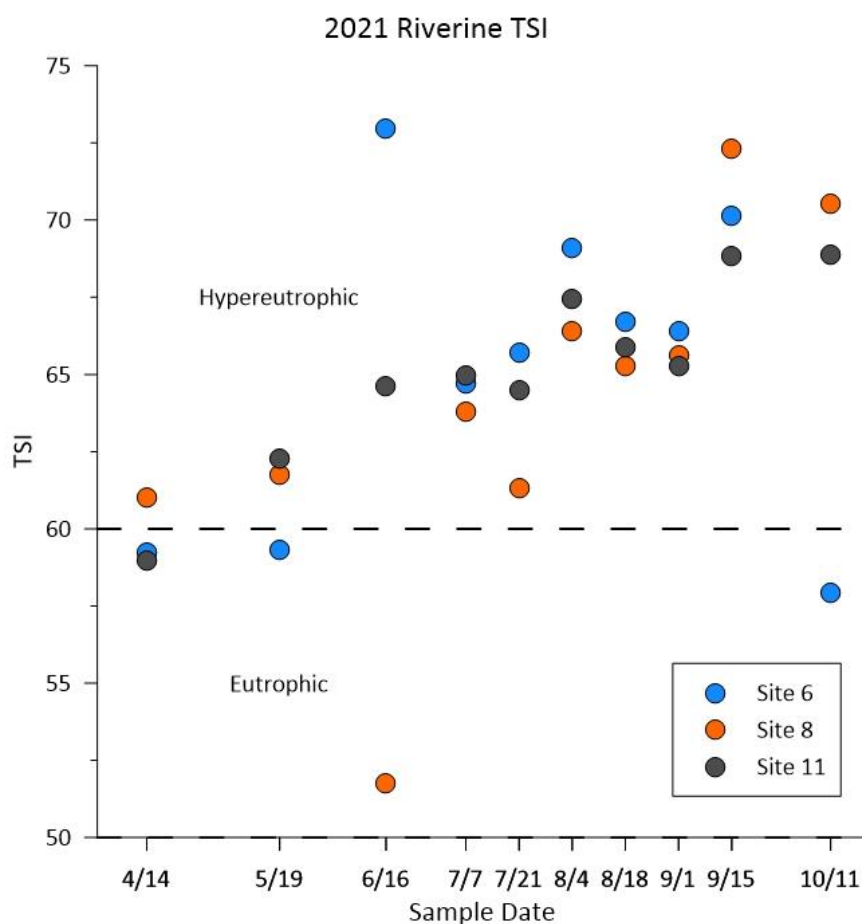


Figure 25. 2021 Carlson's Chlorophyll *a* TSI values for riverine sites. Dashed line delineates ranges for trophic state.

Total Organic Carbon – TOC

Total organic carbon (TOC) is a measure of carbon containing compounds present in a water sample, allowing insight to the amount of organic material present. Sources of these organic compounds include soil and plant detritus and to a lesser degree, even carbon present in living material such as bacteria and plankton (Wetzel, 2001). Wetzel presents median organic carbon content for eutrophic lakes as 12.0 mg/L, oligotrophic lakes as 2.2 mg/L, and rivers as 7.0 mg/L (2001). In 2021, Lake Thunderbird surface TOC values at Site 1 ranged from 5.00 to 7.47 mg/L with a mean value of 6.33 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 creating 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. 2021 Lake Thunderbird Total Organic Carbon (mg/L).

Total Organic Carbon (mg/L)	
04-14-2021	5.00
05-19-2021	5.10
06-16-2021	6.11
07-07-2021	6.29
07-21-2021	6.86
08-04-2021	7.18
08-18-2021	6.12
09-1-2021	7.47
09-15-2021	6.50
10-11-2021	6.69

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 – 2021) 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 ng/L) (Graham et al 2008). Algae produce 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.

2021 T&O odor complaints revealed a different pattern from previous years, with only a handful logged in the first half of the year. **Figure 26** displays the previous three years of T&O complaints the City of Norman has recorded.

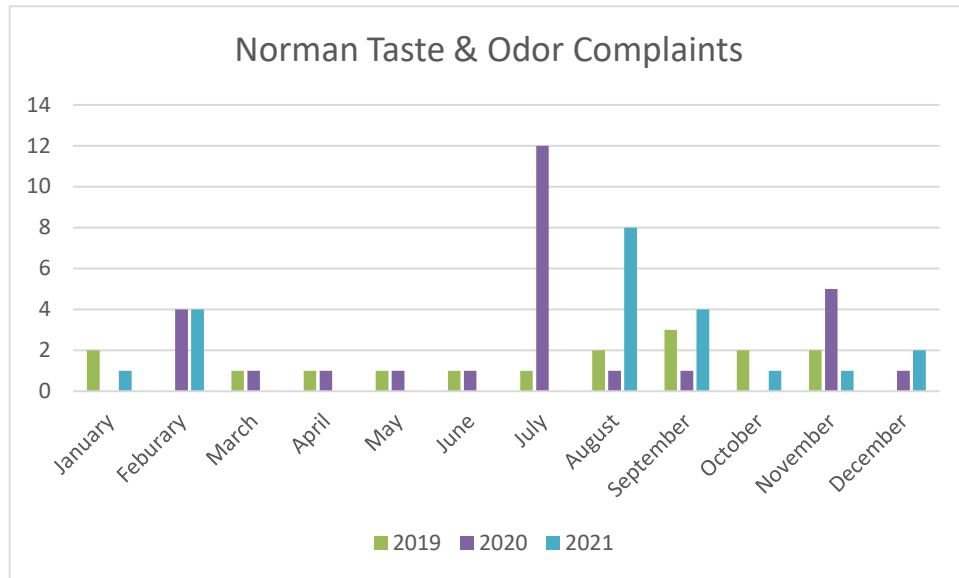


Figure 26. Taste and Odor complaints by month. Data is from personal communication with G. Wellborn, City of Norman, January 31, 2022.

In past years T&O complaints coincided with lake mixing events, when hypolimnetic chemicals cycle into the water column. However, in 2021, Geosmin from raw water prior to chlorination did not peak until November, while MIB at the same source spiked in early October (**Figure 27**). Geosmin's overall average was higher than 2020, largely due to the spike in November. The average for MIB was slightly lower than the 2020.

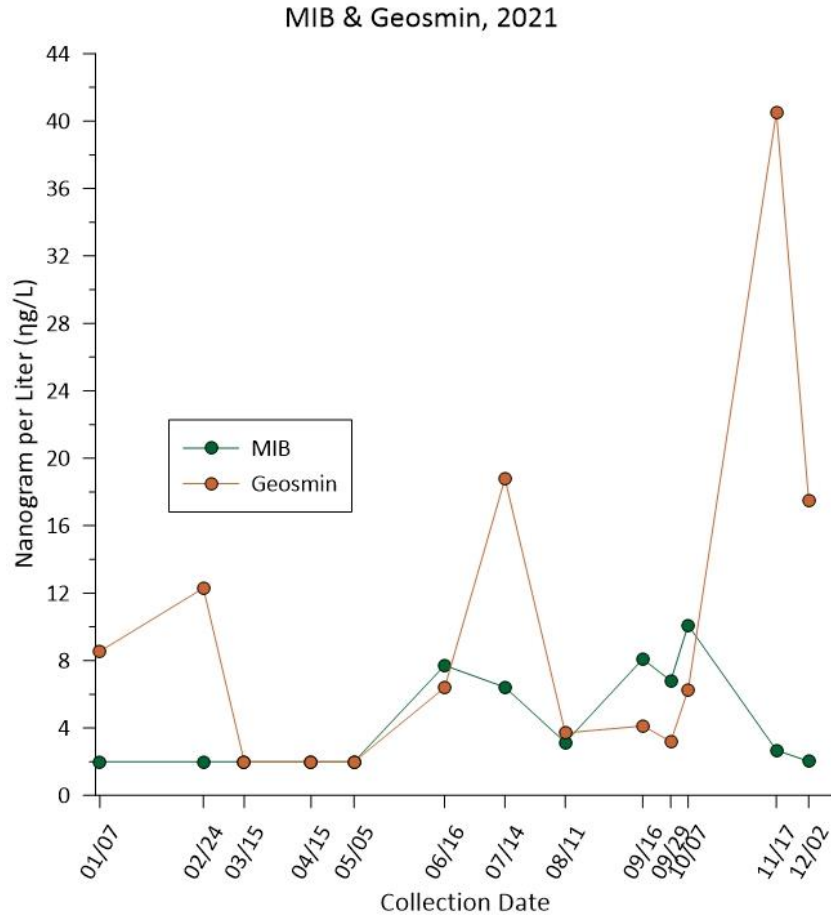


Figure 27. 2021 City of Norman monthly raw water laboratory analysis for Geosmin and MIB. Points graphed at 2.00 are considered non-detect. Data is from personal communication with G. Wellborn, City of Norman, January 12, 2022.

