Oklahoma Water Resources Board

Lake Thunderbird
Water Quality

2015

for the

Central Oklahoma Master Conservancy District

March 31, 2016

FINAL REPORT

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

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Executive Summary

Lake Thunderbird is listed in Chapter 45, Part 5 of the Oklahoma Water Quality Standards (OWQS) as a Sensitive Water Supply (SWS) (OAC 785:45-5-25(C)(4)). In 2015, lake water quality monitoring by the Oklahoma Water Resources Board (OWRB) continued to focus on the effects of the hypolimnetic oxygenation system, which began operation in 2011. The end of 2015 represents 16 years of continuous seasonal monitoring at Lake Thunderbird.

Spring flooding of the lake decommissioned the SDOX system until the start of July 2015. Inflowing floodwaters also brought non-point source pollutants adding an external dissolved oxygen (DO) load greater than previously measured, compared to the internal load driven by algae growth. Unusual climatic temperatures - a cool summer and warm fall - resulted in the slow mixing or graduated entrainment of the hypolimnion, thus dampening the effect of mixis on taste and odor complaints by the City of Norman. While chlorophyll-*a* levels were high, light limitation likely kept peak values from returning to pre-SDOX levels.

The hydraulic residence time for 2015 was 0.51 years, shorter than any other monitored season with the long term average retention time (including 2015) as 3.85 years. Before this, 2007 had the shortest residence time at 0.90 years. In 2015, total inflow was some 20,000 acre-feet greater than the next greatest year, recorded rainfall was more than 9,000 acre-feet greater than the next greatest year and twice the amount of water was released through the dam, totaling 191,835 acre-feet. Although Lake Thunderbird often floods, the flood of 2015 came quicker than normal resulting in rising waters reaching some 3.5 feet above the flood pool (into the surge pool) in May of 2015. The quantity and resulting quality of the floodwaters contributed to the violation of OWQS for dissolved oxygen, chlorophyll-a, and turbidity in 2015.

A comprehensive plan emphasizing active lake and watershed management is required for Lake Thunderbird to meet OWQS for turbidity, chlorophyll-*a* and dissolved oxygen. Primary mitigation efforts should focus on nutrient reduction, affecting two impaired water quality parameters: algae growth and dissolved oxygen. Decreasing the amount of phosphorus, nitrogen and solids washing into the lake from the watershed is critical. In-lake mitigation efforts focused on minimizing the suspension of solids from shallow areas and transfer of these suspended solids from the riverine zones to the main lake body would show the greatest positive impact to turbidity. Although the SDOX system does not appear to completely satisfy the oxygen demand, continuation of the active hypolimnetic oxygenation project provides relief to the lake's DO levels, algal problems, and drinking water taste and odor complaints. Recommended tasks include an evaluation on the SDOX system's ability to deliver oxygen at its' capacity and an estimation of sediment and water column oxygen demand, identification of sediment suspension areas within the lake and updating the bathymetric survey. These steps allow for cost effective decision making toward restoring impaired beneficial uses to Lake Thunderbird.

Introduction

Constructed by the Bureau of Reclamation, Lake Thunderbird began operation in 1966. Designated uses of the dam and the impounded water are flood control, municipal water supply, recreation, and fish and wildlife propagation. Under the authority of the Central Oklahoma Master Conservancy District (COMCD), Lake Thunderbird serves as a municipal water supply furnishing raw water for Del City, Midwest City and the City of Norman. The Oklahoma Water Resources Board (OWRB) has provided water quality-based environmental services for COMCD since 2000. The objective in 2015, in addition to routine monitoring, was to evaluate the performance of Lake Thunderbird's supersaturated dissolved oxygen injection system (SDOX), which was implemented in 2011.

Lake Thunderbird is listed as Category 5 (303d list) in the State's 2012 Integrated Report as waterbody ID OK520810000020_00 and impaired due to excessive turbidity, low dissolved oxygen and excessive Chlorophyll-*a* (Chl-*a*) (http://www.deq.state.ok.us/wqdnew/305b_303d/2012_draft_integrated_report.pdf). As a result of of these impairments, Lake Thunderbird has undergone total maximum daily load (TMDL) analysis by the Oklahoma Department of Environmental Quality (ODEQ) with the resultant TMDL approved by the Environmental Protection Agency (EPA) on November 13th 2013. In short, the TMDL analysis requires a 35% long-term average load reduction of total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) from the 2008-2009 watershed load estimates in order for Lake Thunderbird to meet all current OWQS. This 35% load reduction scenario equates to an annual load reduction of 76,340 kg of total nitrogen per year, 15,006 kg of total phosphorus per year, and 7,470,252 kg of total suspended solids per year. For more information on the findings of the TMDL refer to the TMDL report (http://www.deq.state.ok.us/wqdnew/tmdl/thunderbird/LakeThunderbirdFinalTMDL_ReportNov2013.pdf).

In addition to the water quality impairment listings, collaborative work with the City of Norman illustrated that the water quality impairments have translated into elevated total organic carbon (TOC) in raw drinking water, increased taste and odor complaints in the finished drinking water, and thereby, elevated treatment costs. Every summer Norman rents a powered activated carbon (PAC) unit to reduce taste and odor complaints in the treatment process, but some taste and odor complaints still exist. They are now in the process of installing ozone and ultraviolet treatment into their drinking water train.

In an attempt to mitigate the effects of cultural eutrophication witnessed in the reservoir, the COMCD gained funding through the American Recovery and Reinvestment Act, to install and operate an oxygenation system. By design, the system will oxygenate the deepest portion of the anoxic hypolimnion in the lake while leaving thermal stratification intact. The targeted impacts of providing an oxygenated hypolimnion include attainment of dissolved oxygen OWQS, elimination of reducing conditions in the hypolimnion, reducing overall internal phosphorus load, dissolution of metals, and peak Chl-*a* events. Data collected in 2015 represents the fifth season of SDOX operation.

Water Quality Evaluation

Sampling Regime

In 2015, Lake Thunderbird water quality sampling occurred from April 22 through December 9, monitoring the parameters in **Table 1** at the sites indicated in **Figure 1.** All COMCD sites were sampled during each visit. Sites 1, 2, and 4 represent the lacustrine or open water zones of the lake. Consistent stratification and an underlying hypolimnion are common features of the lacustrine sites. Sites 6, 11 and 8 represent riverine zones of their respective tributaries. Finally, sites 5 and 3 represent the transition zones between riverine and lacustrine portions of the lake. Site 7, in the Clear Creek arm, is not sampled as part of the COMCD project but as part of the OWRB's Beneficial Use Monitoring Program (BUMP) protocols.

On every visit, all COMCD sites had water quality profiles conducted for oxidation-reduction potential (ORP), DO percent saturation and concentration, temperature, specific conductance, total dissolved solids (TDS) and pH. Water quality profiles were recorded at each site, in one-meter intervals from the lake surface to the just above the sediment-water interface. In addition, nutrient samples were collected at the surface of sites 1, 6, 8 and 11 and at 4-meter depth intervals at Site 1 as well as 0.5m off the lake bed. Analyses performed on these samples included phosphorus (P) and nitrogen (N) series. Total organic carbon samples were also collected at the surface of Site 1. Field observations, secchi disk depth, surface Chl-*a*, and turbidity samples were collected at all nine sites.

Table 1. 2015 Water Quality Sample Dates and Parameters.

Date	22-Apr	12-May	3-Jun	17-Jun	1-Jul	15-Jul	29-Jul	12-Aug	26-Aug	9-Sep	23-Sep	12-Oct	9-Dec
Profile	X	X	X	X	X	X	X	X	X	X	X	X	X
Chl-*a*	X	X	X	X	X	X	X	X	X	X	X		X
Secchi Depth	X	X	X	X	X	X	X	X	X	X	X		X
TOC	X	X	X				X	X		X			
Turbidity	X	X		X	X	X	X	X	X	X	X		X
Nutrients	X	X	X		X	X	X	X	X	X	X		X

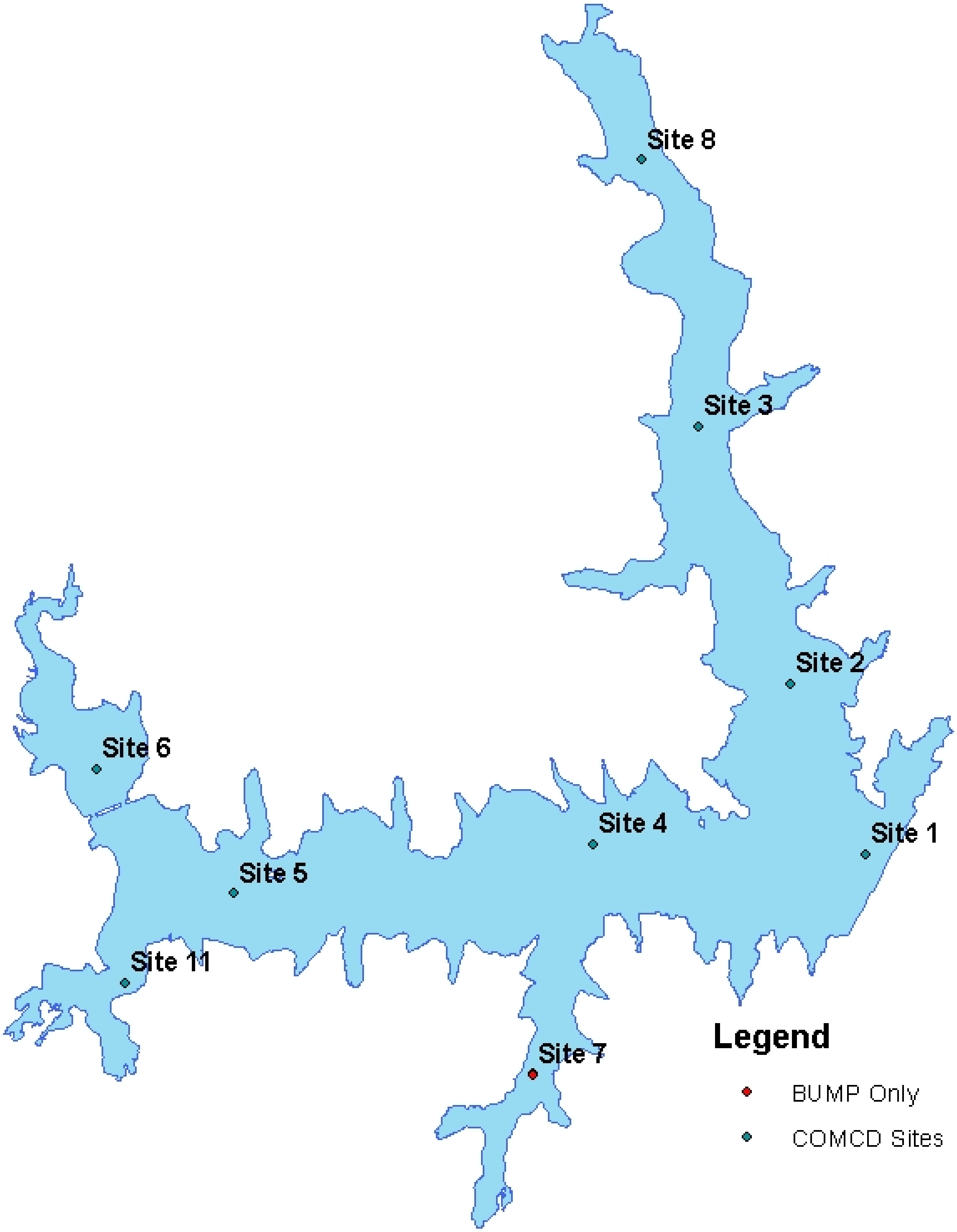


Figure 1. Lake Thunderbird 2015 Sampling Sites

Quality Assurance and Quality Control (QA/QC)

Water quality sampling followed the QA/QC procedures described in the EPA-approved Quality Assurance Project Plan (QAPP) "Clean Water State Revolving Fund Loan and American Recovery and Reinvestment Act ORF-09-0027-CW: Lake Thunderbird Water Quality Monitoring 2010-2012 executed August, 2010. Laboratory quality control samples included duplicates and replicates. Replicate samples were collected at the surface of Site 1 and labeled "Site 1" and "Site 9" respectively, then delivered to the laboratory for analysis. In addition, the Site 1 Chl-*a* sample was split to produce duplicate samples (1a and 1b) during chlorophyll-*a* post processing at the OWRB, then delivered to the laboratory for analysis. Finally, laboratory blank samples were submitted to the laboratory as Site 22. **Appendix A** summarizes laboratory results of duplicate and replicate sampling. Additional chlorophyll-a replicates, were submitted while transitioning between analytical laboratories to increase accuracy and precision of reported values as well as increasing statistical significance. The sample preservation method used by the analytical laboratory for ortho-phosphorus varied from previous methods (by acidifying the sample prior to filtration) likely resulting in overestimates of the laboratory reported value. Comparison of ortho-phosphorus to total phosphorus reports did not show any obvious errors, such as ortho-phosphorus values greater than total phosphorus values.

Duplicate and Replicate Samples

Duplicate samples yield an overall estimate of error either due to sampler or laboratory error. This paired data set yields a measured difference between two relatively identical samples. Site 9 is used as the replicate sample identifier for Site 1 quality assurance surface samples. The percent absolute difference (PAD) statistic is calculated to describe the precision of each laboratory parameter based on the comparison of replicate samples; sites 1 (x_{S1}) and 9 (x_{S9}).

Eq. 1 $$PAD = \left| x_{S1} - x_{S9} \right| / \bar{x} * 100$$

Equation 1 was applied for each replicate sample for each reported parameter. Results were tabulated and statistical summaries were generated using the box and whisker plot function (**Figure 2**). All parameters showed relatively good precision with median PAD below 20 except ammonia. Note that while PAD is good over the entire sampling season, instances of high PAD for Ammonia as N, Ortho-phosphorus as P and Chlorophyll-*a* occurred and are reflected by a large upper quartile. PAD summary statistics were within the acceptable range. Blank samples showed comparatively low-level phosphorus (total or ortho) contamination on 6/3/15, 7/1/15, 7/15/15 and 12/9/15. Significant contamination was noted on 4/22/15, 6/3/15 and 8/12/2015. These phosphorus blank reports were approximately three times the detection limit of 0.005 mg/L. Significant ammonia contamination, close to 4 times the detection limit, was noted in the blank sample on 4/22/15. Finally, significant nitrite contamination was observed in the 8/12/2015 blank sample. These reports were puzzling as no repeatable pattern was noted in the blank sample values, while the environmental sample values seemed normal and well below the blank sample report. Reported laboratory values were adjusted to omit the 8/12/2015 site 1b chlorophyll-a sample, reported at 1.4 µ/L, because of the high difference between it and the site 1a and site 9 values of 29.4 µg/L and 29.5 µg/L respectively. Pheophytin-a, the degradation product of chlorophyll-a, for site 1b was 68.5 µg/L, more than 5 times report of its duplicate, 1a and 11 times it replicate, site 9. The close agreement between 1a and 9 indicates the potential of sample degradation to 1b and led to the omission. A review of all other chlorophyll-*a* and pheophytin-a reports did not reveal any other potential sample degradation.

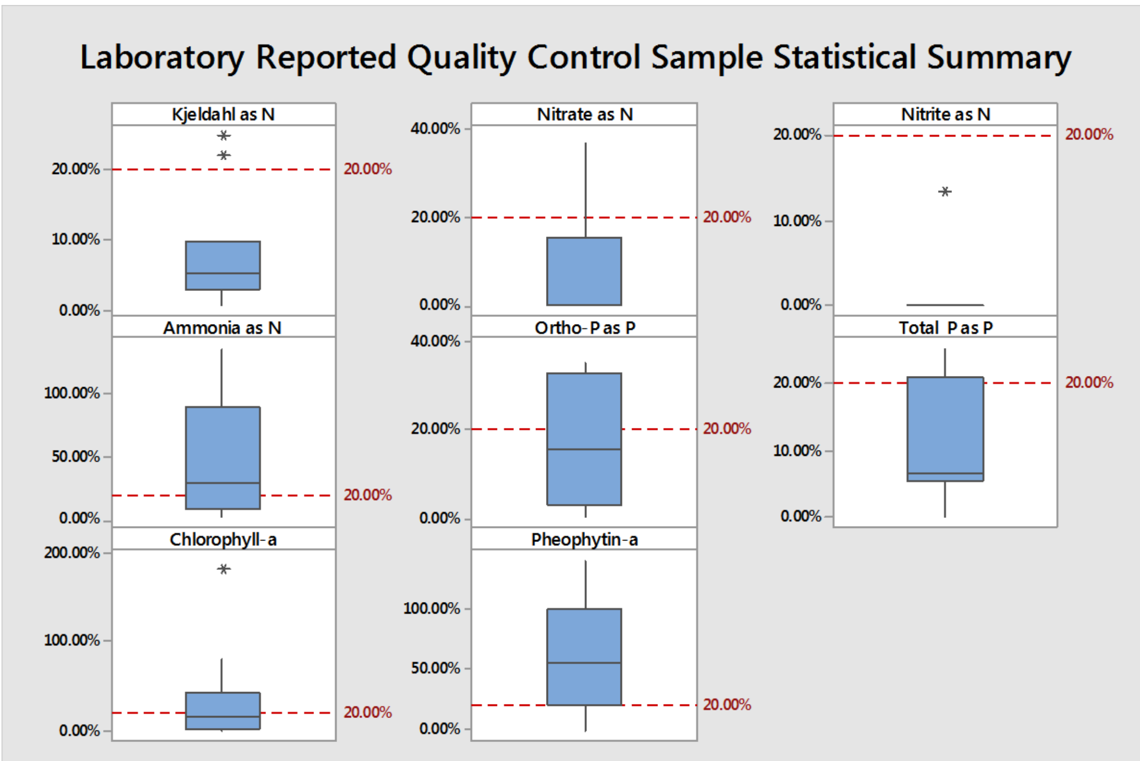


Figure 2. Summary Plots of Percent Absolute Difference for Duplicate Laboratory Samples Lake Thunderbird April 24, 2015 - December 9, 2015. (Box represents the middle 50%, the center bar the median value, top and bottom stems the upper and lower 25% quartile and asterisks as outliers**)**

Climate

Knowledge of potential climatological influences is essential when assessing the water quality of a waterbody. The hydrology and physical processes of a given reservoir significantly influence internal chemical and biological processes. For example, storm water influences nutrient content and composition, sediment loading, sediment suspension and stratification patterns. In addition, changes in lake volume and nutrient concentrations affect the extent of anoxia in the hypolimnion and alter oxidation-reduction potentials. Anoxia, in turn directs the solubility of sediment borne phosphorus and metals.

Figure 3 provides a graphical representation of Lake Thunderbird's rainfall, elevation, inflow, and sampling dates for calendar year 2015. The year was historic with the state and region recording the most rain since the beginning of record keeping. Making the record rainfall even more notable was that the rains effectively ended an extended drought, by coming within a relatively narrow 3-month period of April-June.

Annual precipitation at Lake Thunderbird dam in 2015 totaled 59.78 inches, more than 26 inches above the annual average. The high rainfall and runoff resulted in the highest ever recorded pool elevation on May 24, 2015; 1052.88 MSL was recorded at 0800 hours. On that day more than 5 ½" of rain fell at the dam and the pooled reservoir water stretched over 8,596 surface acres while the daily release rate through the dam was an astonishing 14,880 cfs. The recorded pool elevation was nearly 14' above the conservation pool and 3.5' into the surcharge pool. The lowest pool elevation, 1036.34 not quite 3' below conservation pool, was recorded on February 28, 2015. In addition to hydrology, air temperature influences lake characteristics such as stratification and primary productivity. **Figure 4** compares monthly mean temperatures from 2012 through 2015 to the long-term monthly mean. Deviations from the climatological norm in 2015 dampened the normal erosion of the hypolimnion and timing of complete mixis. This effect was produced by the combination of lower than normal July and August temperatures and warmer than normal September and October.

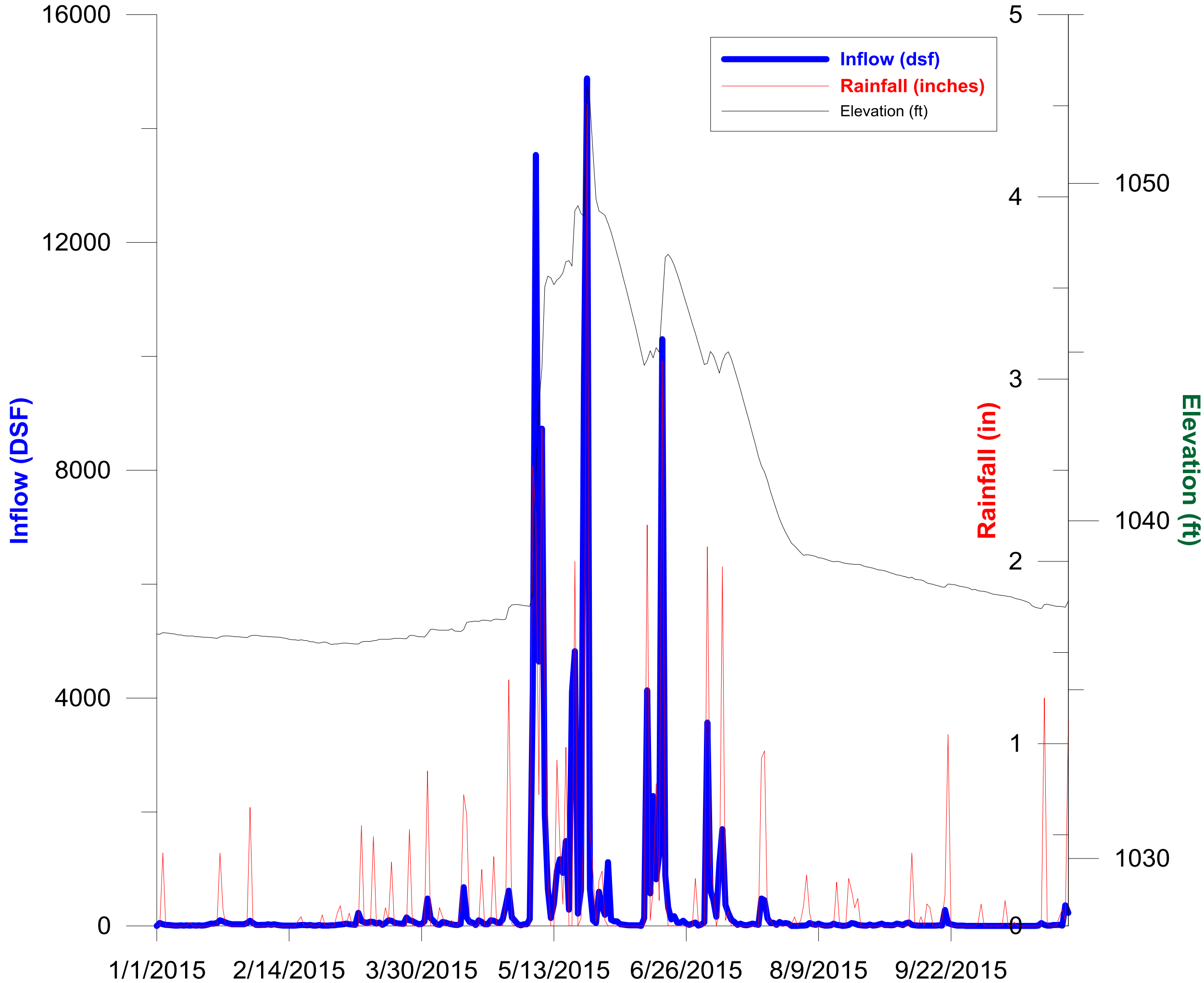


Figure 3. 2015 Inflow, Precipitation, and Elevation Data for Lake Thunderbird, with Sample Dates Indicated.

