Oklahoma Water Resources Board

Lake Thunderbird
Water Quality
2014

for the

Central Oklahoma Master Conservancy District

September 16, 2015
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 2014, 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 2014 represents 15 years of continuous seasonal monitoring at Lake Thunderbird.

The year of 2014 started with a full conservation pool while delay of spring rains until June and July resulted in a generally dropping pool throughout the monitoring season. Also unusual was a July that averaged 4.7 °C cooler than the long term average and an October that averaged 3°C warmer than the long term average. The hydraulic residence time for 2014 was above average at 6.2 years, due to the extended drought. Stratification was detected the first sample date, April 22 2014, with weak stratification noted through each May sample trip. Steady elevation of bottom temperature indicated intermittent mixing throughout the spring season. It is likely that the SDOX contributed to the early increase of hypolimnetic temperature through delay of onset of summer (permanent) stratification. Permanent stratification was noted June 12 and was continuous through early September. Mixing likely had occurred by September 19, 2014 but complete mixis was not noted until the October 20 trip. Even with an October profile that was isothermal, dissolved oxygen steadily declined including depressed values at the surface. These indicated a late turnover event for 2014.

Lake nutrients were not substantially higher in 2014 but the expression of algae as measured via chlorophyll-a rebounded some since the SDOX system has been operational. Early in the season light may have limited algae growth when the lake was at a meso- to eutrophic state. Following mid-summer, chlorophyll-a climbed into a hypereutrophic state until monitoring ended. Since 2011, when the SDOX system was placed into operation, the lake has met the dissolved oxygen criteria. Central Oklahoma Master Conservancy District (COMCD) should request the lake be delisted from Oklahoma's 303(d) list for this impairment as they are actively managing the lake for greater oxygen content and showing measurable positive results. However, additional active lake and watershed management is required for Lake Thunderbird to meet OWQS for turbidity and chlorophyll-*a*. Primary mitigation efforts should focus on nutrient reduction, which would affect two impaired water quality parameters: algae growth and dissolved oxygen. In-lake mitigation efforts focused on minimizing the transfer of suspended solids from the riverine zones to the main lake body would show the greatest positive impact to turbidity. Continuation of the active hypolimnetic oxygenation project provides relief to the lake's DO levels, algal problems, and drinking water taste and odor complaints. However, the current system does not appear to satisfy the oxygen demand. Estimation of sediment oxygen demand would assist in determining an adequate oxygen delivery to the Lake Thunderbird hypolimnion. In addition, evaluating the systems ability to deliver oxygen at capacity is also an item to address.

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 2014, 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 Chl-*a* (http://www.deq.state.ok.us/wqdnew/305b_303d/2012_draft_integrated_report.pdf). Because 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 standard impairment listings, collaborative work with the City of Norman has illustrated 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 elevated treatment costs. The City of Norman has taken steps to reduce taste and odor complaints in the treatment process, but some taste and odor complaints still exist.

In an attempt to mitigate the effects of the cultural eutrophication witnessed in the reservoir, the COMCD applied and was funded, through the American Recovery and Reinvestment Act, to install and operate an oxygenation system designed to oxygenate the deepest portion of the anoxic hypolimnion in the lake while leaving thermal stratification intact. The targeted impact of providing an oxygenated hypolimnion include attainment of dissolved oxygen OWQS, elimination of reducing conditions in the hypolimnion, and reductions of internal phosphorous load, dissolved metals, and peak Chl-*a* events. Data collected in 2014, represents the fourth season of SDOX operation.

Water Quality Evaluation

Sampling Regime

In 2014, Lake Thunderbird water quality sampling occurred from April 22 through October 20 (**Table 1)** at the sites indicated in **Figure 1.** All sites were sampled at each visit. Sites 1, 2, and 4 represent the lacustrine zones of the lake. Site 6 embodies the riverine zone of the Little River arm, while Site 11 represents the riverine zone of Dave Blue Creek. Site 5 represents the transition zone between these two riverine sites to the main body of the lake. Site 8 represents the Hog Creek riverine zone. Site 3 represents the transition zone of the Hog Creek arm.

On every visit, all sites had water quality profiles conducted for oxidation-reduction potential (ORP), DO saturation and concentration, temperature, specific conductance, total dissolved solids (TDS) and pH. Each water-quality profile was measured in approximately one-meter intervals from the lake surface to sediment at each site.

In addition, nutrient samples were collected at the surface of Sites 1, 6, 8 and 11 and at 4-meter depth intervals of Site 1 to the bottom. Analysis performed on these samples included phosphorus (P) and nitrogen (N) series. Total organic carbon samples were also collected at the surface of Site 1. Secchi disk depth, surface Chl-*a*, and turbidity samples were collected at all nine sites.

Table 1. 2014 Water quality sample dates and parameters.

Date	4/22	5/7	5/28	6/12	6/26	7/10	7/24	8/7	8/21	9/4	9/19	10/20
Profile	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	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	X

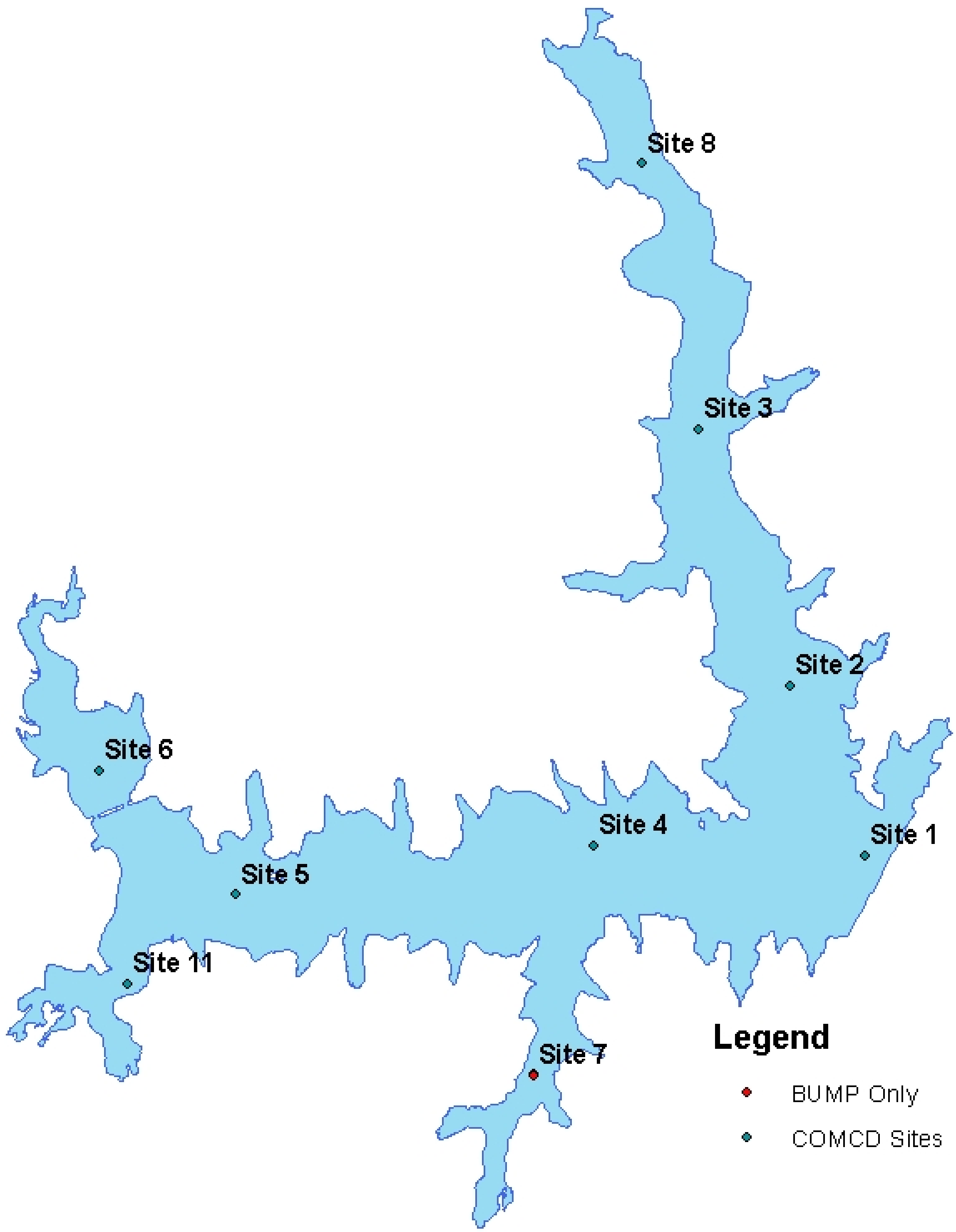


Figure 1. Lake Thunderbird 2014 sampling sites

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. Duplicate samples were taken at the surface of Site 1 and labeled “Site 1” and “Site 9” respectively, and delivered to the laboratory for analysis. In addition, Site 1 Chl-*a* replicate samples were split during post processing at the OWRB lab and then delivered to the laboratory for analysis. On August 21, 2014 site 8 served as the duplicate chlorophyll-a sample site instead of site 1 as usual. **Appendix A** summarizes laboratory results of duplicate and replicate sampling. Additional samples, chlorophyll-a replicates, were used while transitioning between analytical laboratories.

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 difference between the two “identical” samples. Site 9 is the duplicate sample label for Site 1 surface samples. The percent absolute difference (PAD) was used to describe the precision of each laboratory parameter based on the paired comparison of duplicate samples.

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

For each duplicate sample report parameter, equation 1 was applied. 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 25. Note that while PAD is good over the entire sampling season, instances of high PAD for Ammonia as N, Nitrite-Nitrate as N, Ortho-phosphorus as P and Chlorophyll-*a* occurred and is reflected by a large upper quartile. Relative percent difference summary statistics were within the acceptable range. Blank samples showed low-level phosphorus contamination on 8/7/14 and 8/21/14. These reports were close (within two one thousandths parts per million) to the detection limit. Significant Kjeldahl nitrogen contamination, close to 4 times the detection limit, was noted in the blank sample on 8/21/14. This report was puzzling as no other blank parameter was reported above the detection limit and environmental samples reported normal. Duplicate samples of 146 relative percent difference where noted on 7/24/14 for the ammonia parameter. While ammonia increased evenly with depth, no other surface ammonia report was above detection limit on that date. No adjustments to laboratory reported values were made.

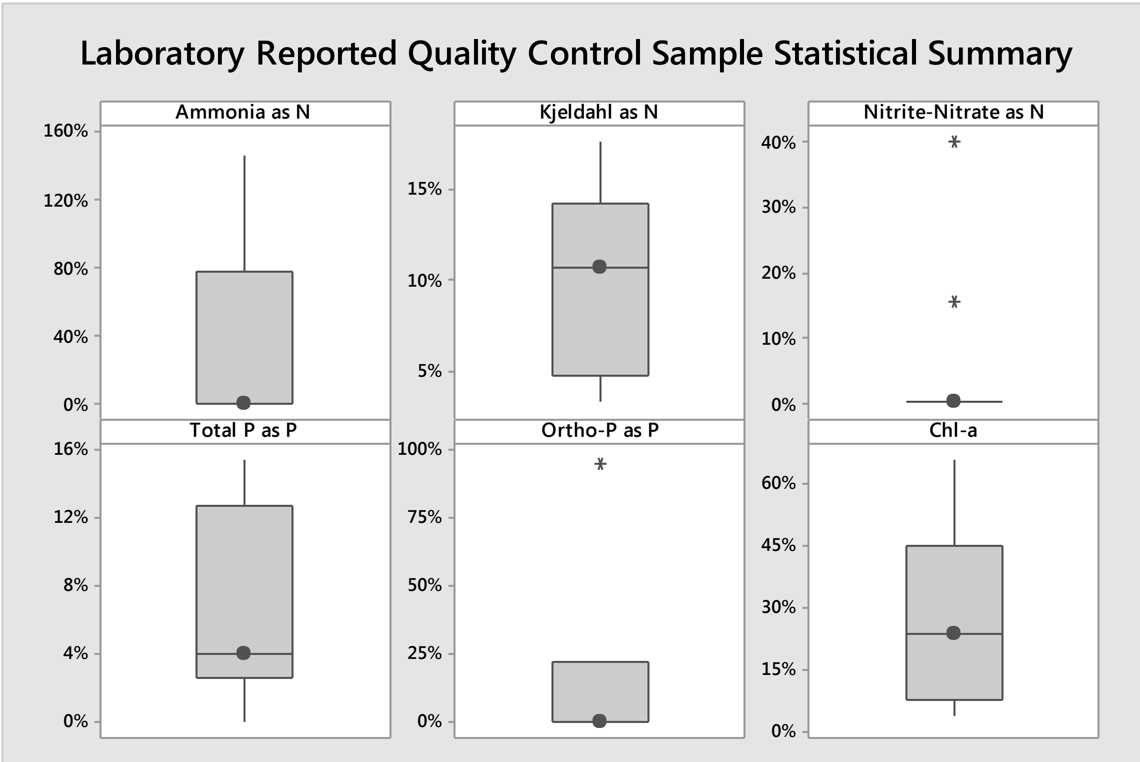


Figure 2. Summary Plots of Percent Difference for Duplicate Laboratory Samples Lake Thunderbird April 22, 2014 - October 20, 2014. (Box represents the middle 50%, the center bar the median value, top and bottom stems the upper and lower 25% quartile and asterisks as outliers**)**

Climate

Knowledge of potential climatologic influences is essential when assessing the water quality of a waterbody. The hydrology or 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 2014. Lake elevations and inflows can vary considerably with rainfall patterns. Annual precipitation at Lake Thunderbird in 2014 totaled 24.3 inches, 10.7 inches below average. The overall low rainfall combined with greatest rainfall during the highest evapotranspiration months resulted in a varied pool elevation from a high of about 0.35 feet above conservation pool (1039' MSL) on January 1st to a low around 2.4 feet below conservation pool in November and December. All sample events were while the reservoir was below conservation pool with May 7, 2014 the highest sample pool elevation at 1038.6 and September

4, 2014 the lowest at 1036.5. In addition to hydrology, air temperature can also influence lake characteristics such as stratification patterns and primary productivity. **Figure 4** illustrates the 2014 average daily temperature values. The lower than average July (3.3 F) and higher than average October (4.3 °F) are notable deviations from the norm during the monitoring season.

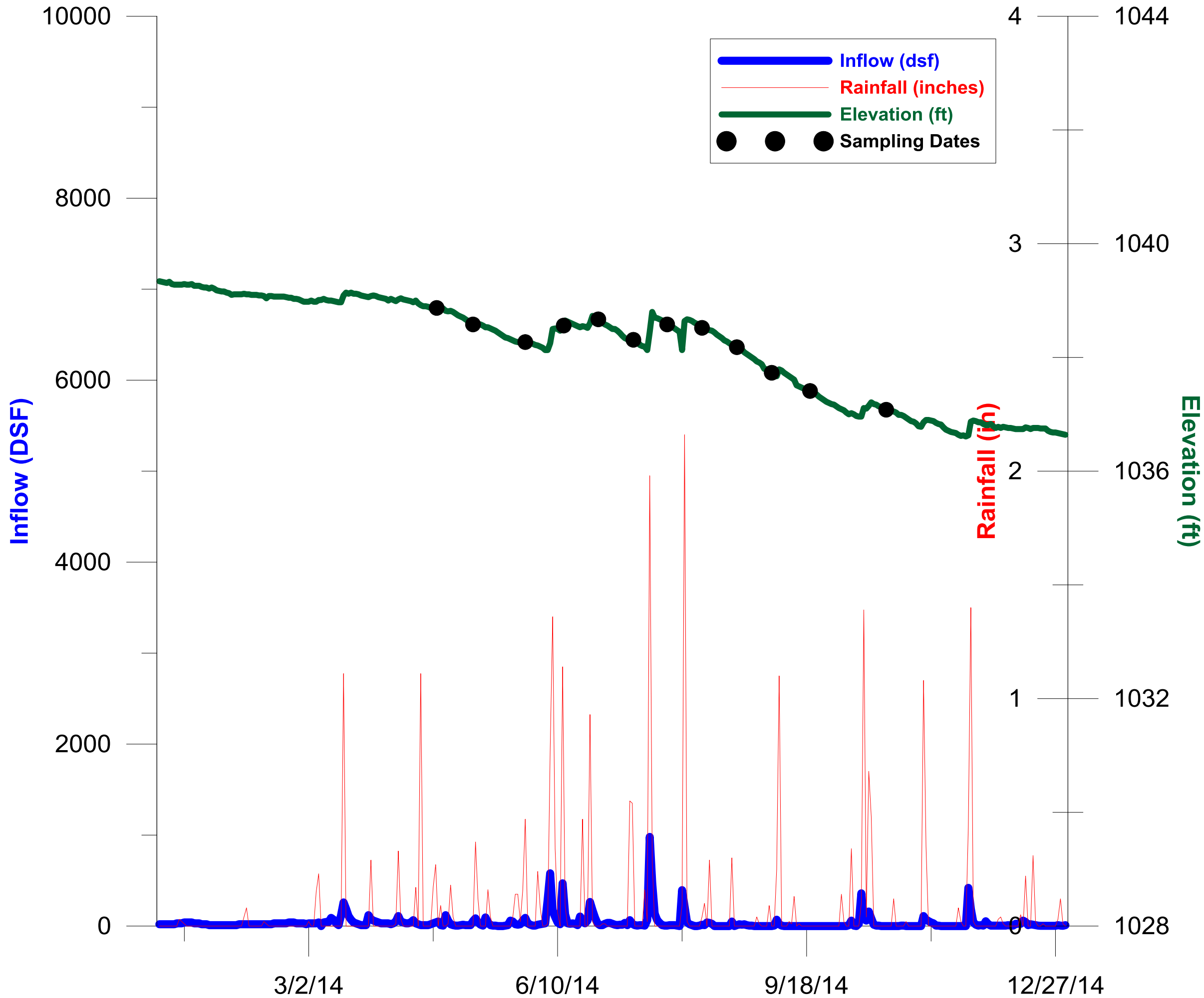


Figure 3. 2014 Inflow, precipitation, and elevation data for Lake Thunderbird, with sample dates indicated.

Figure 4. 2014 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 such as a lake is given by:

Eq 2:

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

Where V = lake volume [L3],

A_s = lake surface area [L2],

Q_{in} and Q_{out} [L3/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, which includes 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 $\boldsymbol{A_s}$ [L^2] is the surface area of the lake.

Daily evaporation rates were calculated and reported by the USACE. Here, empirical equations were used to relate solar radiation, wind speed, relative humidity, and average daily air temperature to the rate of evaporation from the lake. These rates are 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 $\boldsymbol{A_s}$ [L^2] is the surface area of the lake.

Water outputs from Lake Thunderbird generally include gated dam releases and water supply withdraws. Dam releases are reported by the USACE, while COMCD reports water supply withdraws. Change in pool elevation is reported by the USACE at the end of every day. The lake volumes, corresponding to the elevations, were computed and the difference between them is the change in volume for that month. The volumes used were estimated from elevation-capacity curves generated from the OWRB’s 2001 bathymetric survey of the lake.

Results

Water budget calculations were summarized on a monthly basis for Lake Thunderbird as described previously **(Table 2)**. In the table below, 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 budget for Lake Thunderbird showed that estimated inputs and outputs were close to the actual volume changes (as measured by change in pool elevation) with relatively little error. Errors in the hydraulic budget will be discussed in the next section.

Table 2. Lake Thunderbird 2014 water budget calculations expressed in acre-feet.

	INPUTS			OUTPUTS				ERROR TERM		
Month	Inflow	Rainfall	**Total Inputs**	Evaporation	Water Supply	Releases	**Total Outputs**	I-O	ΔV	Error
Jan	1320	9	1329	2193	1121	0	3314	-1985	-1183	802
Feb	555	0	555	382	1008	0	1390	-835	-51	784
Mar	2849	732	3580	2856	1116	0	3972	-392	360	752
Apr	1283	502	1785	3406	1114	0	4520	-2734	-1544	1191
May	1114	463	1577	3723	1533	0	5257	-3680	-2624	1056
Jun	3418	2354	5772	3552	1579	0	5131	641	1646	1005
Jul	2719	2657	5375	4124	1976	0	6100	-725	720	1445
Aug	439	66	506	3875	2003	0	5879	-5373	-4322	1051
Sep	-667	865	198	2236	1851	0	4087	-3888	-3499	390
Oct	-34	1551	1517	1996	1537	0	3533	-2015	-1338	678
Nov	851	1271	2122	1592	1186	0	2778	-656	-206	450
Dec	418	264	682	759	1071	0	1830	-1148	-978	170
Total	14265	10735	25000	30694	17096	0	47790	-22790	-13017	9773

Once a hydrologic budget has been 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 6.18 years for 2014 and an average hydrologic residence time of 4.56 years since 2001 (including 2014 data). This residence time is on par with the drought years of 2010 – 2013 when no gated releases were recorded. For the period of 2014, 57% of the inputs into Lake Thunderbird were from inflows, while the outputs were; 0% releases, 64% lake body evaporation, and 36% water supply (**Figure 5**).