Water Quality Standards

All Oklahoma surface waters are subject to Oklahoma's Water Quality Standards (OAC 785:45) and Implementation Rules (OAC 785:46), designed to maintain and protect the quality of waters of the state. Oklahoma Water Quality Standards 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, 2018). In order to address these impairments, Lake Thunderbird has undergone Total Maximum Daily Load (TMDL) development by the ODEQ with the resultant report approved by the Environmental Protection Agency (EPA) in 2013. The TMDL analysis requires a 35% long-term average load reduction of total nitrogen, total phosphorus, and total suspended solids from the 2008-2009 watershed load estimates in order to restore the lake's beneficial uses. Implementation of the TMDL is underway and point source and non-point source measures are outlined in the Final TMDL Report (Dynamic Solutions, 2013).

The Oklahoma Water Quality Standards Implementation Rules contain Use Support Assessment Protocols (USAP) for Oklahoma waterbodies. This USAP is the statewide methodology for integrated report water quality assessments (i.e., 305(b) and 303(d) reports). 2021 water quality data was assessed in accordance with the USAP to evaluate current conditions relative to OWQS attainment or nonattainment. Physical, chemical, and biological data on Lake Thunderbird were used to assess the lake condition and determine if lake water quality supports its designated beneficial uses and are outlined below.

Dissolved Oxygen – DO

Dissolved oxygen criteria are designed to protect the diverse aquatic communities found throughout Oklahoma waterbodies. For warm water aquatic communities, such as Lake Thunderbird, two assessment methodologies apply to protect Fish and Wildlife Propagation beneficial use: surface and water-column/volumetric (OAC 785:46-15-5). Surface water DO criteria for 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 for not supporting in 2021.

Volumetric criteria for fully supporting the Fish and Wildlife Propagation beneficial use has a threshold of less than 50% of the cumulative lake volume measuring anoxic (< 2.0 mg/L DO). Unfortunately, July of 2021 failed to meet based on volumetric data with 49.13% oxygenated volume. Average percent of oxygenated lake volume between April and October was over 78.8%. Reports for the 2018 and 2019 sample years also highlighted occurrences of the lake failing to meet volumetric criteria.

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 2021, the lake wide chlorophyll average in Lake Thunderbird was 33.45 µg/L, with over 96% of samples exceeding 10 µg/L. Samples collected in 2020 averaged 30.75 µg/L and the 2019 average was 24.3 µg/L. The ten-year (2011-2021) lake-wide average is 27.80 µg/L, with 84% of samples exceeding 10 µg/L. Figure 28. **2021 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*.

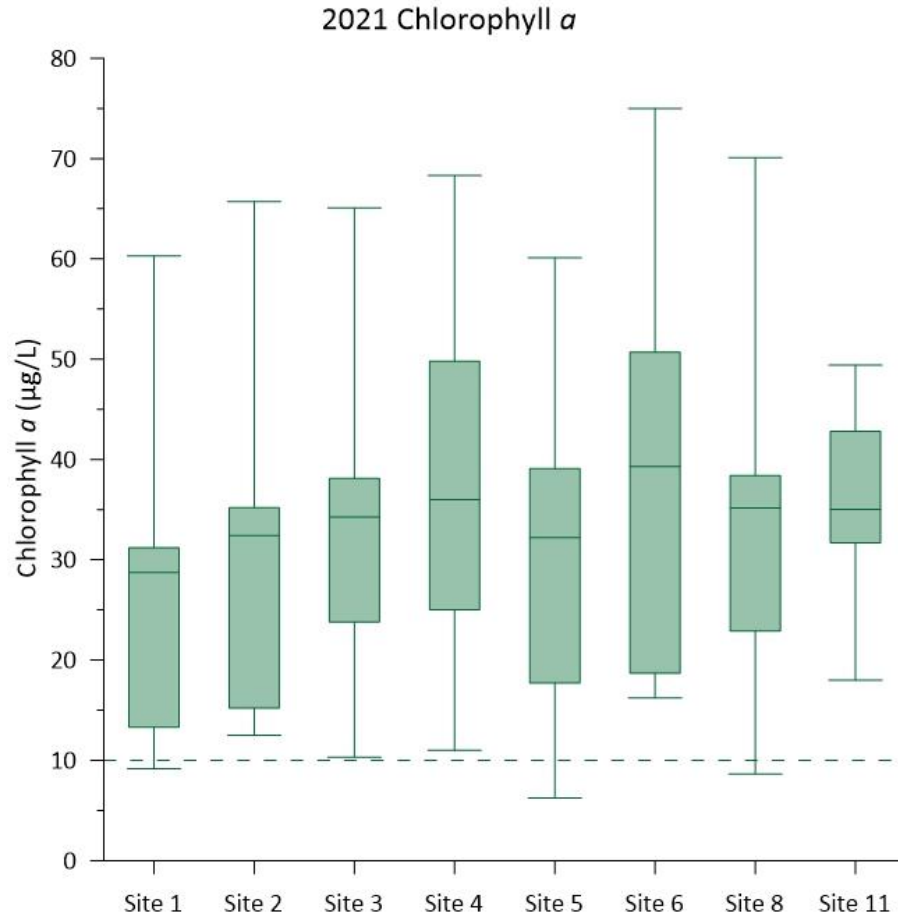


Figure 28. 2021 Lake Thunderbird chlorophyll *a* (µg/L) by site. Boxes represent 25% of the data distribution both above and below the median (horizontal line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Dashed line indicates SWS criteria of 10 µg/L.

Water Clarity

Turbidity and Secchi disk depth are methods of measuring water clarity and the amount of 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, 2021 secchi disk depths ranged 9 cm to 115 cm. Whole lake average of Secchi depth was 56.05 cm, an improvement from 2020's average of 48.76 cm. The lacustrine sites had the deepest Secchi depths while the riverine sites had the shallowest, as is typical of Oklahoma reservoirs (**Figure 29**).

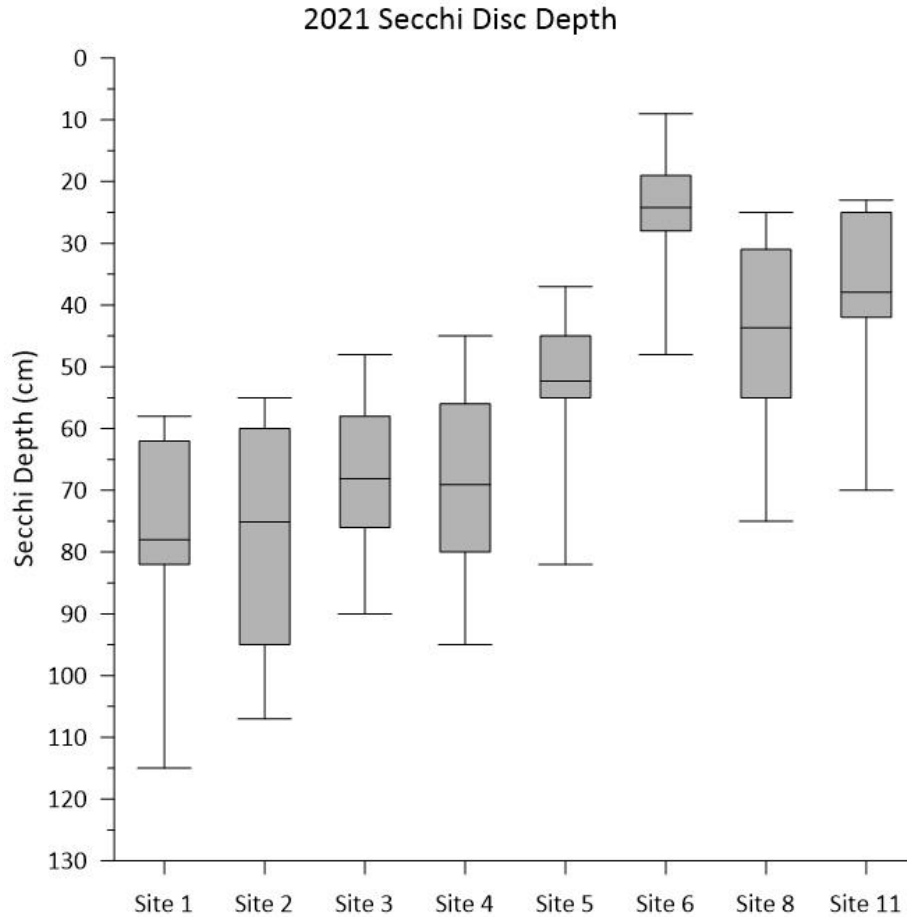


Figure 29. 2021 Lake Thunderbird Secchi Disk Depth (cm) by site. Boxes represent 25% of the data distribution both above and below the median (horizontal line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Depth starts at 0 to represent 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 2021 varied across the lake and ranged from 3.82 NTU to 196 NTU. For reference, the lower the NTU value the clearer the water. The lake-wide turbidity average was 19.10 NTU, with 23.8% of the samples exceeding 25 NTU, all of which were in the riverine or transitional zones of the lake (**Figure 30**). The ten-year lake-wide average is 24.0 NTU, with 26.3% of those samples exceeding 25 NTU. Based on these calculations, Lake Thunderbird fails to be supporting for the Fish and Wildlife Propagation beneficial use with respect to turbidity.