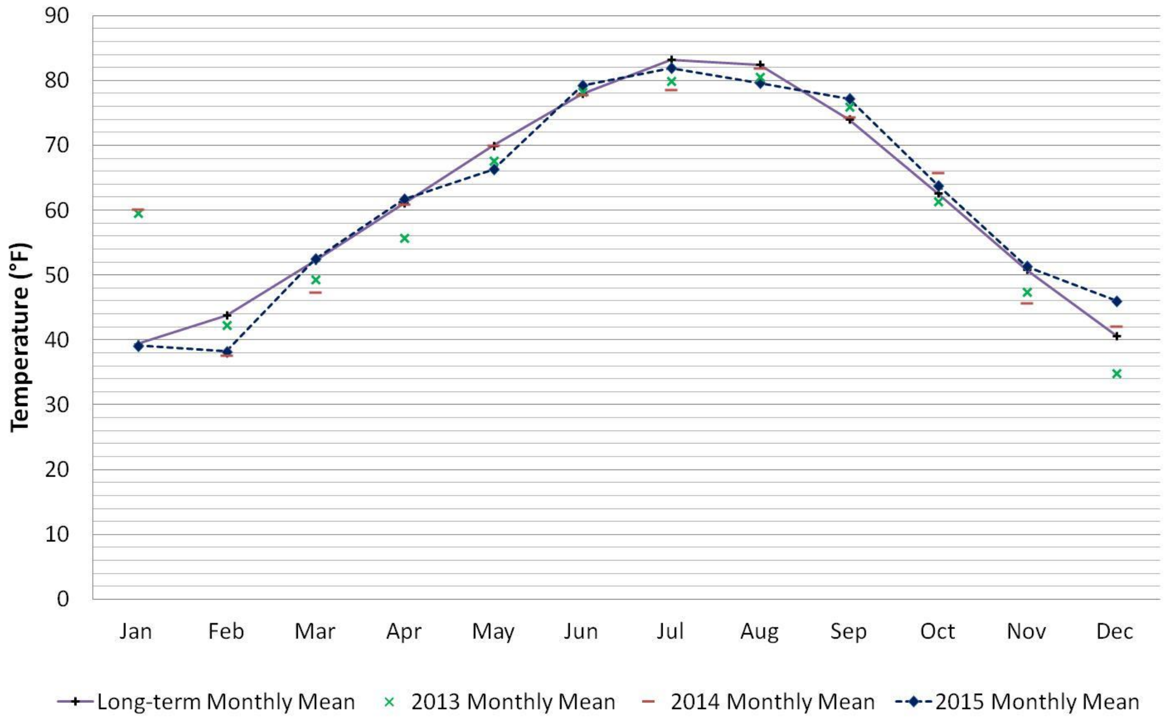


Figure 4. 2015 Average Monthly Temperature at the Norman Mesonet Station; Long Term, 2013 and 2014.

Hydrologic Budget

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

Eq. 2 $$\frac{dV}{dt} = Q_{in} - Q_{out} + PA_s - E_v A_s - W_s$$

Where V = lake volume [L^3],

A_s = lake surface area [L^2],

Q_{in} and Q_{out} [L^3/T] represent net flows into and out of the lake due to tributary inflows and gated releases,

P [L/T] is the precipitation directly on the lake,

E_v [L/T] is the lake evaporation,

W_s is the water exported for water supply use.

In other words, the rate of change in volume of water stored in or on the given area per unit time is equal to the rate of inflow from all sources, minus the rate of outflows. The input or inflows to a lake may include surface inflow, subsurface inflow, and water imported into the lake. The outputs may include surface and subsurface outputs and water exported (e.g. water supply) from the lake. For Lake Thunderbird, subsurface flow is likely insignificant, based on the relatively impermeable lake substrate.

The inputs to Lake Thunderbird include precipitation and inflow from the tributaries - encompassing all surface runoff in the basin. The outputs are evaporation, dam releases (spilled), and water supply intake. Precipitation was estimated from the direct rainfall measurements/data provided by the United States Army Corps of Engineers (USACE). The precipitation contribution to the total inflows was obtained by multiplying the daily rainfall amounts by the surface area of the lake on each date, as shown by:

$$\boldsymbol{Q_p} = \mathbf{P} * \boldsymbol{A_s}$$

where **P** [L/T] is rainfall amount and $\boldsymbol{A_s}$ [L2] is the surface area of the lake.

Daily evaporation rates were calculated and reported by the USACE. Here, empirical equations were applied to relate solar radiation, wind speed, relative humidity, and average daily air temperature to the rate of evaporation from the lake. These rates are then multiplied by the daily average surface area of the lake to give the amount of water evaporated per unit time.

$$\boldsymbol{Q_e} = \boldsymbol{E_v} * \boldsymbol{A_s}$$

where $\mathbf{E_v}$ [L/T] is the evaporation rate and $\boldsymbol{A_s}$ [L2] is the surface area of the lake.

Water outputs from Lake Thunderbird generally include gated dam releases and water supply withdrawals. The USACE reports dam release and change in pool elevation at the end of every day, while COMCD reports water supply withdrawals. The lake volumes, corresponding to the elevations, were calculated and the difference between them is the change in volume for that month. The volumes used were estimates from elevation-capacity curves generated from the OWRB's 2001 bathymetric survey of the lake.

Results

A summary of monthly water budget calculations for Lake Thunderbird is provided below in

Table 2. In this table, 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. 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. The difference between the inflow and outflow is in the I-O column. Total monthly error is calculated as the difference between the change in lake volume based on elevation and I-O.

Examination of the estimated water budget for Lake Thunderbird showed that estimated inputs and outputs were close to the actual volume changes (as measured by change in pool elevation). There was relatively little error but for the months of greatest inflow and release for the year: May, June and July.

Table 2. Lake Thunderbird 2015 Water Budget Calculations Expressed in Acre-feet.

Month	INPUTS			OUTPUTS				ERROR TERM		
	Inflow	Rainfall	**Total Inputs**	Evaporation	Water Supply	Releases	**Total Outputs**	I-O	ΔV	Error
Jan	1,307	359	1,666	1,363	1,070	-	2,433	(767)	(412)	355
Feb	643	279	922	1,434	1,038	-	2,472	(1,549)	(1,235)	315
Mar	2,864	835	3,699	1,936	1,142	-	3,078	621	1,183	(563)
Apr	5,938	1,738	7,676	2,477	1,083	-	3,560	4,116	4,425	(309)
May	137,789	14,096	151,884	2,638	1,049	69,433	73,120	78,764	61,583	17,181
Jun	38,210	4,911	43,121	4,752	1,427	66,694	72,874	(29,753)	(23,120)	6,633
Jul	16,608	3,356	19,964	4,772	1,650	53,643	60,065	(40,101)	(28,452)	11,649
Aug	701	374	1,075	3,269	1,766	1,295	6,330	(5,255)	(3,962)	1,293
Sep	489	900	1,388	3,497	1,731	-	5,228	(3,839)	(2,778)	1,061
Oct	359	1,089	1,448	2,185	1,522	-	3,707	(2,259)	(1,492)	767
Nov	4,877	2,194	7,071	1,259	1,121	-	2,380	4,691	5,145	(454)
Dec	12,654	1,607	14,261	1,319	959	770	3,047	11,214	10,033	1,181
Total	218,636	35,540	254,176	30,900	15,558	191,835	238,294	15,882	20,918	39,109

Once a hydrologic budget is constructed, additional features of reservoir dynamics can be estimated. The hydrologic retention time is the ratio of lake capacity at normal pool elevation to the exiting flow (usually on an annual basis). This represents the theoretical time it would take a given molecule of water to flow through the reservoir. The combination of lake releases and water supply withdrawals give Lake Thunderbird water a hydrologic residence time of 0.51 years for 2015, dropping the 2001 to present average hydrologic residence time to 3.85 years. In 2015, more than twice the volume of the conservation pool flowed into Lake Thunderbird with the majority of this recharge occurring in May. Approximately 74% of the released water occurred May through July. March through May, November and December were months of greater recharge than discharge while all other months had greater discharge than recharge (**Figure 5**).

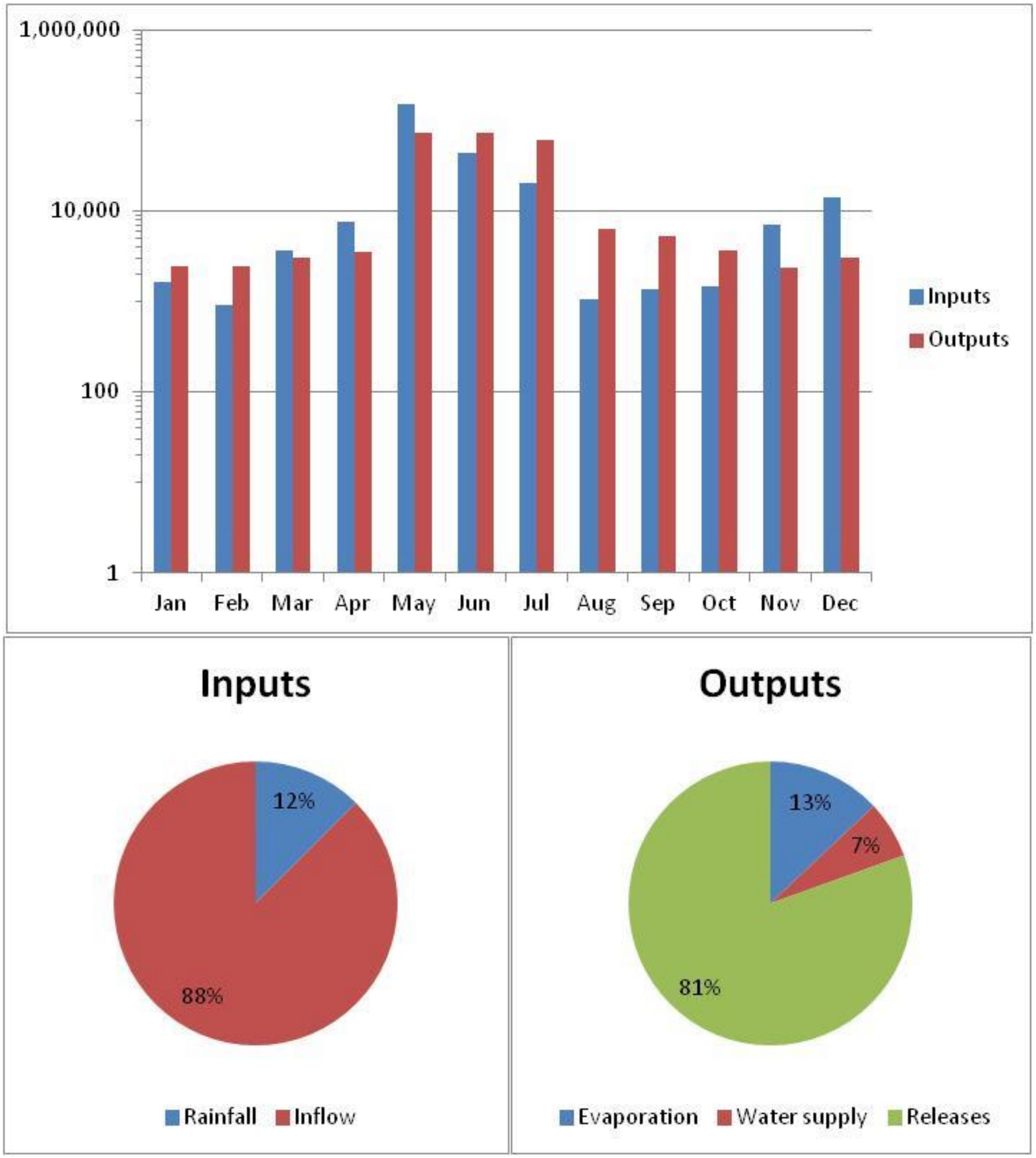


Figure 5. 2015 Lake Thunderbird Water Input and Output Sources by Month, Expressed as the Percent of Total.

Sources of Error

Although robust, the hydrologic budget does contain error. In the 2015 calendar year, the hydrologic budget contains a cumulative annual error of 39,109 acre-feet, with an average monthly error of 3,259 acre-feet. The greatest error was for the month of May when the greatest recharge was recorded; followed by July and June the second and third months of greatest recharge and discharge. Errors in bathymetry and flood pool morphometry are the likeliest explanations for error.

The USACE estimated inflow from the tributaries based on changes in lake volume using their original lake bathymetry. To account for this error, inflows are adjusted according to pool elevation using OWRB determined bathymetry. Additional extrapolations were necessary due to the high pool elevations. Volume and areas estimated from the conservation pool into and above the flood pool were extrapolated using 2007 LIDAR data acquired from the City of Norman and appended to the OWRB's 2001 bathymetric survey (to the top of the conservation pool). The OWRB GIS technician's assessment was that the LIDAR and OWRB lake boundary did not significantly deviate from each other.

The OWRB completed a bathymetric survey, in 2001, estimates a conservation pool sedimentation rate around 400 acre-feet per year. In 2009, additional bathymetric surveying was around the dam area for the hypolimnetic oxygenation system. That survey indicated little sediment accumulation in the dead pool of the lake. Should the estimated sedimentation rate prove correct, newly deposited sediment is predicted to be mostly in the upper portion of the conservation pool with a loss of approximately 5,900 acre-feet. Resurveying the reservoir with current data allows for an accurate estimate of sedimentation based on comparable survey methods and capacity curve for water budget construction. Current bathymetry also reduces error in any water quantity or quality modeling.

Groundwater loss and gain to the lake were assumed negligible. This could be verified with field measurements or through a review of the geology in the area.

While the hydrologic budget contains sources of error, it is still robust enough to support lake nutrient budget development and water quality modeling.

Thermal Stratification, Temperature, and Dissolved Oxygen

Warming of the lake surface throughout spring marks the onset of stratification. Thermal stratification occurs when an upper, less dense layer of water (epilimnion) forms over a cooler, denser layer (hypolimnion). The metalimnion, or thermocline, is the region of greatest temperature and density change and occurs between the epilimnion and hypolimnion (**Figure 6**). Because of these differences, thermal resistance to mixing prevents the epilimnion and hypolimnion from coming in contact during stratification. Therefore, when DO is consumed and depleted by the decomposition processes in the hypolimnion, it is not replenished. This process has been documented by the OWRB at Lake Thunderbird for every monitoring year since 2000, and is inevitable without the influence of outside forces.

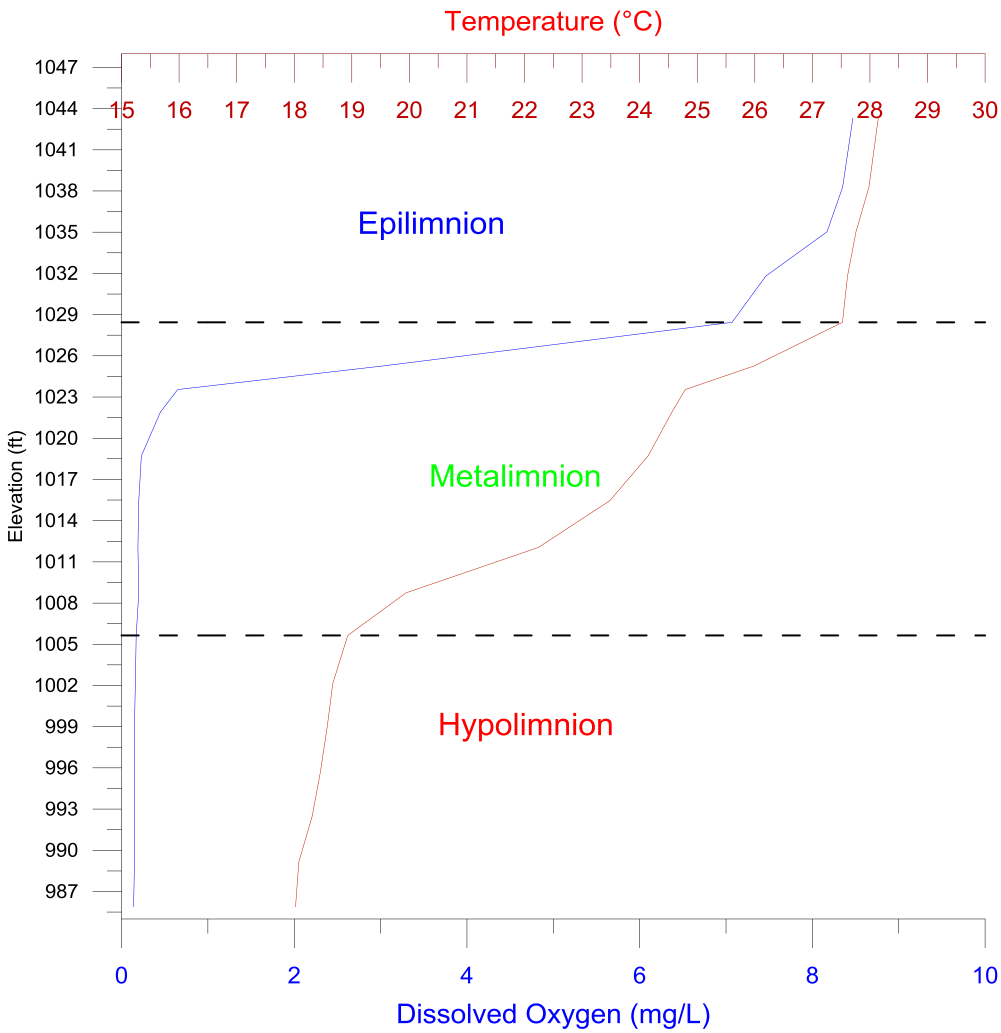


Figure 6. A Typical Temperature and Dissolved Oxygen Vertical Profile for Lake Thunderbird (July 1st, 2015) Approximate Boundaries Between the Epilimnion, Metalimnion and Hypolimnion are Marked with Dashed Lines.

Prior to the onset of stratification, the lake had isothermal conditions throughout the water column. As stratification sets in and strengthens, the epilimnion stays relatively homogenous while the metalimnion (thermocline) changes radically with depth until the hypolimnion is reached. This physical structure maintains until surface temperatures start to decline, the epilimnion cools, eroding the thermocline as the epilimnion mixes with the lower layers. This process is referred to as fall mixing or “turnover”.

Lake stratification has a significant effect on water quality by isolating chemicals in areas of reduced chemical exchange – such as the hypolimnion. An increased loading of nutrients can occur through settling of nutrients from the epilimnion and metalimnion primarily in the particulate form. Increased loading can also occur in the hypolimnion when the sediment bed is exposed to anaerobic conditions and releases inorganic phosphorus and ammonia into the water column. Starting in early fall/late summer these isolated (and largely dissolved) nutrients are brought back into epilimnetic waters in large volumes during mixing events, causing significant fluxes in surface water chemistry. A key feature of the influxes of hypolimnetic waters is a further stimulation of algae growth, which occurs as hypolimnetic nutrients mix into the epilimnion.

Lake stratification can also affect drinking water treatment cost and quality. Treatment cost escalates with rising organic and dissolved metal content, summer time increase in organic content is largely due to the stimulation in algae growth associated with turnover discussed later in this report. The quality of drinking water can also be affected as hypolimnetically stored algal cells are incompletely decomposed and contents of the algal cells are re-circulated into the water column with mixing events. The City of Norman has historically received taste and odor complaints about the finished drinking water at this time of year, and confirmed the presence of algal associated taste and odor compounds, Methyl-Isoborneol (MIB) and Geosmin.

Stratification was detected on the first sample date, April 22, 2015, with continued weak stratification noted at each May sample trip. Stronger thermal stratification was not observed until June 17, 2015. The extremely large influx of storm-water likely contributed to the delayed onset of expected strong stratification. As solar radiation and ambient temperatures increased, the upper portion of the water column began to heat up while the bottom of the lake stayed cooler, strengthening water column stratification. Since the first monitoring event both temperature and dissolved oxygen decreased with depth. By June 17, the hypolimnion was completely anoxic and anaerobic conditions had moved into the metalimnion (**Figure 7**).

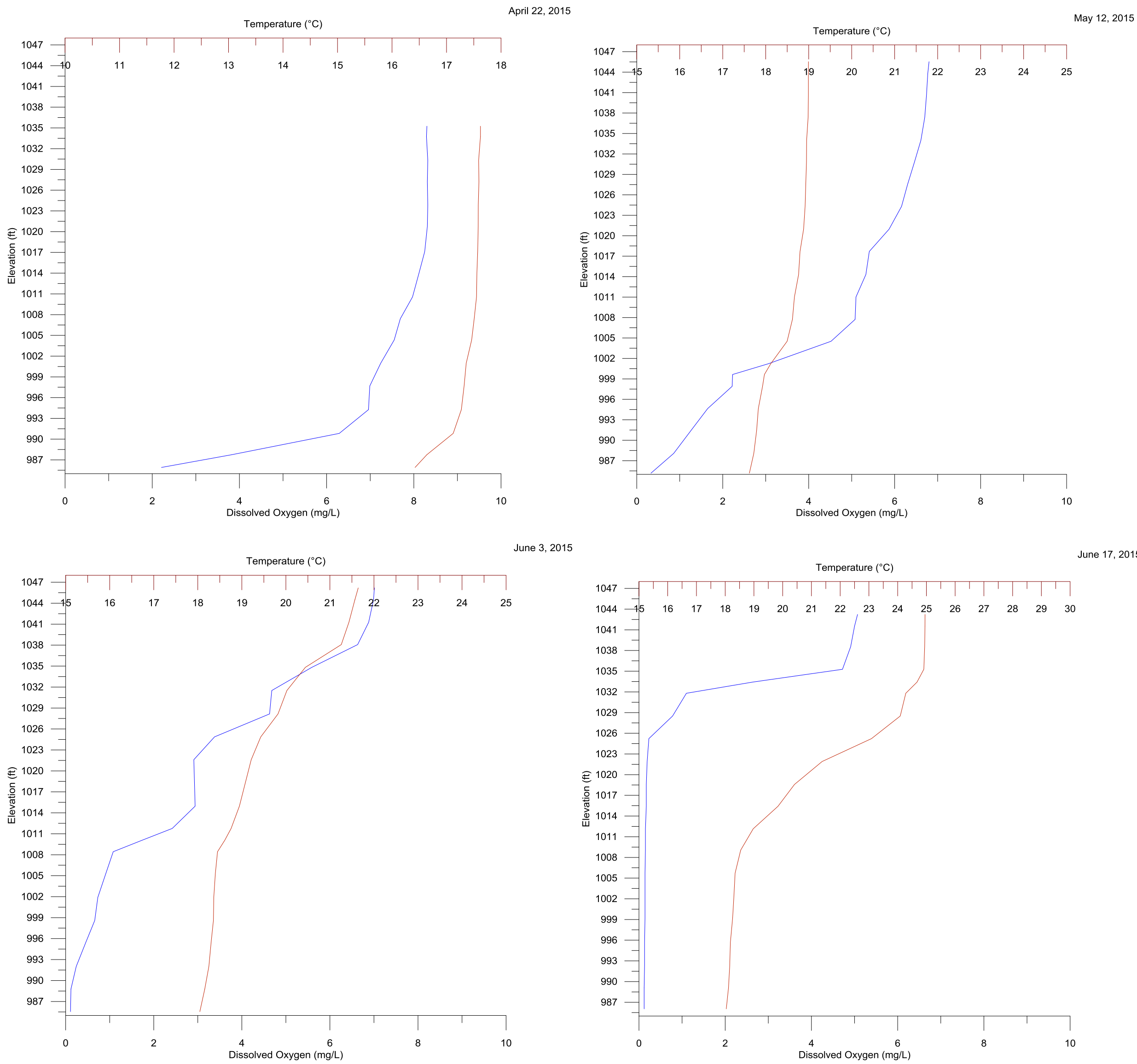


Figure 7. Temperature (red) Dissolved Oxygen (blue) Vertical Profiles. Site 1: April 24, 2015 – June 17, 2015.

