Oklahoma Water Resources Board

Lake Thunderbird Water Quality

2012

for the

Central Oklahoma Master Conservancy District

March 21, 2013

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, Table 5 of the Oklahoma Water Quality Standards (OWQS) as a Sensitive Water Supply (SWS) (OAC 785:45). In 2012, 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 2012 represents thirteen years of continuous monitoring at Lake Thunderbird.

The year of 2012 was marked by below average amounts of precipitation contributing to a dropping pool throughout the summer, and the longer hydraulic residence time of 6.16 years. Data collected in 2012 demonstrated the return of stronger thermal stratification patterns that were missing in the first year of operation of the hypolimnetic oxygenation system. Total mixing of the water column was first detected in the middle of September. Total nitrogen to total phosphorus ratio had an abrupt reversal from its' previous decline (dating back to 2009), indicating strong phosphorous limiting conditions were present throughout much of the summer. This was due to both a decrease in total phosphorous levels in the lake, as well as a rise in nitrogen levels in the lake. Inorganic nutrient concentrations indicated nitrogen limiting conditions; surface inorganic nitrogen concentrations were held below detection limit throughout the summer, while inorganic phosphorous was detected through much of the summer.

Low to negative oxidation-reduction potentials responsible for the solubilization of metals and sediment-bound phosphorus into the water column were still present but found to be greatly reduced from historical averages. While the lake was still found to be hypereutrophic throughout much of the summer, mean and peak chlorophyll-*a* values for the lake were reduced drastically. Taste and odor complaints followed the established annual trend, peaking after lake turnover and coinciding with peak chlorophyll-*a* values.

During 2012, changes in the hypolimnetic oxygenation system at Lake Thunderbird seemed to reduce the impact of mixing in the water column. Noticeable changes were seen in temperature, dissolved oxygen and reduction potential when compared to the historical dataset and the first year of operation. Lake Thunderbird also experienced a period of hypolimnetic supersaturation of oxygen with values exceeding 18 mg/L at the lake bottom.

The 2012 monitoring data supports the 303(d) integrated listing of Lake Thunderbird as impaired due to excessive turbidity and excessive chlorophyll-*a* (Chl-*a)*. Data collected during 2012 does not exceed OWQS in respect to dissolved oxygen.

Active lake and watershed management is required for Lake Thunderbird to meet OWQS for turbidity, dissolved oxygen (DO) and Chl-*a*. Primary mitigation efforts should focus on nutrient reduction. Nutrient reduction would affect two impaired water quality parameters; algae growth (Chl-*a*) 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 and modification of the active hypolimnetic oxygenation project should provide relief to the lake's DO levels, algal problems, and drinking water taste and odor complaints. Further recommendations on future lake management of Lake Thunderbird should include the review of watershed evaluations to spur nutrient reductions in the basin.

Introduction

Lake Thunderbird was constructed by the Bureau of Reclamation and 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 Norman. The Oklahoma Water Resources Board (OWRB) has provided water quality-based environmental services for the COMCD since 2000. The objective in 2012, 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 2010 Integrated Report as impaired due to excessive turbidity, low dissolved oxygen and excessive Chl-*a* (http://www.deq.state.ok.us/wqdnew/305b_303d/2010_draft_integrated_report.pdf). Because of these impairments, Lake Thunderbird is currently undergoing a TMDL analysis by the Oklahoma Department of Environmental Quality (ODEQ). These parameters are evaluated according to the OWQS in this report.

In addition to the water quality standard impairment listings as assessed in the State's 2010 Integrated Report, collaborative work with the City of Norman has documented that the water quality impairments have translated into elevated Total Organic Carbon (TOC) in raw drinking water, been linked to the taste and odor complaints in the finished drinking water, and have 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 result of the cultural eutrophication witnessed in the reservoir, the COMCD applied and was granted funding, through the American Recovery and Reinvestment Act, to install and operate an oxygenation system designed to oxygenate the largest portion of the anoxic hypolimnion in the lake while leaving thermal stratification intact. The targeted impact of providing a largely oxygenated hypolimnion include elimination of reducing conditions in the hypolimnion, and reductions of internal phosphorous load, dissolved metals, and peak Chl-*a* events. Data collected in 2012, representing the second year of SDOX operation, built on the modest water quality improvements observed in 2011.