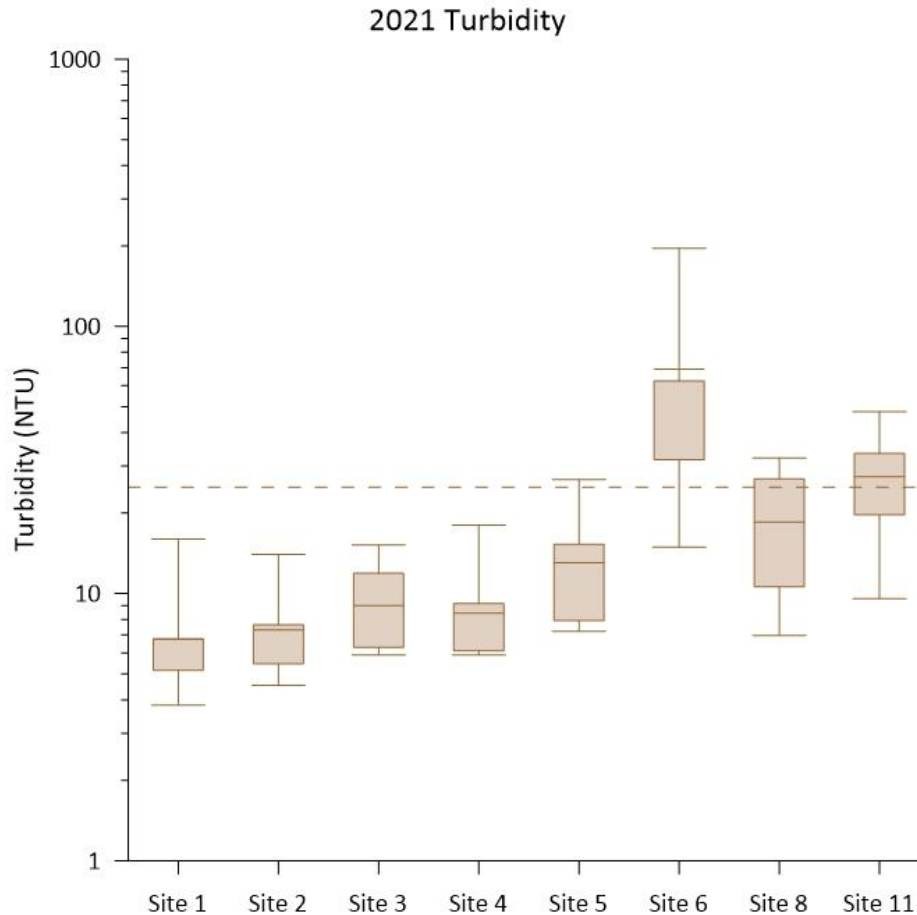


Figure 30. 2021 Lake Thunderbird Turbidity (NTU), by site, on a logarithmic scale. Boxes represent 25% of the data distribution above and below the median (horizontal line), and lines (or whiskers) represent the other 50% of the data distribution bounded by minimum and maximum values. Dashed line indicates the 25 NTU OWQS for turbidity.

Discussion

Since 2000, OWRB has monitored the water quality of Lake Thunderbird and documented the continued 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.

Climactically, Lake Thunderbird had an interesting first quarter. January was slightly warmer than average while February was well-below average due to a polar vortex that engulfed much of the country. March rebounded and was again above average. The remainder of the spring and early summer was below average while last summer through fall ended the year above normal. With air temperatures peaking later in the season, epilimnetic water temperature did not peak until September. Elevation fluctuated considerably in 2021, raising nearly four feet and returning to near normal over a period of seven weeks. Maximum elevation was observed in this period in early July following considerable rain events and was below normal elevation by the middle of August for the remainder of the year. The overall pattern of stratification remained comparable to previous years.

Thermal stratification began to set up by June 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 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 phosphorus 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 2021. 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 is occurring in the lake. Lacustrine nitrogen measurements were generally lower than riverine nitrogen, suggesting tributaries are 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 promote and contribute to the release of ammonia from the sediments and decomposition of organic matter observed during the sample year. Without oxygen, nitrification reactions do not occur; thus, the increase of hypolimnetic ammonia concentrations was both typical and expected. As the lake turns over in the fall, oxygen was introduced, triggering nitrification, which creates nitrite and can further oxidized to nitrate. This phenomenon was observed in September through October by a dramatic decrease in bottom depth ammonia and TN. Data collected in 2021 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 can be attained by recommending a 35% load reduction rate for Total Nitrogen, Total Phosphorus, and Suspended Solids. This waste load allocation is divided amongst the three primary municipalities in the watershed: Moore, Norman, and Oklahoma City (ODEQ, 2013).

Chlorophyll *a* is used as a proxy to measure algal biomass and it is important to understand the factors driving growth, due to its potential to cause drinking water and recreation issues. Lake Thunderbird's SWS classification requires average chlorophyll *a* to be less than 10 µg/L; however, lake wide chlorophyll concentrations in 2021 were more than three times the criteria.

2021 average chlorophyll *a* values increased from 2020 values and remained excessive, representing a need to mitigate conditions driving increased algal biomass. Riverine sites experienced higher chlorophyll *a* levels than lacustrine areas, but high turbidity values likely limited algal growth and prevented even higher chlorophyll *a* values. 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 had a limiting effect on algal growth by minimizing the ability of light to penetrate the water column to drive productivity.

Thunderbird's TSI was examined using the most stable index, Chlorophyll *a*, and determined the lake ranged from eutrophic April through July hypereutrophic 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 are 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 28 in 2020 to 21 in 2021, 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 2020 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 2021 were added to the data set and analyzed for beneficial use impairments in accordance with the USAP (OAC 785:46-15) of the OWQS and Lake Thunderbird was found to be not supporting its Fish and Wildlife Propagation beneficial use due to turbidity. Additionally, Lake Thunderbird 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.

To improve water quality, dynamic in-lake and watershed level activities must be implemented in tandem and designed to facilitate effective, measurable mitigation in the future. Hypolimnetic oxidation is a worthwhile exercise to not only provide aerobic lake habitat, but also improve the quality of raw drinking water for municipalities and reduce recreational health risks due to the growth of harmful algae. Unfortunately, ongoing eutrophication indicates hypolimnetic oxygenation alone will not provide the relief Lake Thunderbird needs to recover its attainment of beneficial uses.

Recommendations

In past years, the monitoring strategy has been modified several times for a multitude of reasons, not the least of which has been budgetary concerns. The effect of 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 2020, at no cost to COMCD, and carried forward in 2021. Regarding monitoring, OWRB recommends those efforts continue and expand to include nutrients across all sites in 2022, as they provided valuable information and minimize data gaps. One of which occurred in August 2021 at Site 8 when TN experienced a dramatic crash. Under the current agreement, monitoring at Site 3 does not include nutrients and being nearest to Site 8, no further conclusions could be drawn or compared.

Due to how the sampling calendar fell in 2021, fall turnover was not definitively captured as in years past. For 2022, OWRB proposes an additional October sampling event of all sites and a single November event at Site 1 and Site 4 to bookend the breakdown of stratification and fall turnover.

In 2021, the COMCD contracted a thorough analysis to quantify the lake's internal nutrient load through direct measurement. Results from this study will provide a host of vital information on baseline and existing conditions within the reservoir to inform and aid decision makers in selecting appropriate in-lake BMPs and further monitoring strategies. This information will also help in researching other in-lake technologies that mitigate anoxic conditions in the hypolimnion.