As the season progressed from late spring through summer, heating at the surface continued even as water was released through the spillway. The epilimnion continued to warm from July to a peak temperature of 29.5°C at site 1 on August 12, 2015. Due to the extremely high pool elevation, the SDOX system was flooded in May and was not back online until June 29, 2015. While anoxia still pushed into the metalimnion, the hypolimnion slowly decreased in size from July through August (**Figure 8**).

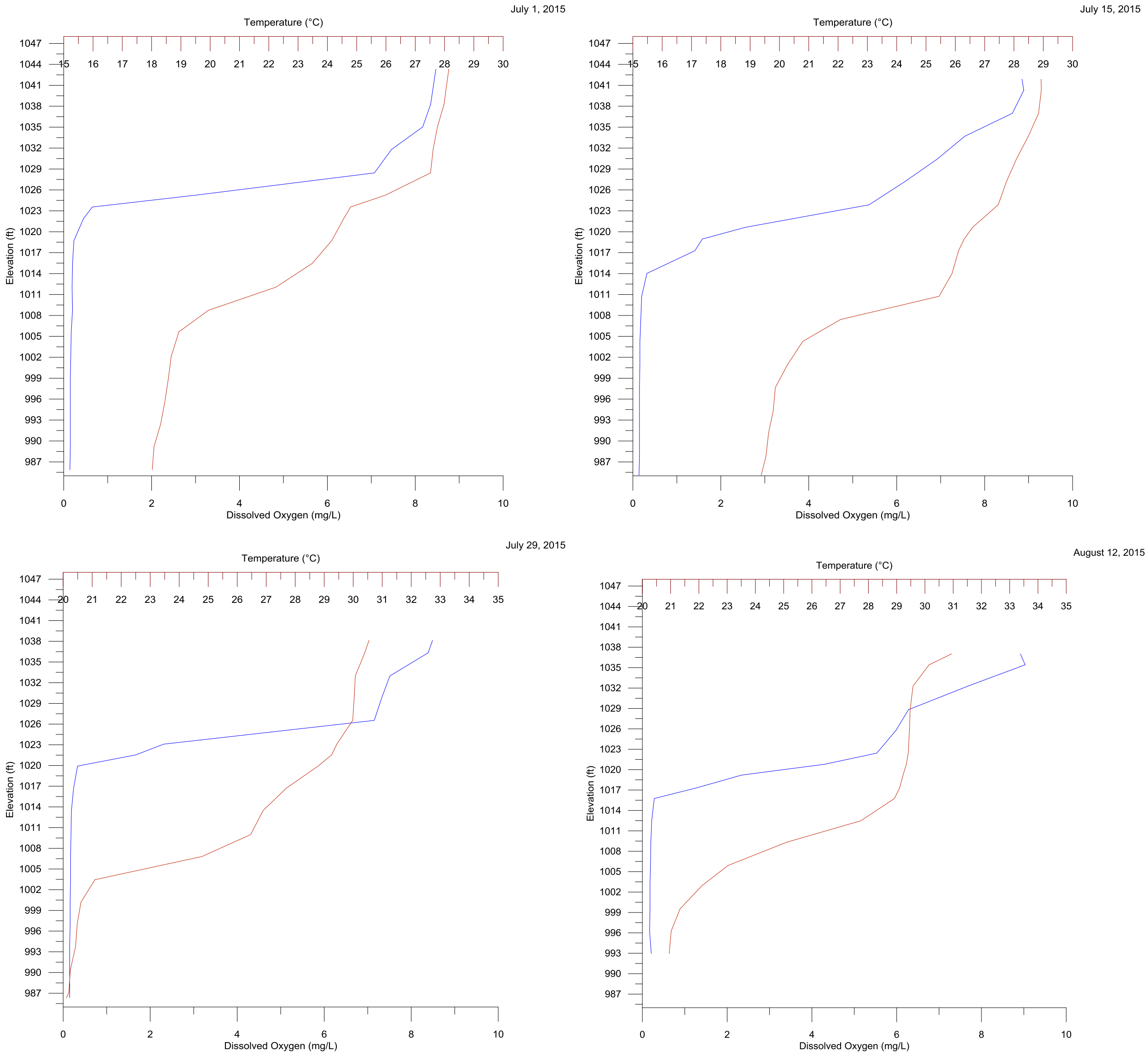


Figure 8. Temperature (red) Dissolved Oxygen (blue) Vertical Profiles Site 1: July 1, 2015 – August 12, 2015.

While no discernible effect of the SDOX on hypolimnetic dissolved oxygen was noted there was an increase in the rate of temperature gain in the hypolimnion that could be attributed to the SDOX. Warming of the hypolimnion was observed starting July 1, 2015 into September. Through August, both the epilimnion and hypolimnion deepened while the metalimnion narrowed (**Figure 9**). A large mixing event occurred in September driving anoxia some nine feet lower from the 1015 MSL elevation noted on August 12, 2015. Following this mixing event, stratification strengthened between August and September samplings and anoxia expanded. September saw a steadily eroding hypolimnion with a small metalimnion near the lake bottom the end of September and compete mixis by October 12, 2015. Even though the thermal profile showed a 0.3°C drop from top to bottom, dissolved oxygen decreased with depth and became anoxic around 1002 MSL on October 12. Monitoring on December 9, 2015 showed an oxidized water column with some drop of oxygen with depth and negligible change in temperature with depth.

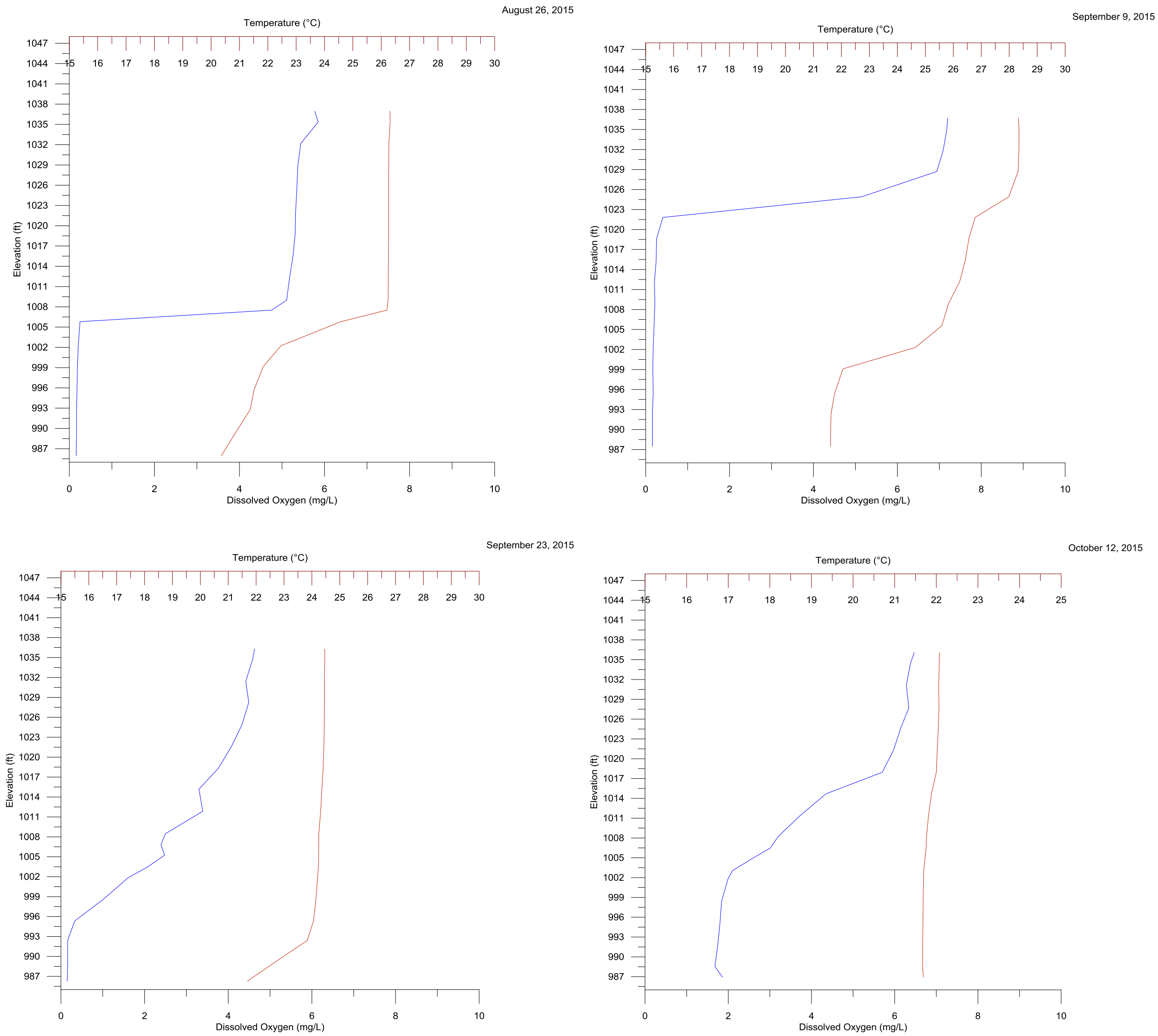


Figure 9. Temperature (red) Dissolved Oxygen (blue) Vertical Profiles Site 1: August 26, 2015 – October 12, 2015.

An alternate method for illustrating physical lake data is by using isopleths. These three-dimensional plots interpolate hundreds of data into one figure to show variation in physical parameters over depth and time. The following isopleths show the same temperature and DO data for Site 1 in a summarized form (**Figure 10**). Site 1 is largely representative of seasonal dynamics of the lacustrine zone of Lake Thunderbird. Each line on the isopleths represents a specific temperature or DO value. Vertical lines indicate a completely mixed water column. When lines run horizontally, some degree of stratification is present. On the temperature plot, warmest temperatures are colored red, graduating to blue as temperature gets cooler, while on the DO plot, lowest DO values are colored red, graduating to blue at the highest DO.

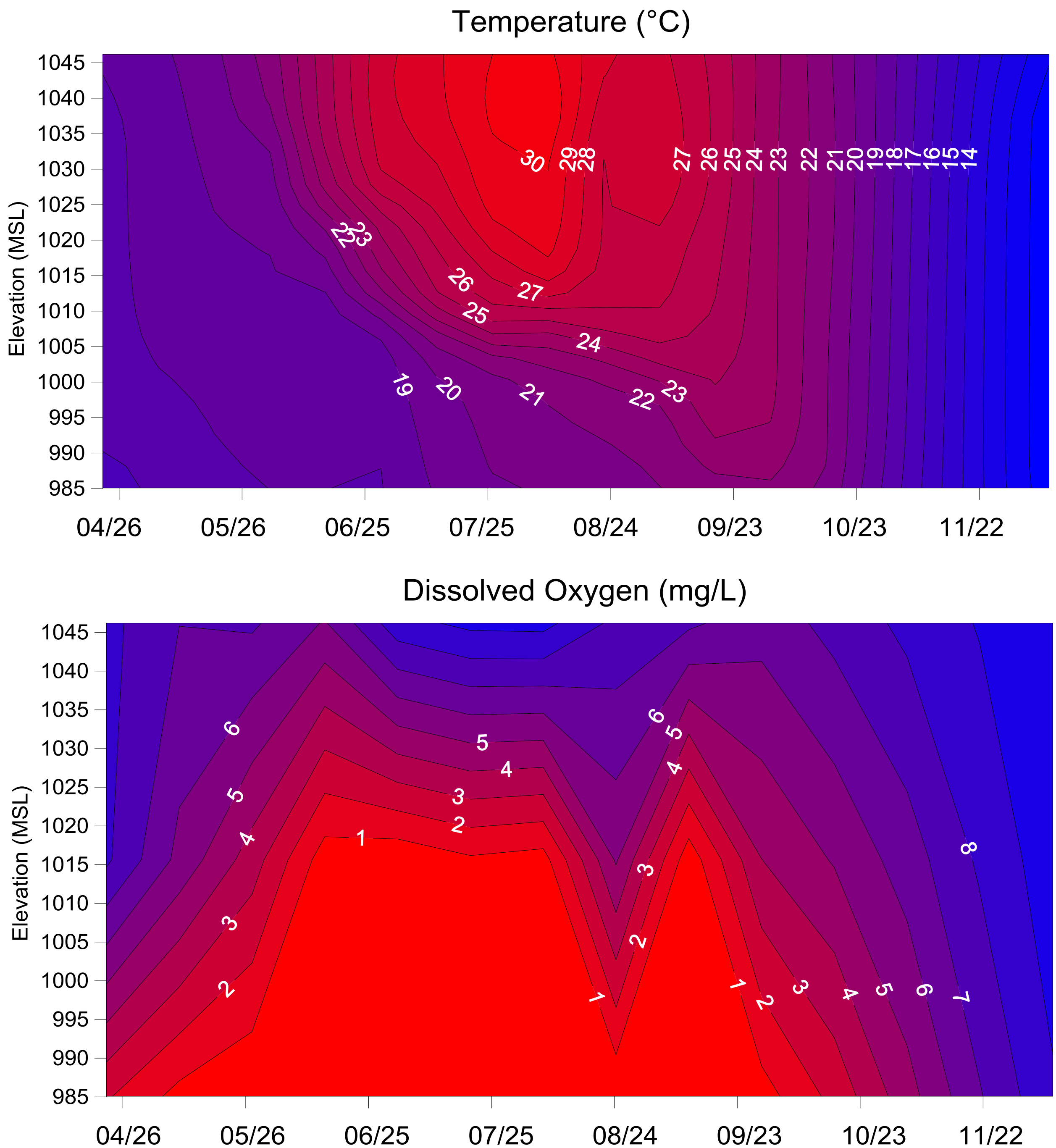


Figure 10. Isopleths of Temperature (°C) and Dissolved Oxygen (mg/L) by Depth (m) Lake Thunderbird 2015.

During 2015, thermal stratification followed a pattern typical in respect to onset and mixing. During late May and June, the upper portion of the water column began to heat up at a faster rate than the bottom, creating thermal stratification. Thermal stratification strengthened in late June and is indicated on the isopleths as the tightening of contour lines that run parallel with the x-axis into September (**Figure 10**). While thermal stratification strengthened in June, measurable dissolved oxygen rapidly dropped through May with significant anoxia in June. A slight, apparent recovery of DO was noted at the end of August, termed such as the DO elevation may be more related to epilimnetic deepening and oxygenation of what was previously metalimnion. Dissolved oxygen levels had plunged following August as the epilimnion rewarmed and stratification strengthened. Complete mixing had occurred by late October, bringing isothermal, but not fully oxygenated conditions throughout the entire water column.

When strong anaerobic conditions occur, elements other than oxygen act as terminal electron acceptors in the decomposition process. This results in nutrients and other constituents being release from the sediment interface into the isolated waters of the hypolimnion. When mixing events occur, these released nutrients trapped in the hypolimnion flux to the surface waters where they can further stimulate algal growth. The partial mixing events are evident when examining the oxygen isopleths as the blue area (higher oxygen content) pushes down toward the red area (lower oxygen content).

Dissolved oxygen concentration is lowered in the epilimnion by high plant and animal respiration rates, but is offset by high photosynthetic rates and physical mixing of atmospheric oxygen into the water. The areas of intense blue at the surface in **Figure 10** represent oxygen production by excess algae growth with epilimnetic (surface) dissolved oxygen percent of saturation well above 100%. Greatest supersaturation occurred in late July. Supersaturation as the epilimnetic water warms is evidence of high algal productivity; epilimnetic waters below the saturation point indicate respiration rates greater than photosynthetic oxygen production and diffusion of oxygen from the atmosphere.

Nutrients and Chlorophyll-*a*

High nitrogen and phosphorus loading, or nutrient pollution, has consistently ranked as one of the top causes of degradation in U.S. waters. In fact, lakes with excess nutrients are 2½ times more likely to have poor biological health (USEPA 2009). Excess nitrogen (N) and phosphorus (P) lead to significant water quality problems including reduced spawning grounds and nursery habitats for fish species, fish kills, hypoxic/anoxic conditions, harmful algal blooms, taste and odor problems in finished drinking water, public health concerns related to recreation and increased organic content of drinking water sources. Sources of these pollutants to Lake Thunderbird are non-point source in origin.

Several measures of N and P were made during monitoring visits, including dissolved and total forms. Dissolved nutrient concentrations consist of nutrients that are available for algal growth, such as ortho-P, ammonia, nitrate and nitrite. High dissolved nutrient concentrations in the epilimnion generally indicate that nutrients are immediately available for (and not limiting to) algal growth, while hypolimnetic concentrations are nutrients that could be available for future algal growth. Nitrogen and phosphorus concentrations in the epilimnion can also indicate what may be limiting algal growth. Generally, when both N and P are readily available, neither is a limiting nutrient to algal growth, and excessive Chlorophyll-*a* values are expected. When high P concentrations are readily available in comparison to very low N concentrations, algal growth may be N limited. High to excessive levels of algal growth, or primary production, can be expected under nitrogen-limited conditions. This can give a competitive advantage to undesirable cyanobacteria (blue-green algae). In the absence of adequate dissolved N, certain blue-greens have the ability to convert atmospheric N into a usable form by way of specialized cells called heterocysts. These blue-green algae are generally implicated for producing harmful toxins and chemicals that cause taste and odor problems in public water supplies. There has been no documentation of blue-green algae blooms at Lake Thunderbird during our monitoring, but the frequency and severity of blue-green algae blooms have increased in Oklahoma, resulting in measurable amounts of cyanotoxins found in afflicted waterbodies. The detection of taste and odor compounds, geosmin and MIB, in recent years, confirms presence of nuisance blue-green populations in Lake Thunderbird.

With regard to nutrient limitation, P as the limiting nutrient is desired for most freshwater systems. Under P limiting conditions, more desirable, green algae will typically be predominant. Dzialowski *et al.* (2005) has broken the molecular ratio of total N to total P (TN:TP) 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 N and P, and waters having ratios greater than 65 are regarded as phosphorus-limited. This interpretation scheme is applicable to Lake Thunderbird. In most eutrophic reservoirs, a co-limitation condition is more of a "no-limitation," where both nutrients are readily available in significant amounts.

Lake Thunderbird has had TN:TP ratios mostly in the 40's to 60's over the years, indicating the lake was phosphorus and co-limited. In 2015, most of the site 1 TN/TP ratios were below 40, much lower than previous (**Figure 11**). Since 2006, when all sample dates in the lake fell within a co-limitation range of N and P, the ratio had trended upward until the past two years (**Figure 12**). Annual data indicated a trend toward nitrogen limiting conditions, with a seasonal average TN:TP ratio of 48 in 2014 and 36 for 2015. Examination of TN:TP constituents showed a low ratio in 2015 due to phosphorus increases greater than nitrogen increases. That both nutrients increased is disturbing. Additionally, average annual phosphorus was higher than the previous nine years.

Under P or N limiting conditions, one would expect that the limiting nutrient would be significantly decreased in concentration, particularly the biologically available inorganic P or N. The aforementioned ratio suggested inorganic P would generally be more available than inorganic N. The 2015 dataset exhibited detectable ortho-P (**Figure 13**) and detectable ammonia

(**Figure 14**) throughout the growing season. These data suggest that limitation of algal growth was more likely due to light limitation than the availability of phosphorus or nitrogen.

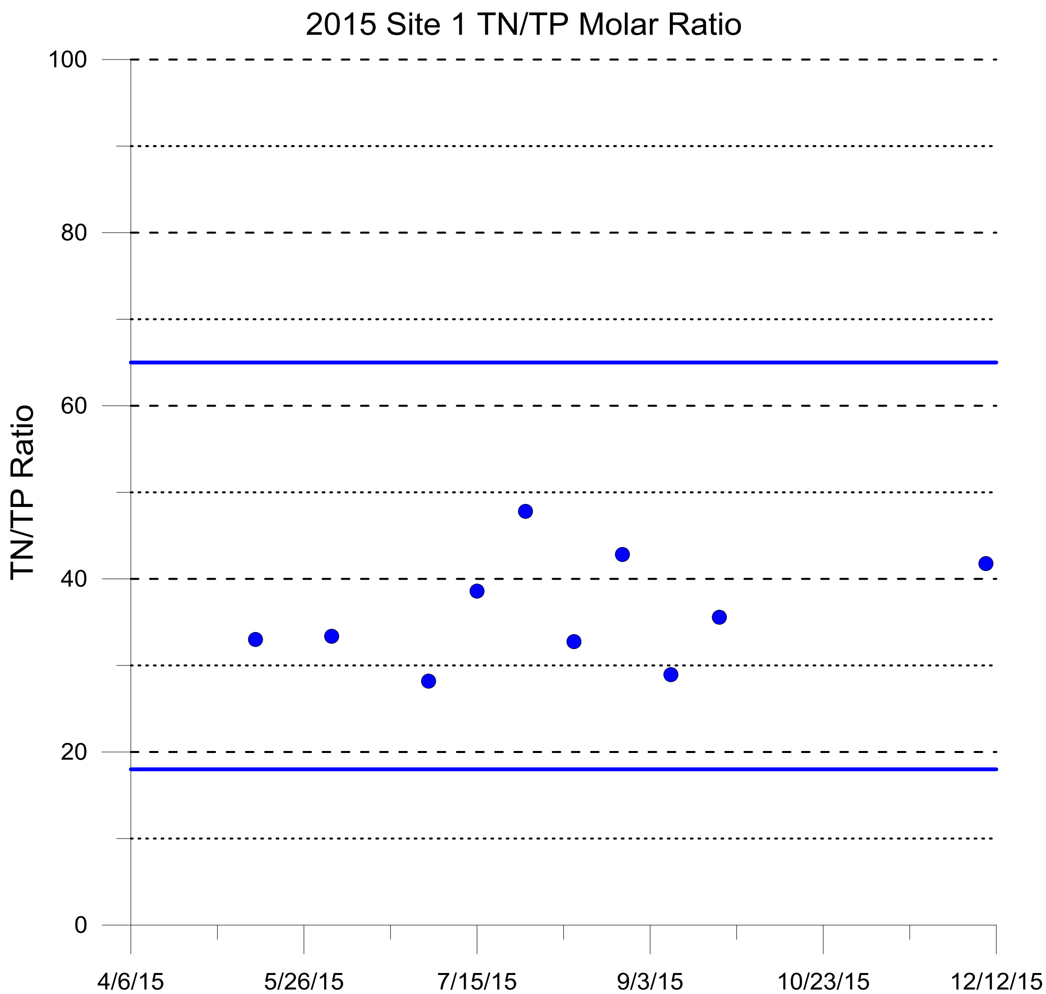


Figure 11. 2015 Site 1 Surface TN:TP Molecular Ratio.