Water Quality Evaluation

Sampling Regime

In 2012, Lake Thunderbird was sampled at the sites indicated in **Figure 1.** Water quality sampling occurred from February 2nd to October 17th. 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. The Hog Creek riverine zone is represented by site 8. Site 3 represents the transition zone of the Hog Creek arm.

Water quality profiles measured at all sites on every visit included oxidation-reduction potential (ORP), DO saturation and concentration, temperature, specific conductance, total dissolved solids (TDS) and pH. These parameters were measured in approximately one-meter vertical intervals from the lake surface to sediment at each site.

In addition, from February 2012 through October 2012, water quality and nutrient samples were collected at the surface of sites 1, 6, 8 and 11 at 4-meter depth intervals of site 1. Analysis performed on these samples included alkalinity, chloride, sulfates, total suspended solids (TSS), and phosphorus (P) and nitrogen (N) series. Total organic carbon samples were also collected at the surface of sites 1, 6, 8 and 11. Secchi disk depth, surface Chl-*a*, and turbidity samples were collected at all nine sites (**Table 1**).

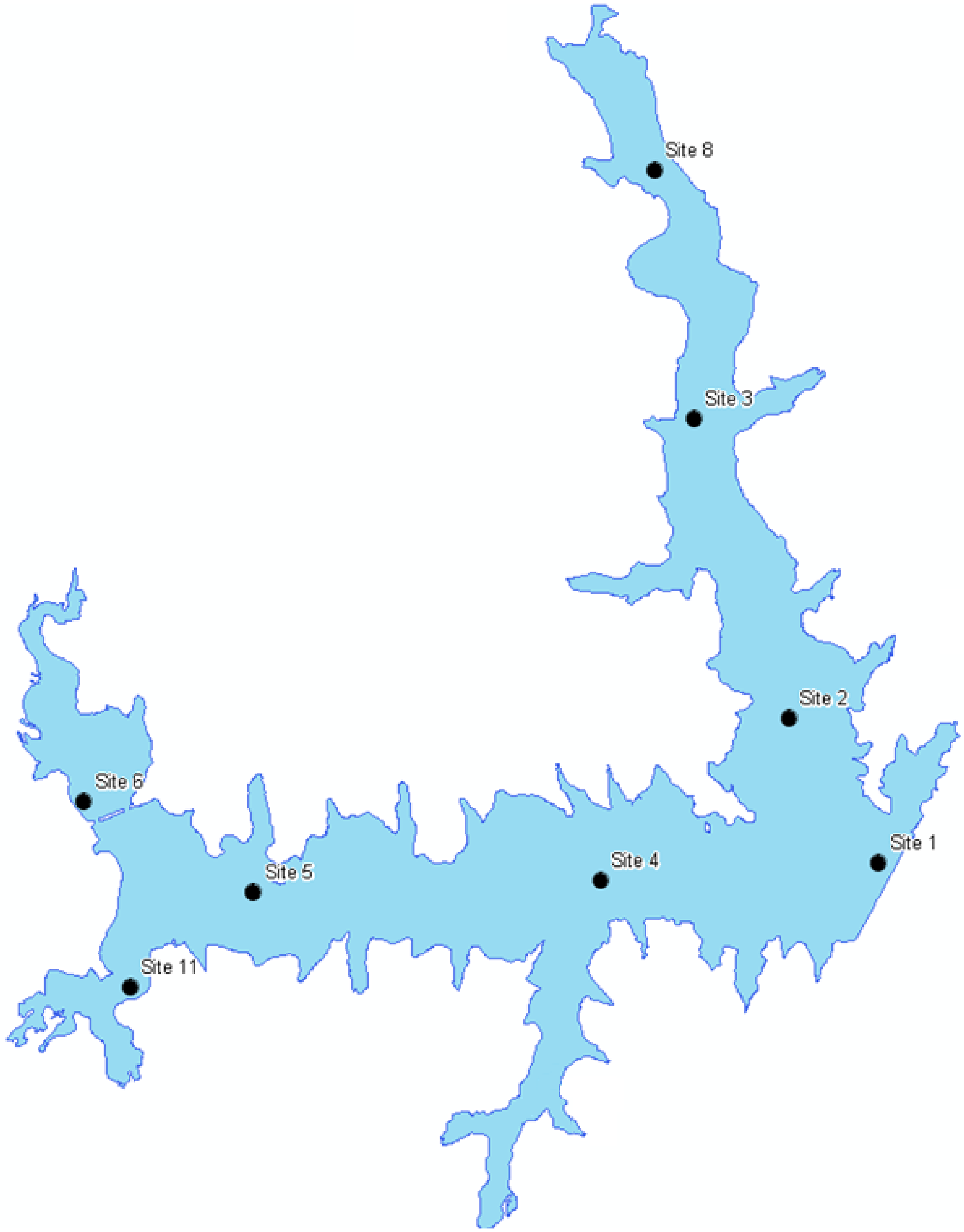


Figure 1. Lake Thunderbird 2012 sampling sites

Table 1. 2012 Water quality sampling dates and parameters measured.

Date	2/2	4/18	5/2	5/23	6/14	6/25	7/6	7/18	8/1	8/15	8/28	9/5	9/13	9/19	10/17
Profile	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Chl-*a*	X	X	X	X	X	X		X		X		X		X	X
Secchi Depth	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
Metals	X	X	X	X	X	X		X		X		X		X	X

Quality Assurance and Quality Control (QA/QC)

Water quality sampling followed the QA/QC procedures described in the EPA approved Quality Assurance Project Plan “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. No major failure occurred during the 2012 sampling season to compromise the integrity of the dataset. One observation worth noting was that ortho-phosphorus (Ortho-P) values for February 2nd and April 18th were higher than that of total phosphorus (TP). Because TP is a measure of all phosphorus types, this guaranteed that one of these two values were false. This anomaly was reported to the lab of analysis (ODEQ-SEL).

Laboratory quality control samples included duplicates and replicates. Duplicate samples were taken at the surface of site 1 for all laboratory analyzed samples 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. **Appendix A** summarizes laboratory results of replicate and duplicate sampling.

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) $PAD = |x_{S1} - x_{S9}| / \ x * 100$

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**). Most parameters showed relatively good precision with median PAD well below 20. Pheophytin-a, a measure of Chl-*a* degradation, was the exception showing much greater variability in the PAD. It should be noted that while PAD seemed good over the entire sampling season, there were instances of high PAD for TP and Ortho-P, reflected by the large upper quartile.