As watershed events continue delivering non-point source pollutants above numeric targets and load allocations prescribed in a TMDL, 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. General ways to accomplish this include:

- Become actively engaged with the communities COMCD supplies water. Attend municipal meetings dealing with water, utilities, and further expansion.
- Lead through example. Adopt LID into COMCD's maintenance and construction practices.
- Work with the Oklahoma Conservation Commission to host and participate in a Blue Thumb Water Quality Education Program, a volunteer stream monitoring program where citizens scientists monitor streams feeding Lake Thunderbird.
- Closely monitor and engage with the recently announced "Access Oklahoma" turnpike initiative that proposes to cut through the watershed and impact nearly all tributaries of Lake Thunderbird.
- Become familiar with the recently released EPA Cyanobacteria Assessment Network tool that aggregates frequent satellite images for the detection of cyanobacteria.
- Continue community involvement through outreach, education, Watershed Management Groups such as the Lake Thunderbird Watershed Alliance, grassroots neighborhood "Protect our Lake" groups, river cleanups, etc.
- Incorporating wetlands into the landscape to ameliorate non-point source pollutant runoff and sediment erosion that further contributing to nutrient loads.
- Planning new vegetated swales and infiltration basins and retrofitting existing vegetated swales and infiltration basins.
- Target the retention of precipitation and runoff to reduce the impact of impervious surfaces in the watershed.

- Encourage municipalities within the watershed to incorporate LID into any new construction within the watershed (Low Impact Development Center, 1999).

Another avenue to improve Lake Thunderbird's water quality health is to continue to foster cooperation and collaboration between all stakeholders – including municipalities and the recently formed Lake Thunderbird Watershed Alliance – to assist in reducing runoff from construction activities and urban land uses within the watershed. Finally, understand that COMCD is neither the cause nor single solution to the issues facing Lake Thunderbird. It will take a vast effort from all stakeholders to improve water quality, but COMCD is positioned to be the catalyst of change.

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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 2021 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 2021 and included replicates and analytical blanks. Replicate samples primarily control for the collection of a representative sample, but these results also include a measure of uncertainty from laboratory analysis. Analytical blanks control for cleaning the equipment, such as the dissolved integrated samplers and Van Dorns.

Replicate samples were collected at the surface of the Site 1 for each parameter and designated as Site 1(12) and Site 1(22) for environmental and replicate samples respectively (**Table 7**).

Table 7. Summary of 2021 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)
4/14/21	0.55	0.05	0.18	0.032	0.0025	12.8
5/16/21	0.58	0.05	0.18	0.029	0.0025	9.16
6/16/21	0.72	0.05	0.025	0.04	0.0025	13.3
7/7/21	0.90	0.05	0.025	0.042	0.0025	23.6
7/21/21	0.91	0.05	0.025	0.032	0.0025	26.5
8/4/21	0.95	0.05	0.025	0.03	0.0025	26.7
8/18/21	0.77	0.05	0.025	0.037	0.0025	26.8
9/1/21	0.87	0.05	0.025	0.048	0.0025	31.2
9/15/21	0.91	0.05	0.025	0.048	0.0025	46.1
10/11/21	1.11	0.05	0.025	0.65	0.0025	60.3

1(22)	TKN (mg/L)	Ammonia (mg/L)	NO2/NO3 (mg/L)	Total P (mg/L)	Ortho-P (mg/L)	Chlorophyll (µg/L)
4/14/21	0.54	0.05	0.18	0.031	0.0025	12.5
5/16/21	0.54	0.05	0.19	0.027	0.0025	6.75
6/16/21	0.69	0.05	0.025	0.04	0.0025	14.3
7/7/21	0.83	0.05	0.025	0.037	0.0025	23.9
7/21/21	0.90	0.05	0.025	0.033	0.0025	27.0
8/4/21	0.83	0.05	0.025	0.029	0.0025	28.8

8/18/21	0.73	0.05	0.025	0.036	0.0025	23.6
9/1/21	0.86	0.05	0.025	0.046	0.0025	31.6
9/15/21	0.85	0.05	0.025	0.048	0.0025	45.2
10/15/21	1.05	0.05	0.025	0.063	0.0025	58.4

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.

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

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.

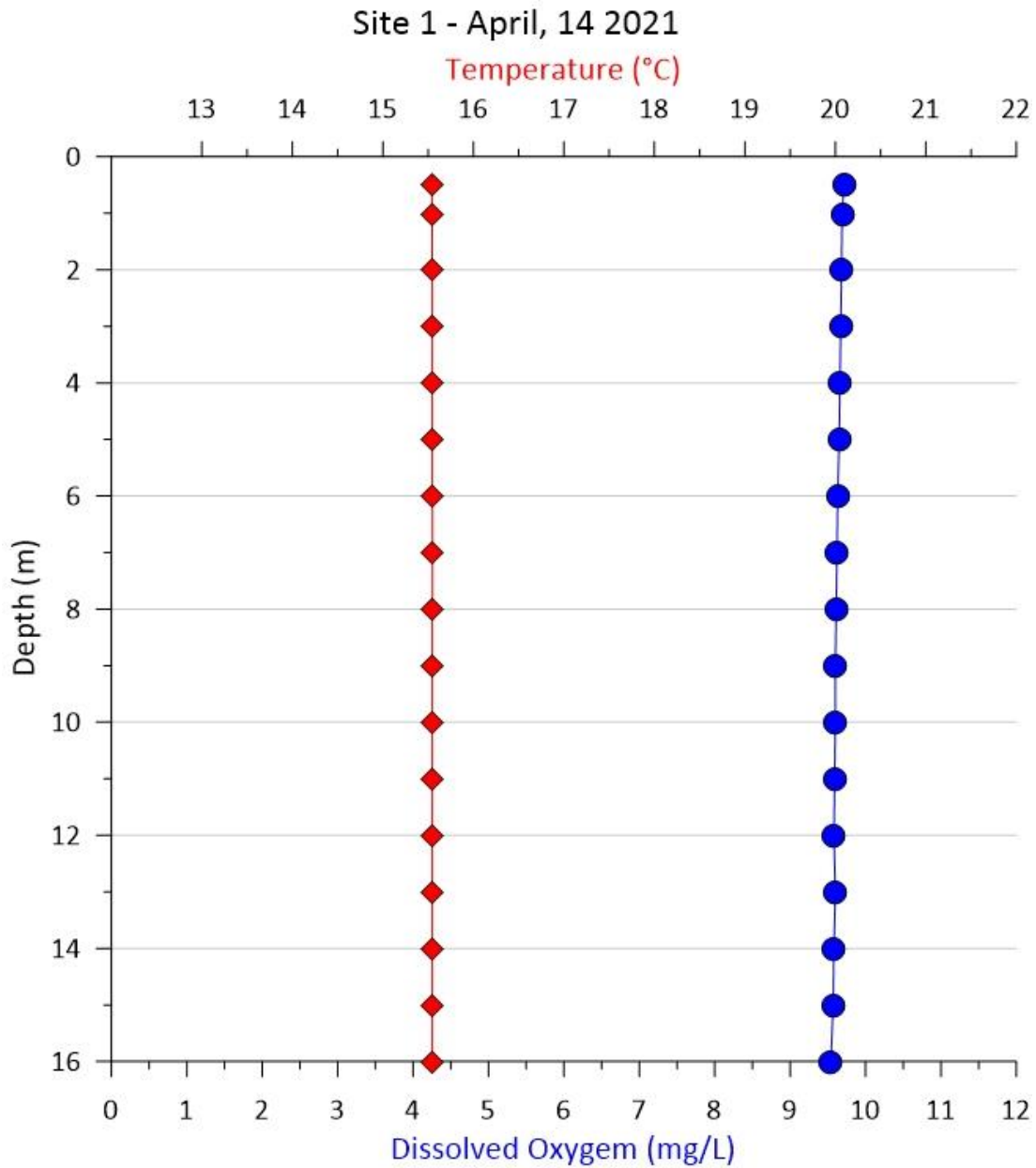
Parameter	Acceptable precision for laboratory replicates	Number of Sample Events Meeting RPD Threshold	Percent of Sample Events Meeting RPD Threshold
Total Kjeldahl Nitrogen	± 20%	9	90%
Nitrate/Nitrite	± 10%	10	100%
Ammonia	± 20%	10	100%
Total Phosphorus	± 10%	9	90%
Ortho-Phosphorus	± 20%	10	100%
Chlorophyll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