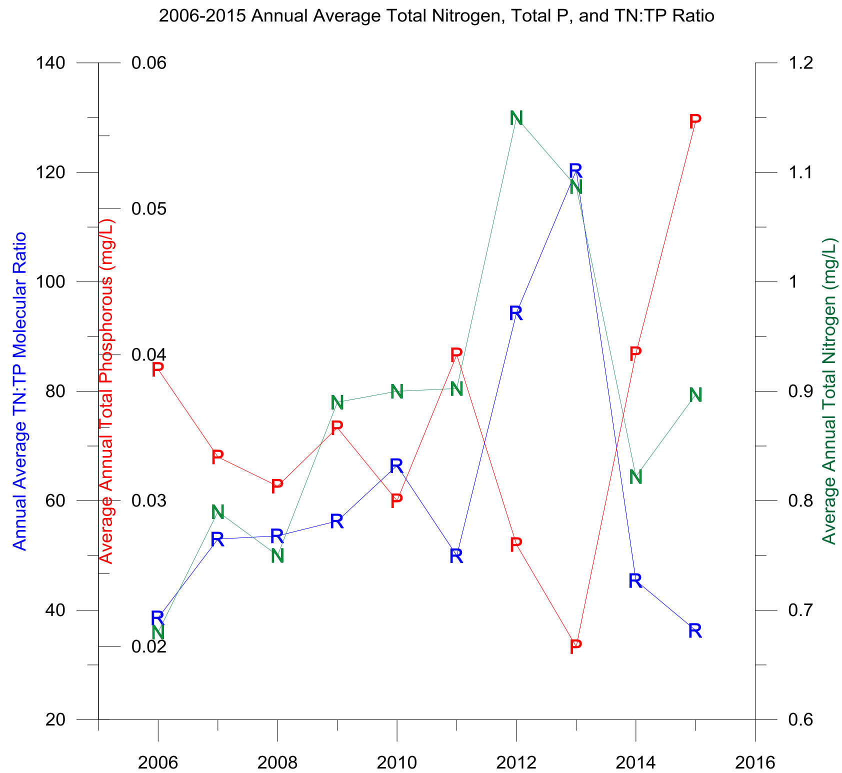


Figure 12. Annual Average Total N, Total P, and TN:TP Ratio for 2006 Through 2015.

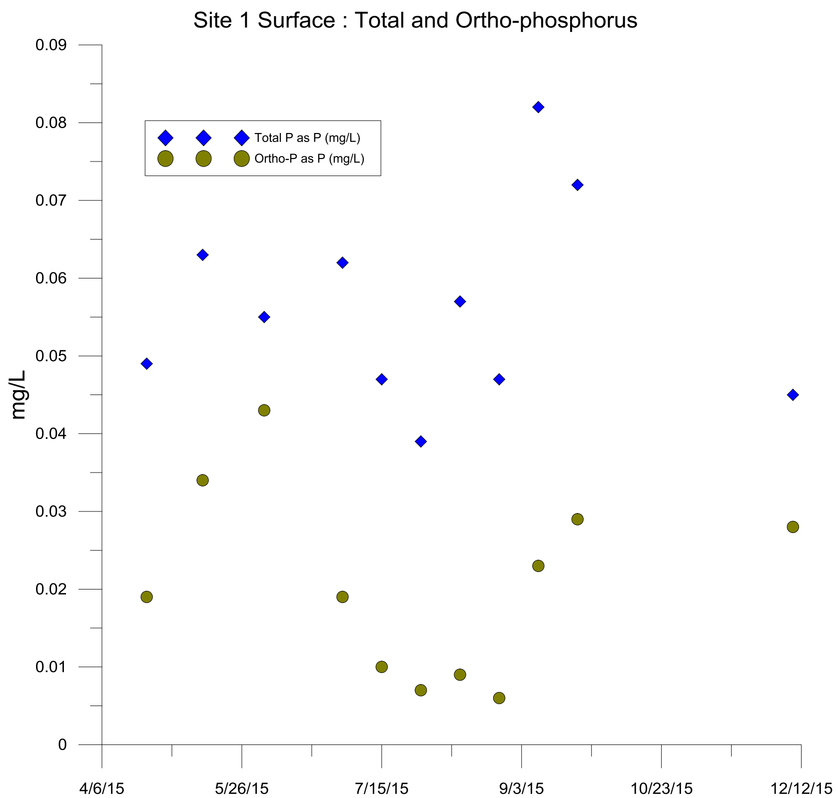
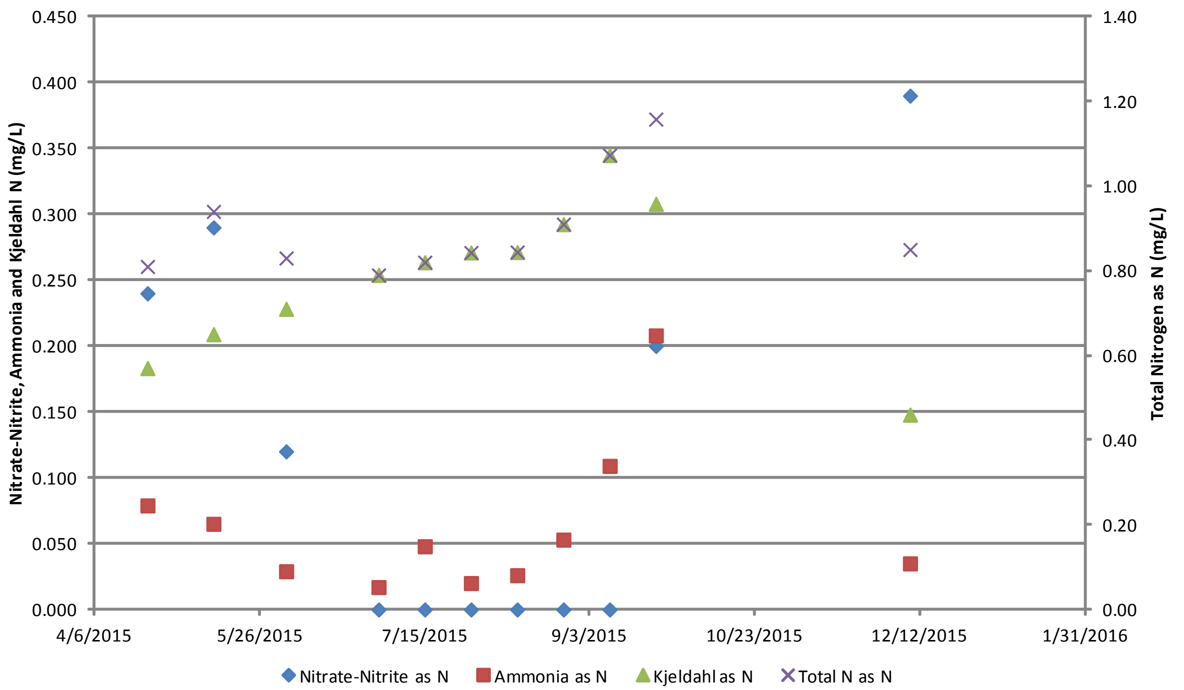


Figure 13. 2015 Lake Thunderbird Surface Ortho-P and TP, by Date, at Site 1.



	4/22	5/12	6/3	7/1	7/15	7/29	8/12	8/26	9/9	9/23	12/9
Ammonia as N	0.079	0.065	0.029	0.017	0.048	0.02	0.026	0.053	0.109	0.208	0.035
Nitrate-Nitrite as N	0.24	0.29	0.12	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	0.20	0.39
Kjeldahl as N	0.57	0.65	0.71	0.79	0.82	0.84	0.84	0.91	1.07	0.96	0.46
Total Nitrogen as N	0.81	0.94	0.83	0.79	0.82	0.84	0.84	0.91	1.07	1.16	0.85

Figure 14. 2015 Site 1 Surface NO_3-NO_2, Ammonia and Total Kjeldahl as N, by Date, at Site 1.

Phosphorus – P

Total phosphorus and ortho-P concentrations produced patterns typical of eutrophic to hypereutrophic lakes (**Figure 15**). The spring and fall spike of TP can be explained by May recharge and the large lake mixing event between August and September.

Bottom and hypolimnetic ortho-P increased throughout the stratification before decreasing following lake destratification. The buildup of hypolimnetic ortho-P is evidence of the settling of matter from the epi- and metalimnion, in addition to active release from the anoxic sediment (**Figure 15).** Rise in surface ortho-P in September coincided with the turnover timeframe, indicating that portions of the nutrient rich hypolimnion were mixing into the less nutrient rich surface waters. This mixing coincides with a depression of metalimnetic and surface DO and lack of significant recharge, confirming the source of the nutrients.

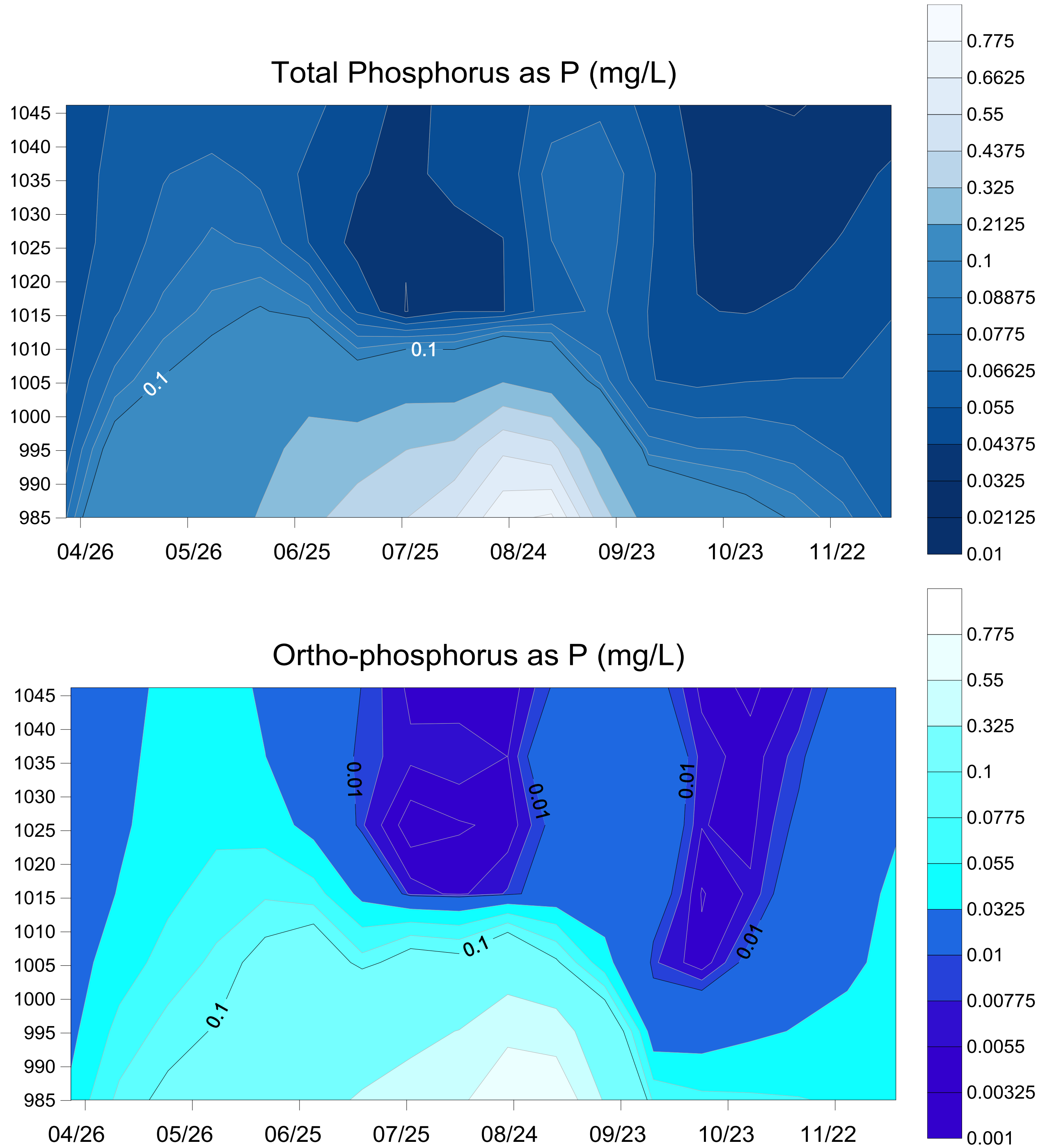


Figure 15. 2015 Lake Thunderbird Total Phosphorus and Ortho-phosphorus. Contours With Depth, by Date, at Site 1.

Phosphorus sampled from the upper arms (riverine portion) of the lake was consistently higher than the open water, lacustrine sites (**Figure 16**). The Little River site 6, had the highest phosphorus and the Hog Creek site 8, the lowest (**Figure 17**). Phosphorus in the upper arms of the lake represents the potential for hypereutrophic algal growth.

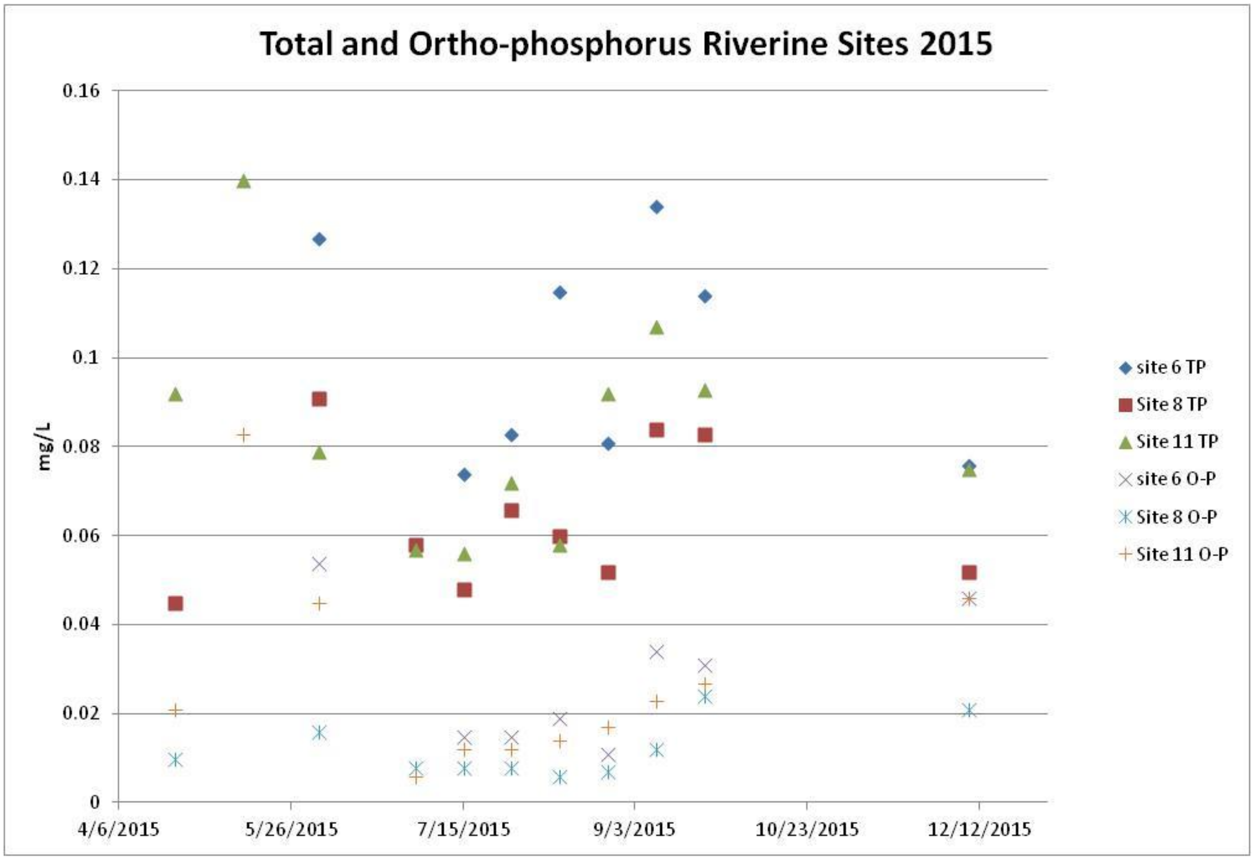


Figure 16. Surface Total and Ortho-P data from the Three Riverine Sites.

For total phosphorus, Sites 6 and 11 were statistically similar and sites 8 and 11 were statistically similar at a 95% confidence using both the Tukey's and Fisher's comparisons. Site 6 showed the highest mean TP concentration of 0.10 mg/L with site 8 the lowest, 0.064 mg/L. For ortho-phosphorus, only the Fisher comparison showed statistical differences at a 95% confidence with site 6 and 11 similar and sites 8 and 6 similar. Sites 6 and 11 indicate ortho-phosphorus were similar at 0.028 mg/L with site 8 the lowest at 0.012 mg/L.

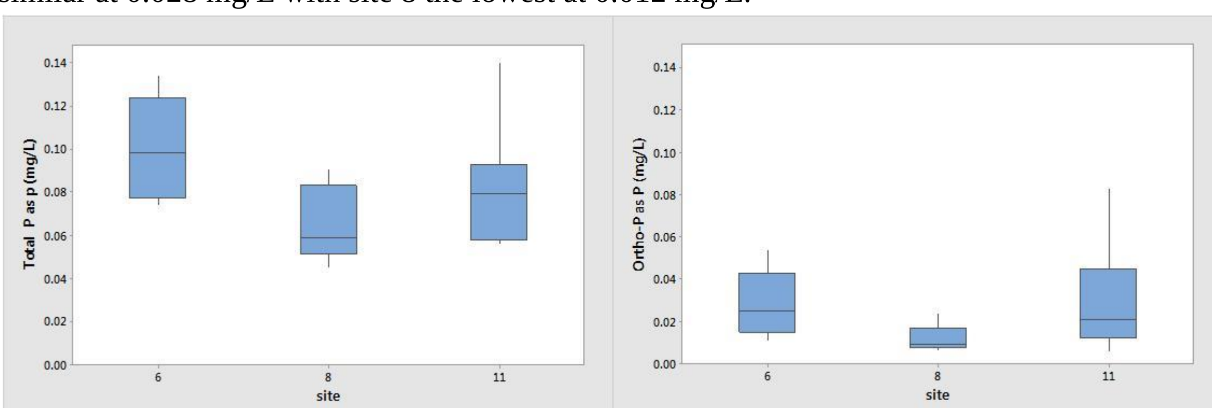


Figure 17. 2015 Phosphorus Series Box and Whisker Plots for the Riverine Sites 6, 8 and 11.

Nitrogen – N

Total and dissolved nitrogen produced patterns somewhat typical of seasonal ecological cycles in lakes (**Figure 18**). Surface total Kjeldahl nitrogen showed a pattern of a general increase over the summer before dropping in the winter while dissolved forms of N fell below detection at the surface beginning in the summer.

The two most likely forces driving the surface N dynamics seen in the dataset are epilimnetic algae growth (uptake) and anoxic sediment release of ammonia. These two forces were seen operating in 2015, as dissolved inorganic N plunged with rising Chl-*a* during the start of summer, while a spike of ammonia was detected in September following complete mixis bringing ammonia rich hypolimnetic waters to the surface.

Examination of ammonia and nitrate distribution with depth and over time showed a general increase in ammonia in the hypolimnion. This is attributed to its release from anoxic sediment and formation as a decomposition product of senescent algae cells and organic material (**Figure 18**). Ammonia concentrations in the hypolimnion gradually increased until the breakdown of thermal stratification mixed these ammonia rich hypolimnetic waters to the surface. In the hypolimnion, nitrate does not serve as a macronutrient, but as an electron source for anaerobic metabolism. Nitrate however, was quite variable as spots of high then low nitrate-nitrite were evident within the hypolimnion from May through August. The spot of high nitrate-nitrite in late-June is likely an artifact of nitrate-nitrite enriched waters flowing into the lake.

No statistical difference between sites was noted for any nitrogen parameter using non-parametric statistics. Independent of site, Kjeldahl nitrogen was variable but generally increased over time until stratification ended. Interestingly, on July 15, 2015 all three riverine sites had the same value, 0.76 mg/L. On two occurrences, at site 11 on April 22, and July 1, ammonia was below detection limit (BDL) (**Figure 19**). The abundance of the most easily assimilated nitrogen nutrient is unusual and contrasted by the 2014 data set where 32 of 35 riverine samples were reported as BDL. Pooled floodwaters allowing localized, intermittent stratification could account for the persistent ammonia signal. Dissolved oxygen profiles showed low to anoxic conditions for 3 to 5 sample events at the three riverine sites in 2015. These conditions would spur bacterial catabolism resulting in production of ammonia and potentially sediment release of ammonia.

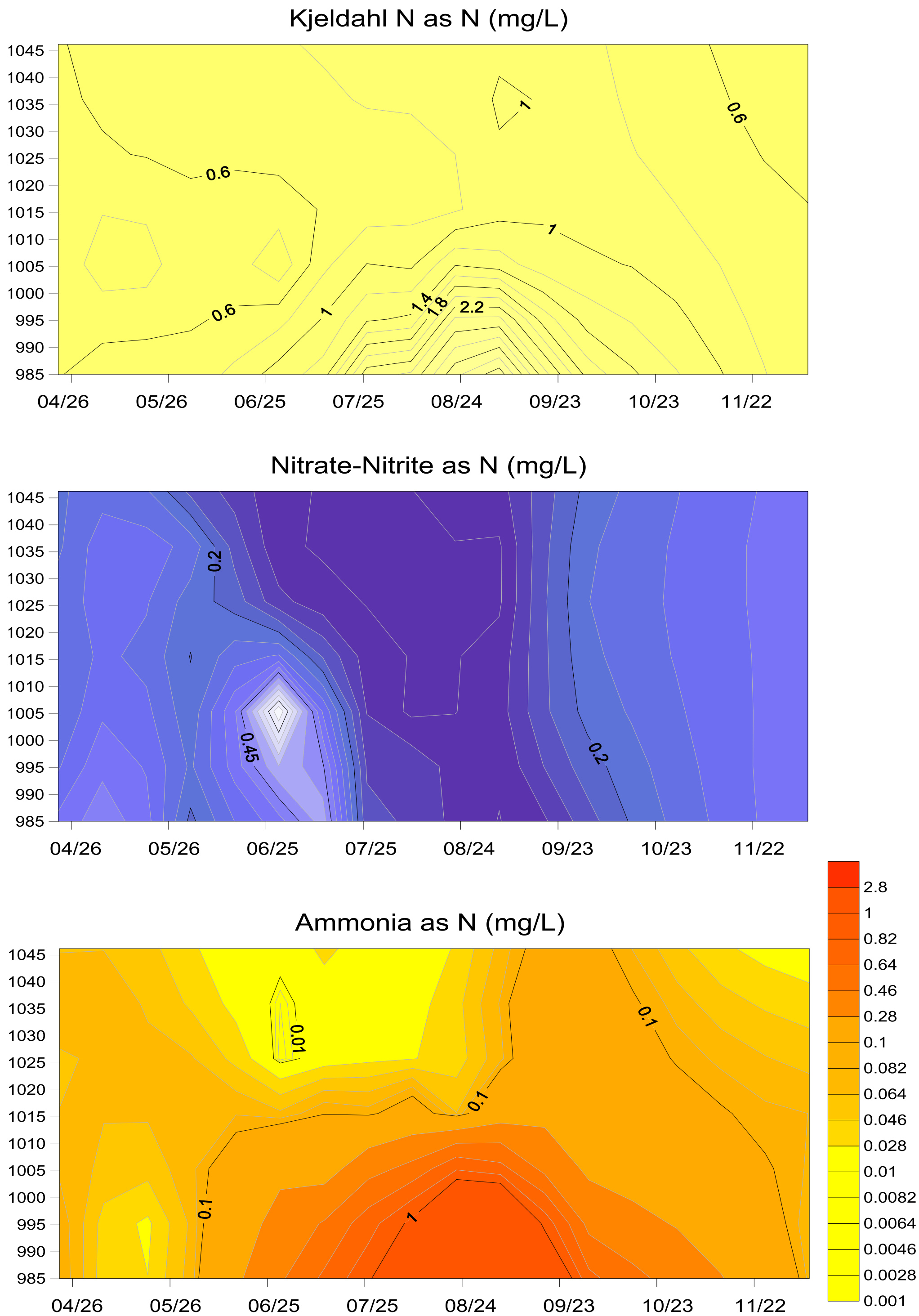


Figure 18. 2015 Lake Thunderbird Total Kjeldahl, NO2-NO3 and Ammonia as N with Depth Over Time at Site 1.