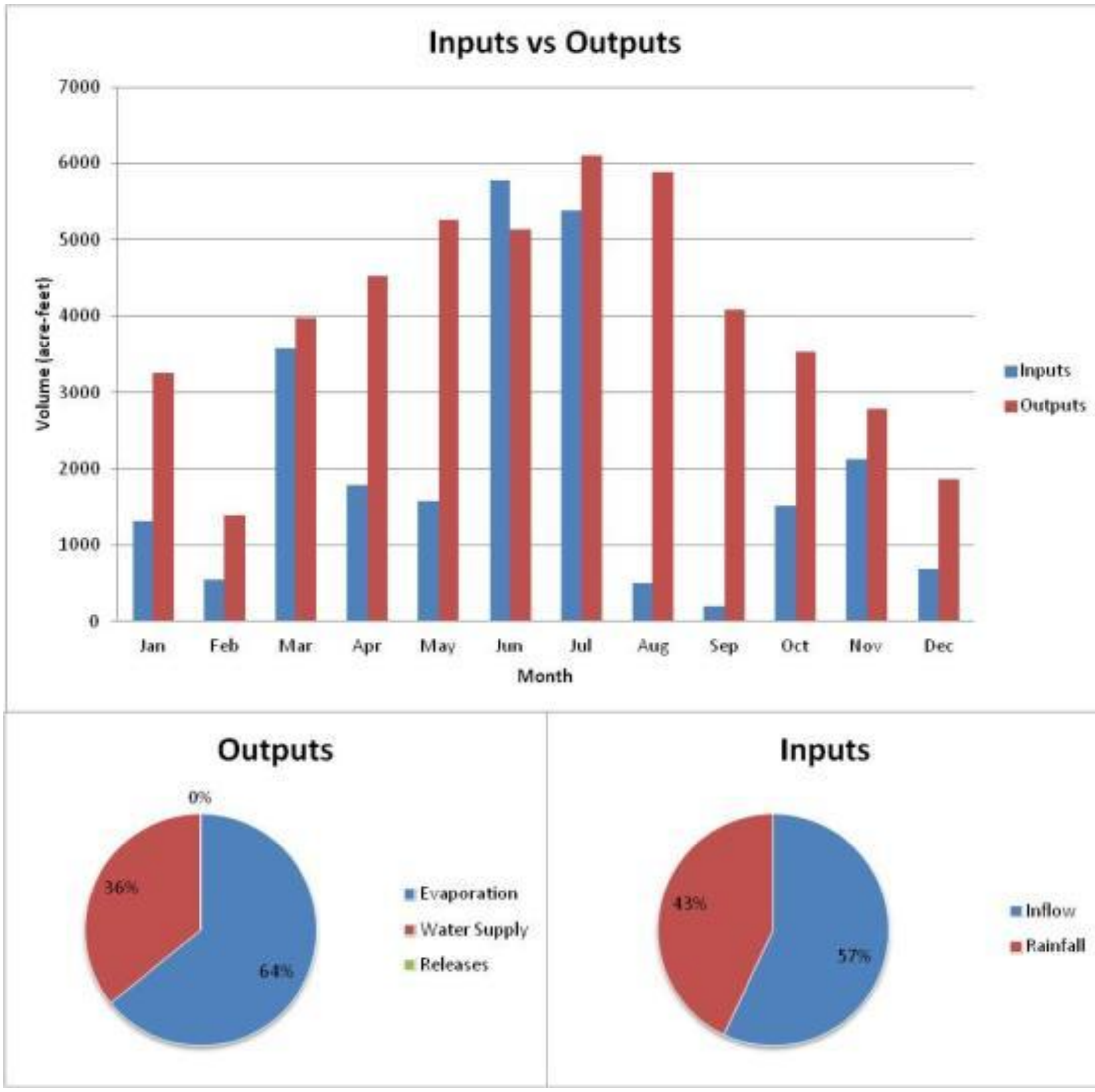


Figure 5. 2014 Lake Thunderbird input and output sources by month, expressed as the percent of totals.

Sources of Error

Although robust, the hydrologic budget does contain error. In the 2014 calendar year, the hydrologic budget contains a cumulative annual error of 9,773 acre-feet, with an average monthly error of 812 acre-feet in 2014. Notable is the consistent under-prediction for every month in 2014.

Inflow from the tributaries was estimated by the USACE based on changes in lake volume using the original lake bathymetry. The 2001 survey estimates a conservation pool sedimentation rate around 400 acre-feet per year. In 2009, bathymetric surveying was performed in the areas around the dam area for design purposes of the hypolimnetic oxygenation system. This survey indicated little sediment accumulation in the dead pool of the lake compared to 2001. Newly deposited sediment is predicted to be mostly in the upper portion of the conservation pool with a loss of approximately 5,500 acre-feet. It should be noted that the method used to calculate capacity in the original design used based in integration of transects, a method using significantly lower information content than the 2001 bathymetric survey, and thereby, resulted in less accurate sedimentation estimates. A new survey using the same method as the 2001 survey would allow for a more accurate estimate of sedimentation based on comparable survey methods.

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 changes and occurs between the epilimnion and hypolimnion (**Error! Reference source not found.**). 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 to date (since 2000), and is inevitable without the influence of outside forces.

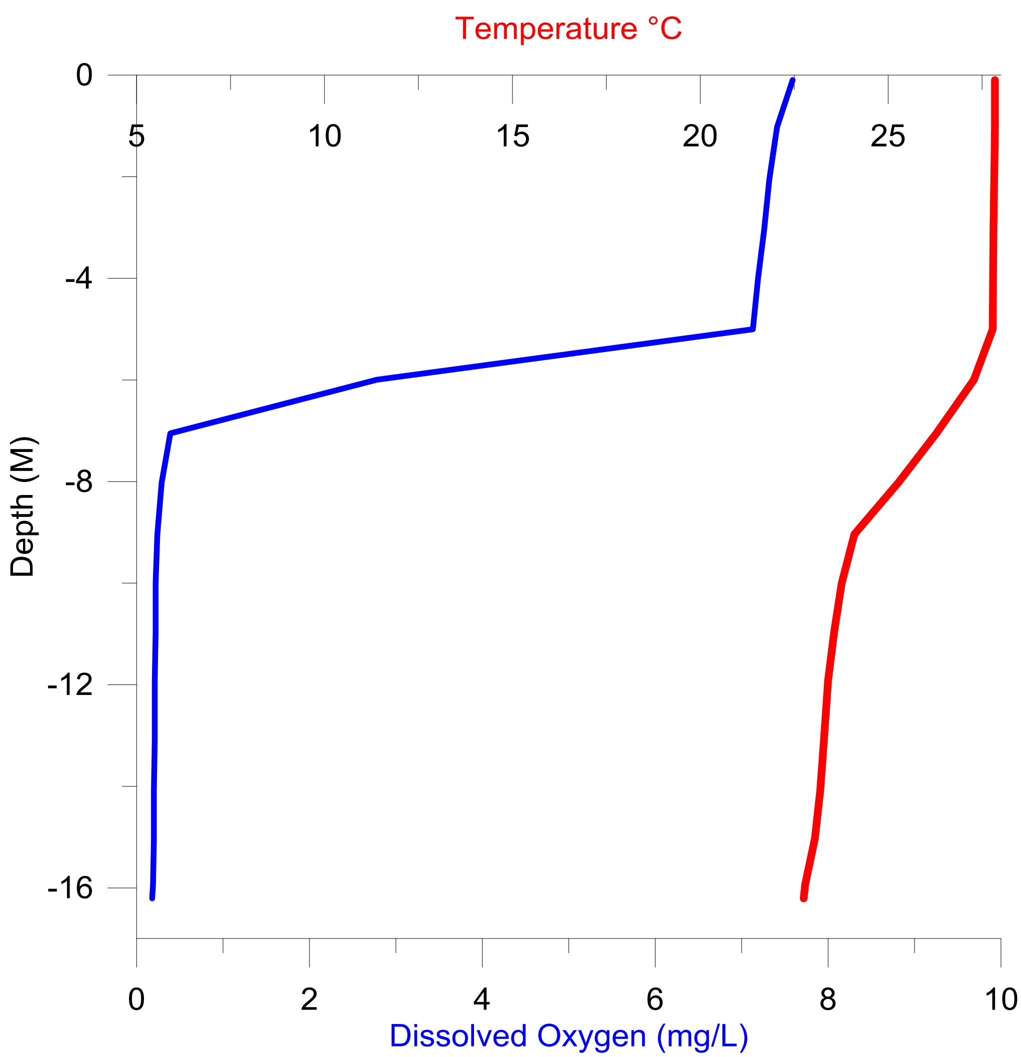


Figure 6. A typical temperature and dissolved oxygen vertical profile for Lake Thunderbird (August 21st, 2014). Oxygenation system had been off for approximately 2 weeks

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 (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 phosphorous 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, as hypolimnetic nutrients are mixed 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. 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, 2014, with weak stratification noted at each May sample trip. 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. Steady elevation of bottom temperature from April through May indicates intermittent mixing throughout the spring season. As stratification, progressed, hypolimnetic dissolved oxygen decreased in May and June (**Figure 7**).

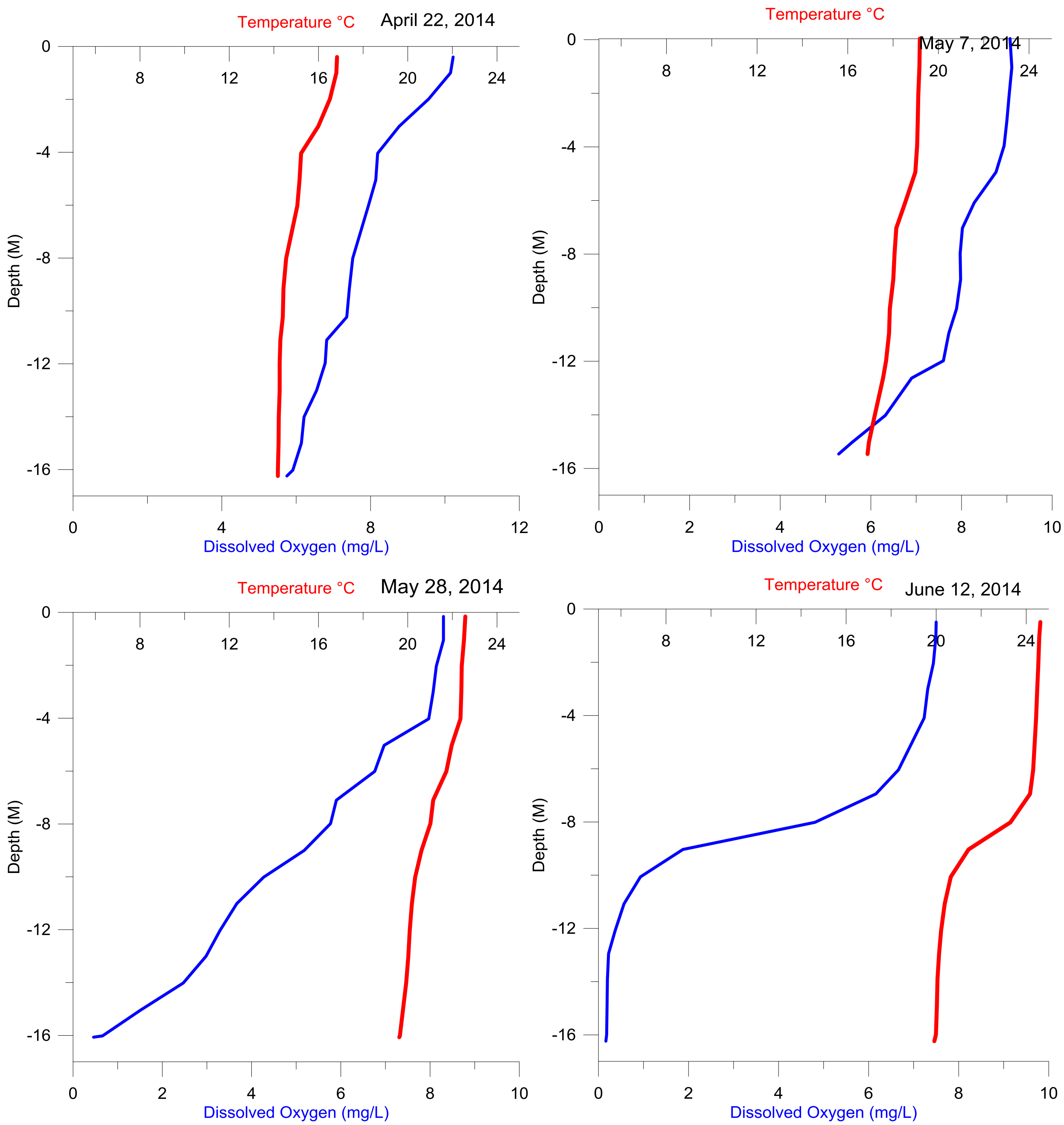


Figure 7. Temperature and Dissolved Oxygen Vertical Profile. Site 1: April 22, 2014 – June 12, 2014.

As the season progressed from late spring through summer, heating at the surface began to occur much more rapidly than at the lake bottom. This caused thermal stratification to strengthen and anoxia was noted at the lake bottom by late May. Anoxia had encompassed the entire hypolimnion by late June. There was a small recovery of dissolved oxygen in late June due to COMCD operation of the hypolimnetic oxygenation unit (Error! Reference source not found.). Through June, July and August only the June 26, 2014 monitoring event reflected an increase in hypolimnetic dissolved oxygen.

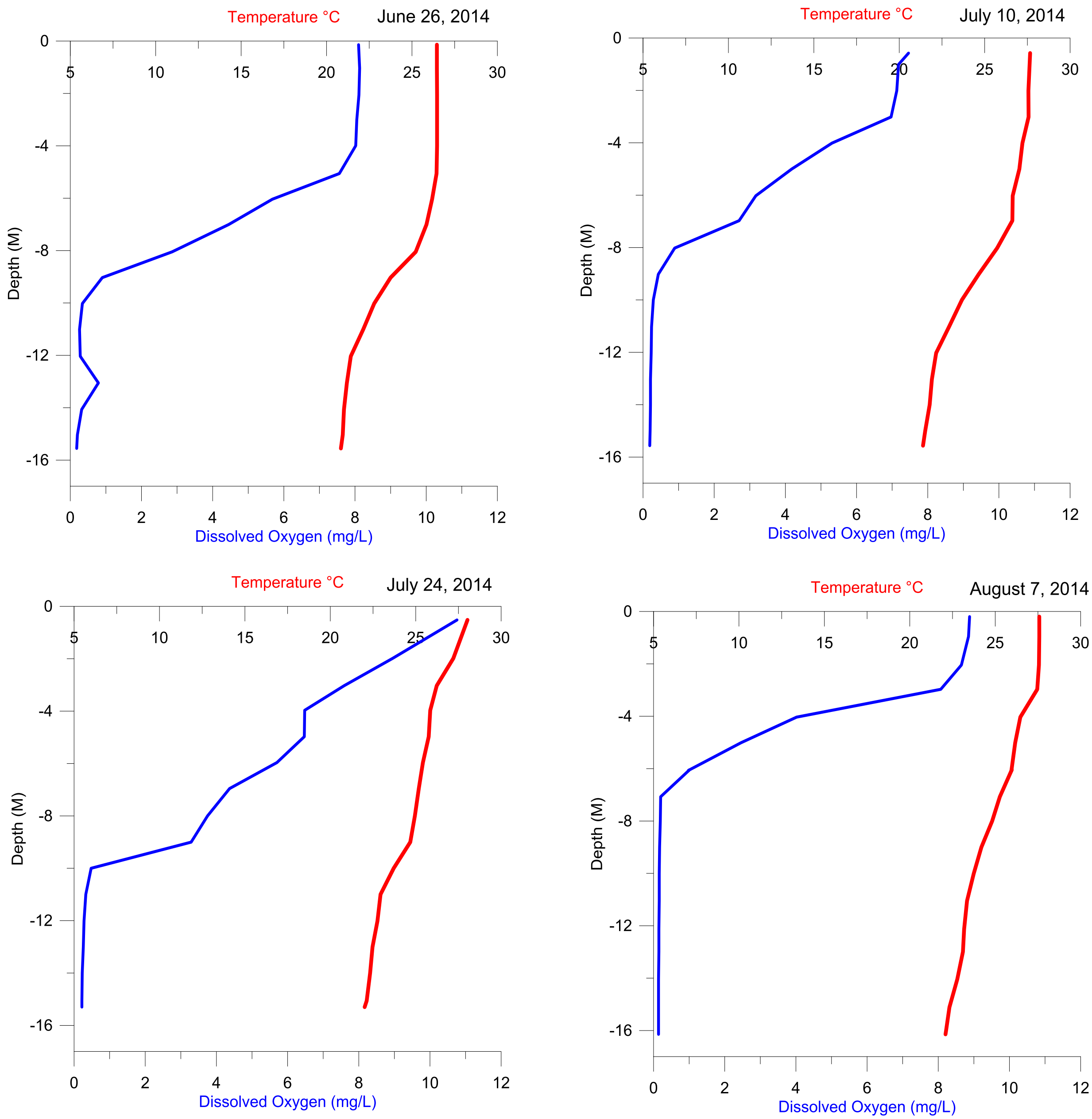


Figure 8. Temperature and Dissolved Oxygen Vertical Profile Site 1: June 26, 2014 – August 7, 2014.

As the ambient temperatures cooled from peak epilimnetic temperatures at the end of July and late August, thermal stratification weakened, increasing the epilimnion from 3 meters on August 7, 2014 to 10 meters on September 4, 2014 (**Error! Reference source not found.**). The effect of SDOX operation with a mild oxygen peak at 13 meters depth on September 4th and on September 19th at 10 meters depth dissolved oxygen rose to 3 parts per million (ppm). By October 20 an isothermal water column was observed, however water column and sediment oxygen demand had not yet been met.

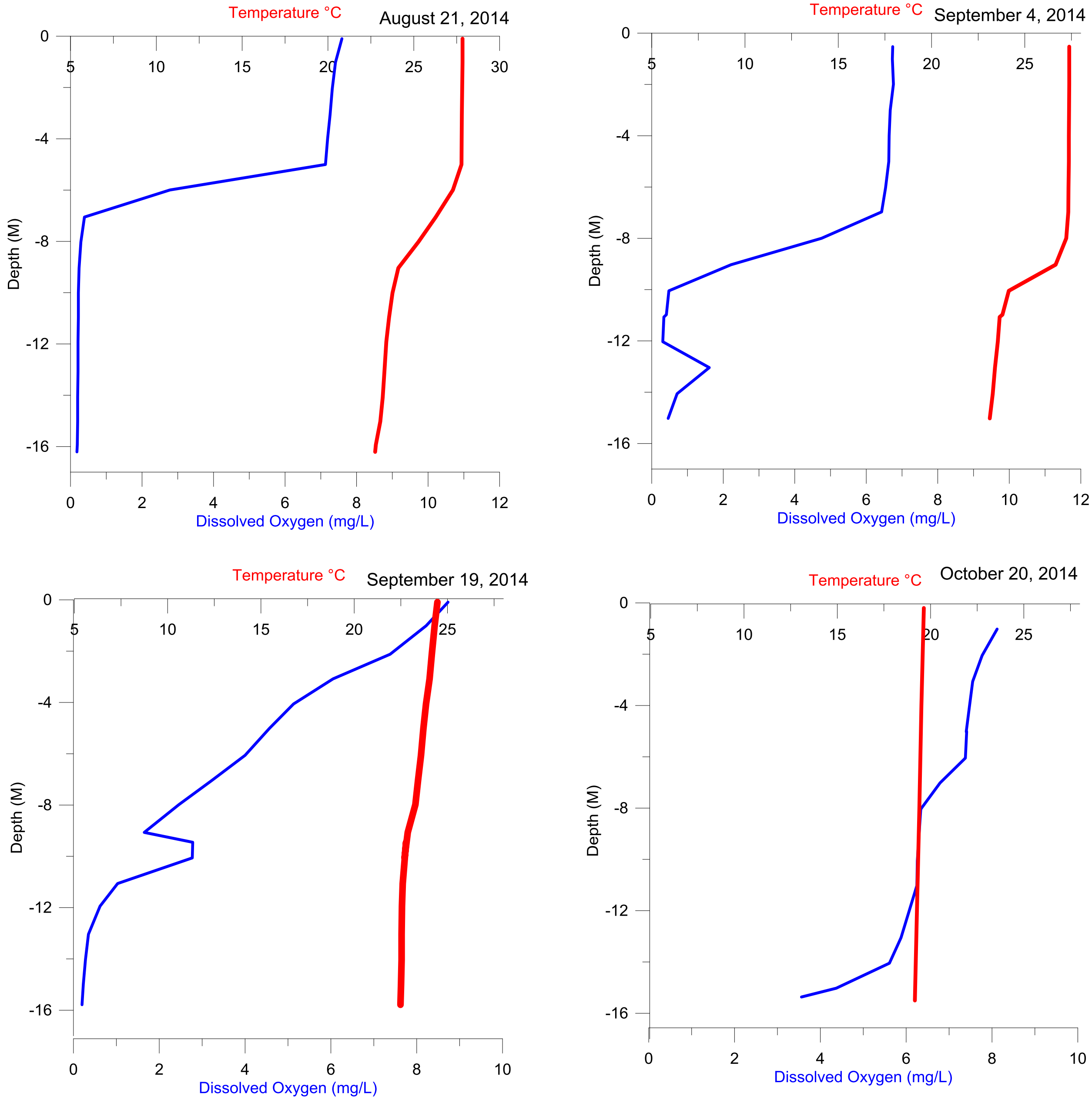


Figure 9. Temperature and Dissolved Oxygen Vertical Profile Site 1: August 21, 2014 – October 20, 2014.