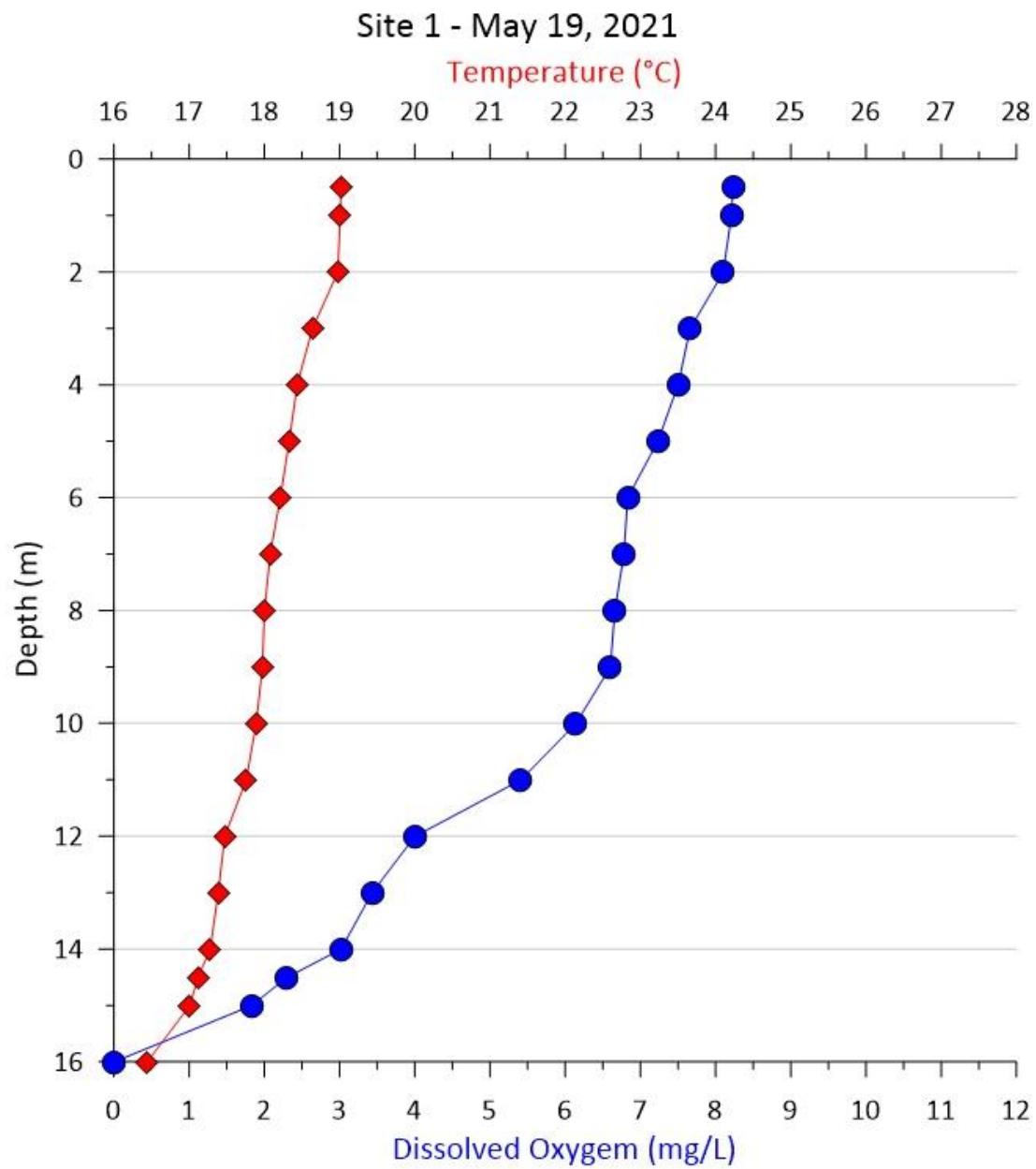
Chlorophyll *a* replicates met precision limits for the majority of the time but were still higher than other parameters. Chlorophyll *a* is a biological parameter that is extracted under extreme care, however, a high degree of variability in the chlorophyll pigment and other pigments between various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