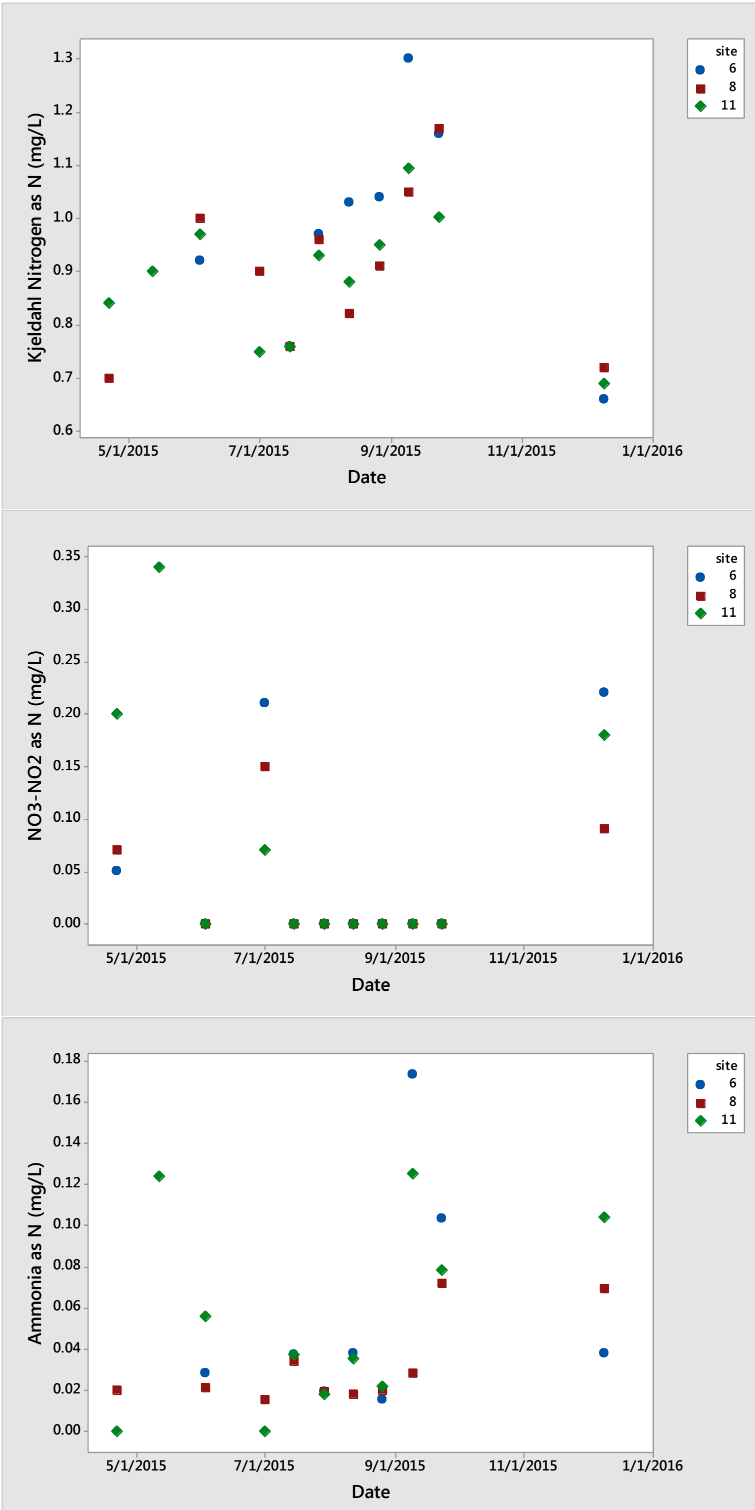


Figure 19. Nitrogen (Ammonia, Nitrite-nitrate and Kjeldalh Nitrogen as N mg/L) Parameters of the Riverine Sites (6, 8 and 11) in Lake Thunderbird 2015.

Nutrient Budget - Phosphorus

A phosphorus budget for Lake Thunderbird was prepared integrating the estimated outflows from the water budget with water quality data. Vertical profiles of physical parameters were combined with reservoir bathymetry to partition total phosphorus reports in one-meter intervals between epilimnetic, metalimnetic and hypolimnetic layers. The cumulative summation of these layers allows the massing of P for each sample date (**Table 3**). Once the lake mass was established, the distribution within the lake and losses were estimated using USACE and COMCD water quantity reports (**Table 2**). Missing from this lake nutrient budget are estimates of phosphorus inflow, dry deposition and sediment flux.

Table 3. 2015 Lake Thunderbird Site 1 Phosphorus Mass (kg) at Depth Intervals by Sample Date (Bold red numbers represent anoxic layers while blue shaded cells represent the epilimnion, clear shaded cells metalimnion and red shaded cells hypolimnion).

Average Elevation	4/22/2015	5/12/2015	6/3/2015	7/1/2015	7/15/2015	7/29/2015	8/12/2015	8/26/2015	9/9/2015	9/23/2015	12/9/2015
1047.55		1461	1349								
1044.20		1245	1250	2577	972						
1039.88		1277	1288		953	824	1224	975			
1037.27	959	1285	1343	1084	866	751	904	846	1733	1534	996
1033.97	855	1000	1295	906	752	568	788	790	1346	1216	817
1030.70	729	960	1245	705	661	568	598	686	1173	1097	881
1027.46	624	861	1067	718	540	503	485	631	1240	910	846
1024.33	756	752	972	675	645	**185**	451		865	842	1004
1021.43	470	667	1638	**700**	382	**253**	27	491	**845**	729	755
1018.49	372	856		**516**	**294**	**324**	436	406	**655**	637	826
1015.34	308	452	720	**909**	**392**	**245**	**467**	328	**471**	545	721
1011.92	260	390	632	**763**	**388**	**231**	**381**	250	**512**	465	411
1008.59	201	289	**513**	**599**	**341**	**601**	**620**	787	**502**	382	263
1005.42	207	290	**371**	**690**	**444**	**570**	**488**	**886**	**399**	206	227
1002.18	78	124	**247**	**423**	**244**	**466**	**429**	**620**	**258**	250	129
999.06		169	**144**	**262**	**155**	**394**	**317**	**549**	**236**	**108**	72
996.11	38	45	**76**	**134**	**83**	**226**	**218**	**316**	**215**	**68**	37
992.89	18	**68**	**33**	**80**	**25**	**105**	**185**	**203**	**140**	**39**	18
989.49	5	**38**	**12**	**24**	**15**	**39**	**-**	**77**	**34**	**14**	6
986.55	3	**7**	**1**	**3**	**3**	**2**	**-**	**9**	**35**	**2**	1
985.81	1	**1**	**-**	**-**	**-**	**5**	**-**	**-**	**-**	**-**	-
TP mass	5,882	12,237	14,194	11,766	8,156	6,861	8,019	8,849	10,659	9,044	8,009
Anoxic TP mass		114	1,397	5,102	2,384	3,646	3,105	2,659	4,302	230	0
%TP mass anoxic		1%	10%	43%	29%	53%	39%	30%	40%	3%	0%
mean conc.	0.050	0.067	0.075	0.070	0.051	0.051	0.062	0.069	0.084	0.072	0.062

The constructed budget demonstrates pre-stratification lake P mass, in 2015, of approximately 5900 kg. This is much larger than the pre-stratification average from the past 6 years of 3200 kg. The total phosphorus mass at the start of stratification was several times greater than in the historical dataset, 4000-5000 kg. Some of this is due to the huge influx of water and increased volume of the reservoir. However, the increase of lake-wide average TP concentration speaks to large amount of phosphorus with the water. Hypolimnetic anoxia contributed to the lake P-mass from July into September.

Finally, it is worthwhile noting that anoxia extended out of the hypolimnion and into the metalimnion starting July 1 then extended into the epilimnion on consecutive sample dates, July 29 and August 12. The extreme anoxia seen in 2015 indicates the possibility of sediment mediated phosphorus release from metalimnetic and even epilimnetic areas. Using calculations based on Nürnberg (1994) and those specifically developed for Lake Thunderbird by OWRB, it was calculated that anaerobic mediated sediment P release had *increased* 70% from the average release from 2005 – 2009. This continues the disturbing reversal seen in 2014 where sediment mediated p-release was estimated to have increased 16% from the pre-SDOX period (2005 – 2009).

Chlorophyll-*a*

Chlorophyll-*a* (Chl-*a)* is a pigment common to all photosynthetic plants and is used as a proxy for measuring algal biomass in aquatic ecosystems. Chlorophyll-*a* samples were collected at the surface of all eight sites for each sampling event during 2015; Chl-*a* peaked in late-September for sites 2 and 4 but peaked on August 21, 2015 for Site 1 (**Figure 20**). In 2015, 86% of samples were eutrophic based on a 7.2 µg/L threshold between mesotrophy and eutrophy (Wetzel 2001). Some 45% of lacustrine samples were hypertrophic or exhibited excessive algal growth in 2015. Tracking averaged chlorophyll-a for site one reflects a leveling off of chl-*a* reductions since the installation of the SDOX device (**Figure 21**). For the 2015 sampling season, the lake wide average Chl-*a* at Lake Thunderbird was 24.9 µg/L; up from the 2014 average of 21.8 µg/L. This is very close to the 2012 lake wide average of 24.5 µg/L and approaches the pre-SDOX (2007-2010 historical) average of 25.9 µg/L. The historical plot of site 1 annual average chlorophyll-a shows 2015 chlorophyll-*a* similar to that seen in 2013 and 2014 (**Figure 22**). Observed peak lacustrine chl-*a* was also reduced from the previous five years with Site 4 maximum value of 39.8 µg/L representing a step up from the 2013 low (since 2007).

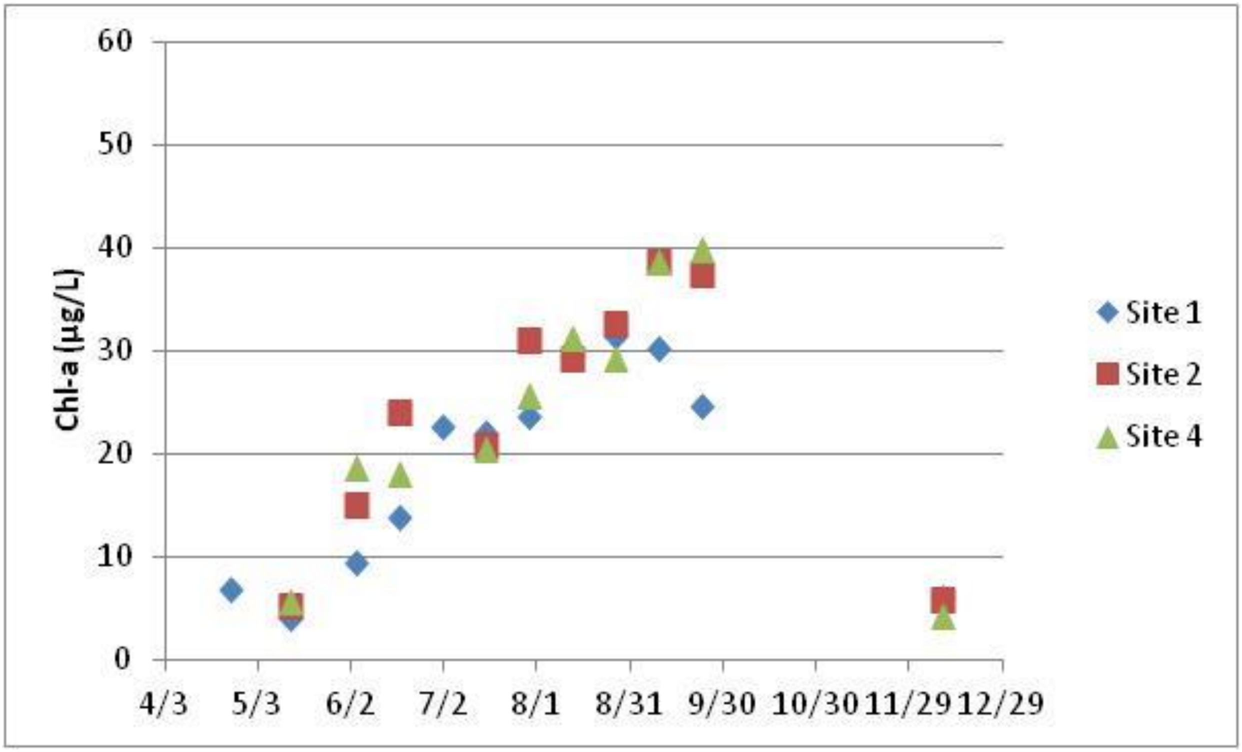


Figure 20. Lake Thunderbird Lacustrine Surface Chl-*a* (µg/L) by Site; April through December 2015.

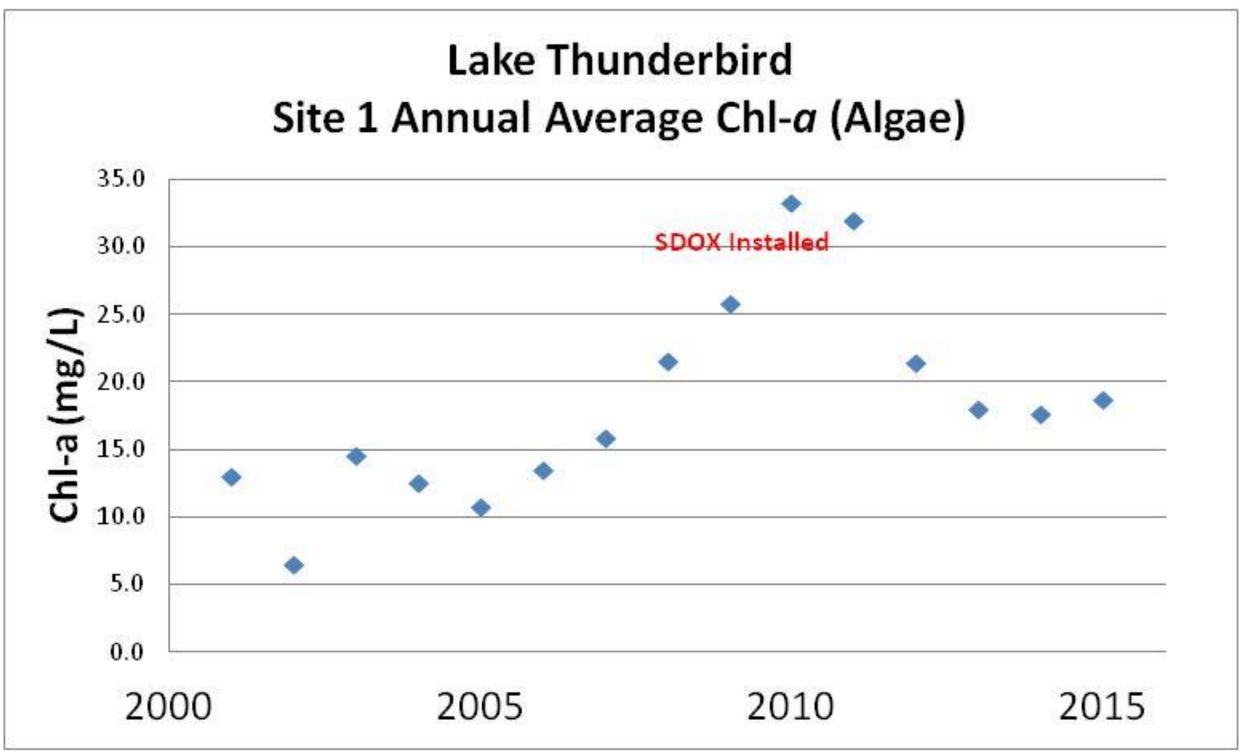


Figure 21. Lake Thunderbird Site 1 Average Seasonal Chlorophyll-a from 2005 Through 2015.

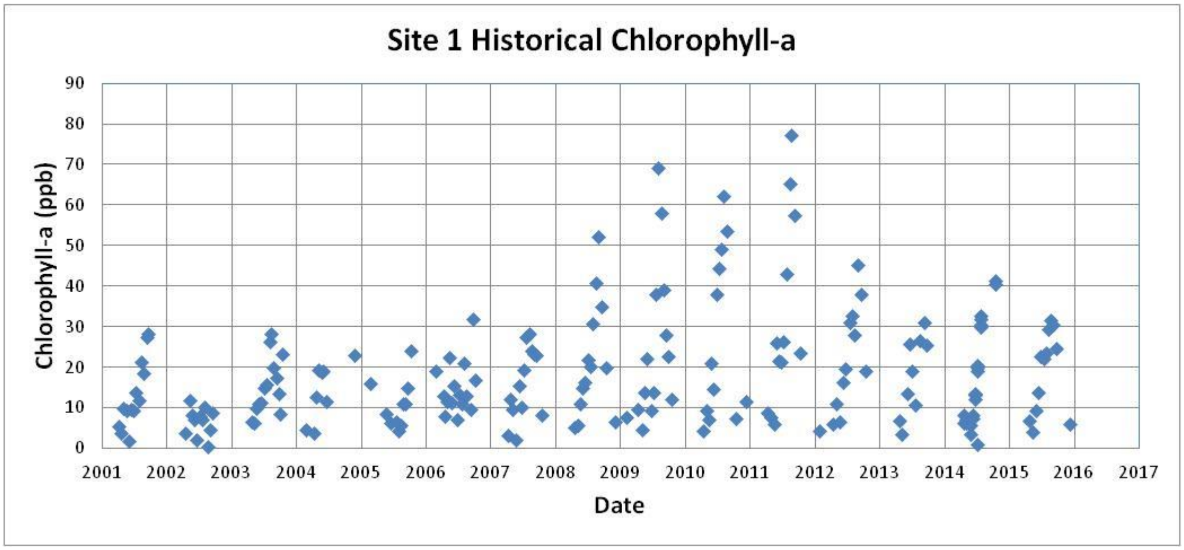


Figure 22. 2001-2015 Lake Thunderbird Surface Chl-*a* µg/L (or ppb) at Site 1

General Water Quality

Total Organic Carbon - TOC

Total organic carbon (TOC) is an additional measure of organic content and productivity, and an important drinking water treatment parameter. Total organic carbon samples were collected at the surface of Site 1 during 2015. Like 2014, lacustrine TOC did not track Chl-a (**Figure 23**). TOC and chlorophyll-*a* seem to track with general increases through July but in August TOC drops while chlorophyll-a continues to increase. Again, like in 2014 the regression between TOC and chlorophyll-*a* carried little statistical significance and a flat scatter plot. Tracking the annual and accumulative regressions between TOC and chlorophyll-a shows a steady increase of the y-intercept (baseline TOC) and reduced slope (response of TOC to chlorophyll-a). These suggest that algal growth has exerted less influence over TOC in 2014 and 2015.

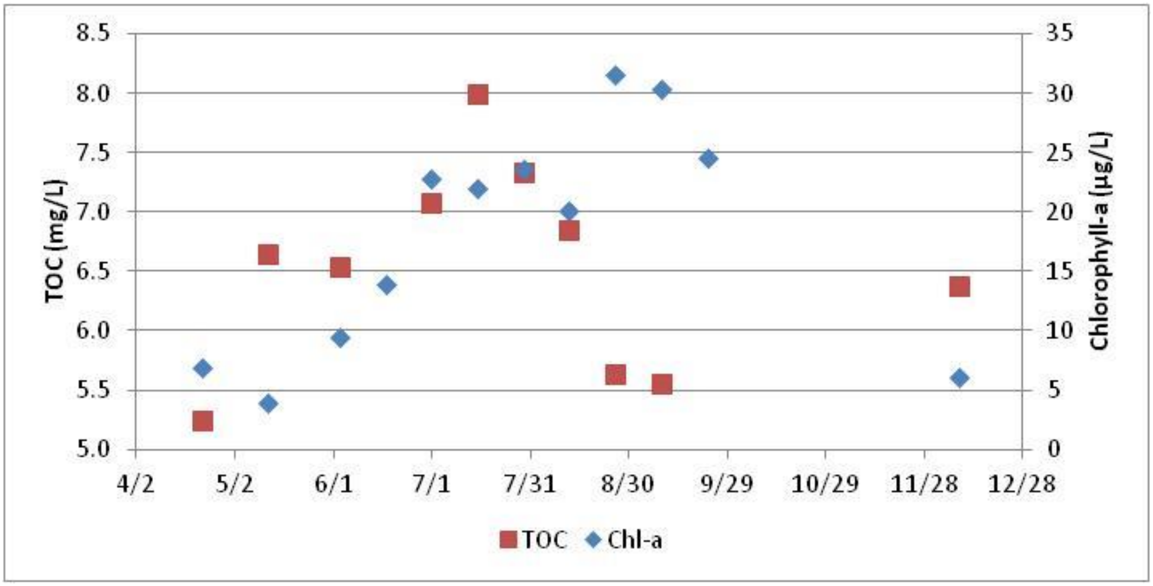


Figure 23. Site 1 surface TOC and Chl-*a* at Lake Thunderbird 2015.

Trophic State Index - TSI

Trophic state is defined as the total algal biomass in a waterbody at a specific time and location. For lakes and reservoirs, Carlson's trophic state indices (TSI) are the most common measure of index algal biomass (1977). Here, three surface variables, chlorophyll-a (Chl-a), Secchi depth (SD) and total phosphorus (TP), were indexed as estimates of algal biomass (Carlson 1977, Kratzer 1981). Of these three, chlorophyll yields the most accurate measure, as it is the most direct measure of algal biomass. Secchi depth, a more indirect measure, is historically the most inaccurate at Lake Thunderbird as high-suspended solids, due to the clay watershed soil, lead to relatively low water clarity throughout the year. In general, TP represents the potential for algal growth in Lake Thunderbird as most TP over-predicts TSI with unused inorganic phosphorus (detectable ortho-phosphorus) in the water column. Whichever measure, indexing is on a range from zero to 100. Trophic ranges have been categorized as follows: 0 to 40 as oligotrophic or low algal growth, above 40 to 50 as mesotrophic or increasing algal growth, above 50 to 60 as eutrophic or high algal growth to finally ≥ 60 as hypereutrophic or excessive algal growth.

Lake Thunderbird's TSI for each of the three variables is displayed in **Figure 24** ranging from 44-79 throughout 2015. TSI(CHL) , a reflection of actual or realized algae growth, showed site 1 to have been mesotrophic through May. From the mesotrophic low in late May, TSI(CHL) steadily increased to hypereutrophic by the start of July. From there, TSI(CHL) remained in the hypereutrophic range throughout the sample season until the December 12, 2015 sample date. Also notable was the shift between the TSI(CHL) and TSI(TP). TSI(TP) consistently over-predicted TSI(CHL) until mid-July when TP consistently under predicted Chl-a through August. This time period also indicates when TSI(CHL) transitions to a hypereutrophic state. September and December saw TSI(TP) again over-predicting TSI(CHL). This mid-summer flip in the Chl-*a*/TP relationship likely represents a change in the algae community to one better able to convert phosphorus into chlorophyll-a, such as *Cylindrospermopsis*.