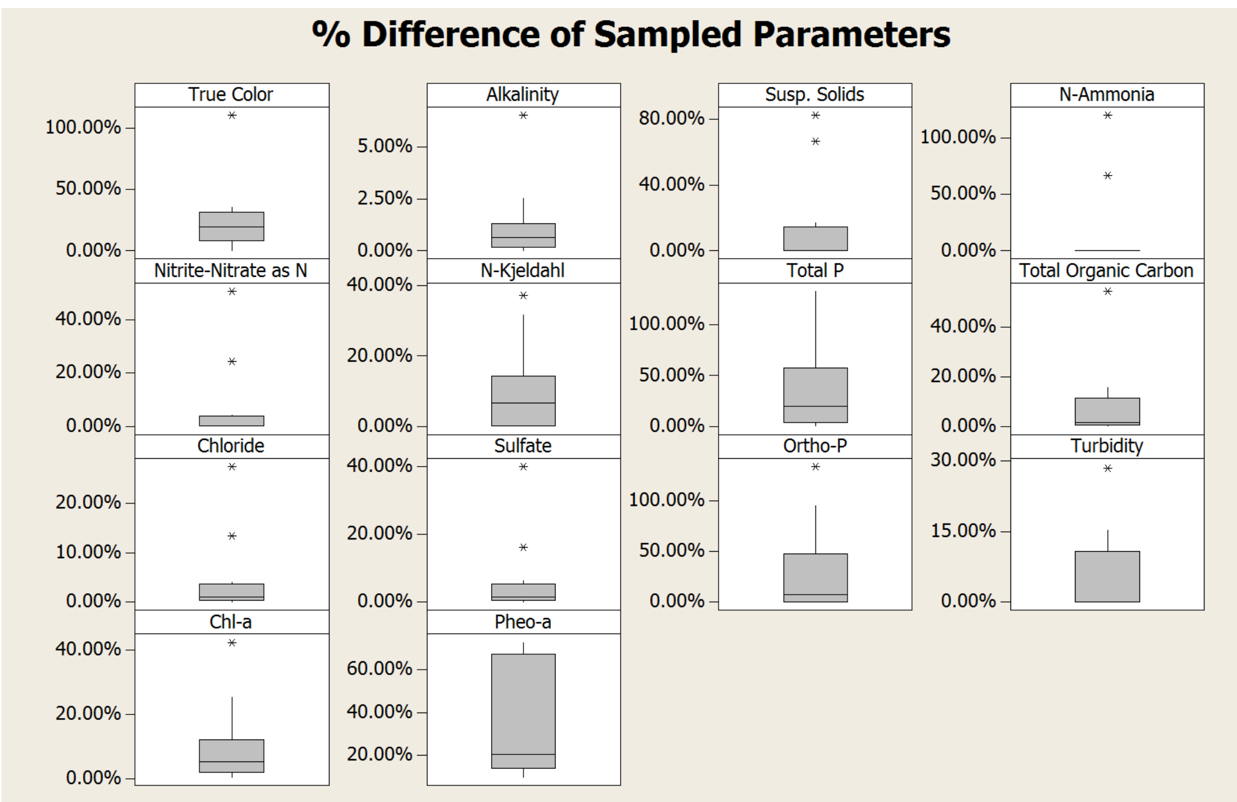


Figure 2. Statistical summary of Lake Thunderbird duplicate samples February 2nd, 2012- October 17, 2012. (Box represents the middle 50%, the center bar the median value, top and bottom stems the upper and lower 25% quartile and asterisks as outliers**)**

Climate

Knowledge of potential climatologic influences is essential when assessing the water quality of a waterbody. The hydrology of a given lake, including dynamic inflows and capacity, can have significant impacts on internal characteristics and processes, both chemical and biological. Storm water inflows can increase nutrient and sediment loading into the lake, re-suspend sediments, and alter stratification patterns. In addition, changes in lake volume and nutrient concentrations can affect the extent of anoxia in the hypolimnion and alter oxidation-reduction potentials. This can lead to changes in the solubility of phosphorus and metals from the sediments.

Figure 3 provides a graphical representation of Lake Thunderbird's rainfall, elevation, inflow, and sampling dates for calendar year 2012. Annual precipitation at Lake Thunderbird in 2012 totaled 19.91 inches, 15.89 inches below average. Lake elevations and inflows can vary considerably with rainfall patterns. Pool elevation varied from a high of about 1.75 feet below conservation pool (1039' MSL) in mid-April to a low around 7.5 feet below conservation pool in late December. In addition to hydrology, air temperature can also influence lake characteristics such as stratification patterns and primary productivity. The 2012 average daily temperature values are illustrated in **Figure 4.** The average daily temperature was above the historical average by approximately 2.4°F. More notably, an intense heat wave encompassed the central part of the state from the start of June through early September.