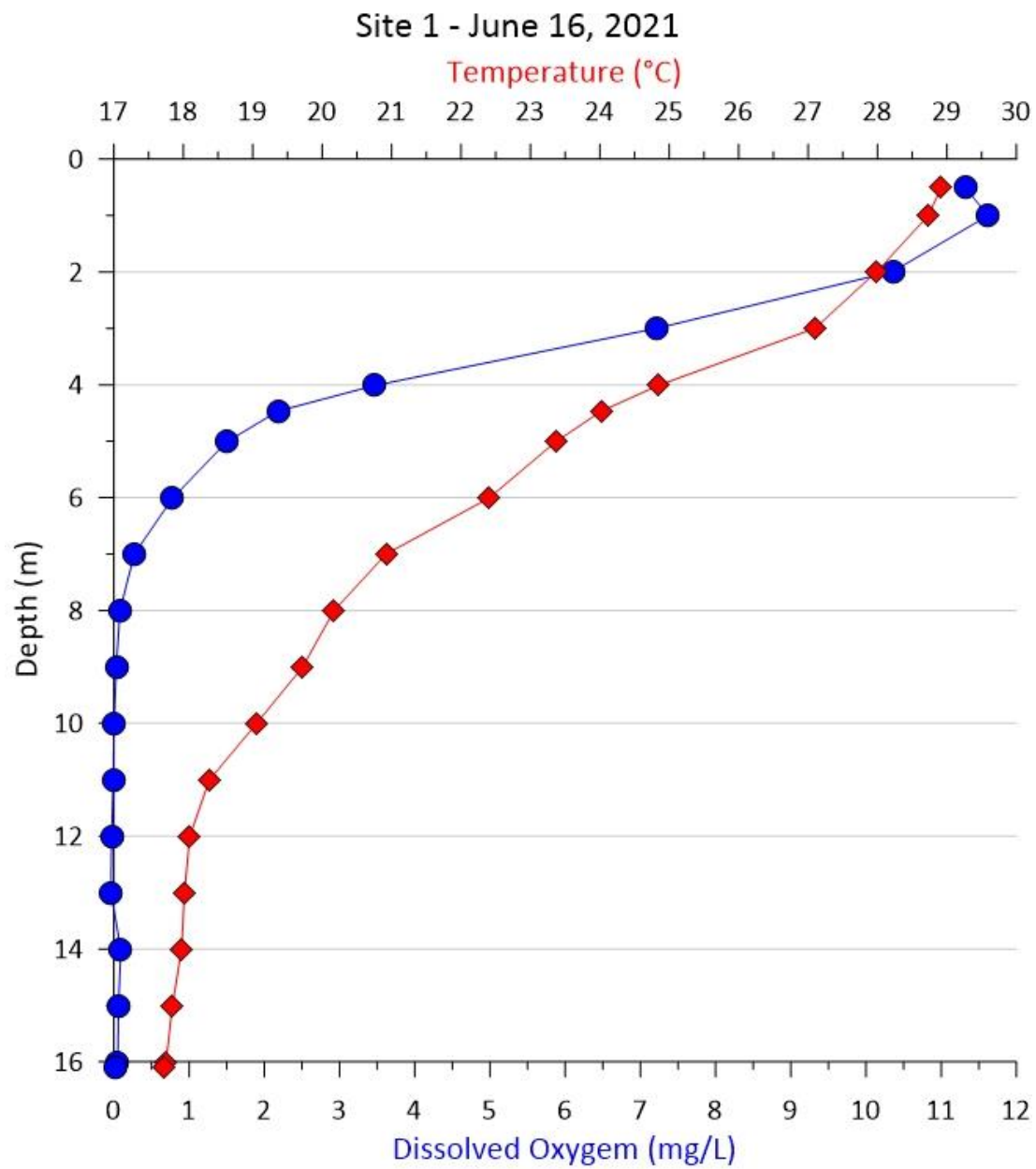
Appendix B

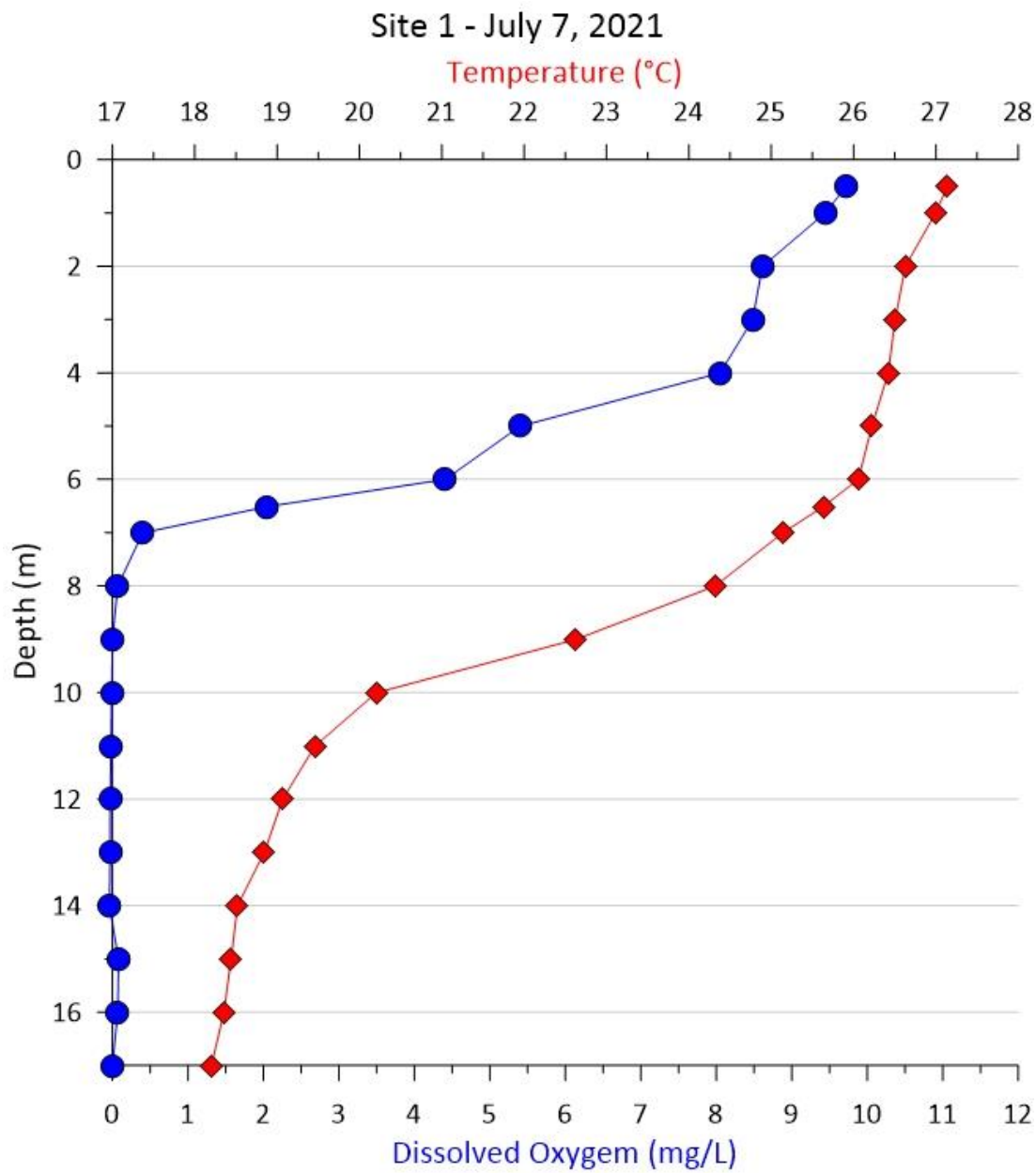
Temperature and Dissolved Oxygen with Depth

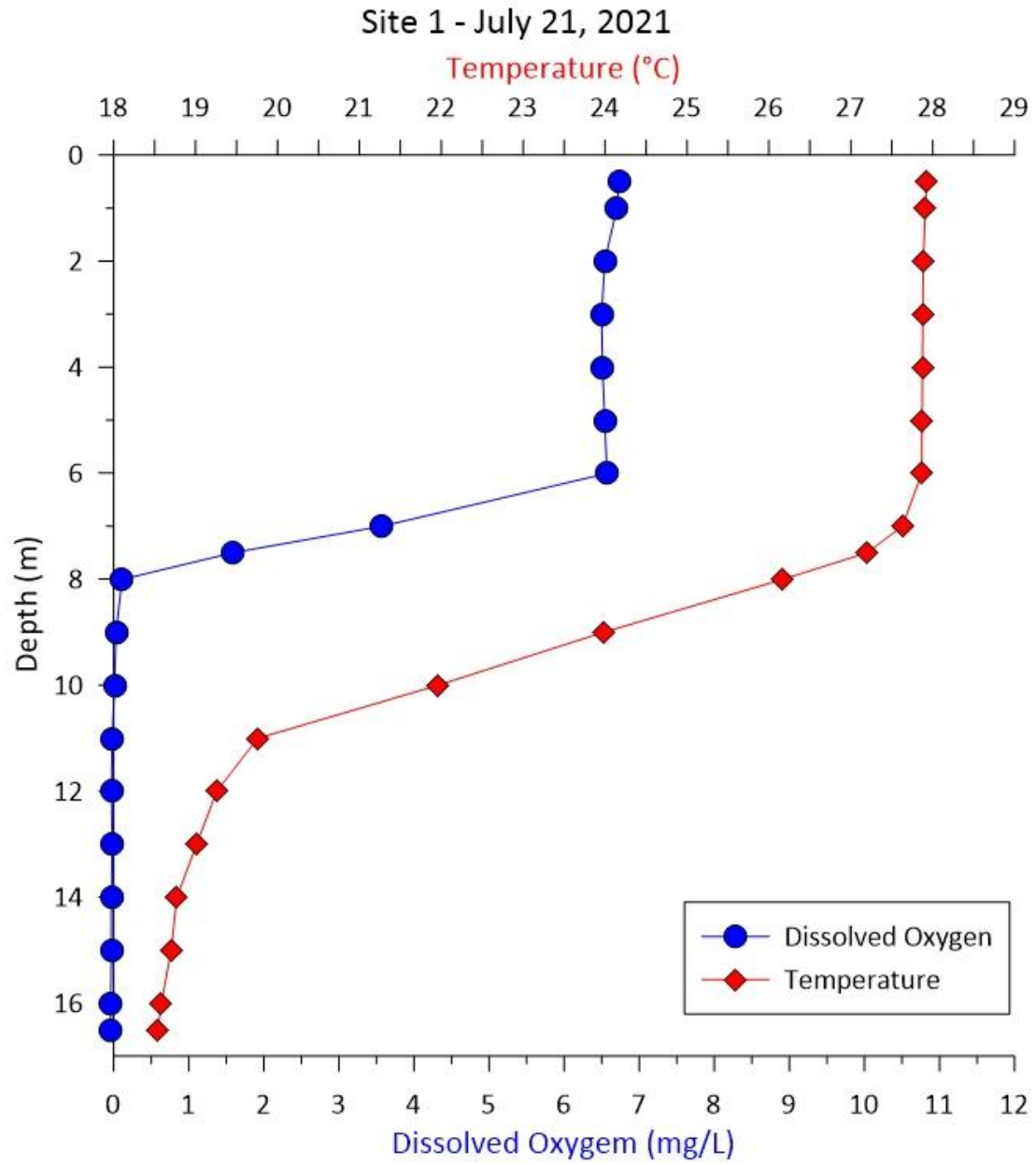
Temperature is denoted as Red Diamond Markers while Dissolved Oxygen is denoted as Blue Circle Markers.