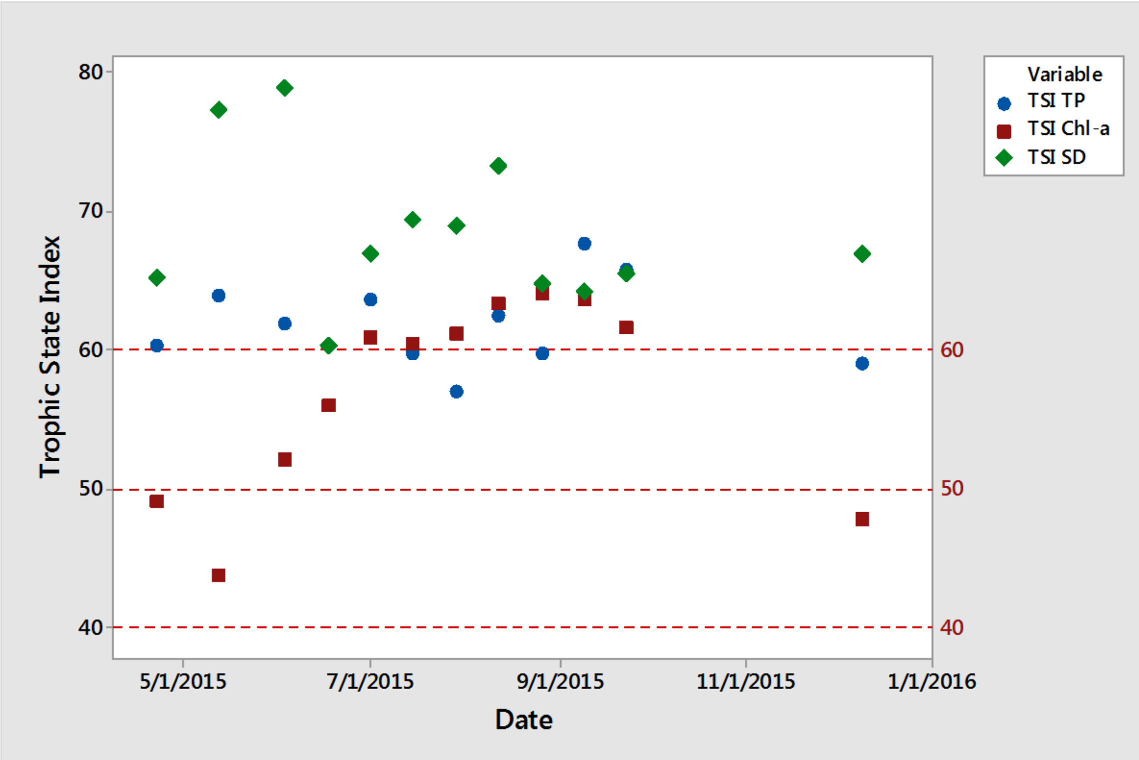


Figure 24. Carlson's Trophic State Index Values for Lake Thunderbird 2015 at Site 1.

By examining the interrelationships between TSI variables one can also discern algal limitation (Carlson 1991). In **Figure 25,** TSI (CHL) - TSI (TP) is plotted on the vertical axis with TSI(CHL) - TSI(SD) plotted on the horizontal. In this plot, no data is noted to the right of the vertical axis suggesting that transparency was dominated by non-algal factors such as color, turbidity and small particles. All of these factors could have contributed in Thunderbird with turbidity the most likely in such a high inflow year. The predominance of samples below the horizontal axis points towards increasing surplus of phosphorus for algal growth. These data suggest that light availability rather than phosphorus or nitrogen kept chlorophyll-*a* from reaching even higher values in 2015.

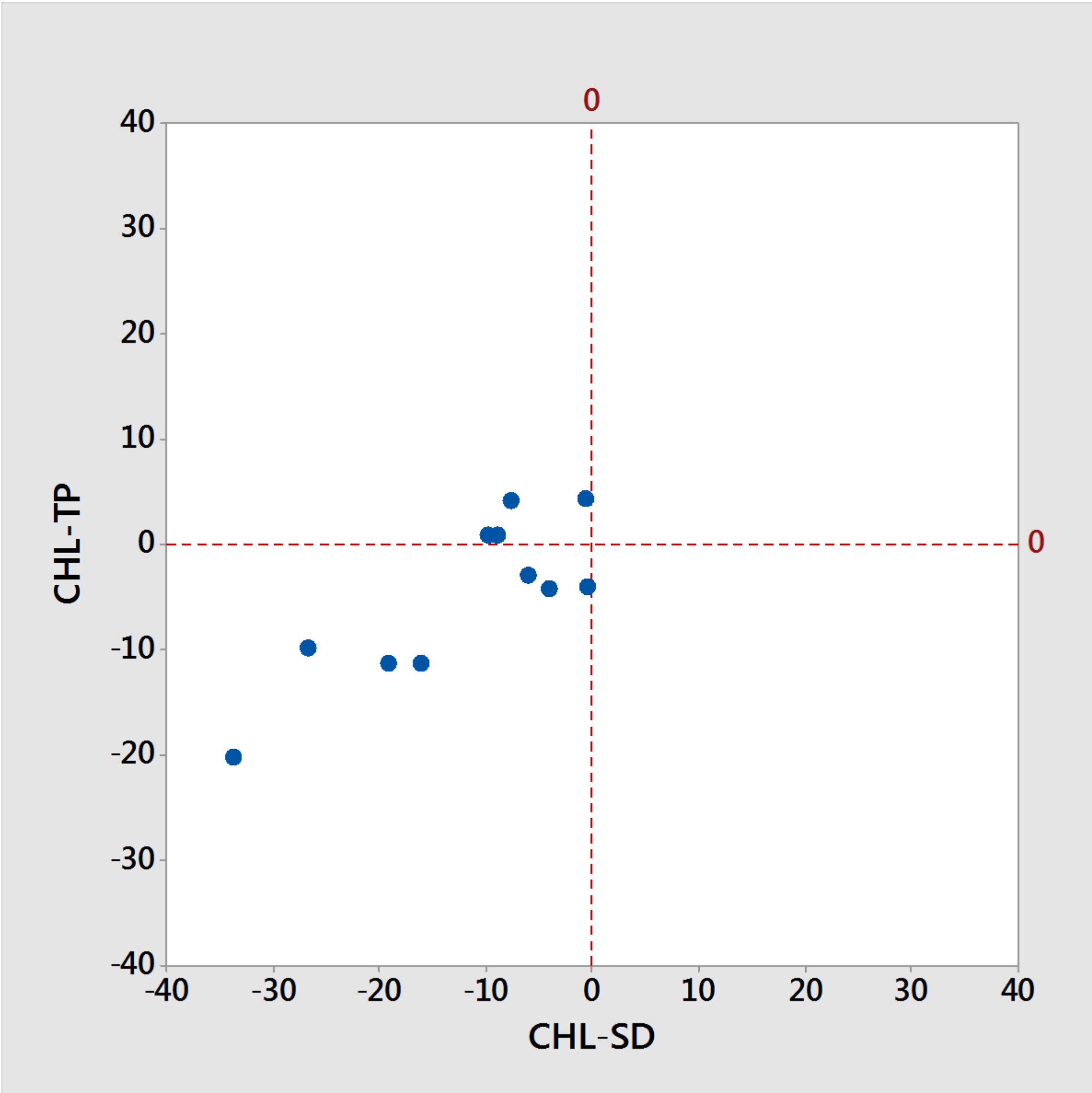


Figure 25. Trophic State Indices (TSI) Plot of TP and TSI(SD) Deviation from the TSI(CHL) Used to Suggest Means of Algal Growth Limitations at Site 1, 2015.

pH, Oxidation-Reduction (ORP) Potential, and Dissolved Metals

Increases in surface pH during the summer months indicate high rates of photosynthesis, while lower hypolimnetic pH is due to the buildup of bacterial respiration byproducts. Sinking organic matter in summer months (due to high algal production or influx of organic material from the watershed) stimulates decomposition processes in the hypolimnion by pushing pH and ORP down. In general, high and low pHs correspond to peaks in algal productivity. High rates of photosynthesis will temporarily elevate pH as carbon dioxide is stripped from the water column (generally in the epilimnion), while catabolism of the settling algae depresses pH (generally in the hypolimnion).

Lake Thunderbird followed a typical eutrophic pattern of pH in 2015 in lacustrine sites (1,2 and 4), where pH peaked in mid-summer at the surface during the time of highest algal productivity and was lowest at the lake sediment interface (pH of approximately 6.7) due to decomposition processes within hypolimnion (**Figure 26**). These lower pHs were only noted in the hypolimnion toward the beginning of stratification immediately following the flood events. Without any impinging biological processes such as photosynthesis and respiration, baseline pH for Lake Thunderbird would be 8.2, the common pH of bicarbonate buffered systems.

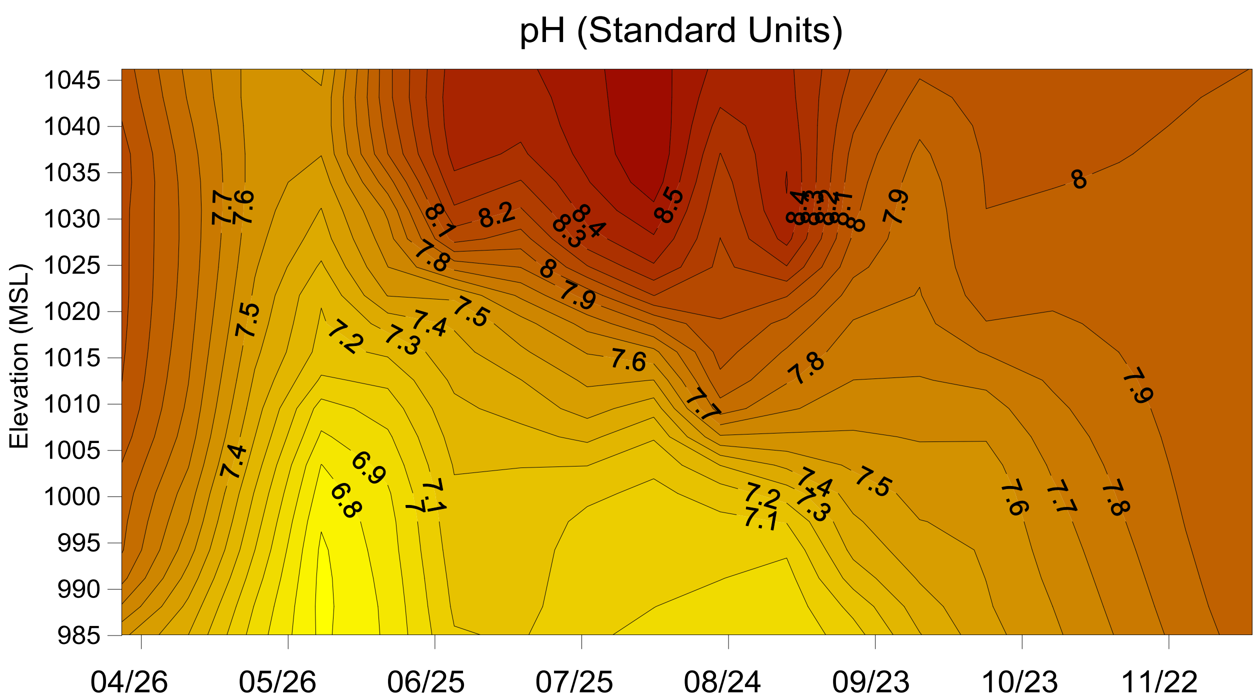


Figure 26. 2015 Lake Thunderbird Site 1 pH (S.U.) Versus Depth (m) Over Time

The biogeochemical cycling of inorganic nutrients is largely regulated by changes in oxidation-reduction potential (ORP) or redox states. Redox state plays a major role in the recycling of sediment bound phosphorus, iron, and manganese. Under oxygenated conditions, redox potentials remain highly positive (300-500 mV). Normally, as oxygen concentrations approach zero, redox potential drops in proportion to anaerobic metabolism. Generally, as the ORP drops towards 100mV or lower, solids such as phosphorus and metals are dissolved into the water column.

The 2015 sampling season began with anoxic conditions at the bottom yet maintaining a relatively high ORP (**Figure 27**). By early June, anoxia had encompassed the hypolimnion but ORP was still oxic and relatively high. Throughout the month of June, the hypolimnion was anoxic as ORP dropped into reducing conditions. From July into early September, hypolimnetic ORP was low and strongly reducing. By the late September sample event a large portion of the hypolimnion had mixed into the epilimnion and oxic (higher ORP) conditions returning with mixis. It is important to note that along with sediment bound phosphorus and common metals, such as iron and manganese, production of sulfide and methane is common as electron acceptors for anaerobic metabolism become scarce. Therefore, the duration and extent of strong reducing conditions have a direct impact on the desorption of these compounds as well. Finally, low redox conditions slows the oxidation (breakdown) of organic materials such as the contents of dead and dying algal cells allowing these chemicals to build up in the hypolimnion.

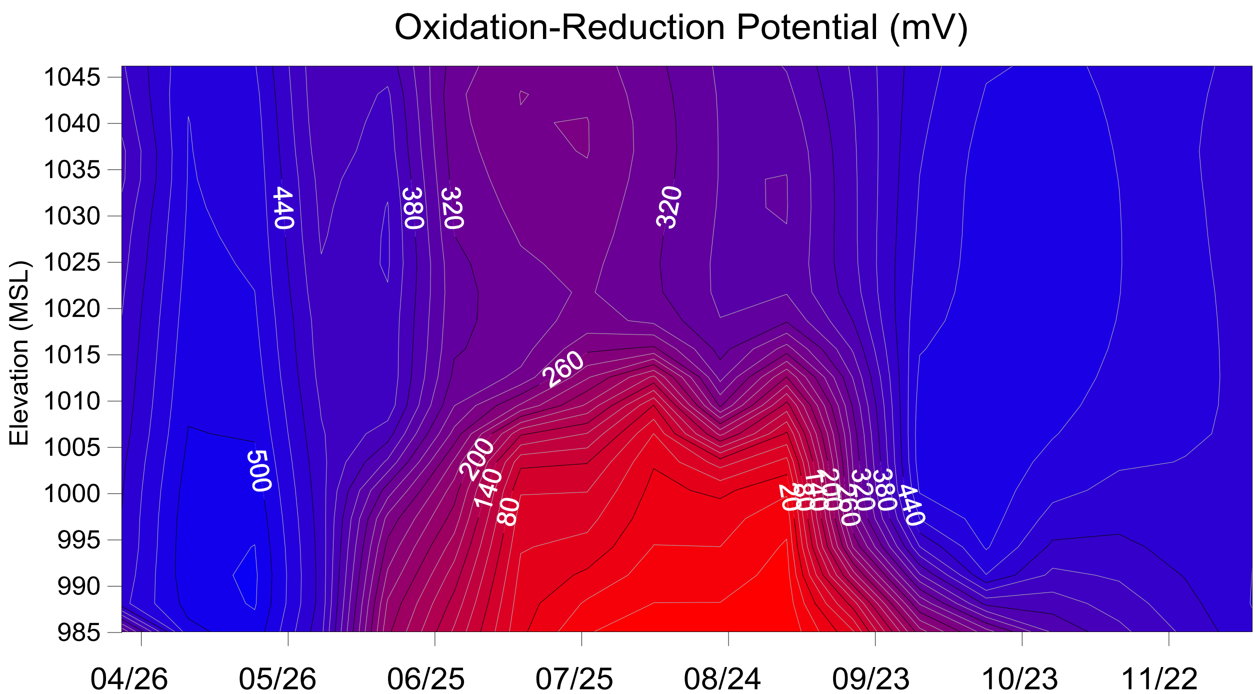


Figure 27. 2015 Site 1 Lake Thunderbird Oxidation-reduction Potential (ORP) as Millivolts (mV) Versus Depth (m).

Taste and Odor Complaints

The City of Norman provided data on the number of taste and odor complaints from their water customers in 2015. Lake Thunderbird is the major source of raw water for the city; changes in water quality parameters in the lake are often correlated with complaints in the final finished water. Consumers at the tap can detect taste and odor causing compounds in extremely low concentrations (~ 5 ng/L) (Graham et al 2008). The majority of these compounds are by-products of high algal productivity. The most commonly known drinking water taste and odor compounds, geosmin and 2-methylisoborneol (MIB), are produced primarily by cyanobacteria.

Historically, the lake has had a spike in complaints coinciding with high chl-*a* (algal content) values and during the fall turnover timeframe. The timing of taste and odor complaints for 2015 followed the traditional (September) break up of summer stratification (**Figure 28**). What was unusual was the magnitude of impact: a peak of three complaints for the month of October. The number of complaints was far below expected when compared with previous years when the SDOX system was not in operation or down (**Figure 29**). Two factors likely played into dampening taste and odor complaints: unusual climatic events leading to a graded mixing of the hypolimnion and influx of oxidized water with flood events.

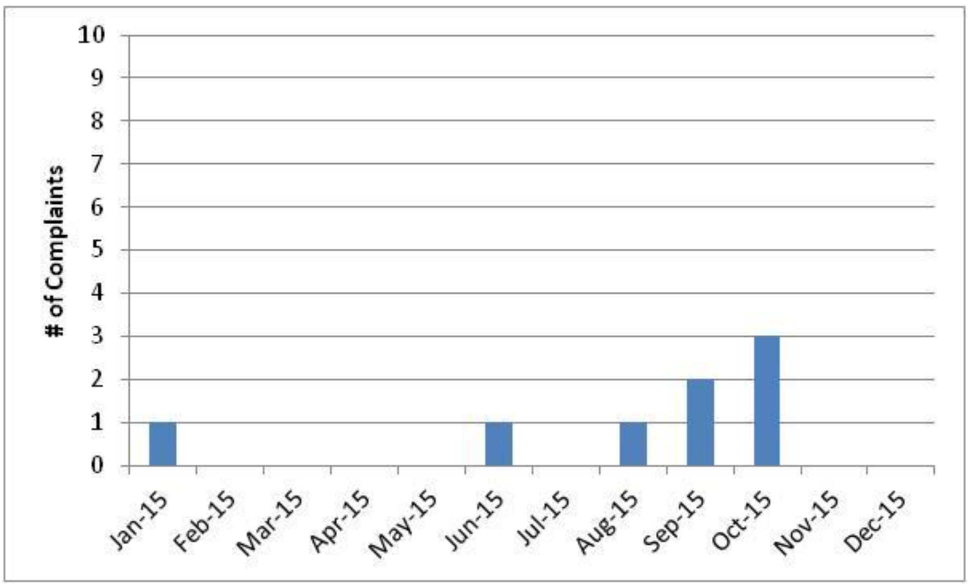


Figure 28. Monthly Taste and Odor Complaint Totals Recorded by the City of Norman in 2015.

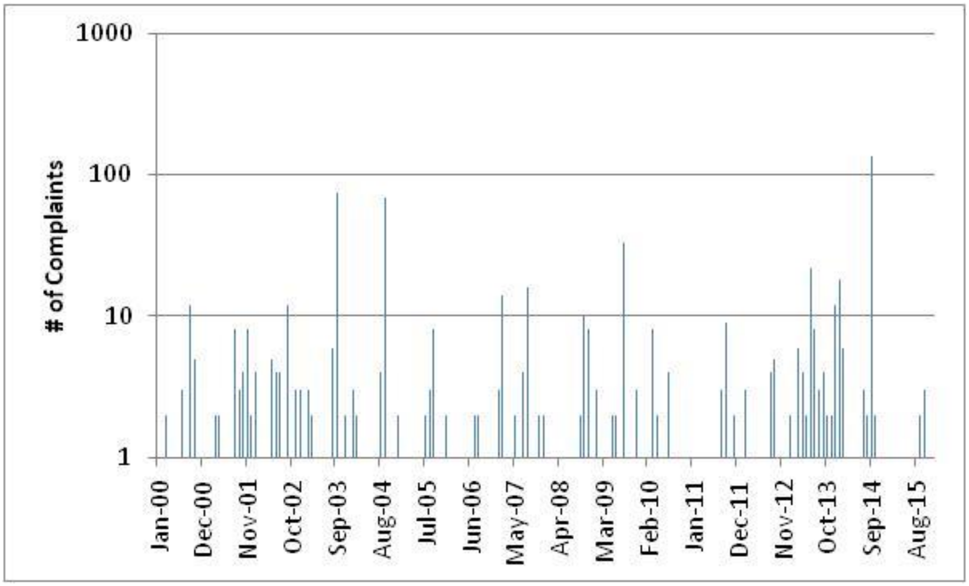


Figure 29. Taste and Odor Complaints to the City of Norman from 2000 through 2015.

Water Quality Standards

All Oklahoma surface waters are subject to Oklahoma's Water Quality Standards (OAC 785:45) and Implementation Rules (OAC 785:46), designed to maintain and protect the quality of the waters of the state. Oklahoma Water Quality Standards (OWQS) are a set of rules adopted by Oklahoma in accordance with the federal Clean Water Act, applicable federal regulations, and state pollution control and administrative procedure statutes. Water Quality Standards serve a dual role: they establish water quality benchmarks and provide a basis for the development of water-quality based pollution control programs, including discharge permits, which dictate specific treatment levels required of municipal and industrial wastewater dischargers.

Identification and protection of beneficial uses are vital to water quality standards implementation. Currently recognized beneficial uses listed in the OWQS Appendix A for Lake Thunderbird (listed as waterbody ID OK520810000020_00) include Public and Private Water Supply, Fish and Wildlife Propagation, and Primary Body Contact Recreation. Because of its designated beneficial use as a Public and Private Water Supply, and its relatively small watershed, the OWQS also designates Lake Thunderbird a Sensitive Public Water Supply (SWS). Physical, chemical, and biological data on Lake Thunderbird were used to ascertain the condition of lake waters and determine if lake water quality supports the beneficial uses and SWS criterion.

The Oklahoma Water Quality Standards Implementation Rules contain Use Support Assessment Protocols (USAP) for Oklahoma waterbodies. Developed in coordination with all Oklahoma environmental agencies, the USAP establish a consistent and scientific decision methodology for determining whether beneficial uses are supported. Lake Thunderbird's water quality parameters are discussed in the following sections, with an emphasis on their accordance with the OWQS. Sites 1 through 6 are historical sites originally monitored by Oklahoma's Beneficial Use Monitoring Program. Sites 8 and 11, are additional monitoring sites added to gain perspective on the two other main tributaries of the lake, but are not used for USAP purposes.

Dissolved Oxygen – DO

Dissolved oxygen criteria are designed to protect the diverse aquatic communities of Oklahoma. For warm water aquatic communities, such as Lake Thunderbird, two assessment methodologies apply to protect fish and wildlife propagation: surface and water-column/volumetric (OAC 785:46-15-5). Surface water criteria is a seasonal threshold with a minimum DO while the volumetric criteria examines one-time events with a threshold of volume (50%) as anoxic (< 2 ppm DO).

No other volumetric violations occurred. No surface water violations occurred in 2015, with minimum surface DO registered at 4.6 mg/L on September 23, 2015 at Site 1. This 4.6 mg/L was above the summer minimum surface criteria of 4.0 mg/L but signified a recent hypolimnetic mixing event. Lake Thunderbird violated the volumetric criteria on June 17, 2015 when water column anoxia peaked at 55% (**Table 4**).

Table 4. Tabular Summary of Percent Anoxic Volume by Sample Date for the 2015 Sample Season.