An alternate method for illustrating physical lake data is by using isopleths. These three-dimensional plots show variation in physical parameters over depth and time. The following isopleths show the same temperature and DO data for Site1 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 yellow, graduating to black as temperature gets cooler, while on the DO plot, lowest DO values are colored black, graduating to yellow at the highest DO.

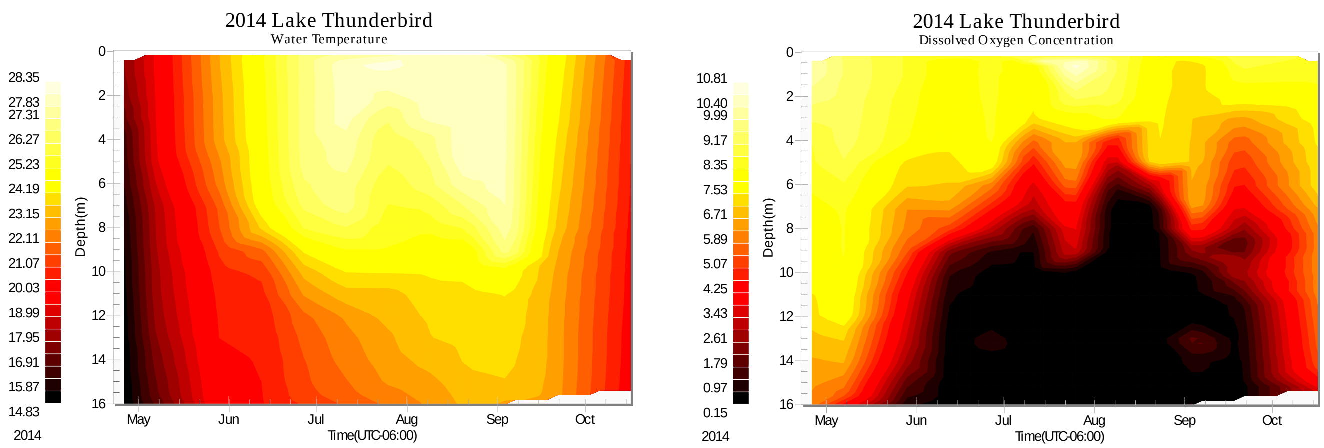


Figure 10. Isopleths of temperature (C) and dissolved oxygen (mg/L) by depth (m) Lake Thunderbird 2014.

During 2014, thermal stratification followed a pattern typical in respect to set up and break up. 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 can be observed on the isopleths as the tightening of contour lines that run parallel with the x-axis (**Figure 10**). While thermal stratification strengthened in June, measurable dissolved oxygen rapidly dropped through early July. A slight, apparent recovery of DO was noted at the end of July. This is termed apparent as the DO elevation may be more related to epilimnetic shallowing and partial epilimnetic incorporation into the metalimnion than any other action. Dissolved oxygen levels had plunged following July when dissolved oxygen concentrations approached zero in waters eight meters and below. The entire hypolimnion was anoxic but for the monitoring event in late September. Complete mixis had occurred by late October, bringing isothermal, but not fully oxygenated conditions throughout the entire water column.

Dissolved oxygen profiles and isopleths reveal unusual patterns of dissolved oxygen distribution in the hypolimnion. Normally, bacterial respiration and consumption of dead algae depletes oxygen trapped in the hypolimnion due to the lack of mixing with the upper water layer. On two occasions in 2014 the top (8-11 meters) had a lower concentration of dissolved oxygen than the middle of the hypolimnion (11-13 meters). This is most evident on the June 26 sampling event where dissolved oxygen concentrations approach zero from nine to ten meters before rebounding above one mg/L from twelve to fifteen meters throughout September (**Figure 10**).

When strong anaerobic conditions occur, elements other than oxygen are utilized as terminal electron acceptors in the decomposition process. This results in nutrients and other constituents being released from the sediment interface into the isolated waters of the hypolimnion. When mixing events occur, these released nutrients trapped in the hypolimnion are fluxed to the surface waters where they can further stimulate algal growth. The partial mixing events are evident when examining the oxygen isopleths as the yellow area (higher oxygen content) pushes down toward the black area (lower oxygen content). While this principle holds true for the 2014 season, the increased presence of oxygen in the hypolimnion equated to a reduction in the release of the nutrients and other constituents from the sediment and should reduce turnover associated rise in algal biomass.

Dissolved oxygen is also 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 yellow 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 that oxygen diffuses 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 for more than a decade. 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.

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 Chl-*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, which can also 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 recently increased in Oklahoma, resulting in measurable amounts of cyanotoxins to be found in afflicted waterbodies. The taste and odor compounds, geosmin and MIB, which have been detected in recent years, confirms that nuisance blue-green populations exist 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. 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–limited and co-limited. 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 2014 (**Figure 11**). In 2014, sampling data indicated a trend toward nitrogen limiting conditions, with a seasonal average TN:TP ratio of 48 (**Figure 12**). Examination of TN:TP constituents showed a low ratio in 2014 due to decreasing nitrogen and increasing phosphorus concentrations harkening to what was noted in 2011 and 2006.

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 2014 dataset exhibited detectable ortho-P toward the end of the growing season (**Figure 13**) and detectable inorganic N only in the beginning of the sample season (**Figure 14**). Laboratory detection limits are not equal though with ammonia detection limit (0.1 mg/L) being 20 times that of ortho-P (0.005 mg/L). While TN:TP ratios indicate co-limitation there is a strong tendency toward nitrogen limitation.

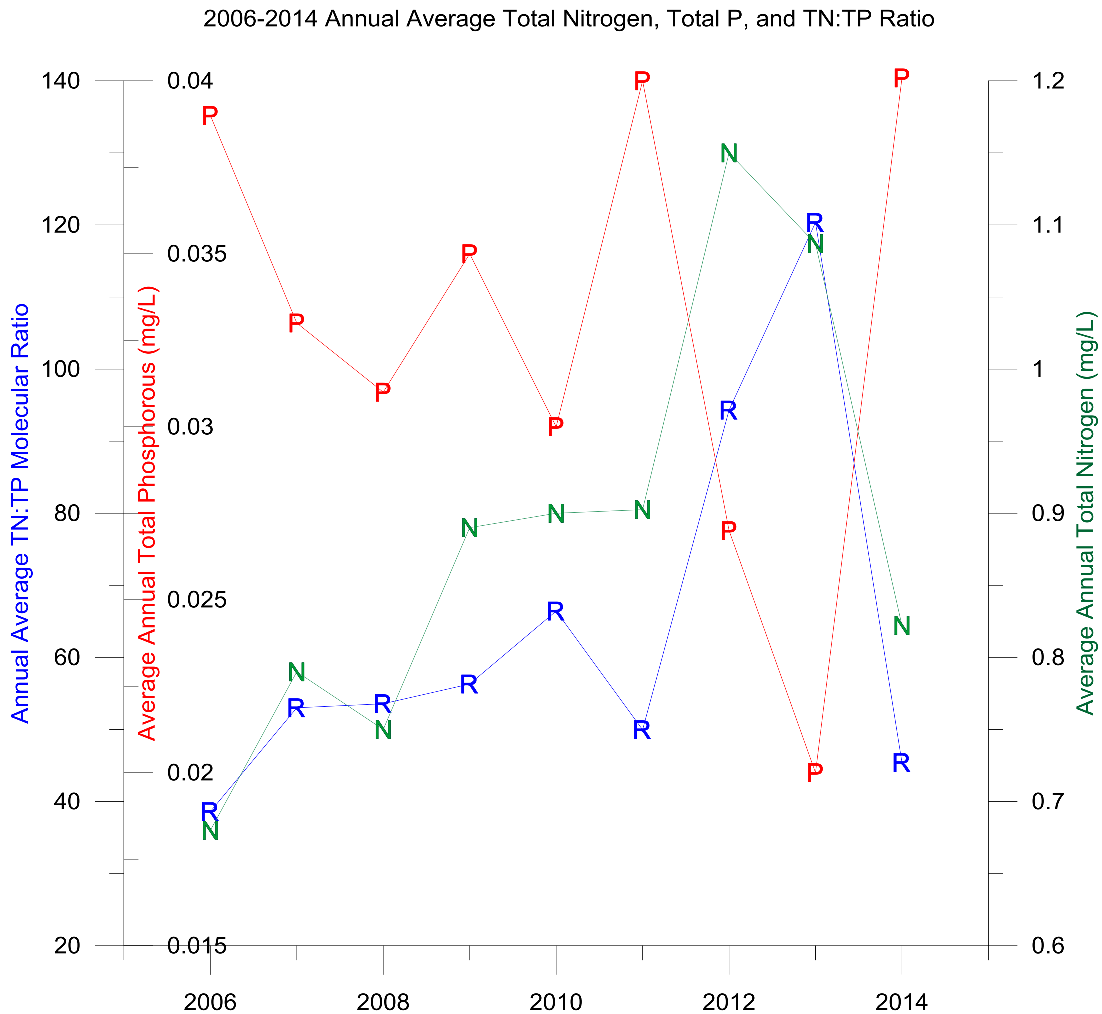


Figure 11. Annual average Total N, Total P, and TN:TP ratio for 2006 through 2013

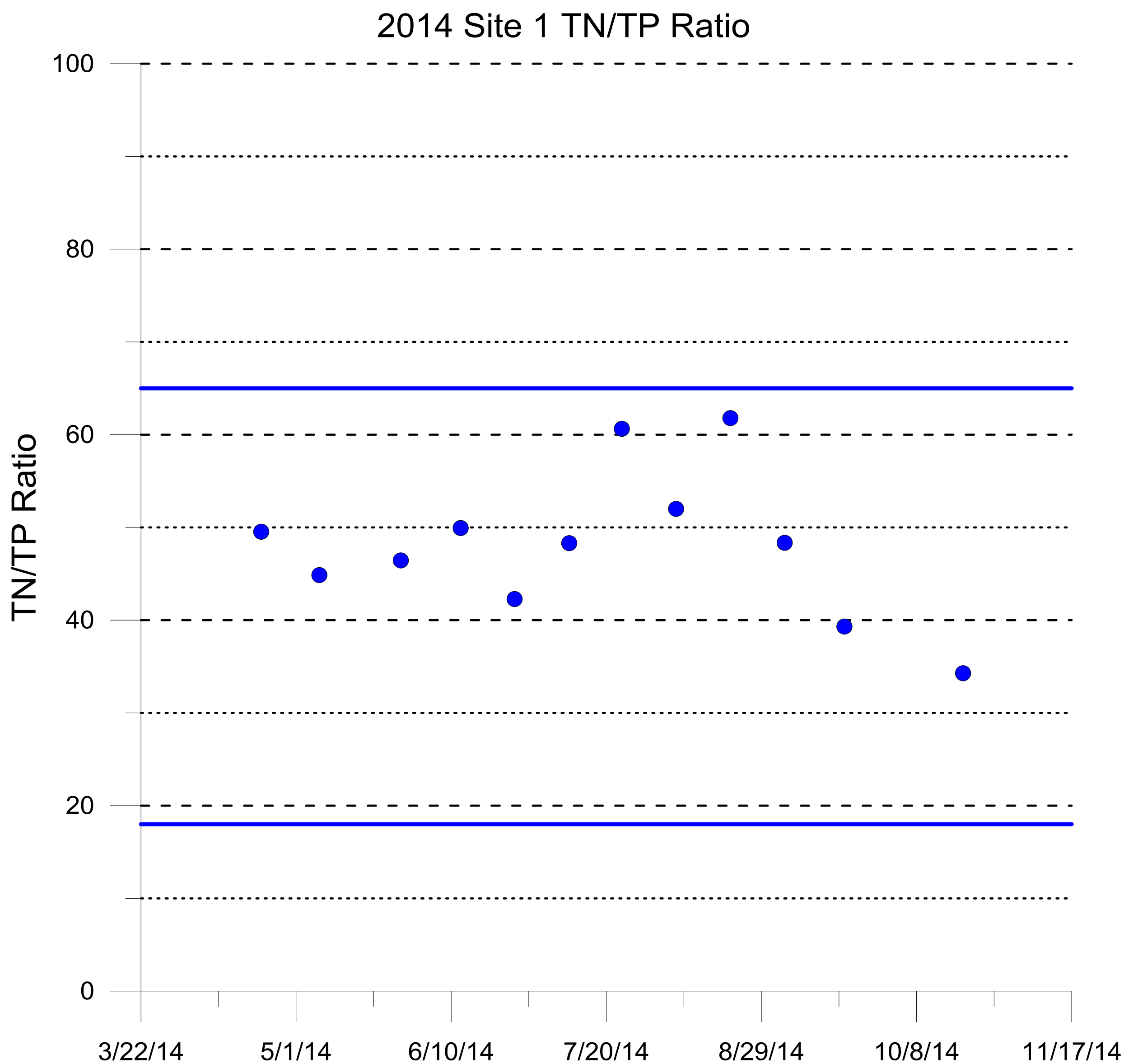


Figure 12. 2014 Site 1 surface TN:TP molecular ratio

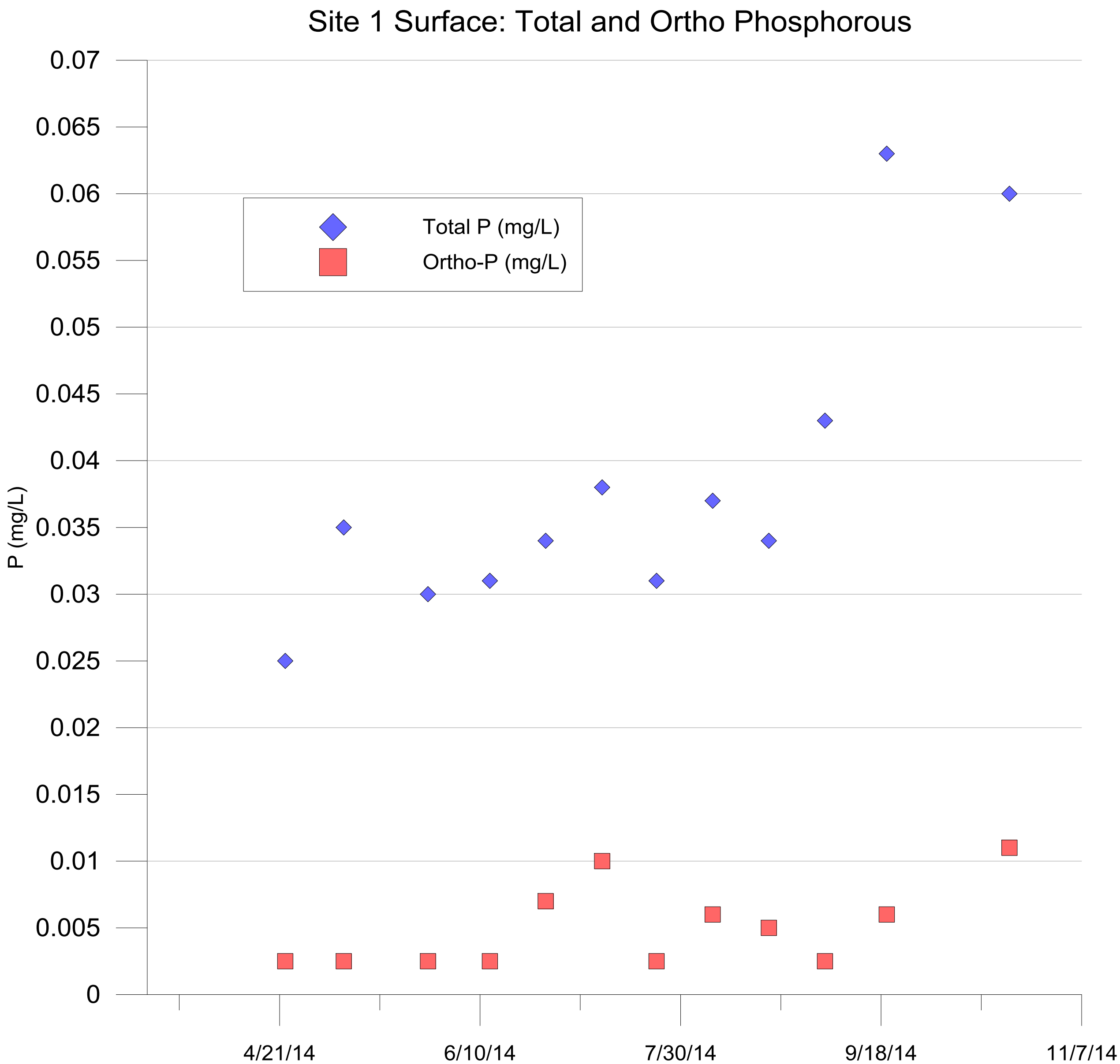
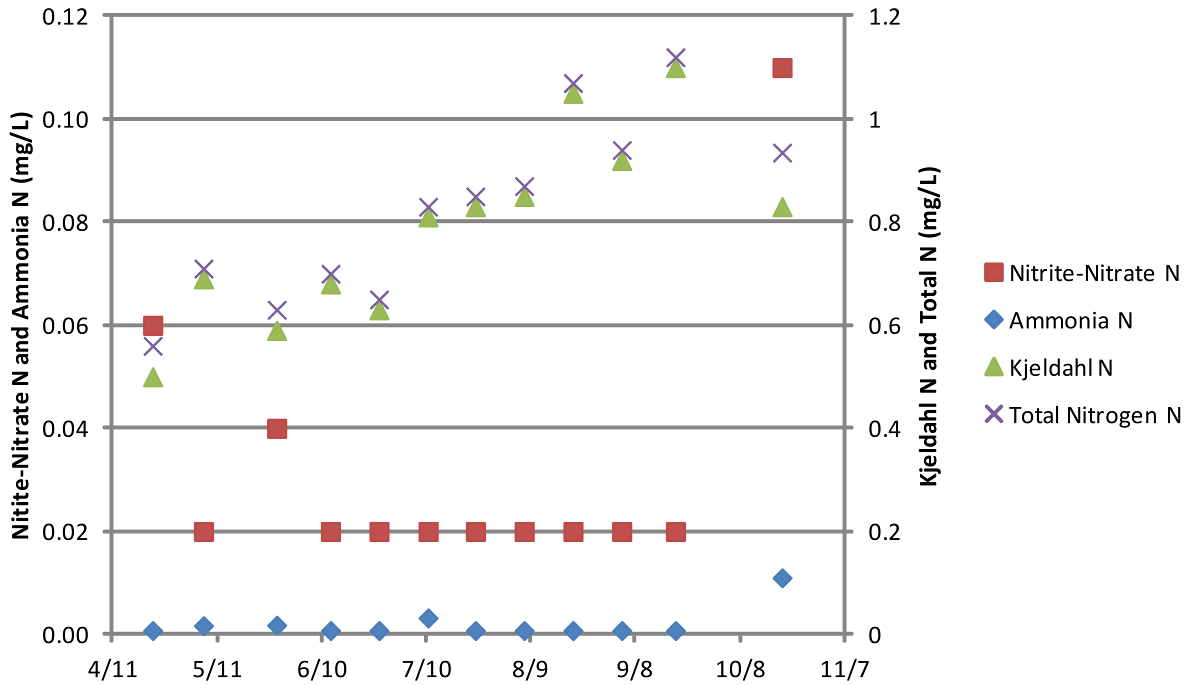


Figure 13. 2014 Lake Thunderbird surface Ortho-P and TP, by date, at Site 1.