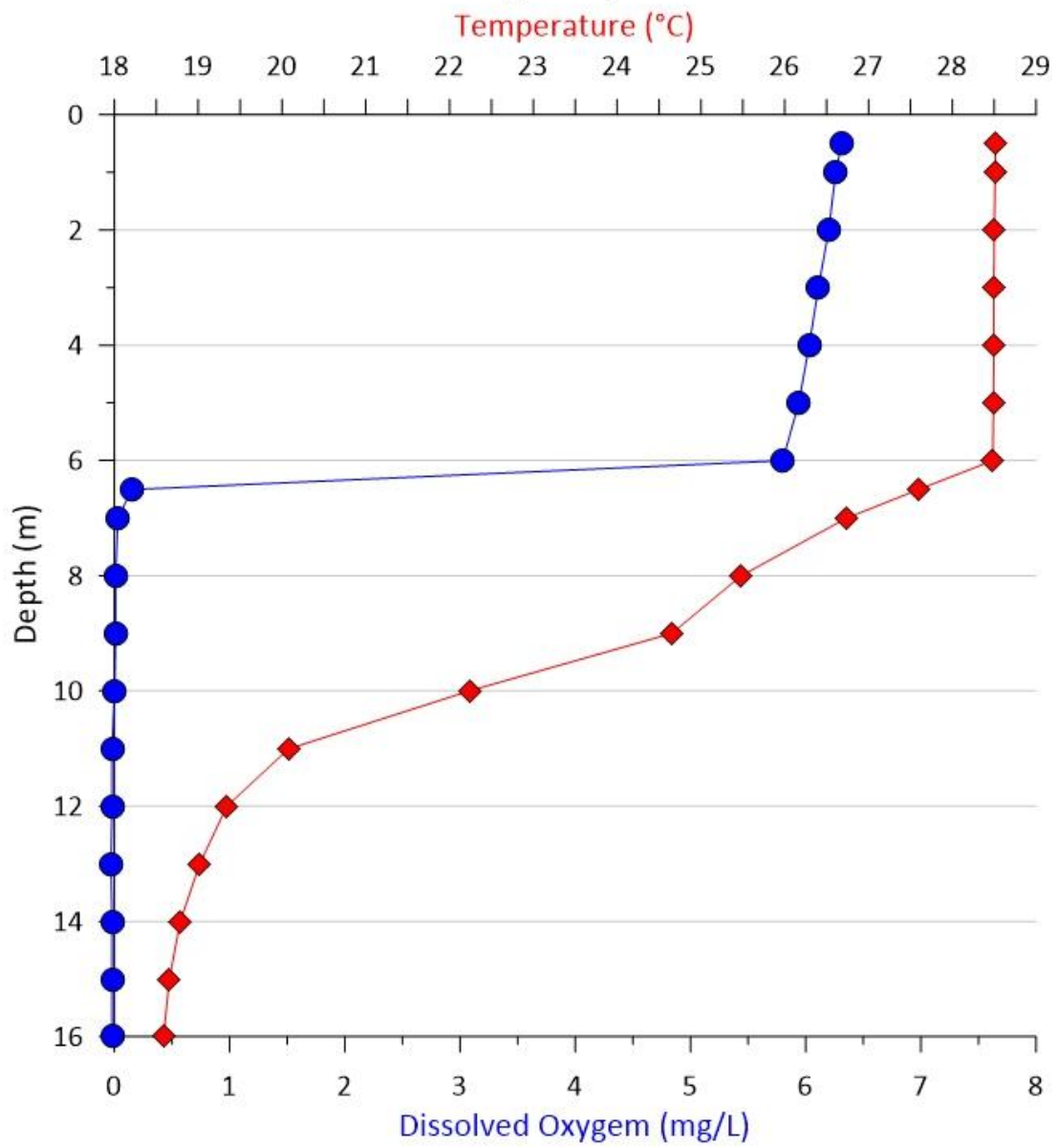




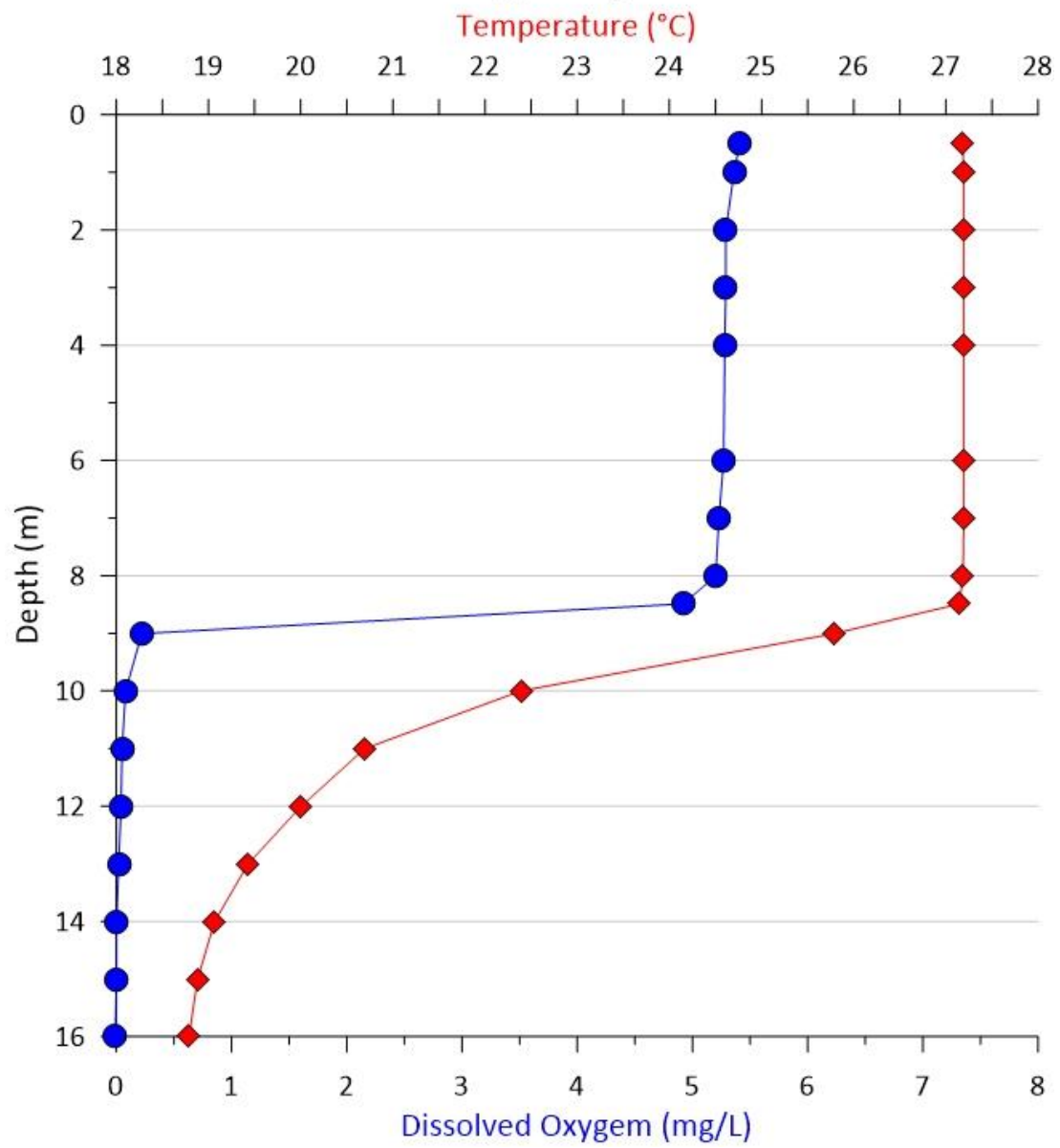




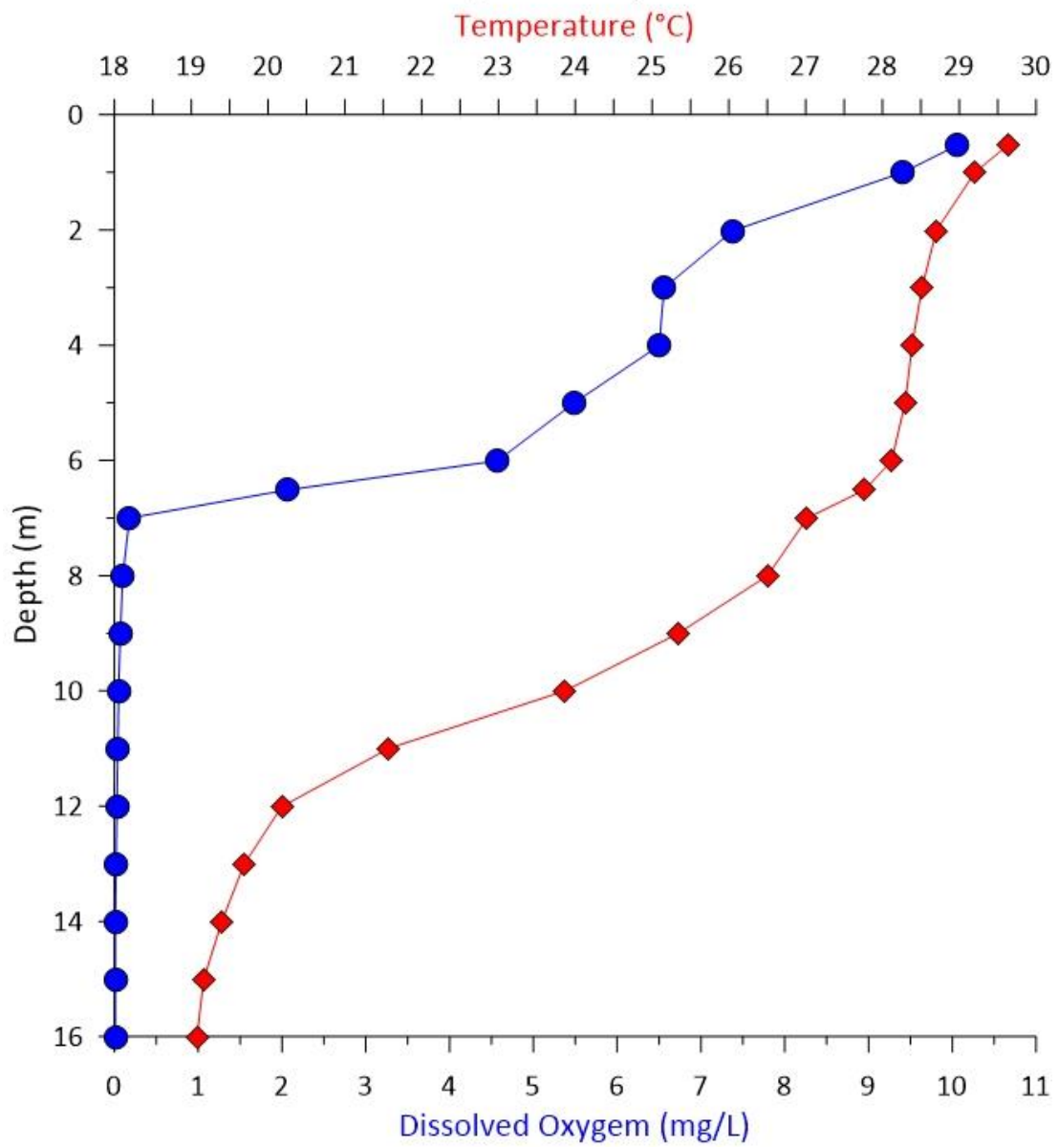
Site 1 - August 4, 2021



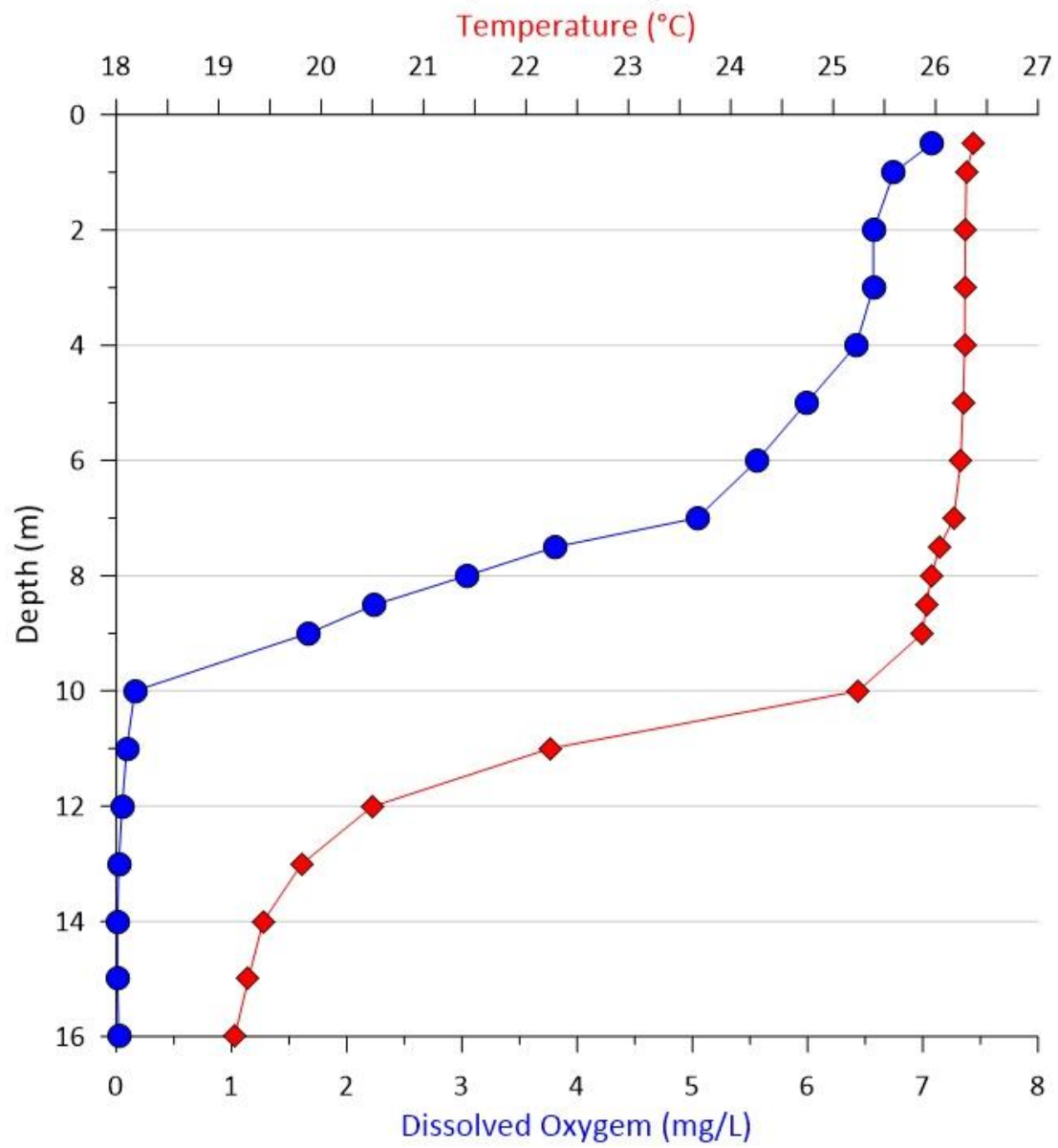