Date	Pool Elevation	% Anoxic Volume
4/22/2015	1037.03	0.0%
5/12/2015	1047.20	0.6%
6/3/2015	1047.90	8.0%
6/17/2015	1045.00	55.4%
7/1/2015	1044.95	33.5%
7/15/2015	1043.57	23.8%
7/29/2015	1039.66	35.5%
8/12/2015	1038.84	26.9%
8/26/2015	1038.62	6.8%
9/9/2015	1038.33	39.3%
9/23/2015	1038.11	4.0%
10/12/2015	1037.75	3.7%
12/9/2015	1038.70	0.0%

Chlorophyll-*a* – Chl-*a*

Oklahoma surface water drinking supplies are sensitive and vulnerable to eutrophication - high biological productivity (algae and aquatic macrophytes) driven by excess nutrients. Communities can experience substantial hardship and high costs to treat water adversely affected by excess algae. Specifically, blue-green algae (cyanobacteria) blooms are considered a principal source of compounds that cause taste and odor problems. Blue-green algae also produce several toxic and carcinogenic compounds such as microcystins – a known hepatotoxin. For this reason, OWQS has identified a class of public water supplies known as Sensitive Public and Private Water Supplies (SWS), where additional protection is needed from new point sources and additional loading from existing point sources. Lake Thunderbird is listed as a SWS within OWQS and as such, is required not to exceed the long-term ten year average Chl-*a* concentration criterion of 10 µg/L at a depth of 0.5 meters. For the 2015 sampling season, the lake wide Chl-*a* average in Lake Thunderbird was 24.9 µg/L, exceeding the SWS Chl-*a* criterion by more than double. This is about equal to the lake wide average of 24.6 µg/L in 2012 and less than the 36 µg/L average in 2011, but greater than the ten-year historical average of 23.2 µg/L (**Figure 21**). Eighteen percent of the chlorophyll-a samples were within the 10µg/L limit in 2015 (**Figure 30**). All samples though May were less than 10 µg/L except for sites 8 and 11 on April 22, 2015. By June 3, 2015, only site 1 met the chlorophyll-*a* standard. Thereafter, all sample sites exceeded the standard until the December 9, 2015 event when only site 6 exceeded 10µg/L.

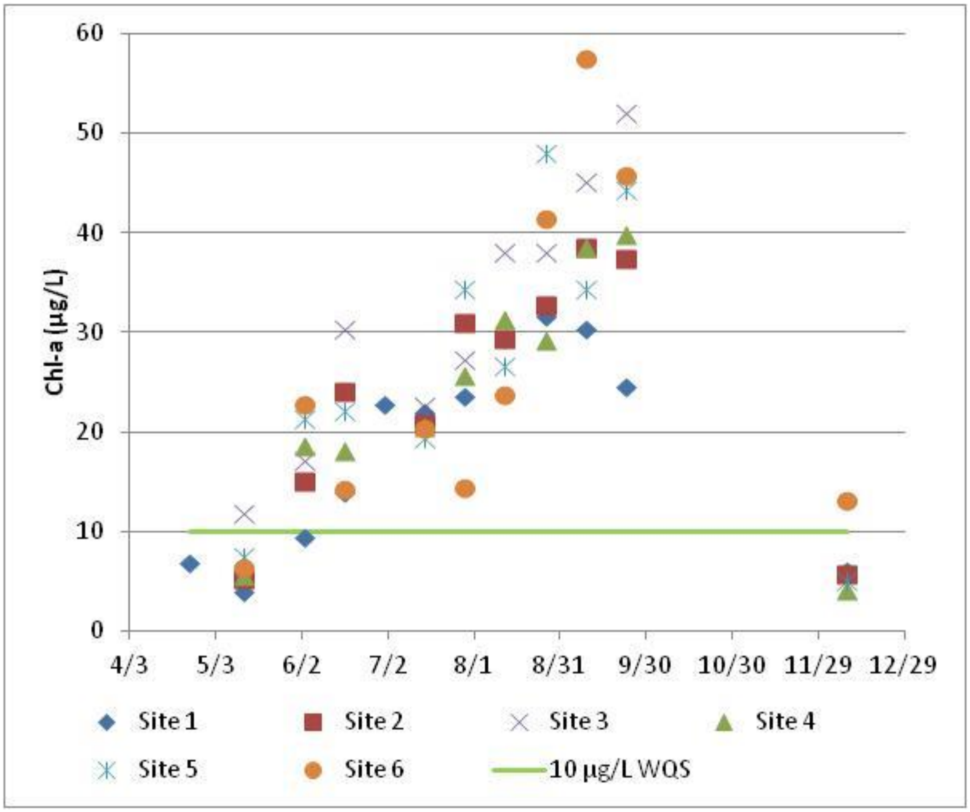


Figure 30. Chlorophyll-a Comparison to the Water Quality Standard for Sites 1 - 6 2015.

Water Clarity

Turbidity and Secchi disk depth are ways of measuring the water clarity and amount of suspended particles in a lake. While natural to pristine lakes often have Secchi disk depths of several meters, Oklahoma reservoirs typically have a majority of Secchi depth readings measuring less than one meter. In Lake Thunderbird, Secchi disk depths ranged from a 2015 mean of 25.1 centimeters at Site 6 to a mean of 60.6 centimeters at Site 4. The lacustrine sites (1, 2, and 4) had the deepest Secchi depths, while the riverine or transition zone sites (6, 8 and 11) had the shallowest (**Figure 31**).

The turbidity criterion for the protection of the beneficial use of Fish and Wildlife Propagation is 25 NTU (OAC 785:45-5-12 (f)(7)). If at least 10% of collected samples exceed this screening level in the most recent 10-year dataset, the lake is deemed not supporting its beneficial use, and is thus impaired for turbidity. In 2015, 21% of Lake Thunderbird samples exceeded the 25 NTU criteria (**Figure 32**). At the end of 2013, 23% of samples in the 10-year dataset exceeded the WQS. It is clear that the storm-water inflow associated with the May rains spiked turbidity as seen in **Figure 33**. The impact of storm-water inflows to turbidity was relatively short lived as the box plots show the May data as outliers for almost each site and the data distribution within each site follows the traditional pattern of decreasing turbidity as one approaches the dam.

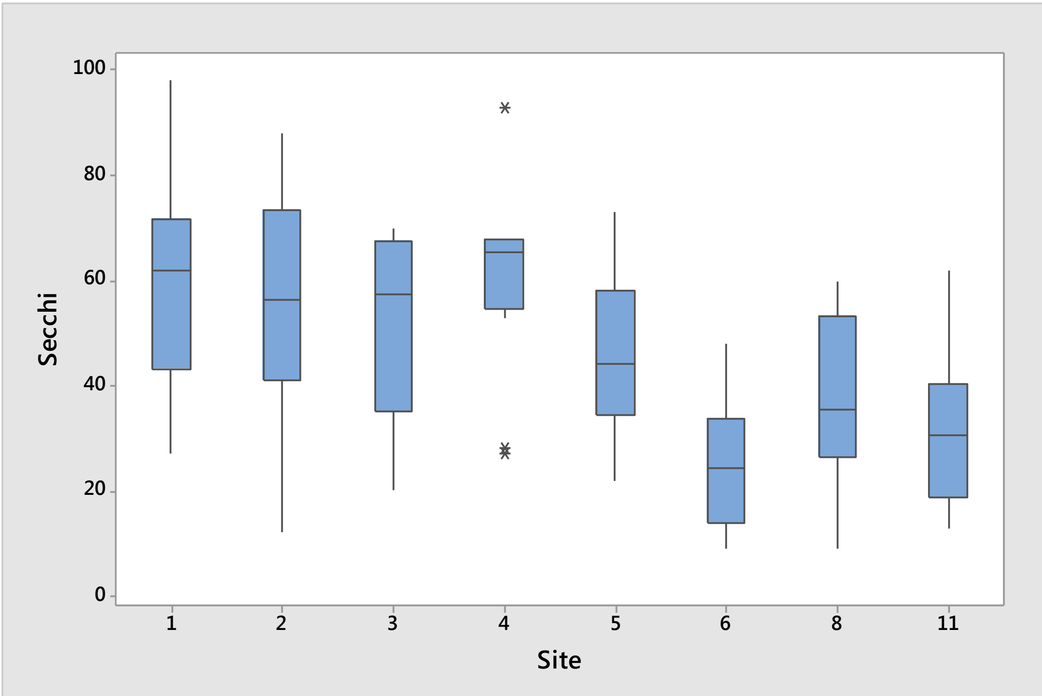


Figure 31. 2015 Lake Thunderbird Secchi Disk Depth (in centimeters) by Site, Where Boxes Represent 25% of the Data Distribution Above and Below the Median (horizontal black line), and Lines (or whiskers) Represent the Other 50% of the Data Distribution.

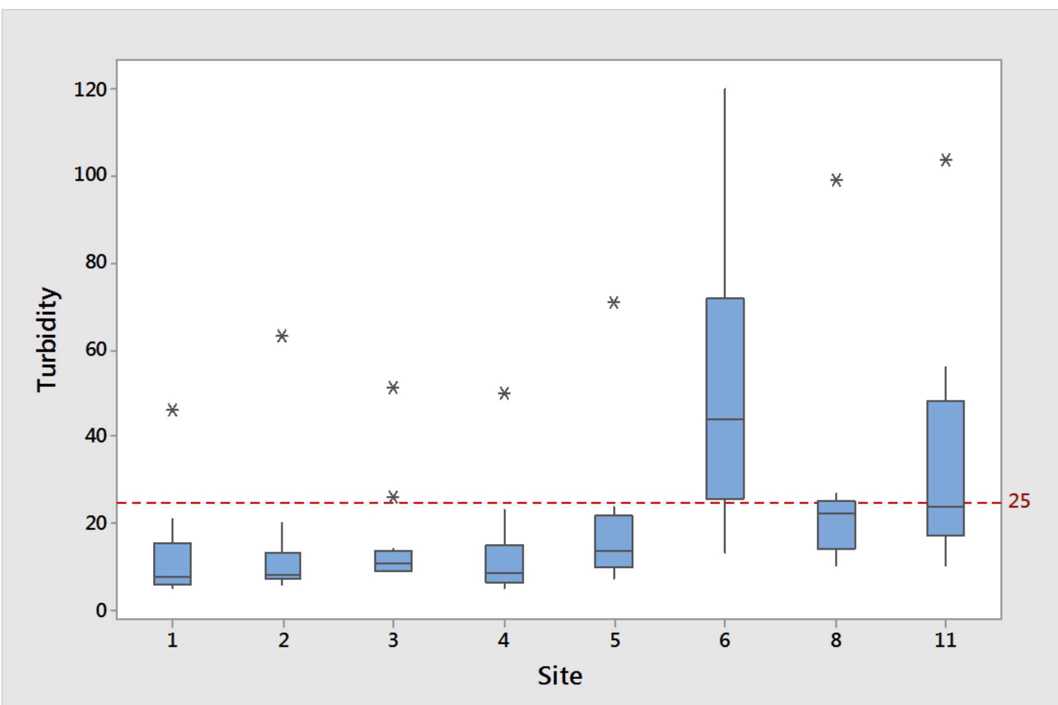


Figure 32. 2015 Lake Thunderbird Turbidity (NTU), by Site, where Boxes Represent 25% of the Data Distribution Above and Below the Median (horizontal black line), and Lines (or whiskers) Represent the Other 50% of the Data Distribution (dashed horizontal line represents state water quality standard).

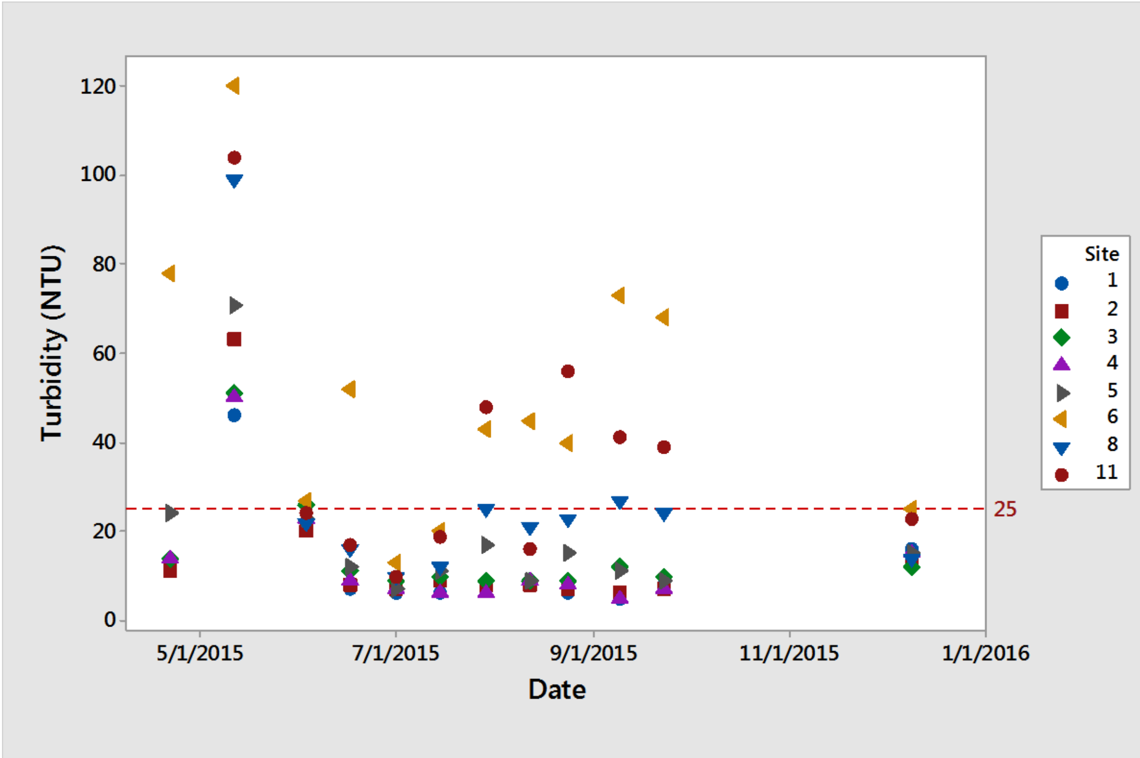


Figure 33. Plot of Turbidity in Standard Units (SU) for the 2015 Monitoring Season. Dashed line indicates the 25 NTU water quality standard.

Supersaturated Dissolved Oxygen Injection System (SDOX)

The summer of 2015 marked the fifth season of operation for the supersaturated dissolved oxygen injection system (SDOX) installed at Lake Thunderbird in 2010. It is designed to operate through the entire stratification window, oxygenating the lower five meters of the lake without disrupting thermal stratification (**Figure 34** and **Figure 35**). The system works by withdrawing water from the deepest area of the hypolimnion approximately 16 meters in depth (at conservation pool), supersaturating this water under pressurized conditions, and then re-injecting it at a separate location 12 meters in depth. At full capacity, this system is designed to treat 1,536 gallons per minute while delivering 5,202 lb DO/day, providing oxidant to the bottom 2000 acre-feet of the lake, encompassing 480 acres of nutrient rich sediment.

This monitoring season marked the third year of operation at optimal design, as large modifications occurred in both the system's components and operation. Data from the first two years of operation suggested that the system was inducing vertical mixing within the water column (OWRB 2012). After reviewing all options with the system owner/operator, COMCD, and the system manufacturer, BlueNGreen, a decision was made to change the discharge nozzle to help diffuse the force from one opening to many openings (**Figure 36**). In addition to the change in the nozzle, the system was modified to run at full capacity out of the south line, and all operation out of the north line ceased. The SDOX system has run with these modifications since 2013. In May of 2015, flooding into the surge pool inundated the SDOX system requiring rewinding of the pump motors and replacement of the VFD. The system went back online on June 29, 2015. Assuming the SDOX shut down September 24, 2015 then the SDOX delivered 297,245 pounds of oxygen over an approximate 87- day period: estimating a system running for 66% of the potential time (87 of 132 days) and delivering oxygen at 66% capacity. In 2014, the SDOX system delivered 217,627 pounds of oxygen over an approximate 120- day period (89% of the time) delivering oxygen at 35% capacity.

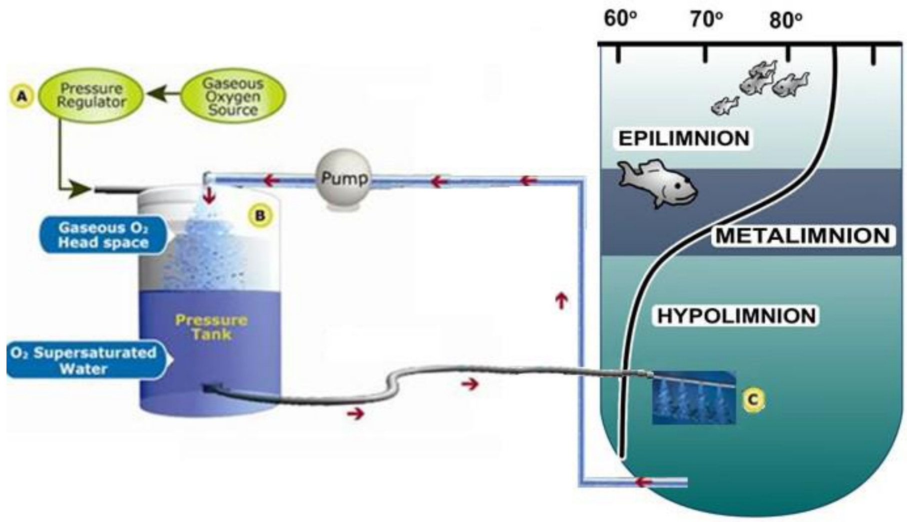


Figure 34. Conceptual Illustration of the SDOX System at Lake Thunderbird

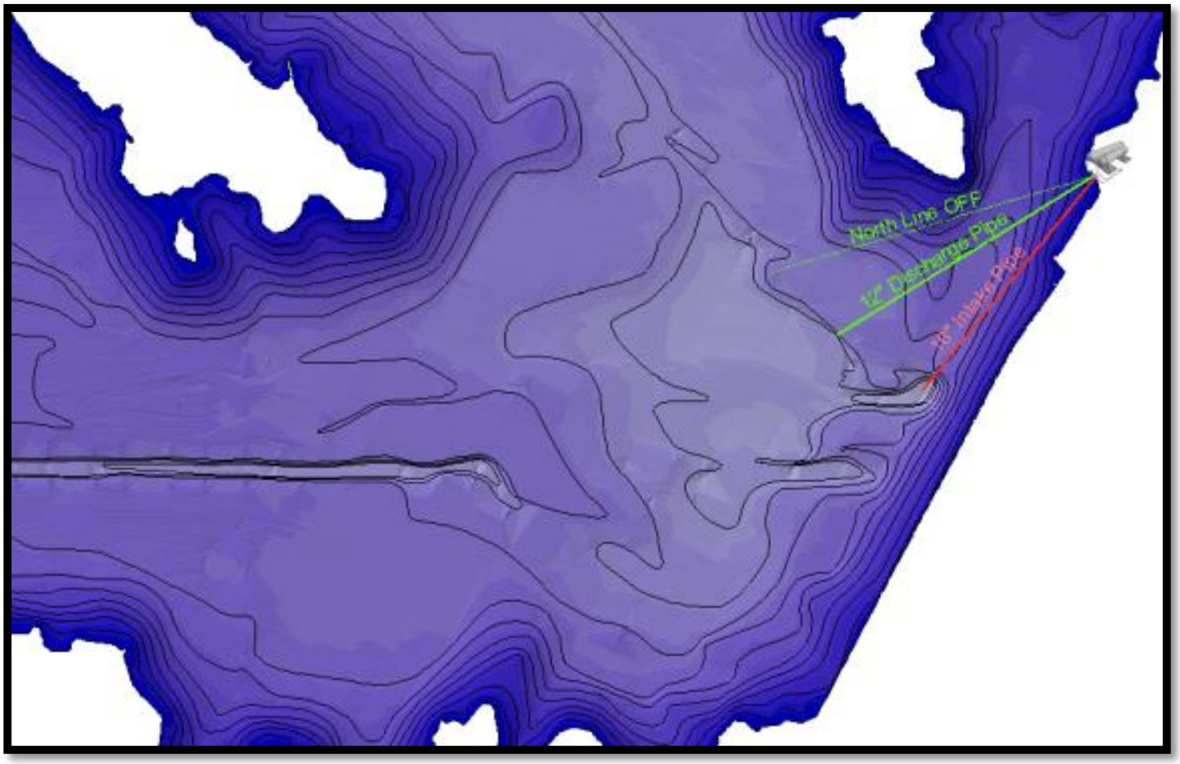


Figure 35. Map of SDOX Location and Current Configuration.

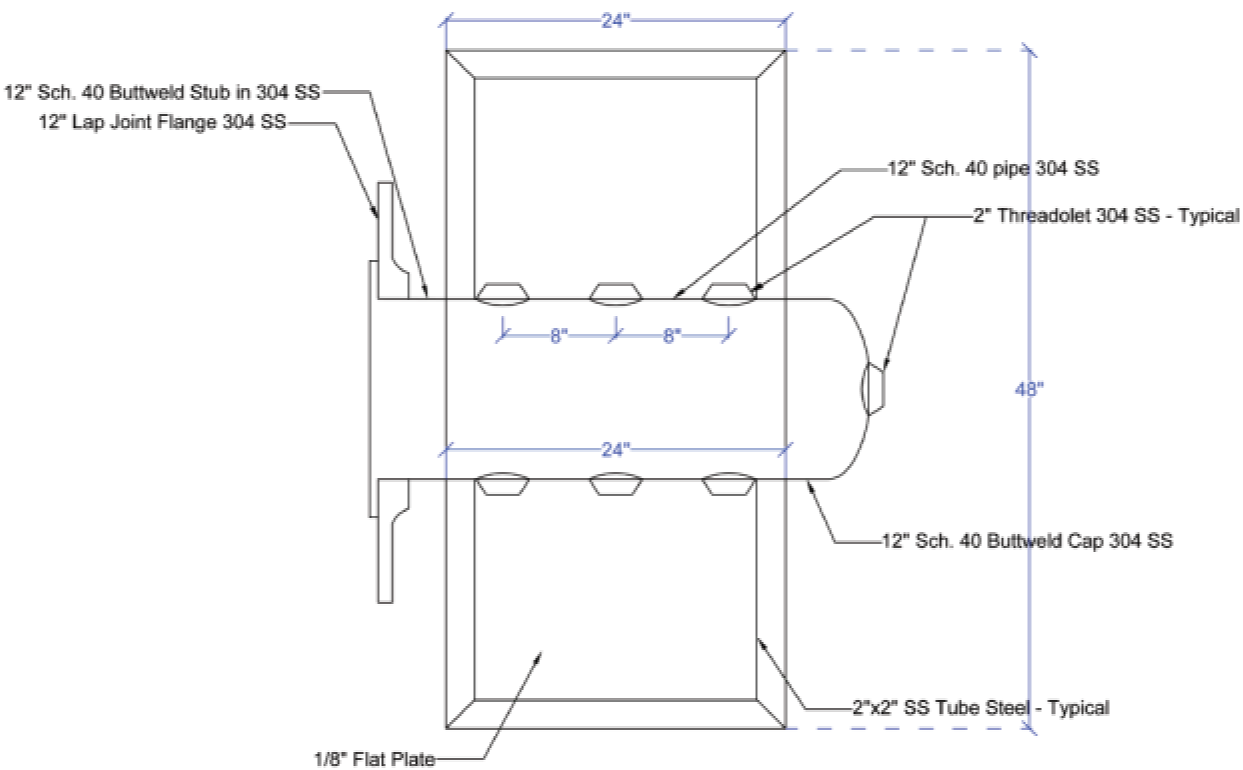


Figure 36. Schematic of the Modified Nozzle

When oxygen is present, it is used as the terminal electron acceptor in respiration, allowing the oxidation-reduction potential in the hypolimnion to be spared from the drop that is witnessed when other compounds are reduced through anaerobic respiration. Reducing conditions reflected by low redox potential increases the solubility of a wide range of nutrients and metals, causing a large sediment flux during the late summer months. If the SDOX system is able to provide an oxygenated hypolimnion, potential benefits include reduction of the internal nutrient load by minimizing the recycling of nutrients from the sediment. Consequently, mitigation of peak Chl-*a* values would be observed. The introduction of oxygen in the hypolimnion should also lower dissolved metals, such as iron and manganese, in the water column.