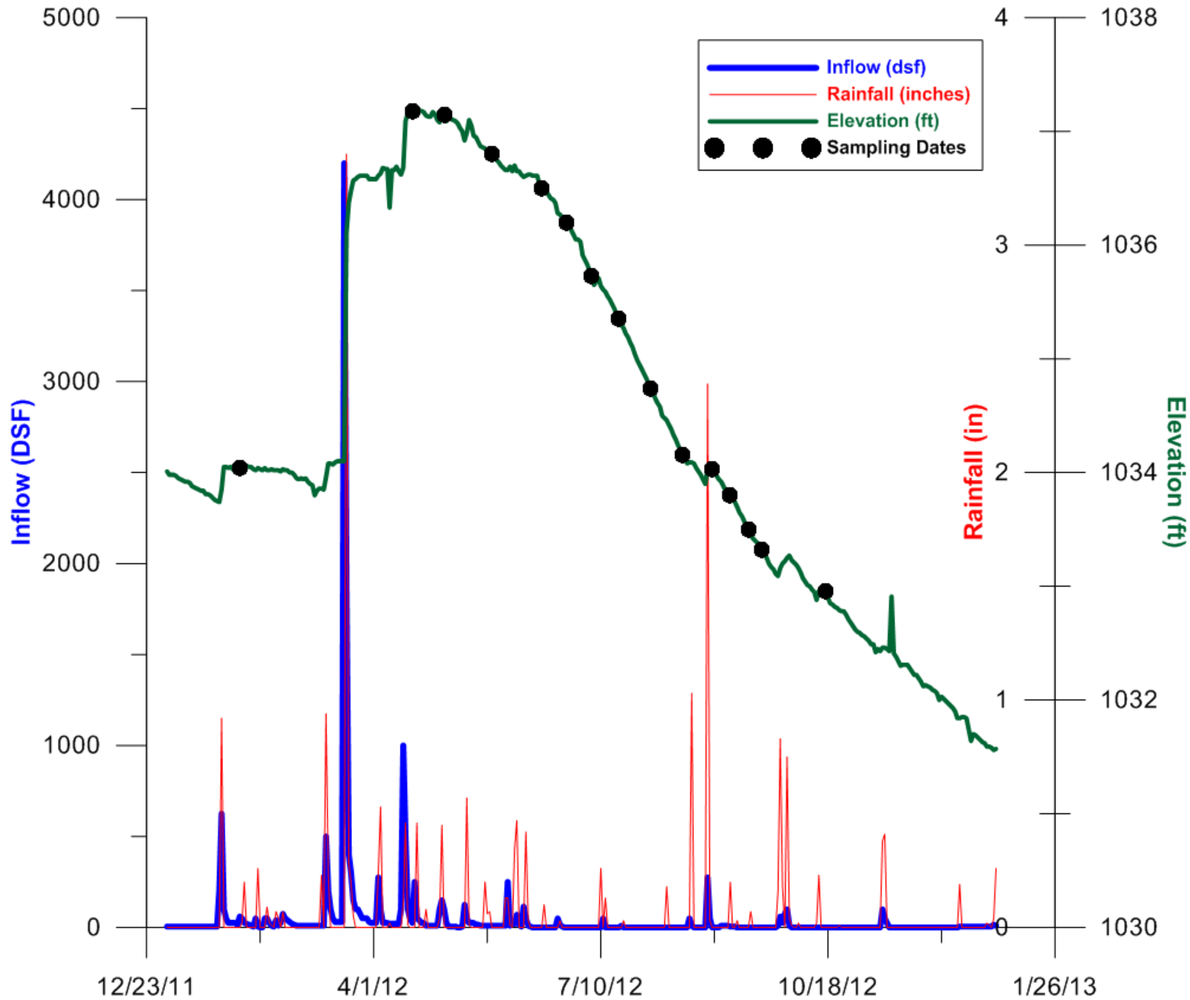


Figure 3. 2012 Inflow, precipitation, and elevation data for Lake Thunderbird, with sample dates indicated.