	4/22	5/7	5/28	6/12	6/26	7/10	7/24	8/7	8/21	9/4	9/19	10/20
Ammonia as N	BDL	0.02	0.02	BDL	BDL	0.03	BDL	BDL	BDL	BDL	BDL	>0.11
Nitrite -Nitrate as N	0.05	BDL	0.03	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.11
Kjeldahl Nas N	0.50	0.69	0.59	0.68	0.63	0.81	0.83	0.85	1.05	0.92	1.10	0.83
Total Nitrogen as N	0.55	0.71	0.64	0.68	0.63	0.84	0.83	0.85	1.05	0.92	1.10	1.00

Figure 14. 2014 Site 1 Surface NO2-NO3, N-Ammonia and Total Kjeldahl N, by date, at Site 1. Note unless posted laboratory detection limit for Ammonia is 0.1 and 0.04 for Nitrite-Nitrite as N.

Phosphorus – P

Total phosphorus and ortho-P concentrations produced patterns typical of eutrophic to hypereutrophic lakes (**Figure 15**). The gradual increase of TP from April through September could be explained by the uncharacteristic June and July recharge events and the more predictable diffusion of accumulated orthophosphorus. The end of season surface TP spike corresponds with hypolimnetic mixing (**Figure 13**).

Surface ortho-P started the season high before decreasing throughout the spring and early summer, reaching a stable level around 0.007 mg/L. Bottom and hypolimnetic ortho-P followed an opposite trend, starting the year at low concentrations and increasing throughout the stratification period before lake destratification mixed the water column. The buildup of hypolimnetic ortho-P is evidence of the settling of decomposing algae 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 in surface DO, confirming the source of the nutrients.

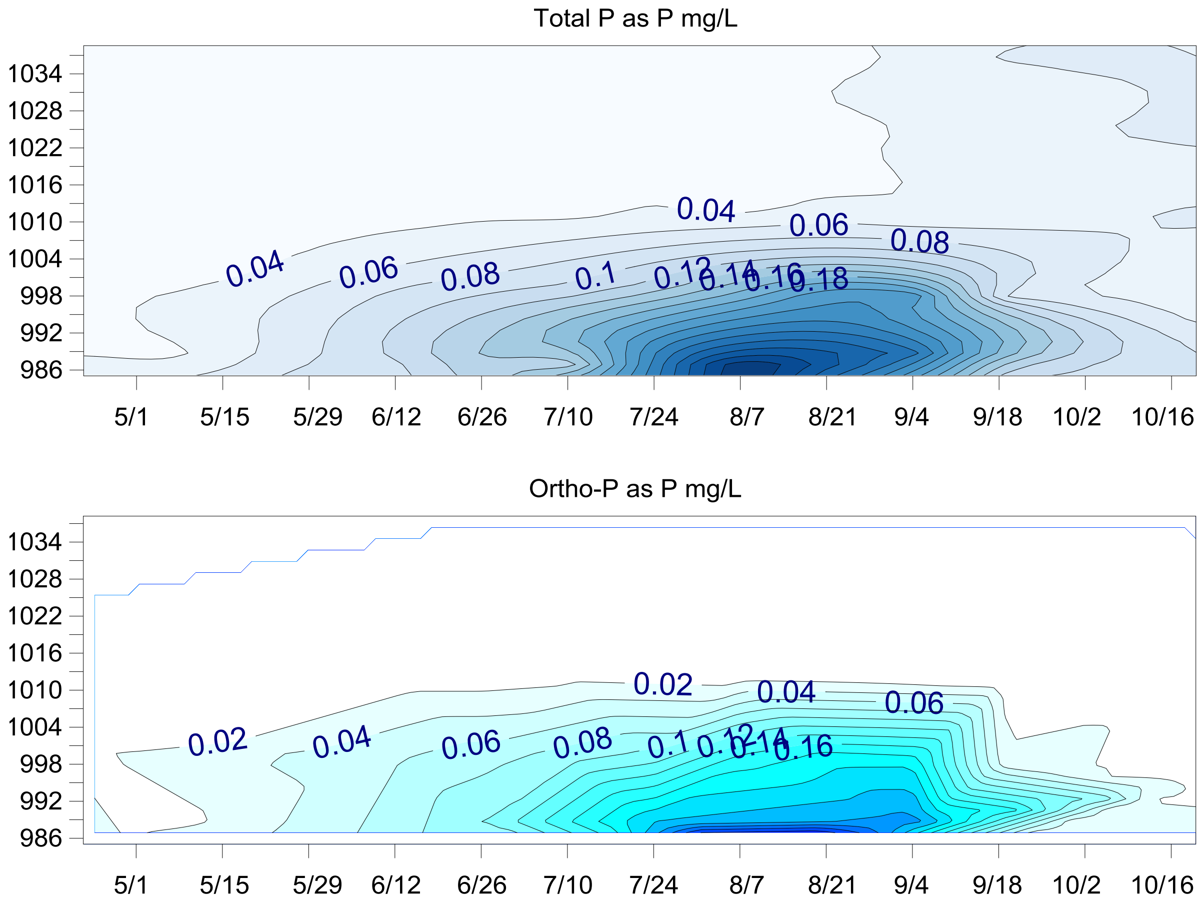


Figure 15. 2014 Lake Thunderbird total phosphorus and orthophosphorus. Contours with depth, by date, at Site 1.

Phosphorus sampled from the upper arms (riverine portion) of the lake was consistently higher than the open water, lacustrine sites (**Figure 16**). In general, site 6, the Little River arm, had the highest phosphorus and the Hog Creek, site 8, the lowest. Non-parametric statistical analysis showed Site 8 to be significantly lower than sites 6 and 11 at the 85% confidence interval. Of all riverine samples, two of the Hog Creek samples (in the spring) had orthophosphorus below detection while all other samples detected inorganic phosphorus. Phosphorus in the upper arms of the lake represents the potential for hypereutrophic algal growth.

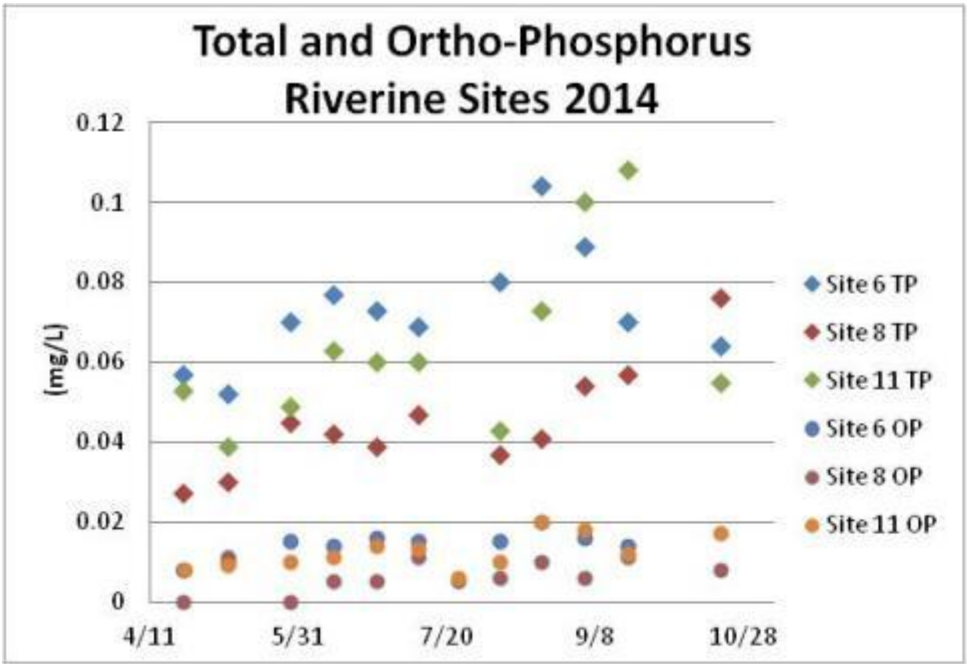


Figure 16. Surface Total and Ortho-P data from the three riverine sites.

Nitrogen – N

Total nitrogen and DO concentrations also produced patterns somewhat typical of seasonal ecological cycles in lakes (**Figure 17**). 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 2014, as dissolved inorganic N plunged with rising Chl-*a* during the start of summer, while a spike of ammonia was detected in October 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 over time as ammonia is released from anoxic sediment and formed as a decomposition product of senescent algae cells and organic material (**Figure 18**). Ammonia concentrations in the hypolimnion gradually rose 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. These data highlights the impact of hypolimnetic oxygenation providing oxidant to transform ammonia to nitrite then nitrate. Unfortunately, not

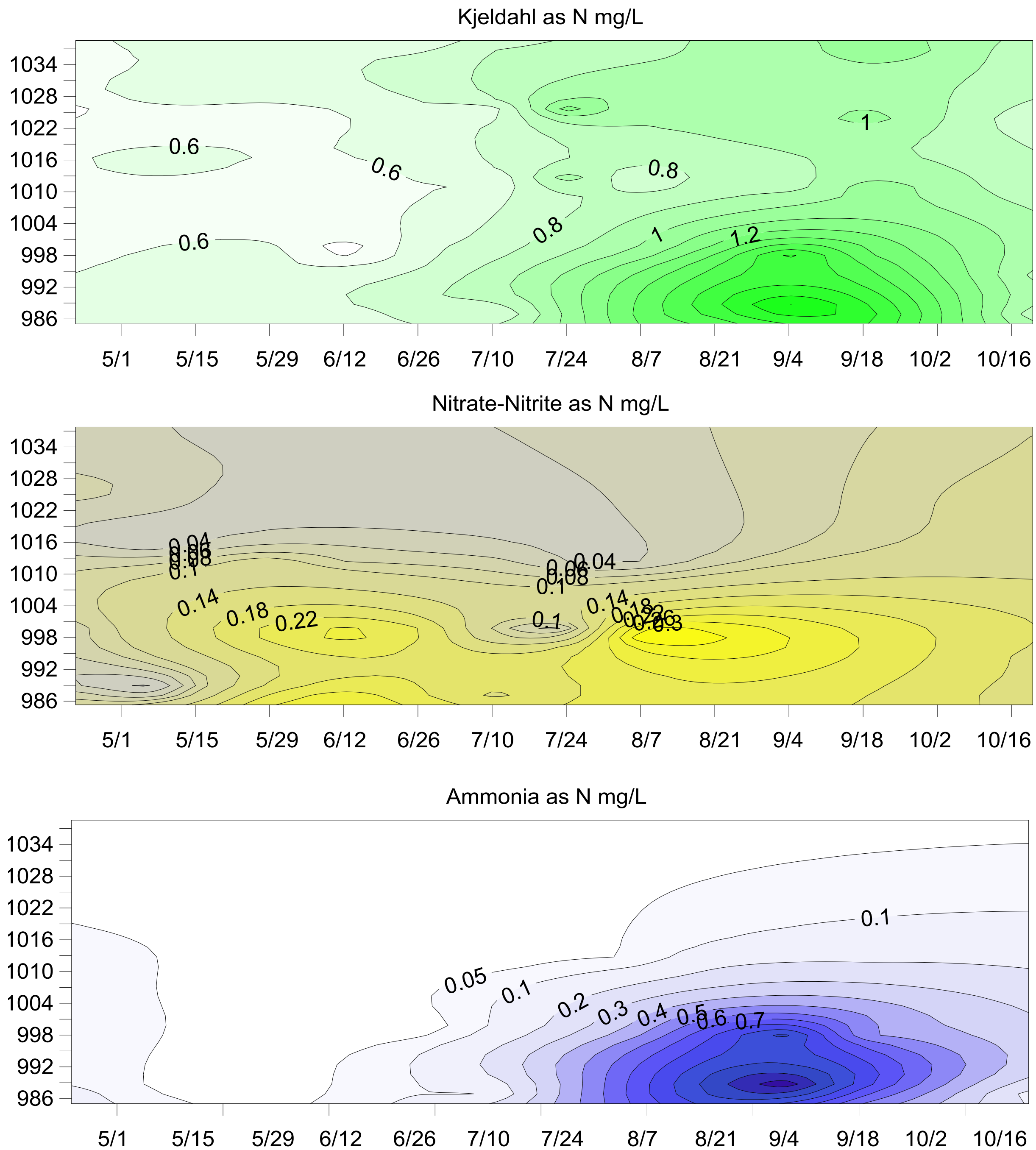


Figure 17. 2014 Lake Thunderbird Total Kjeldahl NO2-NO3 and Ammonia as N with depth over time at Site 1.

enough oxidant was furnished to consistently affect nitrogen oxidation. Should the SDOX be feeding enough oxidant to consistently overcome the hypolimnetic oxygen deficit then a consistent presence of hypolimnetic nitrate-nitrite nitrogen would be expected. Late summer appearance of nitrate indicates the impact of SDOX on hypolimnetic chemistry and biology. The effect on biology is because the transformation of ammonia to nitrite then nitrate is microbially mediated. Unlike, the phosphorus analysis most riverine samples did not detect inorganic nitrogen except for those likely associated with inflow events (July 10, 2015 sample event) (**Figure 19**). In addition, no statistical difference between sites was noted for any nitrogen parameter using non-parametric statistical analysis.

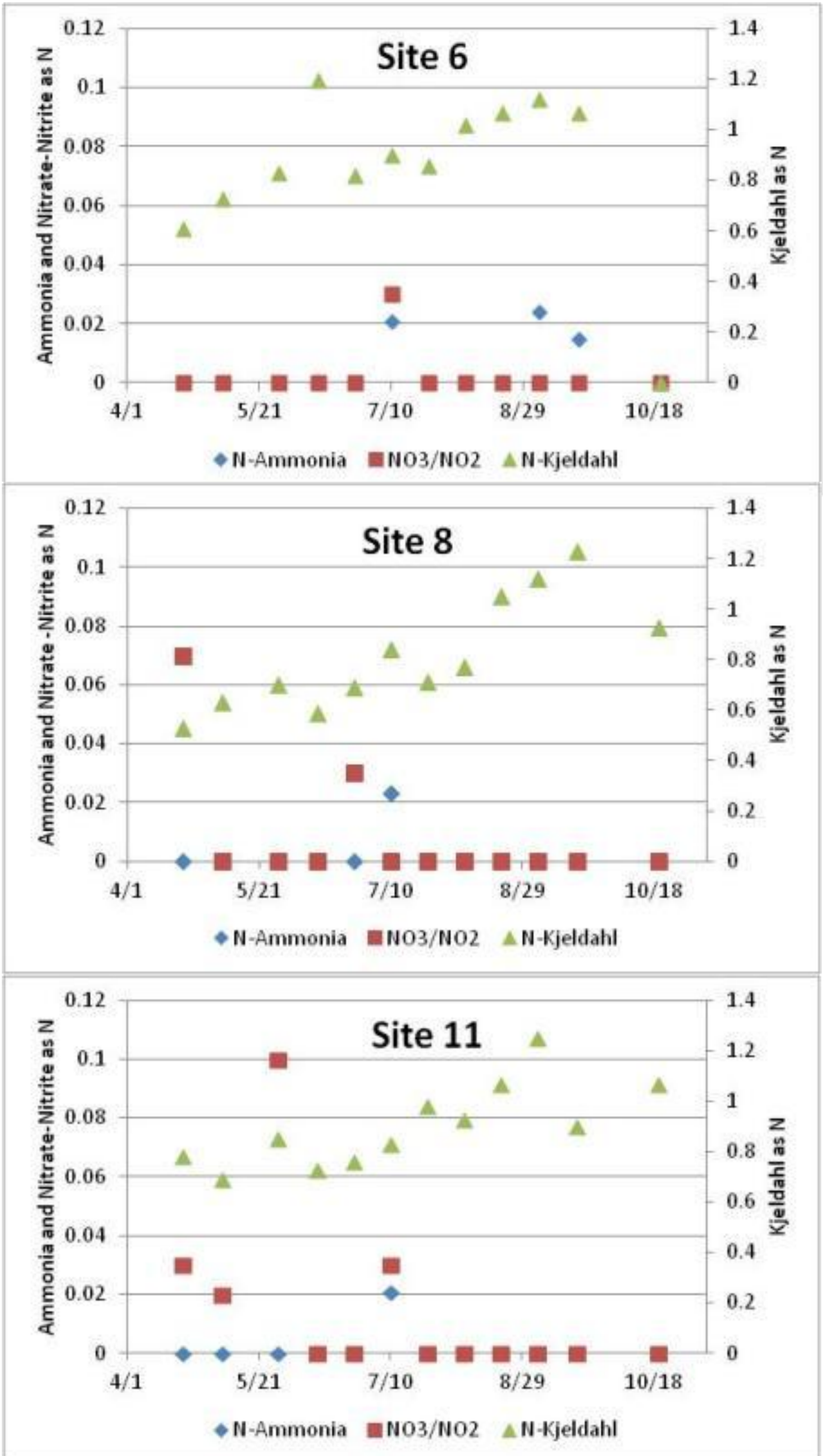


Figure 18. Riverine surface ammonia, nitrite-nitrate and Kjeldalh nitrogen as N in mg/L Lake Thunderbird 2014.

Nutrient Budget - Phosphorus

A phosphorus budget for Lake Thunderbird was prepared integrating the estimated outflows from the water budget with lake water quality data. Vertical profiles of physical parameters were combined with reservoir bathymetry to partition total phosphorus reports in one-meter intervals between epilimnetic 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. 2014 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).

Depth (m)	22-Apr	7-May	28-May	12-Jun	26-Jun	10-Jul	24-Jul	7-Aug	21-Aug	4-Sep	19-Sep	20-Oct
0 - 1	320	788	538	369	678	322	949	598	643	388	1130	923
1 - 2	446	711	521	544	663	668		717	620	760	1122	1058
2 - 3	404	599	430	497	574	583	608	561	533	627	834	904
3 - 4	361	508	412	477	562	526	508	550	433	568	769	846
4 - 5	328	492	389	687	507	406	538	440	447	484	611	879
5 - 6	304	521	340	263	382	389	402	405	500	456	766	585
6 - 7	506	308	298	261	353	250	384	292	410	336	377	460
7 - 8	251	279	262	280	277	270	354	**201**	**375**	339	197	380
8 - 9	159	181	268	353	323	**312**	411	**434**	**578**	545	382	308
9 - 10	98	159	267	**228**	**364**	**379**	492	**619**	**758**	748	**238**	268
10 - 11	72	82	196	**171**	**277**	**292**	**379**	**544**	**591**	**584**	**253**	183
11 - 12	54	71	142	**86**	**210**	**225**	292	**371**	**416**	**462**	**47**	121
12 - 13	28	63	83	**56**	**138**	**129**	225	**270**	**342**	**276**	**89**	20
13 - 14	14	10	46	**28**	**76**	**68**	131	**174**	**152**	**138**	**44**	6
14 - 15	5	2	**20**	**9**	**36**	**29**	71	**94**	**70**	**64**	**20**	2
15 - 16	0		**7**	**0**	**9**	**7**	8	**31**	**25**		**6**	0
16+							5	**1**				
x												
Total	3351	4774	4219	4309	5428	4854	5759	6301	6892	6774	6886	6942
Anoxic Mass			27	578	1109	1441	1112	2739	2354	1523	445	0
Anoxic % of Total Water Column			1%	13%	20%	30%	19%	43%	34%	22%	6%	

The constructed budget demonstrates pre-stratification lake P mass in 2014 of approximately 3350 kg. This falls in line with the pre-stratification average from the past 5 years of 3300 kg (2009:3600 kg, 2010:3700 kg, 2011:4100 kg, 2012:1024 kg, 2013: 3200kg). The total phosphorous mass at the start of stratification, May and June, was in line with the historical dataset, 4000-5000 kg. As summer progressed to fall hypolimnetic anoxia contributed to the increase of lake P-mass between 6,700 to 7,000 kg through October. Again, this followed the historical trend as the hypolimnion accumulates phosphorus.