Thermal Stratification

One of the advertised advantages of SDOX over traditional aeration techniques is the ability to oxygenate without disruption of thermal stratification. In the first year of operation, thermal gradation was greatly reduced from the historical dataset, creating a water column that had much more uniform temperatures from top to bottom. It was also noted that the bottom temperature continually increased throughout the entire summer of 2011 until isothermal conditions were reached precipitating the turnover event. In 2012, a somewhat similar situation was observed where bottom water conditions were much warmer than normal and heated at a higher rate than what is observed in the historical dataset. After the system modifications occurred in early July of 2012, the rate of temperature increase at the bottom slowed noticeably at 0.034 C°/day from July through August) compared to the pre-SDOX modification rates of 0.085 C°/day from July through August. In 2013 and 2014, the effect of the system modification continued to be observed with a post-modification rate of heating noted in the lake bottom at 0.033 C°/day from mid-June through September of 2013 and 0.037°C/day from July through August of 2014. The 2015 rate of heating was estimated at 0.058 C°/day from July through September. This rate is relatively higher than other years but still less then pre-SDOX years.

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

The main goal of the SDOX system was to provide an oxygenated hypolimnion from 12 meters in depth and below through much of the summer. While it was not designed to prevent anoxia (<2mg/L DO) in the entire hypolimnion under maximum stratification, it was expected to raise DO levels in the deepest 2000 acre-feet of the lake. Anaerobic conditions at the lake bottom were noted May 12, 2015, while ORP was highly oxic. It was not until the July 1, 2015, sample event that ORP had dropped into strongly reducing conditions even though the hypolimnion had been anoxic throughout the month of June. On June 29, 2015, the SDOX system went back online; delivering oxygen at an average of 66% capacity. Anoxia deepened while operating the SDOX, and encompassed all or most of the metalimnion throughout the entire stratification period. On three sample dates, July 29, September 9 and September 23 of 2015, anoxia was noted in the epilimnion. The apparent extreme anoxia noted in 2015 can be best explained by a large influx of non-point source pollutants from the watershed; 130% of the normal pool capacity washed into the lake in May with over twice (205%) normal pool capacity entering the lake by the end of July. Most notable was that the low ORP (<100mV) followed anoxia by about a month and was largely contained to the hypolimnion (**Figure 37**). Only on the September 9, 2015 sample date did anoxia and low ORP match in depth. On all other sample dates, the anoxia was significantly higher in the pool elevation than the low ORP. It is likely that the SDOX system after going online June 29, 2015 contributed to minimizing the extent of low ORP water.

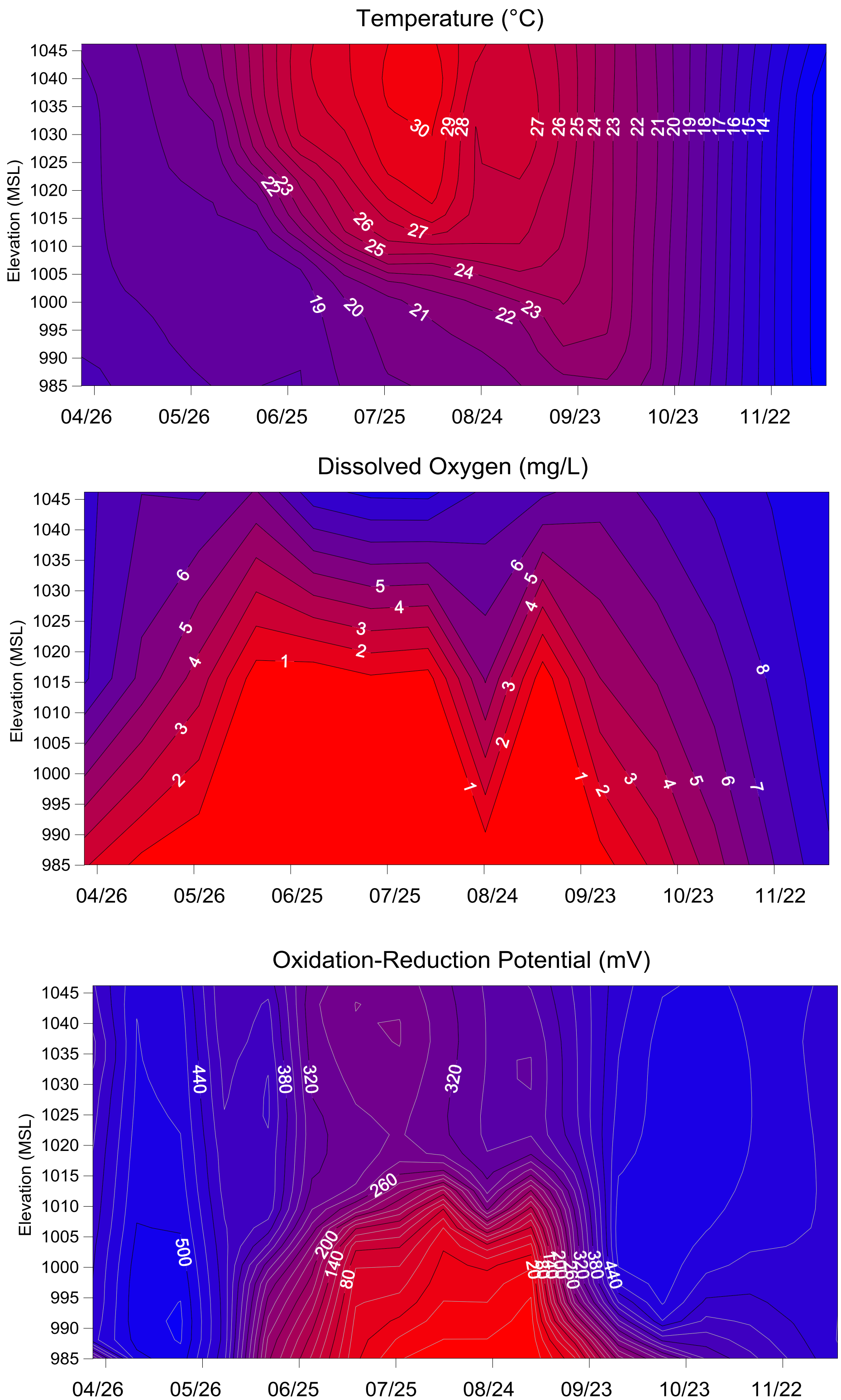


Figure 37. Temperature, Dissolved Oxygen and Oxidation-reduction Potential (ORP) by Elevation for 2015 Site 1 Lake Thunderbird; Highlighting the Temporal Disparity Between Onset of Stratification (Temperature), Anoxia (Dissolved Oxygen) and Reducing Conditions (ORP).

Duration of low ORP was 3 months, similar to pre-SDOX years, but the extent within the water column was much less (2015 did not intrude as high in the water column) as in 2009.

Another metric of SDOX performance is the anoxic factor (AF). This metric was developed to estimate sediment mediated phosphorus release (Nürnberg, 1994). The AF gives a measure of the lake's oxygen state by integrating the number of days that sediment (equal to the surface area of the lake) is overlain by anoxic water. This metric is well suited to assess SDOX annual performance.

Eq. 3 $$AF = \sum_{i=1}^{n}(t_i * a_i)/A_o$$

Where n = number of time intervals

t = time interval

a = area of anoxic sediment within time interval

A_o = area of lake

The area of anoxic sediment within a given sample event was determined using the dissolved oxygen profiles for site one. The depth when anoxia was first met is noted and the corresponding area is ascertained from the 2001 area-depth table. Application of this equation to the historical dataset provided an insight to SDOX performance (**Table 5**). We used the average of 2005 – 2009 to represent pre-SDOX conditions to be used as a comparison against AF calculated for the following years. A marked reduction (lower AF and higher RPD) was noted for the first three full seasons of operation (2011 – 2013). However, a marked reduction of SDOX impact was noted in 2014 and 2015. Significant and extended breaks in SDOX operation in both years help to account for the reversal in AF values toward greater extent and duration of anoxia. The large influx of non-point source pollutants, along with the extreme recharge events of 2015 also helps account for the unusually large AF and negative Relative Percent Difference (RPD).

Table 5. Summary of Anoxic Factor by Year Including Relative Percent Difference (RPD) for 2005 Through 2015.

Year	AF (day^{-1})	RPD
2005	41.99	-27%
2006	26.87	19%
2007	33.66	-2%
2008	31.89	3%
2009	30.76	7%
05 — 09 Average	***33.03***	**0%**
2011	21.47	35%
2012	25.50	23%
2013	13.07	60%
2014	38.26	-16%
2015	56.28	-70%

Nutrients, and Chlorophyll-a

The SDOX system induces physical changes (increased dissolved oxygen and oxidation-reduction potential) in the hypolimnion to trigger biological changes that would ultimately reduce phosphorus sediment loading. This sediment-derived load has been documented in previous years to fuel the rise in Chl-*a* during the late-summer/fall turnover timeframe, in-turn causing a rise in TOC, drinking water treatment costs, potential for carcinogenic disinfectant by-products in finished drinking water, and taste and odor complaints.

The delay of SDOX going on-line due to massive dam releases and flooding of the SDOX pumps added to the large influx of non-point source pollutants with the floodwaters fueling bacterial catabolism all combined to preclude any easily detected impact to water quality. A spot of nitrite-nitrate was noted in the middle of the water column on the July 1, 2015 sample date (**Figure 18**) but is more likely due to inflowing water than SDOX system impact.

Examination of the 2015 chlorophyll-*a* suggests that while algal biomass had increased from the gains seen in 2013, it had not returned to pre-SDOX years. Higher than usual turbidity due to storm water inflow is a likely contributor to lower chlorophyll-*a* values. It is also possible that previous years of operation had satisfied much of the sediment oxygen demand and this has dampened a return to pre-SDOX conditions. While the phosphorus content of the lake was much greater than other years, an influx of nutrient rich waters from the watershed can account for the bulk of the phosphorus documented in Lake Thunderbird.

Sediment Phosphorus Analysis

Traditional use of sediment phosphorus concentration has been used as an input for estimating phosphorus release. While this is useful for estimating nutrient release under variable water quality conditions, no metric has been developed to gauge the ability of sediment to retain phosphorus. With the operation of the SDOX system actively inhibiting the release of phosphorus and enhancing the sorption of phosphorus to the sediment, a measure of the sediment's phosphorus binding ability would be useful. Two metrics commonly used for soil fertility is the Phosphorus Saturation Ratio (PSR) and Soil Phosphorus Storage Capacity (SPSC) (Vimala 2010). The underlying foundation of both measures is that iron and aluminum represent the primary binding factors responsible for release or uptake of phosphorus (Zhang 2005). Chemically and mathematically, via the oxalate extraction, aluminum and iron account for 100% of the sediment phosphorus binding ability under the PSR. Many biogeochemical factors other than aluminum and iron content influence phosphorus binding in lake sediments suggesting a tenuous use of a terrestrial index to track aqueous sediment dynamics. However, as iron is a primary factor binding phosphorus and aluminum plays a role in aqueous phosphorus dynamics, examination of the PSR poses merit for tracking sediment binding ability. Furthermore, the associated soil tests are standardized and relatively inexpensive. These make the PSR attractive as an option to track potential effects the SDOX equipment and the continual rain of organic matter to the phosphorus dynamics of the lake bottom.

Samples collection occurred at three sites in Lake Thunderbird in November of 2014, May and December of 2015. Sediment taken at site 1 is considered the index site as it is the area of lake bottom most affected by the SDOX system. Sediment taken at sites 6 and 8 serve to contrast epilimnetic to hypolimnetic (site 1) sediment and may shed light on the ability of the sediment to bind influent phosphorus. Cores were taken at each site with two sets of analysis done for each core: the top 2 centimeters and the 5 to 10 centimeter zone. These two depth samples are designed to represent the surficial sediment layer (0 - 2 cm) and the deeper buried sediment (5 – 10 cm). Wide-mouth polyethylene bottles held the samples and they were kept at 40°F until delivered to the laboratory for analysis. Sample analysis was performed by Oklahoma State University's Soil Water Forage Analysis Laboratory (SWFAL) in Stillwater where acidified ammonium oxalate is used as an extractant to the sediment and the elutriate analyzed for phosphorus, aluminum and iron. Test results were used to calculate the Phosphorus Saturation Ratio (PSR) as a molar ratio using the equation:

Eq. 4 $$PSR_{Ox} = (\text{Oxalate-P}) / [(\text{Oxalate-Fe}) + (\text{Oxalate-Al})]$$

The underlying assumption is that the oxalate extraction represents a reasonable measure of aluminum and iron where as these elements represent 100% of the phosphorus binding capability. Using the calculated PSR values comparisons were made between sites and (within each site) between seasons (**Table 6**). Nonparametric comparison of means concluded that the PSR of each site, regardless of depth were significantly different at a 5% confidence interval. Also interesting was the consistent drop of PSR at each site and depth zone between seasons at site 1. These may indicate a recharging of the sediment with the ability to sorb phosphorus. Processes to explain include a new layer of unbound iron and aluminum or that the previously bound phosphorus has undergone further diagenesis opening up additional iron and aluminum binding sites. Non-parametric statistical comparison also showed that sites 1 and 4 had the highest PSR and site 2 the lowest. This suggests that site 2 has the greatest potential to bind the least. Terrestrial application of the PSR suggests values greater than 0.25 are samples saturated with phosphorus. While, the importance of these statistics is not clear, it is apparent that the PSR is sensitive to differences between Lake Thunderbird sample sites. These results indicate usefulness for indexing the ability of Lake Thunderbird sediments to sequester and retain phosphorus.

Table 6. Phosphorus Saturation Ratio of Lake Thunderbird Sediment.

Date	Season	Site	Depth	PSR_{ox}
11/11/2014	winter	1	0-2	0.117
5/12/2015	spring	1	0-2	0.104
12/09/2015	winter	1	0-2	0.116
11/11/2014	winter	1	5-10	0.113
5/12/2015	spring	1	5-10	0.097
12/09/2015	winter	1	5-10	0.113
12/09/2015	winter	2	0-2	0.088
12/09/2015	winter	2	5-10	0.088
12/09/2015	winter	4	0-2	0.111
12/09/2015	winter	4	5-10	0.113

Discussion

For the past 16 years, OWRB has monitored the water quality at Lake Thunderbird; observing the consequences of cultural eutrophication and degraded water quality. Over time, these consequences have become more severe, including increasingly high chlorophyll-*a*, elevated total organic carbon, elevated pH and supersaturation of dissolved oxygen. 2013 represented the first year where the downward trend was resolutely reversed; then in 2014, the evidence was not as resolute, but still showed oligotrophication. Flooding in 2015 shut down the SDOX for the first six weeks of operation resulting in severe anoxia; fortunately, algal growth was not much higher, on average, than that of 2013 and 2104. The extended anoxia caused phosphorus and metal release into the water column throughout the extended fall. The gradual mixing of the hypolimnion with the epilimnion helped to dampen taste and odor complaints following fall turnover. However, the extensive anoxia predicted significant release of sediment phosphorus.

Harmful algal blooms, or HABs, are another consequence of cultural eutrophication that can lead to many environmental problems. Cyanobacteria, or blue-green algae, are the most common group of harmful algae in freshwaters. Several species of cyanobacteria occur in and dominate phytoplankton communities in Oklahoma waters, including Lake Thunderbird. Taste and odor causing compounds such as geosmin and 2-methylisoborneol (MIB) are released from blue-green algal cells following lyses, or senescence, and decomposition. This causes problems in public drinking water supply lakes because of the difficulty in removing these chemicals beyond detection limits in the treatment process. The City of Norman has historically received taste and odor complaints directly attributable to the presence of these compounds in finished drinking water. Geosmin and MIB are detectable in raw and finished drinking water and in 2014, Lake Thunderbird set an all-time high for quantity of MIB in its treated waters. In addition, blue-green algae have the capability to produce multiple toxins that can cause skin irritations, harm or lethality to humans, livestock, and pets that drink from untreated contaminated water sources. The significant lowering of peak and average Chlorophyll-*a* in 2015 indicates that while slipping, the lake is still in better condition than prior to SDOX implementation. However, even with the SDOX in use, cultural eutrophication continues to stress this reservoir ecosystem.

Lake Thunderbird is listed on Oklahoma's 2012 303(d) list of the Water Quality Integrated Report as impaired due to low dissolved oxygen, with the official cause of these impairments unknown. Monitoring data, collected in 2015, were 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 DO and turbidity. Additionally, Lake Thunderbird did not meet the 10 μg/L Chl-*a* requirement for Sensitive Public and Private Water Supply (SWS). Nutrient and solids reductions are necessary for the lake to meet these water quality standards. The severe flooding in 2015 had a profound impact on Lake Thunderbird by recharging it with non-point source pollutants and decommissioning the system designed to mitigate low dissolved oxygen. These factors help account for a measure of SDOX performance, the Anoxic Factor (AF), which was higher than any other year. The past two years contrasted to the first several years of SDOX operation, which highlight the value of the SDOX system to not only provide aerobic lake habitat but also improve the quality of raw drinking water for the municipalities and reduce recreational health risks due to the growth of harmful algae. SDOX operation alone will not provide continued relief without concomitant improvements in the watershed. The strength of the SDOX is its ability to facilitate and accelerate lake recovery with watershed improvements.

Recommendations

Data from 2014 and 2015 show that the SDOX system has not run close to its capacity. Assessment of SDOX system capacity to deliver oxygen and assessment of water column and sediment's ability to assimilate oxygen is a next logical step toward optimizing SDOX efficiency. Additional actions to develop in-lake best management practices (BMPs) include the development of a plan to reduce sediment suspension and transport. Areas of high sediment suspension can be identified and measures to minimize should be implemented. Similarly, areas of high shoreline erosion can be identified and the means to mitigate should be implemented. However, as long as watershed events deliver non-point source (NPS) pollutants above the Total Maximum Daily Load the effectiveness of in-lake measures will be reduced. Finally, an updated bathymetric survey minimizes error when estimating DO load during SDOX assessment, it allows for field verification of lake dispositional areas identified from a sediment suspension and transport model and increases the accuracy of any future water quality (nutrient enrichment/eutrophication) response model.

Aggressive watershed BMP implementation is needed to reduce nutrient and solids movement into waterways. General ways to accomplish this include:

- Incorporating wetlands into the landscape to ameliorate NPS pollutant runoff
- Planning new vegetated swales and infiltration basins and retrofitting existing vegetated swales and infiltration basins
- Target the retention of precipitation and runoff to reduce the impact of impervious surfaces
- Adopt Low Impact Development (LID) into COMCD's practices for maintenance and construction (Low Impact Development Center, 2014).
- Encourage municipalities within the watershed to incorporate Low Impact Development (LID) into any new construction within the watershed (Low Impact Development Center, 1999).

Fostering cooperation and collaboration between all stakeholders within the Lake Thunderbird watershed will assist in reducing runoff from construction activities and urban land uses.

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Appendix A: Quality Control Data

Tabular Summary of Chlorophyll-a Quality Control Samples: duplicate (Sites 1 a & b) and replicate sample as Site 9

Date	Site 1a	Site 1b	Site 9	average	sd
4/24/2015	6.41	7.35	6.73	6.83	1.67
5/13/2015	4.76	3.78	3.33	3.95667	1.17
6/3/2015	11.7	11.6	4.91	9.40333	1.33
6/17/2015	11.7	19.3	10.7	13.9	0.62
7/1/2015	25.6	20.6	22	22.7333	0.72
7/15/2015	22.2	22.3	21.6	22.0333	8.37
7/29/2015	21.6	26.4	22.9	23.6333	1.33
8/12/2015	29.4	1.4	29.5	29.45	0.61
8/26/2015	32.1	33.2	29.4	31.5667	16.02
9/9/2015	15.7	37.5	37.9	30.3667	11.21
9/23/2015	25.4	24.5	23.9	24.6	1.87
12/9/2015	6.48	6.05	5.52	6.01667	0.71

sd – standard deviation

Blank Sample Results

Date	Site 22	Kjeldahl mg/l	Nitrate mg/l	Nitrite mg/l	Ammonia mg/l	Ortho-P mg/l	Total P mg/l
4/24/2015	BLANK	<0.11	<0.02	<0.02	0.062	<0.005	0.019
5/13/2015	BLANK	<0.11	<0.02	<0.02	<0.015	<0.005	<0.005
6/3/2015	BLANK	<0.11	<0.02	<0.02	0.034	0.006	0.012
7/1/2015	BLANK	<0.11	<0.02	<0.02	<0.015	<0.005	0.005
7/15/2015	BLANK	<0.11	<0.02	<0.02	0.015	0.005	0.005
7/29/2015	BLANK	<0.11	<0.02	<0.02	< 0.015	<0.005	< 0.005
8/12/2015	BLANK	<0.11	<0.02	0.35	< 0.015	<0.005	0.012
8/26/2015	BLANK	<0.11	<0.02	<0.02	< 0.015	<0.005	< 0.005
9/23/2015	BLANK	<0.11	<0.02	<0.02	<0.015	<0.005	<0.005
12/9/2015	BLANK	<0.11	<0.02	<0.02	<0.015	0.006	0.007

Replicate Sample Results

Date	Site	Kjeldahl as N (mg/l)	Nitrate as N (mg/l)	Nitrite as N (mg/l)	Ortho-P as P (mg/l)	Total P as P (mg/l)	Ammonia as N (mg/l)
4/22/2015	9	0.58	0.17	0.08	0.019	0.046	<0.015
5/13/2015	9	0.61	0.26	<0.02	0.033	0.062	0.071
6/3/2015	9	0.69	0.14	<0.02	0.035	0.068	0.039
7/1/2015	9	0.87	<0.02	<0.02	0.022	0.066	0.058
7/15/2015	9	0.78	<0.02	<0.02	0.007	0.044	0.035
7/29/2015	9	0.80	<0.02	<0.02	0.005	0.037	0.021
8/12/2015	9	0.85	<0.02	<0.02	0.01	0.049	0.032
8/26/2015	9	0.73	<0.02	<0.02	0.007	0.038	0.046
9/9/2015	9	1.01	<0.02	<0.02	0.017	0.069	0.075
9/23/2015	9	0.93	0.03	0.16	0.029	0.072	0.212
12/9/2015	9	0.59	0.37	<0.02	0.039	0.058	0.092
4/22/2015	1	0.57	0.17	0.07	0.019	0.049	0.079
5/12/2015	1	0.65	0.18	0.11	0.034	0.063	0.065
6/3/2015	1	0.71	0.12	<0.02	0.043	0.055	0.029
7/1/2015	1	0.79	< 0.02	< 0.02	0.019	0.062	0.017
7/15/2015	1	0.82	< 0.02	< 0.02	0.010	0.047	0.048
7/29/2015	1	0.84	< 0.02	< 0.02	0.007	0.039	0.02
8/12/2015	1	0.84	< 0.02	< 0.02	0.009	0.057	0.026
8/26/2015	1	0.91	< 0.02	< 0.02	0.006	0.047	0.053
9/9/2015	1	1.07	< 0.02	<0.02	0.023	0.082	0.109
9/23/2015	1	0.96	0.04	0.16	0.029	0.072	0.208
12/9/2015	1	0.46	0.39	<0.02	0.028	0.045	0.035