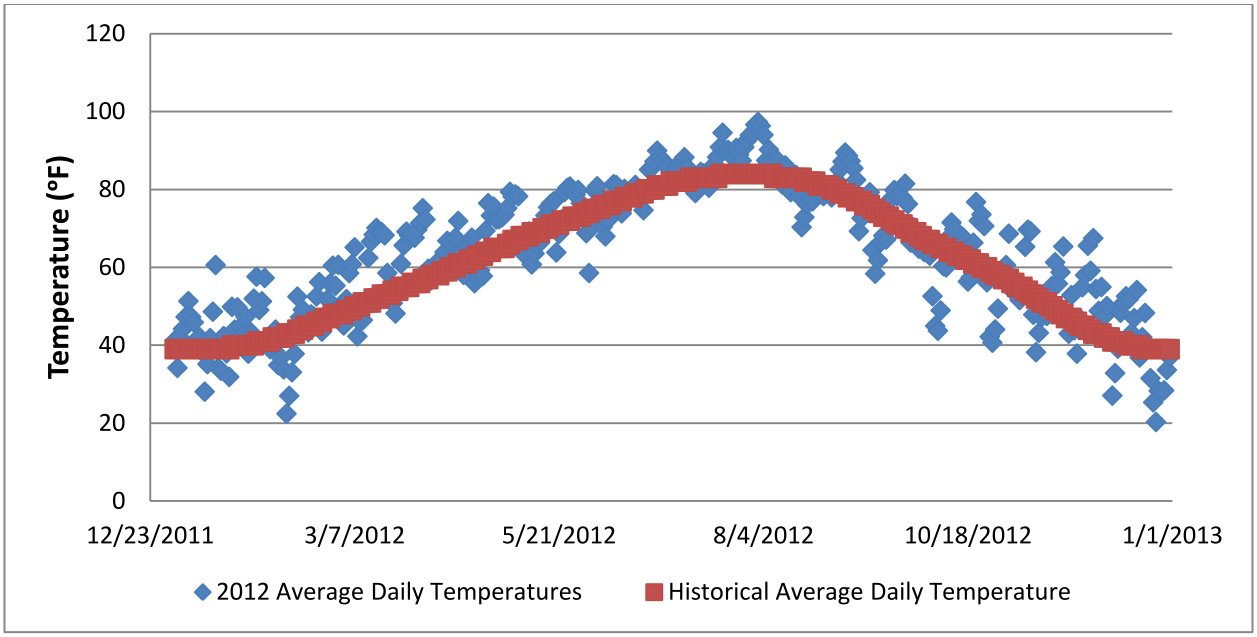


Figure 4. 2012 Average daily temperature values at the Norman mesonet station.

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 1:

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

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, we will assume that subsurface flow is 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 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 include gated dam releases and water supply withdraws. Both are reported by the USACE. Change in volume or storage was recorded 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