Lastly, it is worthwhile mentioning that reduction in extent and duration of anoxia (areal anoxia) within the water column, when compared to the 2005-2009 average, has corresponded to a reduction in anaerobic mediated sediment P release since the modification in 2012 of the SDOX nozzle. Using calculations based on Nurnberg (2005) and specifically developed for Lake Thunderbird by OWRB, it was calculated that anaerobic mediated sediment P release had *increased* 16% from the average release from 2005 – 2009. This is in contrast to the decreases estimated from 2011 through 2013 (five years prior to SDOX deployment).

Chlorophyll-*a* – Chl-*a*

Chlorophyll-*a* (Chl-*a)* is a pigment common to all photosynthetic plants and is used as a proxy for algal biomass in aquatic ecosystems. Chlorophyll-*a* samples were collected at the surface of all eight sites for each sampling event during 2014; Chl-*a* peaked in mid-September (**Figure 19**). In 2014, 88% of samples were eutrophic based on a 7.2 µg/L threshold between mesotrophy and eutrophy (Wetzel 2001). This is a small step back from the trend of oligotrophication when in 2013 85% of samples were eutrophic. Tracking averaged chlorophyll-a for site 1 reflects a leveling off of chl-*a* reductions since the start up of the SDOX device (**Figure 20**). For the 2014 sampling season the lake wide average Chl-*a* at Lake Thunderbird was 21.8 µg/L While not a continued series of reductions since 2011, 2014 does represent a reduction from the lake wide average of 24.5 µg/L from 2012, 36 µg/L from 2011, and the 2007-2010 historical average of 25.9 µg/L. The historical plot of site 1 annual average chlorophyll-a shows 2014 chlorophyll-*a* similar to that seen in 2013. Observed peak lacustrine chl-*a* was also reduced from the previous five years with Site 1 maximum values of 41.4 µg/L representing a step up from the 2013 low (since 2007) (**Figure 21**).

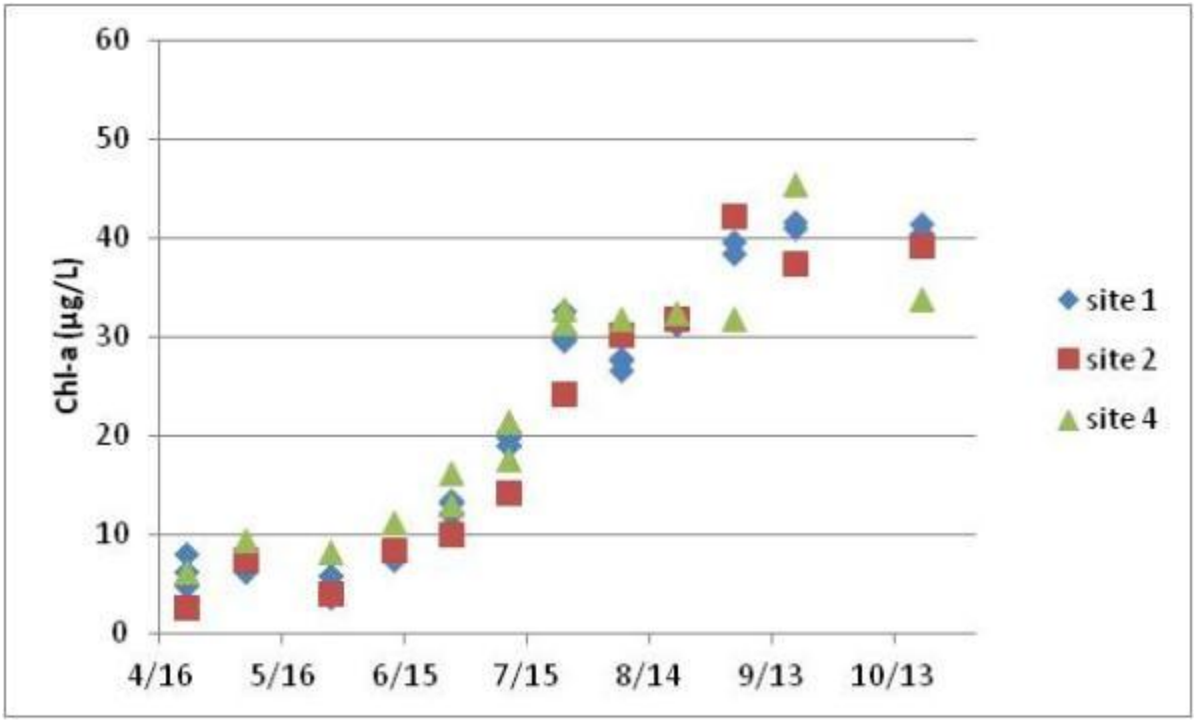


Figure 19. Lake Thunderbird lacustrine surface Chl-*a* (µg/L) by site; April through October 2014.

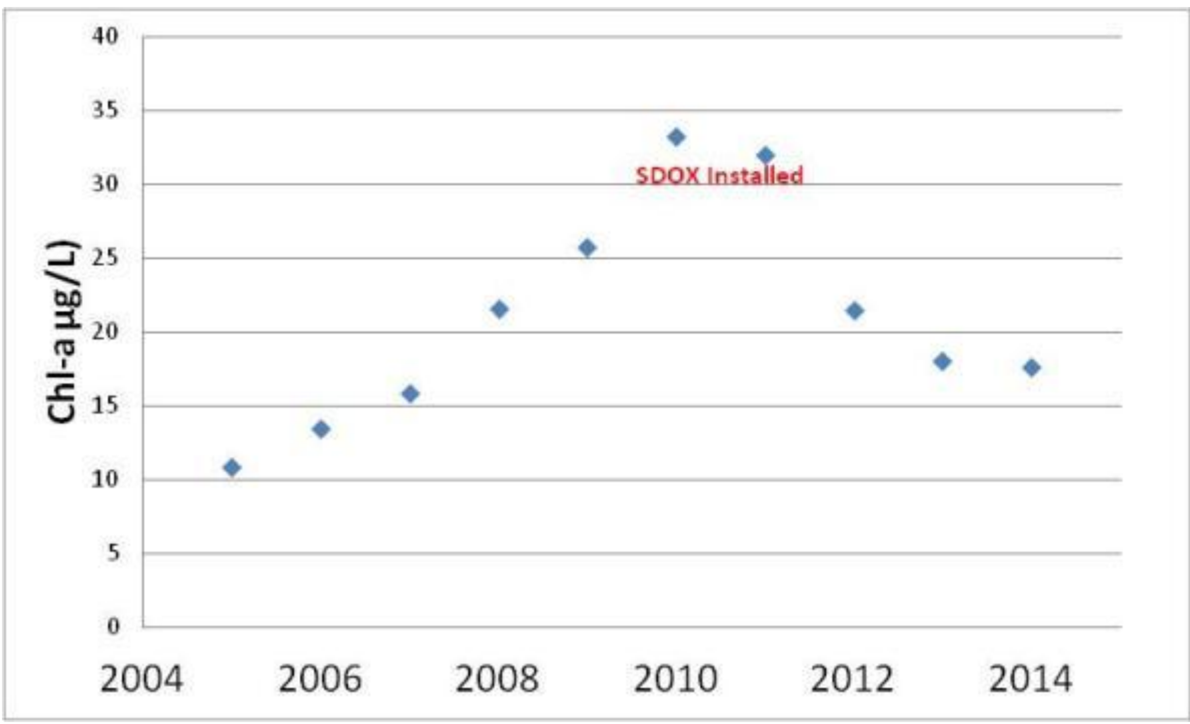


Figure 20. Lake Thunderbird site 1 average seasonal chlorophyll-a from 2005 through 2014.

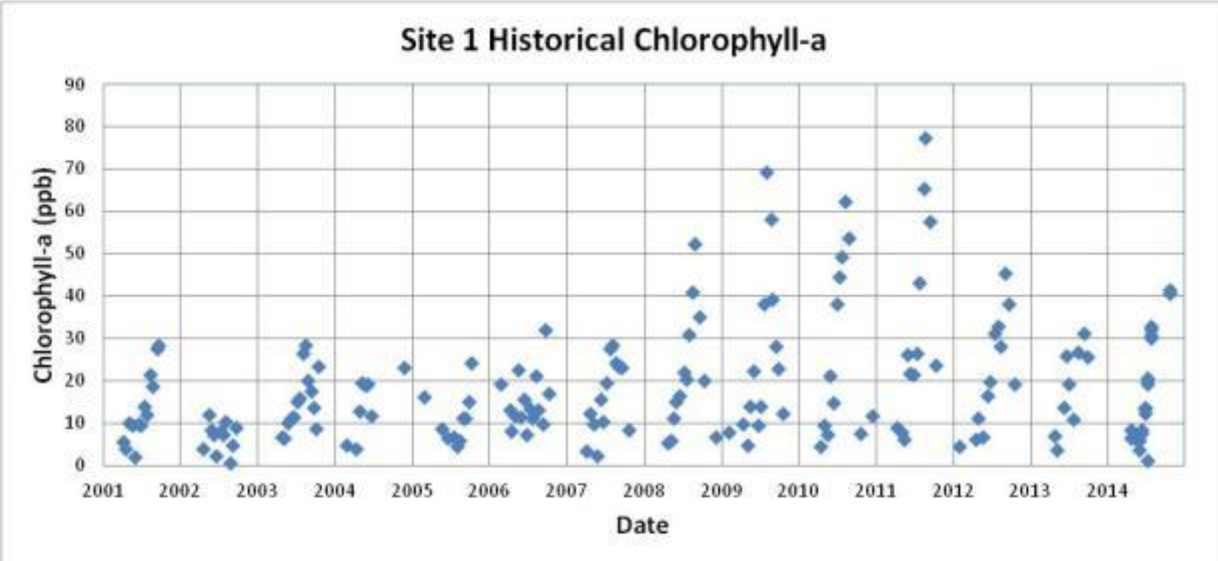


Figure 21. 2001-2014 Lake Thunderbird surface Chl-*a* µg/L (or ppb) at Site 1

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 2014. Unlike previous years, lacustrine TOC did not follow Chl-*a* during 2014 (**Figure 22**). TOC started the year relatively high, peaked in July and then decreased in September and October. As noted earlier in this report chlorophyll-a started relatively low then steadily increased through June, July and August to peak in the low 40 µg/L in September. Previous year's datasets has tracked the statistical relationship between these two parameters. The regression for the 2014 reported a TOC to chlorophyll-a with a R^2 of 0.12% with an accompanying flat scatter plot.

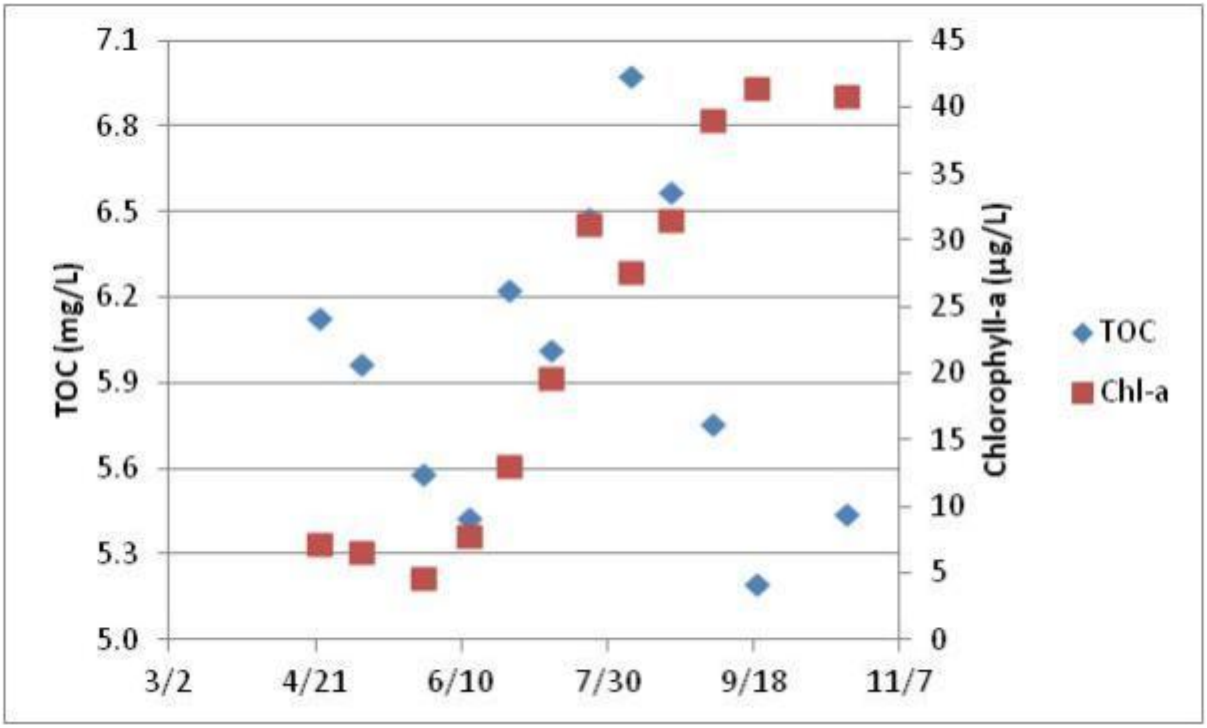


Figure 22. Site 1 surface TOC and Chl-*a* at Lake Thunderbird 2014.

While the relationship between algae and TOC was close to nil in 2014, the data was added to the accumulated dataset for an updated regression (**Figure 23**) with a cumulative R^2 of 24.3% (compared to cumulative R^2 of 36% in 2013). It is evident that TOC and Chl-*a* are intimately related parameters. High algae growth affects other basic water quality parameters and has been previously linked with increased drinking water treatment costs (OWRB 2011). The cumulative (2010 through 2014) regression of TOC vs Chl-*a* yields a baseline TOC of 5.2 without elevated algae growth and predicts a 0.2 ppm change in TOC per 10 µg/L Chl-a.

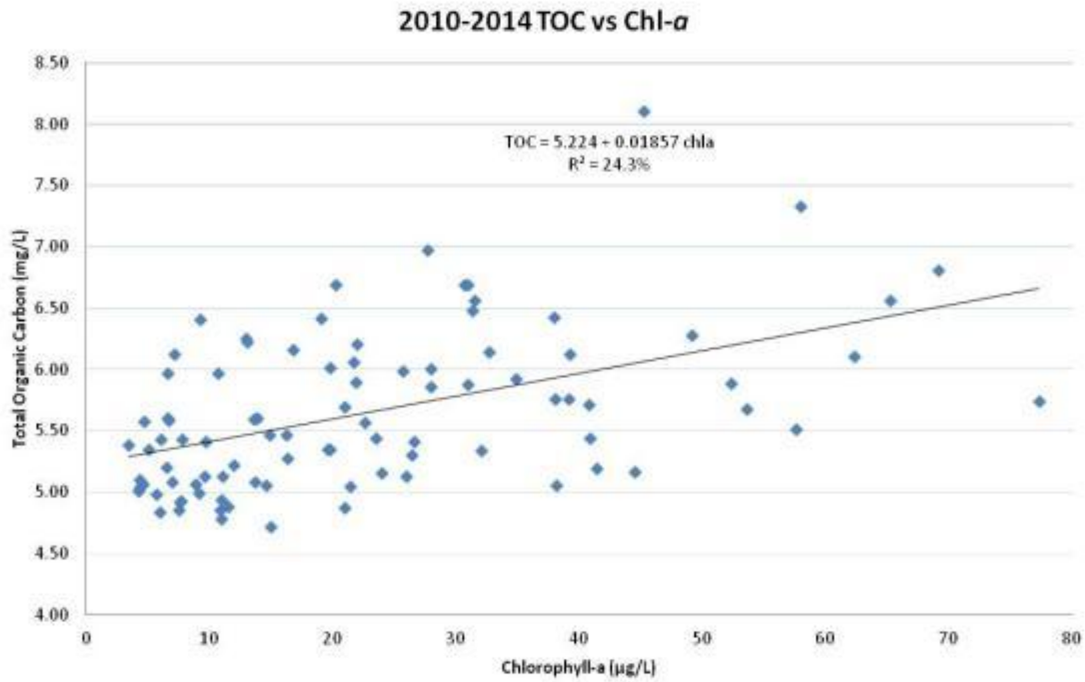


Figure 23. Cumulative (2010 to 2014) surface TOC vs Chl-*a* plot with accompanying regression.

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) is the most common measure of index algal biomass (1977). Here, three surface variables; chlorophyll-a (Chla), Secchi depth (SD) and total phosphorus (TP) were used 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, leads 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. Whatever measure, indexing is on a range from zero to 100. Trophic ranges have been categorized into >40 as oligotrophic or low algal growth, from 40 to >50 as mesotrophic or increasing algal growth, from 50 to >60 as eutrophic or high algal growth to finally ≤ 60 as hypereutrophic or excessive algal growth.

Lake Thunderbird's TSI for the three variables are displayed in **Figure 24** ranging from 45-87 throughout 2014. Chla TSI, a reflection of actual or realized algae growth, showed site 1 to have been eutrophic to mesotrophic through May. From the mesotrophic low in late May, Chla TSI steadily increased to hypereutrophic by the end of July. From there Chla TSI remained in the hypereutrophic range throughout the sample season. Also notable was the shift between the Chl-a TSI and TP TSI. TP TSI consistently over-predicted Chl-a TSI until late-June when all three TSI were approximately equal. From July, when trophic state increased to hypereutrophic, TP TSI consistently under-predicted Chla-TSI until September 19, 2014 when the two TSIs were again about equal. This mid-summer flip in the Chla/TP relationship represents a change in the algae community to one better able to convert phosphorus into chlorophyll-a.

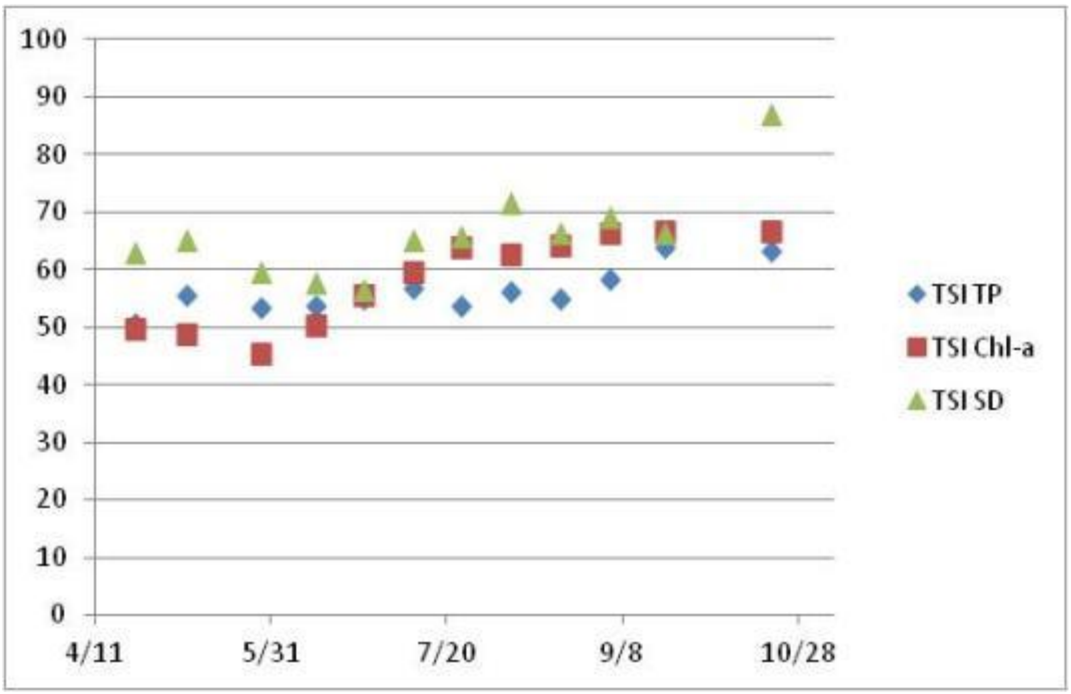


Figure 24. Carlson's Trophic State Index values for Lake Thunderbird 2014 at Site 1.