Site 1 - August 18, 2021



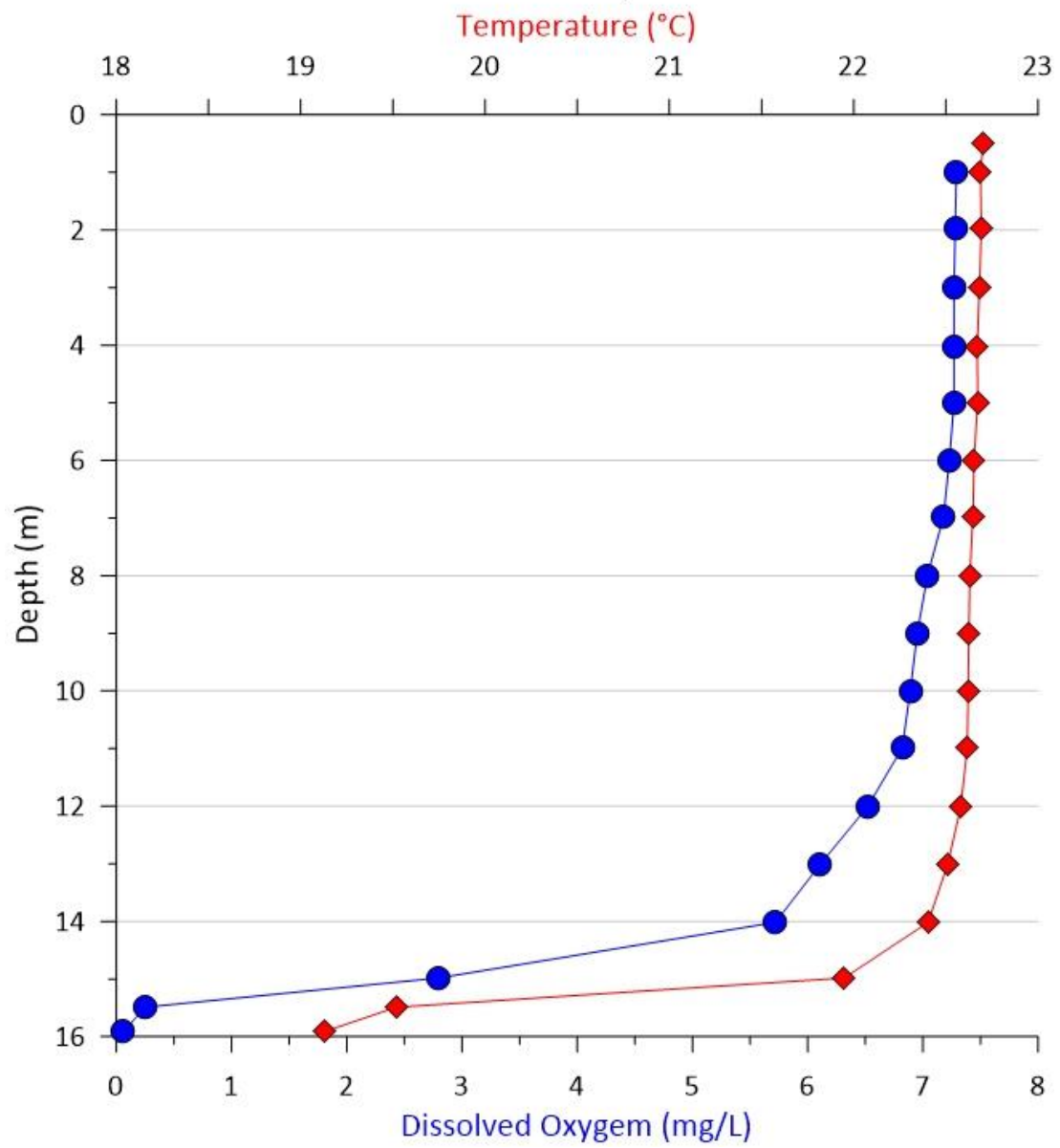
Site 1 - September 1, 2021



Site 1 - September 15, 2021



Site 1 - October 11, 2021



Appendix C

Relative Thermal Resistance Plots