By examining the interrelationships between TSI variables one can also discern algal limitation. In **Figure 25,** TSI (Chl-*a*) - TSI (TP) is plotted on the vertical axis with TSI (Chl-*a*)-TSI (SD) plotted on the horizontal. In this plot no data is noted in the upper left quadrant indicating no samples in 2014 tended toward phosphorus limitation. One-third of the data fell into the lower left quadrant, indicating that light (not a chemical such as nitrogen or phosphorus) was the nutrient limiting algal growth during this period. The bulk of the data falls into the lower right quadrant indicative of nitrogen as the nutrient limiting algal growth. By combining the visual progression of the data presented in **Figure 24** to the diagnostic plot of **Figure 25**, it can be seen that as the growing season progresses, the over prediction of TSI (Chl-*a*) by TSI (TP), indicating light limitation, decreased and as summer progressed to TP TSI under-predicting Chla-TSI when nitrogen was the most likely limiting nutrient to algal growth.

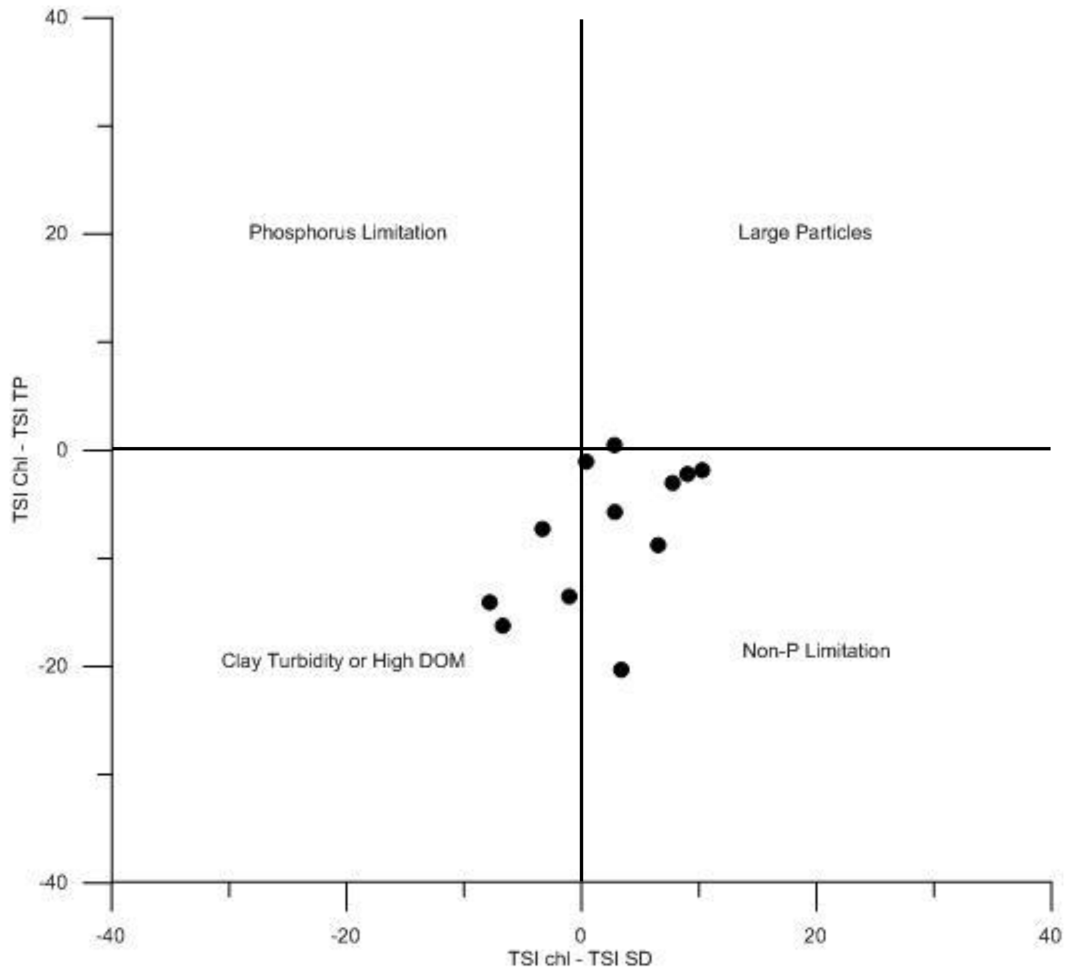


Figure 25. Potential nutrient limited and non-nutrient-limited causes for the deviation of biomass-based trophic state index.

pH, Oxidation-Reduction (redox) Potentials, 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) stimulates decomposition processes in the hypolimnion. High and low pH corresponds to peak 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 2014 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 6.8) due to decomposition processes within hypolimnion (**Figure 26**). These lower pHs were only noted in the hypolimnion toward the end of stratification. 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.

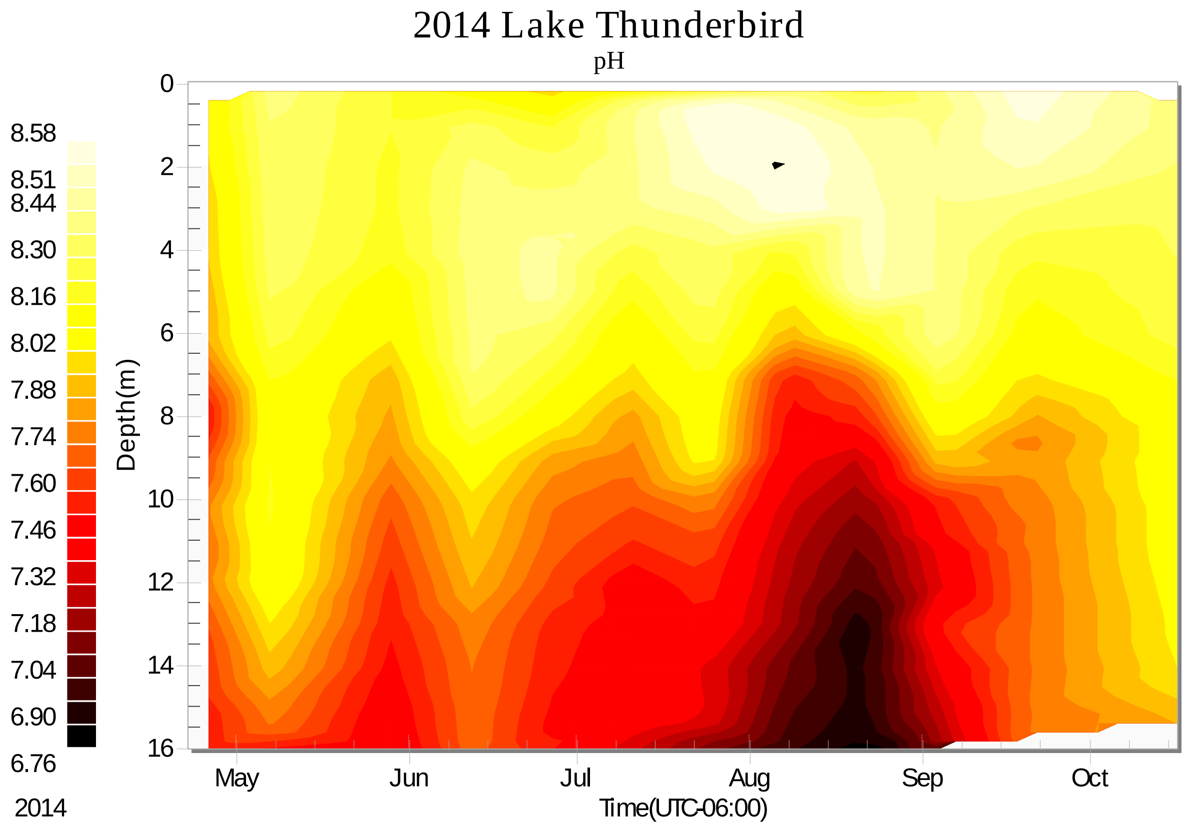


Figure 26. 2014 Lake Thunderbird Site 1 (S.U.) versus Depth (m) Over Time

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 phosphorous, 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 solids such as phosphorus and metals will be dissolved in the water column.

In early 2014, oxygenated conditions were present throughout the water column and redox potential remained high. At the May 28 sample event, thermal stratification was evident and oxygen below 2 mg/L was noted at the site 1 sediment-water interface (**Figure 27**). By mid-June the hypolimnion was completely anoxic while ORP levels were still relatively high except at the sediment water interface. It was mid-July that ORP began to significantly drop in the water column while staying above the 100mV threshold. Also notable was the mid-summer push of anoxia past the hypolimnion and into the metalimnion. Hypolimnetic and metalimnetic anoxia is a clear sign of excessive algae growth. From mid-July and past the reach of low ORP water increased to which indicates strong reducing conditions. By August 15, strong reducing conditions were observed from 7 meters and below. These low redox conditions remained in place until a mid-September mixing event. 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 also 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.

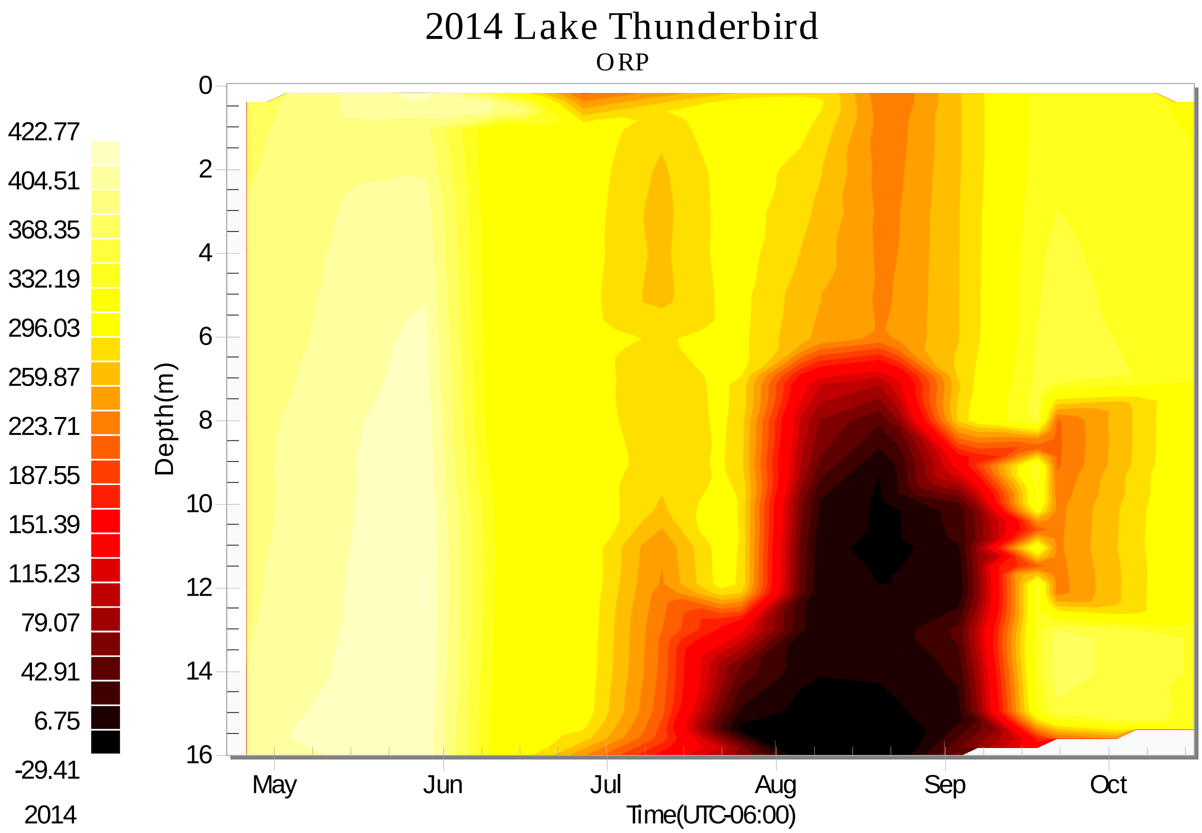


Figure 27. 2014 Site 1 Lake Thunderbird oxidation-reduction potential (ORP) as millivolts (mV) versus depth (m).

Taste and Odor Complaints

The City of Norman provided data on the number of taste and odor complaints from their customers in 2014. Because Lake Thunderbird is the major source of raw water for the city, water quality parameters in the lake can be correlated with complaints in the final finished water. Taste and odor causing compounds can be detected by individuals at the tap 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) and the fall turnover timeframe. Lab work on the finished drinking water revealed the presence of MIB and Geosmin during these high complaint times, indicating the presence of blue-green algae in the reservoir. The timing of taste and odor complaints for 2014 followed the traditional (September) break up of summer stratification (**Figure 28**). What was unusual was the magnitude of impact: over 100 complaints about the taste of finished water for September 2014; the highest monthly complaints since the OWRB provided lake monitoring. September also corresponded to the highest amounts of geosmin and methylisoborneol (MIB) noted in Lake Thunderbird raw and finished water to date (**Table 4**). Chris Mattingly, with the City of Norman, reported the taste and odor event started September 15th, peaked over the 21st to 22nd and tapered off through the 30th (C. Mattingly, personal communication, 9/30/2014). This time span closely matches water quality monitored events.

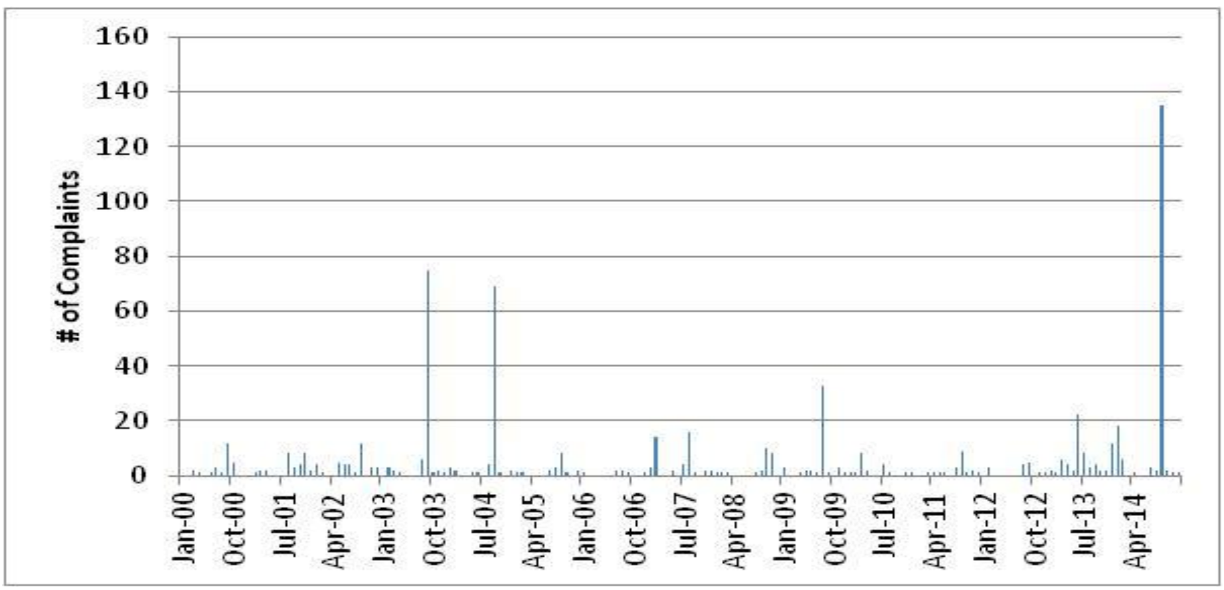


Figure 28. Taste and odor complaints to the City of Norman during 2012.

Table 4. City of Norman test results for select taste and odor compounds in raw and finshed water taken September 25, 2014.

Table 5. City of Norman test results for select taste and odor compounds in raw and finshed water taken September 25, 2014

Analyzed		Analyte	Sample ID	Result
		201409250153	**Raw**	
09/25/2014	02:23	Geosmin		10
09/25/2014	03:25	Methylisoborneol		470
		201409250154	**Tap**	
09/25/2014	12:50	Geosmin		9.4
09/25/2014	02:54	Methylisoborneol		410

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 a waterbodies beneficial uses are supported, outlining minimum data requirements for that decision methodology. In the following sections, Lake Thunderbird's water quality parameters will be discussed with an emphasis on their accordance with the OWQS. Sites 1 through 6 are historical sites originally monitored by the states Beneficial Use Monitoring Program, Sites 8 and 11 were added as additional monitoring sites 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).

Lake Thunderbird fully supports both its surface and volumetric criteria for the monitoring period in 2014. Maximum water column anoxia peaked at 43% of the lake volume on August 7, 2014, bringing the lake well under the 50% volumetric threshold for anoxia. No surface water violations occurred in 2014 with minimum surface DO registered at 6.74 mg/L on September 4, 2014 at Site 1, above the summer minimum surface criteria of 4.0 mg/L but also signifying a hypolimnetic mixing event.

Chlorophyll-*a* – Chl-*a*

Oklahoma surface drinking water supplies are sensitive and vulnerable to eutrophication. Communities can experience substantial hardship and costs to treat water adversely affected by excess algae. Blue-green algae (cyanobacteria) blooms are considered a principal source of compounds that cause taste and odor problems. Several toxic and carcinogenic compounds are also produced by blue-green algae. For this reason, OWQS has identified a class of public water supplies, where additional protection from new point sources and additional loading from existing point sources is needed, as Sensitive Public and Private Water Supplies (SWS). Lake Thunderbird is listed as SWS within OWQS and as such is required not to exceed the long-term average (10 years) Chl-*a* concentration criterion of 10 µg/L at a depth of 0.5 meters. For the 2014 sampling season the lake wide average Chl-*a* at Lake Thunderbird was 22.6 µg/L, exceeding the SWS Chl-*a* criterion, but less than the lake wide average of 24.6 µg/L in 2012 and 36 µg/L in 2011 and the ten year historical average of 23.2 µg/L (**Figure 21**). Twenty nine percent of the chlorophyll-a samples were within the 10µg/L limit in 2014 (**Figure 20**). All samples though May with the exception of Site 6 (on May 28th) were less than 10 µg/L. On June 26th 2014 only sites 2 and 3 had chlorophyll-a at or below 10 µg/L. Thereafter all sample sites exceeded the standard.

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 2014 mean of 25.3 centimeters at Site 6 to a mean of 81.1 centimeters at Site 1. 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 lowest (**Figure 29**).

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 2014, 12% of Lake Thunderbird samples exceeded the 25 NTU criteria (**Figure 30**). At the end of 2013, 23% of samples in the 10-year dataset exceeded the WQS.

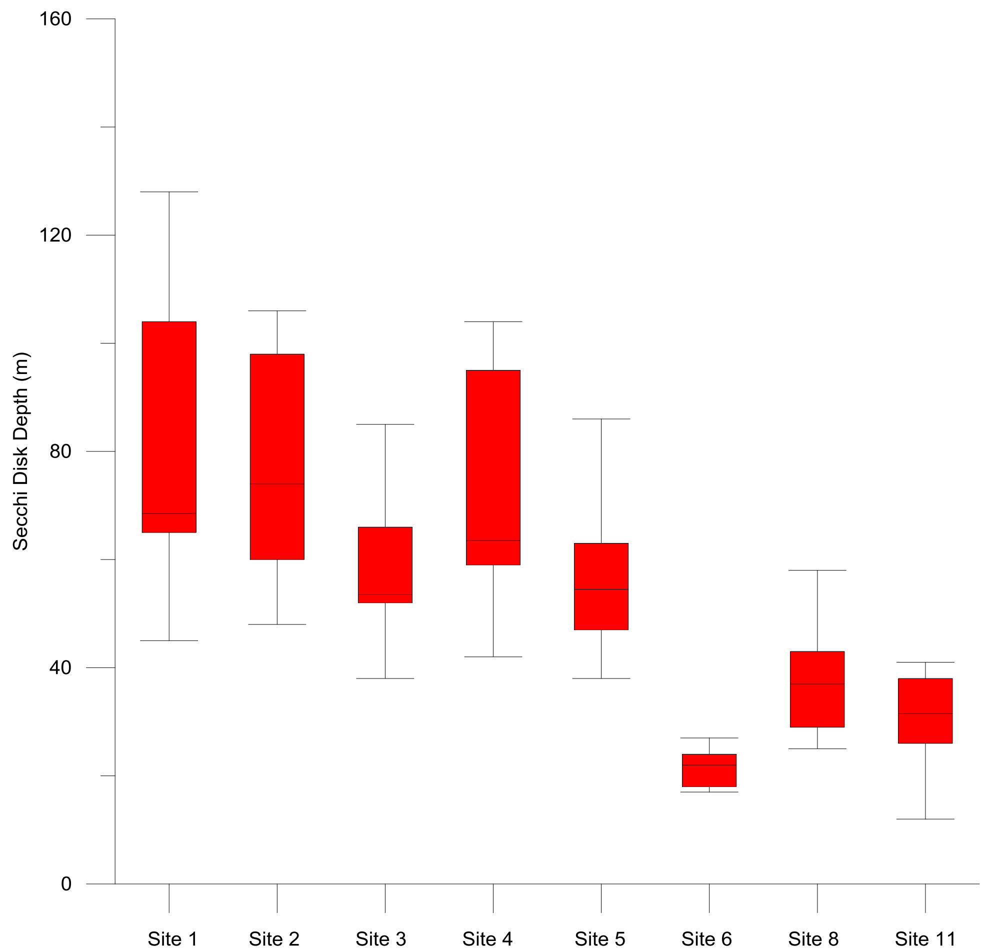


Figure 29. 2014 Lake Thunderbird Secchi disk depth (in centimeters) by site, where boxes represent 25% of the data distribution above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution.

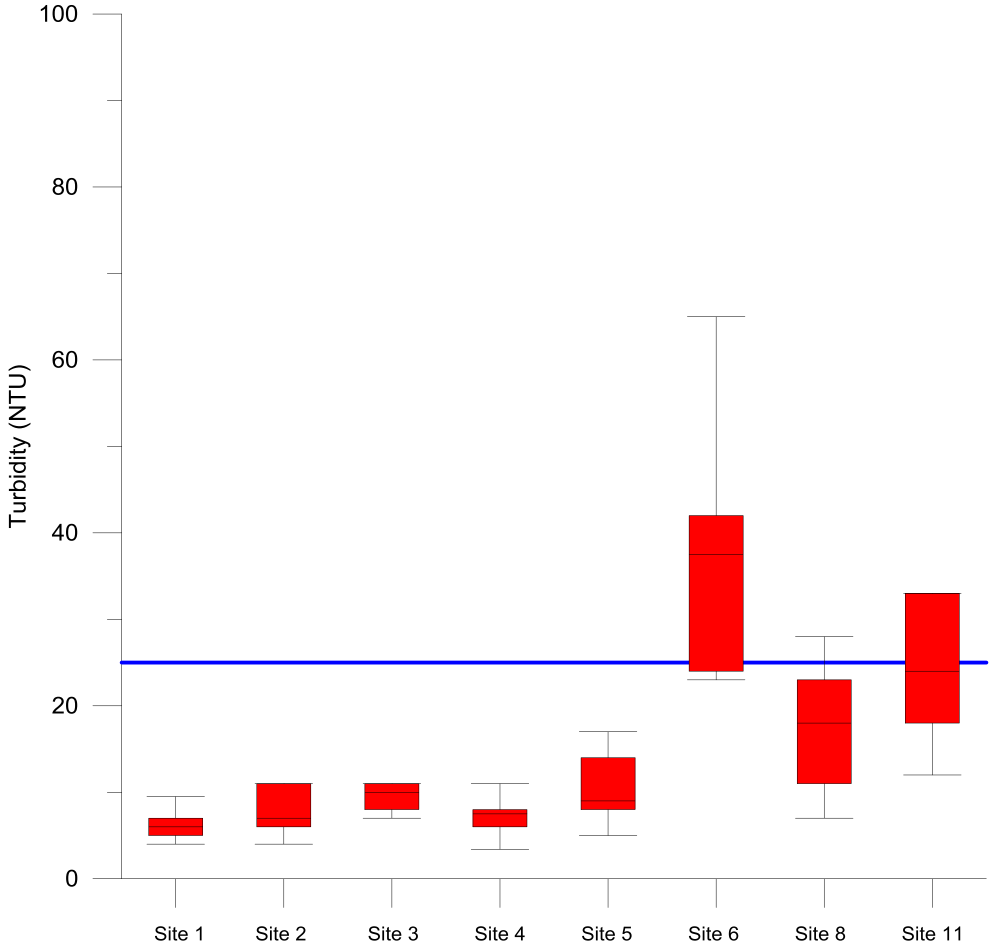


Figure 30. 2014 Lake Thunderbird turbidity (NTU), by site, where boxes represent 25% of the data distribution above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution (horizontal blue line represents state water quality standard).

Supersaturated Dissolved Oxygen Injection System (SDOX)

The summer of 2014 marked the fourth 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 31** and **Figure 32**). 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.

2014 marked the second full 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, it was decided to change the discharge nozzle to help diffuse the force from one opening to many openings (**Figure 33**). In addition to the change in nozzle, the system was also 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 season delivering 217,627 pounds of oxygen into Lake Thunderbird in 2014. There was an 11-day, continuous, break in operation of a potential 135 days from July 29th through August 10th, 2014 when the motor required rewinding. In summary, the SDOX system delivered 217,627 pounds of oxygen over an approximate 120 day period; estimating a system running at 35% capacity.

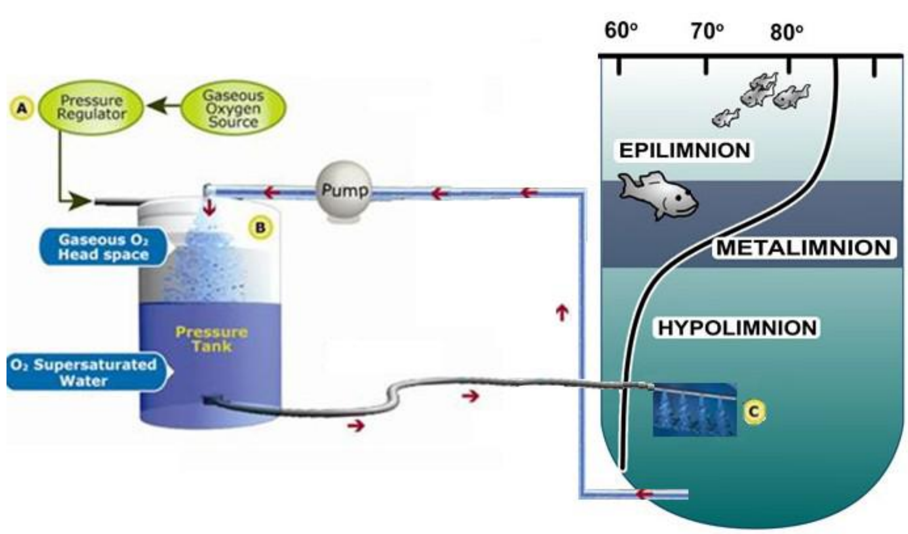


Figure 31. Conceptual Illustration of the SDOX System at Lake Thunderbird

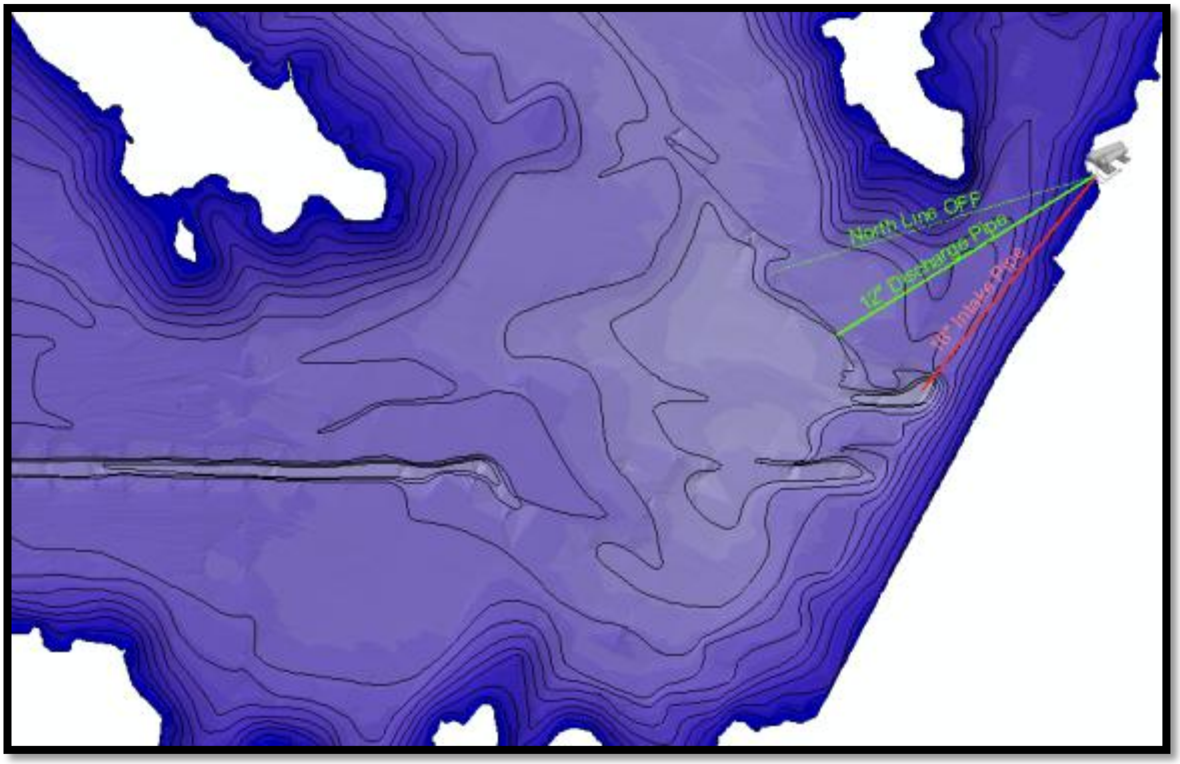


Figure 32. Map of SDOX location and current configuration.

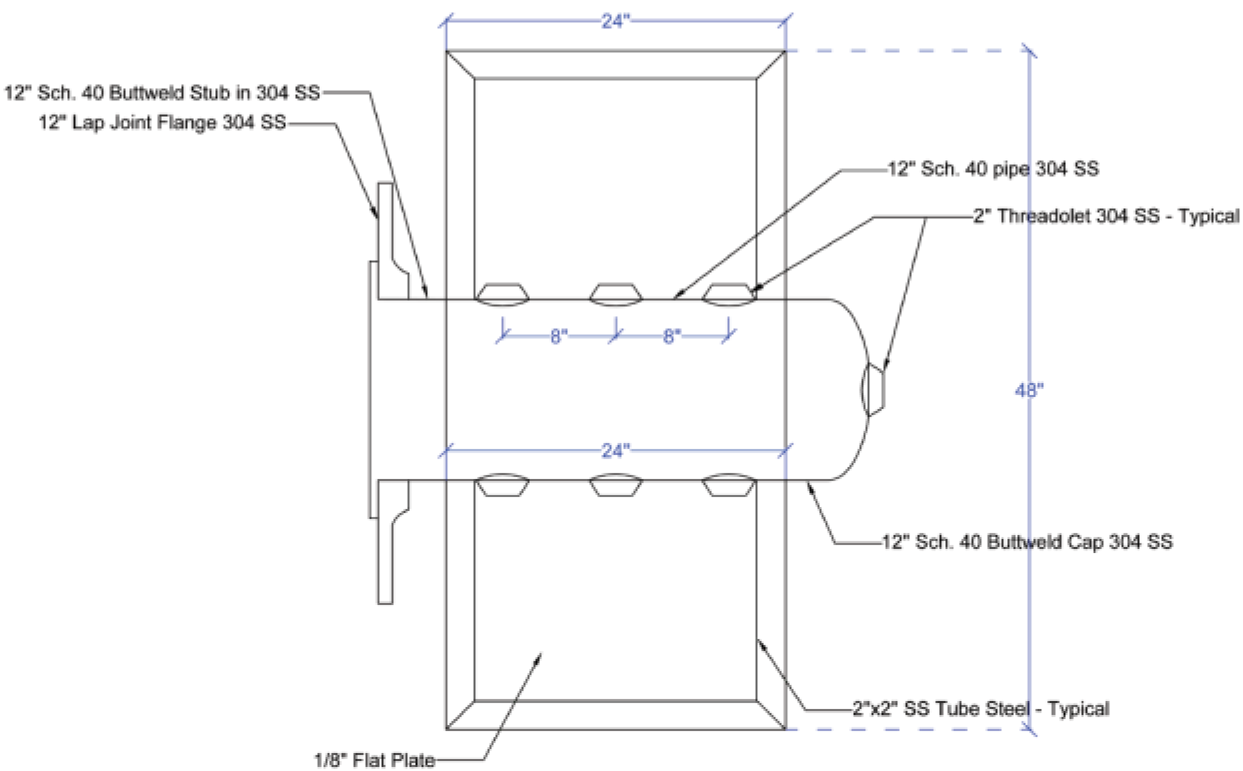


Figure 33. Schematic of the modified nozzle

When oxygen is present, it is used as the terminal electron acceptor in respiration, allowing the reduction-oxidation 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 nutrient load by minimizing the recycling of nutrients from the sediment and mitigation of peak Chl-*a* values. 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 creating 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 noted in the historical dataset. After the system modifications occurred in early July of 2012, the rate of temperature increase at the bottom slowed noticeably (0.034 C°/day {July 6, 2012-August 28, 2012} compared to the pre-SDOX rates of 0.085 C°/day {July 7, 2011- August 25, 2011}). 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 (0.033 C°/day {June 19, 2013-September 25, 2013} and 0.037°C/day {June 26, 2014-August 21, 2014}). A comparison of relative thermal resistance over the last several years illustrates the SDOX systems effect on heat distribution throughout the water column.

Reduced thermal gradation in the pre-modification operational window was apparent in the relative thermal resistance plot (**Figure 34**). Note the bimodal, metalimnetic peaks in year 1 and 2 of the SDOX operation verses one metalimnion in 2010 (no SDOX operation). This reduced thermal resistance to mixing is seen by the small bars at the 8 to 11 meter mark. Oxygenated water is released at a deeper depth, around 13 meters deep. Here is where the released, oxygenated water has mixed upward with little thermal difference from its surrounding layers. That the small RTM bar is several meters above the release point shows upward mixing. After the system modifications occurred in 2012, the mixing layer appeared to drop by two meters to approximately 10 meters in depth, confining the mixing largely within the hypolimnion, resulting in a more normalized thermal gradient. In 2013 and in 2014, the changes witnessed in late 2012 continued, confining thermal resistance mixing to a tight band (**Figure 35**). Essentially mixing the bottom of the hypolimnion but leaving a substantial metalimnion (thermal barrier to mixing).

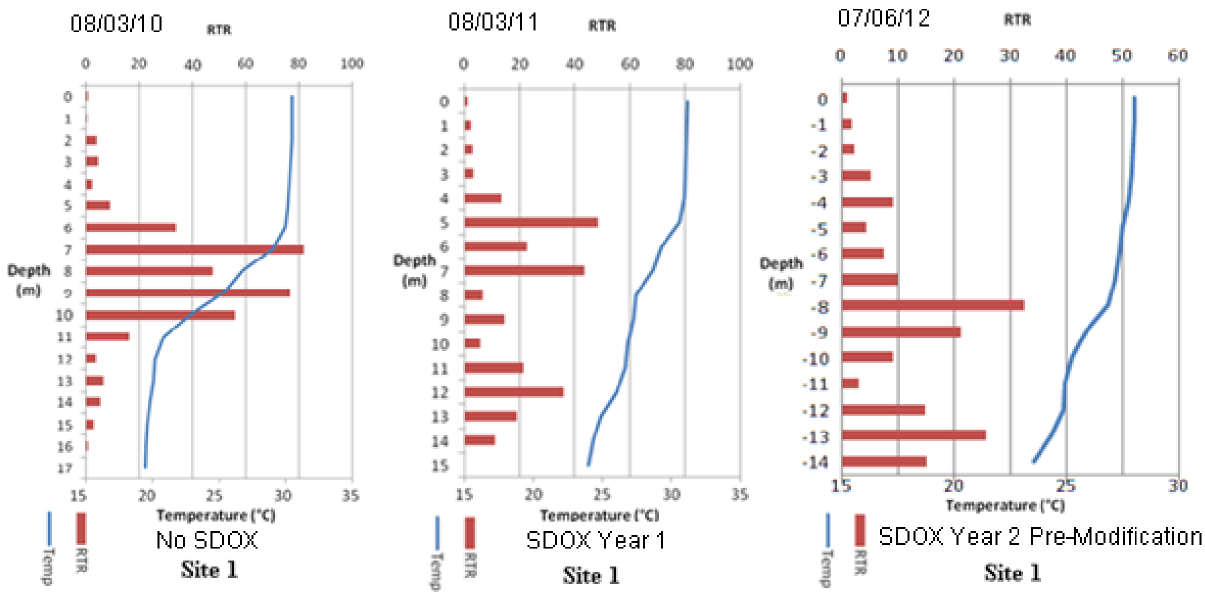


Figure 34: Relative Thermal Resistance Plots from 2010, 2011, and early 2012. Demonstrating the thermal resistance to mixing throughout the water-column before the SDOX was implemented and the first two years of operation before system modifications were made.

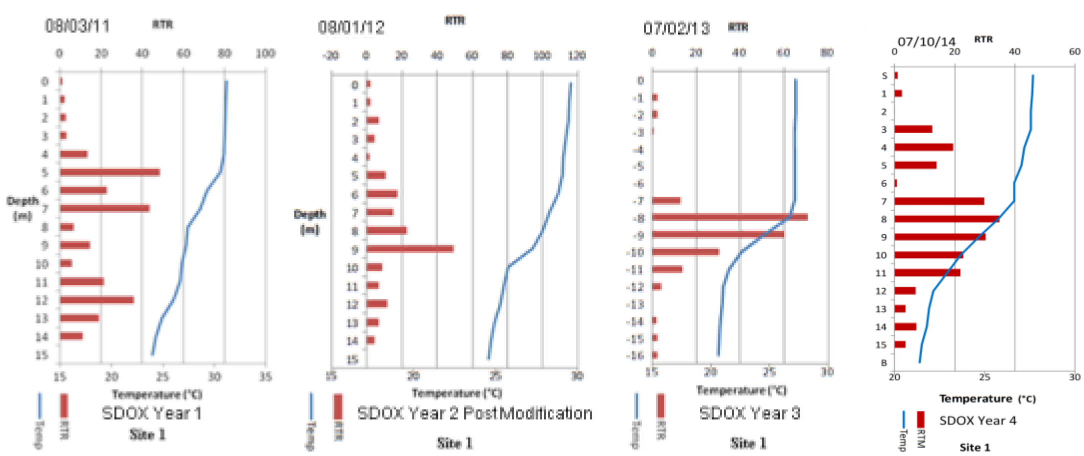


Figure 35: Relative Thermal Resistance plots for 2011, 2012, 2013 and 2014. Demonstrating the thermal resistance to mixing throughout the water-column during the first year of operation, and post modifications (2012, 2013 and 2014).

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

The spring/early summer of 2014 was marked by an early development of anoxia. While similar to earlier years when anoxia rapidly followed stratification, permanent summer stratification did not set in until late May when only the lower 3 meters had dissolve oxygen below 2 mg/L at Site 1. Anoxia deepened to encompass the entire hypolimnion by the beginning of June. A direct effect on dissolved oxygen by the SDOX system was noted on June 26, September 4th and 19th in 2014 (**Figures 8 & 9**). For the June 26th and September 4th events the dissolved oxygen increased near the 13 meter depth mark (the depth range of the SDOX nozzle) but oxygen here remained below 2 mg/L. Only during the September 19th sample event was an increase of oxygen above 2 mg/l noted in the hypolimnion. While the SDOX did not appear to have a marked effect on temperature or dissolved oxygen, its effect on oxidation-reduction potential (ORP) was marked (**Figure 36**). Unfortunately hypolimnetic ORP fell below the 100mV threshold mid-July with volumetric expansion of the <100mV ORP volume water concurrent with the 11 day SDOX shut down. While the shutdown exacerbated reducing conditions, it is evident that before the system shutdown the SDOX was not able to keep pace with reducing conditions.

Raising the redox potential in the otherwise anoxic hypolimnion decreases the solubility of nutrients and metals from the sediment (Lerman 1978). In 2011, 2012, and 2013 strong reducing conditions were largely eliminated throughout the water column during much of the summer. **Figure 37** allows for a comparison of ORP data from 2009, 2011, 2012, 2013 and 2014. Since the start of SDOX operation ORP data has not followed the historical (2009) data. It was observed and expected, for instances when DO concentration approached zero, for ORP values to drop to values indicating strong reducing conditions (<100 mV). With the operation of the SDOX unit in 2011, 2012, 2013 and 2014 this was no longer the case. In 2011 and 2012, mixing documented earlier in the section could be responsible for the increase in redox potential; in 2013 and 2014, mixing was not evident but high redox potential values were still observed.

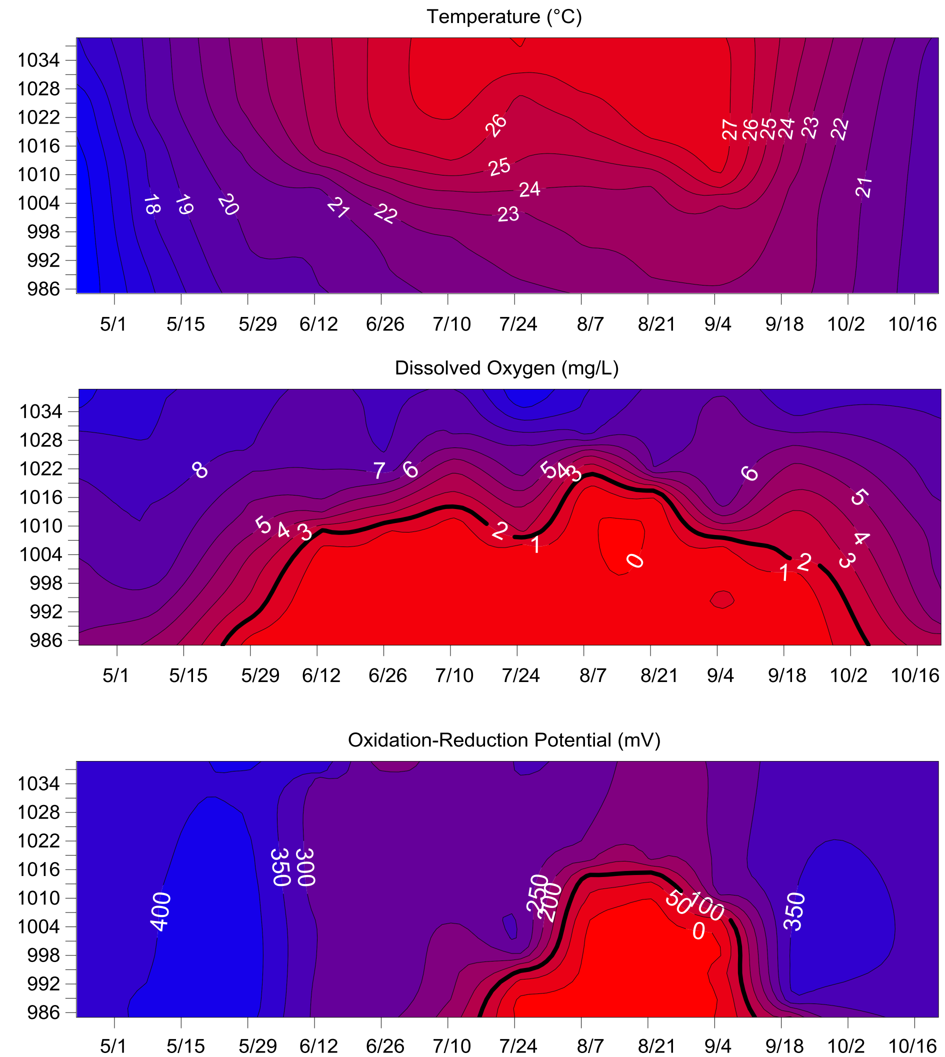


Figure 36 Temperature, dissolved oxygen and oxidation-reduction potential (ORP) by elevation for 2014 Site 1 Lake Thunderbird; highlighting the temporal disparity between onset of stratification (Temperature), anoxia (Dissolved Oxygen) and reducing conditions (ORP).

Also worth noting, in 2011 and 2012, reducing conditions were significantly reduced in extent and duration but strong reducing conditions still formed during SDOX system operation. In 2013, strong reducing conditions did not form until much later in the season and only after the SDOX had not been operational for a significant period of time. The much later turnover timeframe for 2013 (October 10), compared to 2011/2012 (early September), exaggerates the duration of reducing conditions in 2013 compared to the previous two seasons. In 2014 the onset of low ORP was somewhere between 2013 and the 2011/2012 seasons with a 2 month duration, more similar to the 2011/2012 seasons.

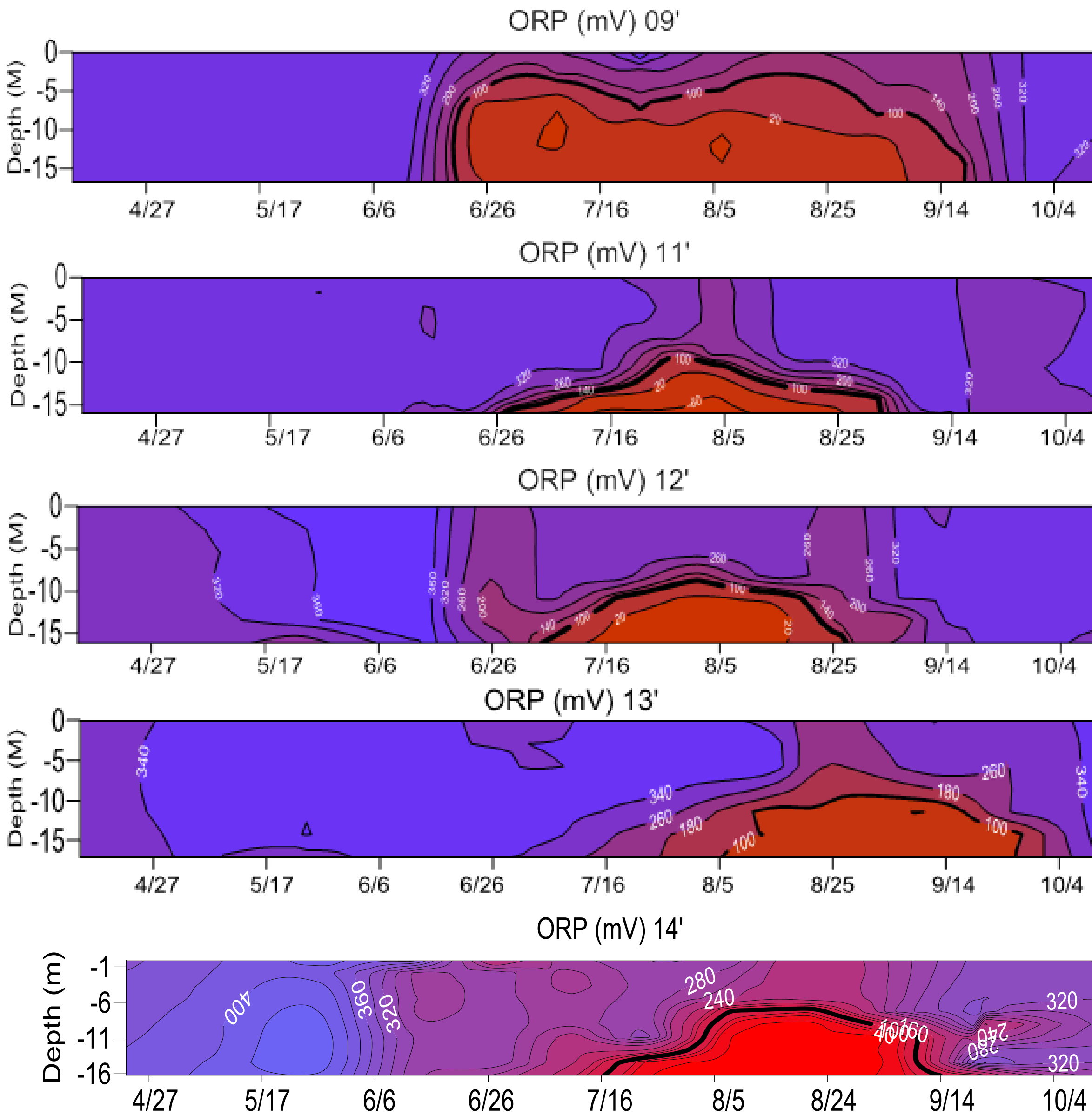


Figure 37. Lake Thunderbird 2009, 2011, 2012, 2013 and 2014 oxidation-reduction potential isopleths.

Nutrients, and Chlorophyll-a

The SDOX system induced physical changes (increased dissolved oxygen and oxidation-reduction potential) in the hypolimnion to trigger biological changes that would ultimately reduce phosphorous sediment loading. This sediment derived load has been documented 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 most visible chemical & biological impact of the SDOX in 2014 was nitrogen dynamics. **Figure 18** shows hypolimnetic nitrite-nitrate during much of the season while. Most indicative are the maximum levels seen at the 998 elevation mark, proximate to the SDOX system release depth. Even though there were clear indicators of SDOX impact the extent of impact was far short of previous years, in particular 2013. The inconsistent results for 2014 are puzzling and suggest a SDOX system overwhelmed with a dissolved oxygen deficit.

Examination of chlorophyll-a for 2014 suggests that while algal biomass had increased from the gains seen in 2013, it had not returned to pre-SDOX years. It is likely that had the SDOX system not been in use higher peak algal biomass would have been charted in 2014.

In addition to the observed empirical TP values in the lake and lowered algal biomass, a method developed by Nurnberg (2005) to calculate anaerobically mediated sediment P release provides an idea of the amount of sediment P release reduction. This was done by comparing the areal anoxia and sediment phosphorous release rate of 2014 to the values calculated for 2005 to 2009 (OWRB 2011). Based on the Nurnberg method and assuming a constant release rate under anoxic conditions, it was calculated that sediment P release was increased 16% above the five-year average.

Sediment Phosphorus Analysis

Traditional use of sediment phosphorus concentration has been 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 were taken at three sites in Lake Thunderbird in November of 2014 and May 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 (cm) and the 5 to 10 cm zone. These two samples are meant to represent the surficial sediment layer (0-2 cm) and the deeper buried sediment (5 – 10 cm). Wide-mouth polyethylene bottles were used to hold 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 as used as an extractant to the sediment and the elutriate analyzed for phosphorus, aluminum and iron. Test results were used to calculate the Phosphorous Saturation Ratio (PSR) as a molar ratio using the equation:

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

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. . 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 site 6 has the highest PSR and site 11 the lowest. This suggests that site 11 has the greatest potential to bind phosphorus and site 6 the least. Terrestrial application of the PSR suggests values >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 indicating 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}	**Seasonal Change**	**RPD**
11/11/2014	winter	1	0-2	0.117	0.0133	12%
5/12/2015	spring	1	0-2	0.104		
11/11/2014	winter	1	5-10	0.113	0.0164	16%
5/12/2015	spring	1	5-10	0.097		
11/11/2014	winter	6	0-2	0.119	0.0043	4%
5/12/2015	spring	6	0-2	0.114		
11/11/2014	winter	6	5-10	0.125	0.0045	4%
5/12/2015	spring	6	5-10	0.121		
11/11/2014	winter	8	0-2	0.044	0.0004	1%
5/12/2015	spring	8	0-2	0.044		
11/11/2014	winter	8	5-10	0.045	0.0095	24%
5/12/2015	spring	8	5-10	0.035		

Discussion

The 2014 calendar year marked the fourth season of operation for the supersaturated dissolved oxygen system. This system is designed to oxygenate water throughout the lakes normally anoxic hypolimnion while leaving thermal stratification intact. Data in 2014 verified that the modifications had reduced mixing outside the target zone. Indicators of SDOX effectiveness include a largely oxic hypolimnion and hypolimnetic nitrite-nitrate production. Unfortunately the duration and extent of anoxia was greater than in recent years and sediment mediated phosphorus release appeared to be relatively unchecked by SDOX operation. These seemingly conflicting results in 2014 chlorophyll-a somewhere between the most recent low of 2013 and 2011/2012 post SDOX years. The parameter most indicative of change in the hypolimnion seems to be temperature. While the rate of increase was not excessive the actual temperature was higher than recent. Higher sediment temperatures results in greater metabolic rates for bacterial community. This could account for an increased P-release rate in the hypolimnion. Why the hypolimnion started at a higher temperature is not clear. The simplest explanation would be SDOX operation delayed the onset of summer stratification; setting the initial hypolimnetic temperature higher than normal. Usually this shortens the duration of summer stratification as the epilimnion does not have to cool down as far for turnover. However, September of 2014 was almost 4°C warmer than the long-term average; extending the duration of a warmer epilimnion and summer stratification. Extended stratification into the late summer early fall, when the water is at it's warmest would maximize bacterial activity and sediment mediated p-release. This seems to be the most likely explanation of how, while most measures appeared "normal", p-release increased from pre-SDOX measures. Data from the 2014 season also suggest that the system did not run near its capacity to deliver oxygen into the hypolimnion.

Assessing the systems ability to deliver oxygen as needed as well as assessing the hypolimnetic oxygen demand are useful actions for the next monitoring season.

Discussion

Water Quality

For the past 15 years, OWRB has monitored the water quality at Lake Thunderbird observing the consequences of cultural eutrophication, degraded water quality, which over time have become more severe, including increasingly high Chl-*a*, elevated TOC, elevated pH and supersaturation of DO. As 2013 represented the first year where the trend was resolutely reversed, the lowered algal biomass (measured through Chl-*a*) was directly responsible for the relief witnessed in pH and surface DO measures. Trophic State Index Chl-*a* indicated mesotrophic conditions in the early spring, with eutrophic then hypereutrophic conditions throughout the summer and fall. Although high, absent are the hypereutrophic TSI Chl-*a* values in the 70's and 80's that have been present in the past. Anoxia occurred during the summer months, but was broken up by the SDOX system's influence in the 12 to 15 meter range. Strong reducing conditions were absent throughout half the season only appearing just prior to the extended SDOX system shut down. During this time, phosphorous and metals were released back into the water column and likely entrained during fall turnover. The infusion of hypolimnetic waters with external oxygen by the SDOX system installed in 2010 and operating in 2014, clearly helped reduce the extent and duration of low dissolved oxygen and low to negative ORP and likely anaerobically mediated sediment P release as well. Unfortunately, the magnitude of impact to the lake resulted in a larger than baseline release of sediment phosphorus to the water column.

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 MIB (2-methylisoborneol) 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 attributable to the presence of these compounds in finished drinking water and detected these compounds in the raw and treated waters in 2014 setting a high for quantity of MIB in the raw and finished drinking water. 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 Chl-*a* in 2014 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.

State Water Quality Standards

Lake Thunderbird was listed on Oklahoma's 2010 303(d) list of the Water Quality Integrated Report as impaired due to low DO, with the official cause of these impairments unknown. Data collected in 2014 were analyzed for beneficial use impairments in accordance with the USAP (OAC 785:46-15) of the OWQS. In 2014, Lake Thunderbird was found to be supporting its Fish and Wildlife Propagation beneficial use in regard to DO. The USAP assessments are done on the most recent 10-year dataset. Therefore, the last 4 years of meeting the surface and volumetric DO criteria will not remove Lake Thunderbird from the 303(d) list for DO. However, as the COMCD has been actively managing the reservoir for increased volumetric dissolved oxygen and the implemented system has provided measurable benefits attributed to the implemented system, the COMCD should request the lake be delisted for DO impairment. However, Lake Thunderbird was not meeting the 10 μg/L Chl-*a* requirement for Sensitive Public and Private Water Supply (SWS) or the 25 NTU standard of turbidity indicating a need for continued, improved water quality.

Recommendations

During the past few years, significant achievements have been made understanding the effect of internal and external loadings to the quality of Lake Thunderbird. Regression analysis with Lake Thunderbird water quality data and City of Norman drinking water treatment data, indicate that organic enrichment through increased algal biomass is increasing TOC within the reservoir. The implementation of the SDOX system has mitigated the impact of cultural eutrophication to Lake Thunderbird. Calendar year 2012 represented the first year of reduced chlorophyll-a since 2007. While 2014 represented another large reduction in Chl-*a* it is apparent that the SDOX system has not furnished the quantity of oxygen necessary to completely oxidize the hypolimnion or effectively mitigate in-lake loading of phosphorus (via sediment release). 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. Additionally, reduction of external nutrient loading from the watershed should be facilitated and encouraged to allow SDOX operation to get a step ahead of cultural eutrophication and further reduce chlorophyll-a toward the state water quality standard of 10 μg/L.

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Appendix A: Quality Control Data

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

Date	ODEQ			ODAFF			
	Site 1a	Site 1b	Site 9	Site 1a	Site 1b	average	sd
4/22/2014	8.18	6.21	4.86			6.42	1.67
5/7/2014	6.27	6.98	8.55			7.27	1.17
5/28/2014	5.84	3.59	5.95			5.13	1.33
6/12/2014	8.26	7.39				7.83	0.62
6/26/2014	12.20	13.30	12.00	13.53	13.36	12.88	0.72
7/10/2014	19.80	19.10	19.10	0.93*	20.41	15.87	8.37
7/24/2014	32.70	32.00	29.70	30.57	29.83	30.96	1.33
8/7/2014			26.64	27.60	27.78	27.34	0.61
8/21/2014	35.32		57.98			46.65	16.02
9/4/2014			19.74	39.73	38.52	32.66	11.21
9/19/2014			38.23	41.13	41.73	40.36	1.87
10/20/2014	41.40	40.40				40.90	0.71
						Average sd	3.80

*Pheophytin-a reported at 41.39 suggesting chlorophyll-a degradation
sd – standard deviation

Blank Sample Results

Date	Site 22	Ammonia as N mg/L	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
4/22/2014	BLANK	<0.015	<0.11	<0.02	<0.02	<0.005	<0.005
5/7/2014	BLANK	<0.015	<0.11	<0.02	<0.02	<0.005	<0.005
7/10/2014	BLANK	<0.015	<0.11	<0.02	<0.02	<0.005	<0.005
7/24/2014	BLANK	<0.015	0.39	<0.02	<0.02	<0.005	<0.005
8/7/2014	BLANK	<0.015	<0.11	<0.02	<0.02	<0.005	0.006
8/21/2014	BLANK	<0.015	0.11	<0.02	<0.02	0.007	0.007
9/4/2014	BLANK	<0.015	<0.11	<0.02	<0.02	<0.005	<0.005
9/19/2014	BLANK	<0.015	<0.11	<0.02	<0.02	<0.005	<0.005

Duplicate Sample Results

Date	Site	Ammonia as N mg/L	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
4/22/2014	Site 9	<0.015	0.54	0.06	<0.02	<0.005	0.029
5/7/2014	Site 9	<0.015	0.62	<0.02	<0.02	<0.005	0.030
5/28/2014	Site 9	<0.015	0.53	0.03	<0.02	<0.005	0.026
6/12/2014	Site 9	<0.015	0.57	<0.02	<0.02	0.007	0.033
6/26/2014	Site 9	<0.015	0.61	<0.02	<0.02	0.007	0.035
7/10/2014	Site 9	0.015	0.72	<0.02	0.02	0.008	0.038
7/24/2014	Site 9	0.048	0.87	<0.02	<0.02	<0.005	0.030
8/7/2014	Site 9	<0.015	0.88	<0.02	<0.02	0.007	0.036
8/21/2014	Site 9	<0.015	0.90	<0.02	<0.02	0.008	0.050
9/4/2014	Site 9	<0.015	0.96	<0.02	<0.02	<0.005	0.041
9/19/2014	Site 9	<0.015	1.06	<0.02	<0.02	0.007	0.063

Date	Site	Ammonia as N mg/L	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
4/22/2014	Site 1	<0.015	0.50	0.05	<0.02	<0.005	0.025
5/7/2014	Site 1	0.02	0.69	<0.02	<0.02	<0.005	0.035
5/28/2014	Site 1	0.018	0.59	0.03	<0.02	<0.005	0.030
6/12/2014	Site 1	<0.015	0.68	<0.02	<0.02	<0.005	0.031
6/26/2014	Site 1	<0.015	0.63	<0.02	<0.02	0.007	0.034
7/10/2014	Site 1	0.032	0.81	<0.02	<0.02	0.010	0.038
7/24/2014	Site 1	<0.015	0.83	<0.02	<0.02	<0.005	0.031
8/7/2014	Site 1	<0.015	0.85	<0.02	<0.02	0.006	0.037
8/21/2014	Site 8	<0.015	1.05	<0.02	<0.02	0.010	0.054
9/4/2014	Site 1	<0.015	0.92	<0.02	<0.02	<0.005	0.043
9/19/2014	Site 1	<0.015	1.10	<0.02	<0.02	0.006	0.063
10/20/2014	Site 1	0.06	0.83	0.06	0.05	0.011	0.060