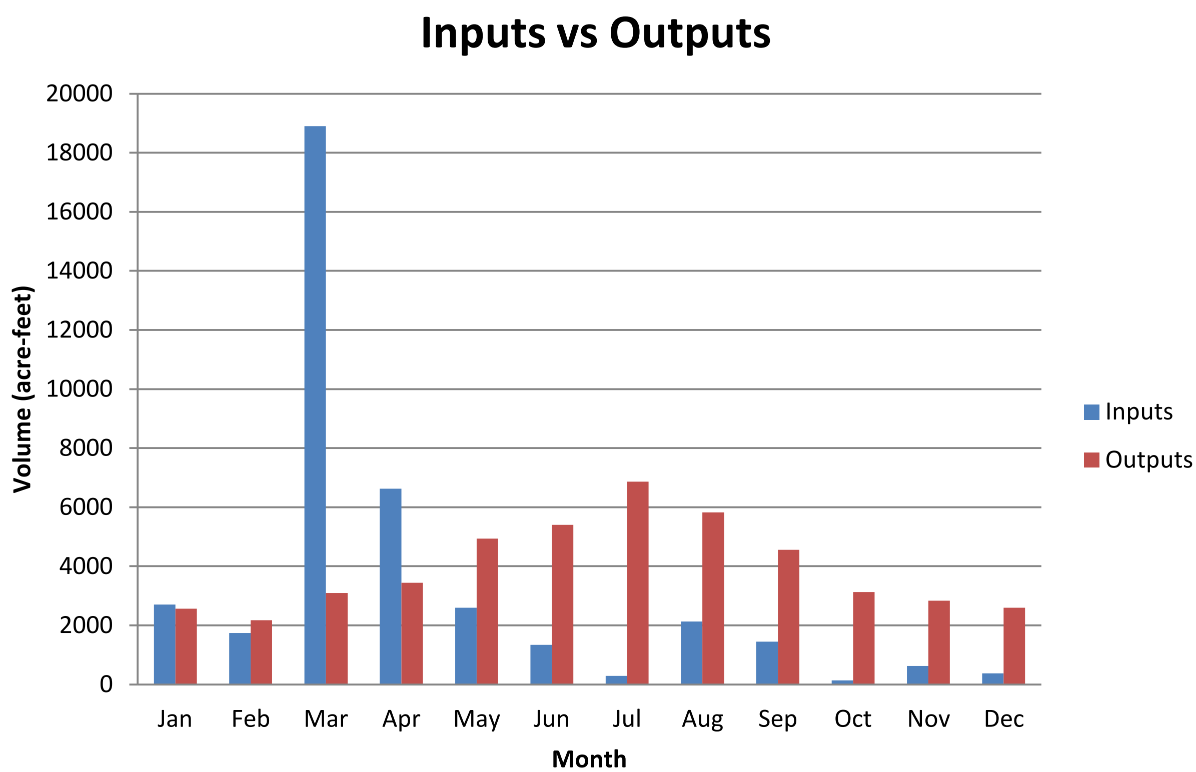
Water budget calculations were summarized on a monthly basis for Lake Thunderbird as described previously **(Table 2).** Total input is the sum of all the flows into the lake. Total output is the sum of all the outflows from the lake. From equation 1, the difference between the inputs and the outputs 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 shows that estimated inputs and outputs are close to the actual volume changes with relatively little error. Errors in the hydraulic budget will be discussed in the next section.

Table 2. Lake Thunderbird 2012 water budget calculations expressed in acre-feet.

Month	INPUTS			OUTPUTS				RESULTS		
	Inflow	Rainfall	**Total Inputs**	Evaporation	Water Supply	Releases	**Total Outputs**	I-O	ΔV	Error
Jan	2360	342	2702	1559	1004	0	2562	140	0	140
Feb	1448	293	1741	1260	918	0	2177	-437	-538	102
Mar	16760	2136	18897	2019	1074	0	3093	15804	12648	3156
Apr	5802	822	6624	2297	1139	0	3436	3188	2573	616
May	1904	689	2593	3367	1565	0	4932	-2339	-2418	79
Jun	764	581	1344	3584	1814	0	5398	-4054	-3087	-967
Jul	119	168	287	4684	2176	0	6860	-6573	-6204	-370
Aug	764	1363	2127	3828	1992	0	5820	-3693	-3614	-79
Sep	645	799	1444	2788	1771	0	4559	-3115	-4066	951
Oct	20	118	138	1704	1427	0	3131	-2994	-2259	-735
Nov	347	275	622	1686	1145	0	2830	-2208	-2010	-197
Dec	198	176	375	1445	1148	0	2593	-2219	-1975	-243
Total	**31131**	**7763**	**38894**	**30222**	**17170**	**0**	**47392**	**-8499**	**-10952**	**2453**

Once a hydrologic budget has been constructed, retention times 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 1/6 years for 2012 and an average hydrologic residence time of 4¼ years since 2001 (including 2012 data). The relatively high 2012 residence time reflects the sustained drought experienced in 2012 that prevented any water releases from occurring. The only known outflow of water during 2012 was from COMCD water withdrawals for water supply purposes. All but 900 acre-feet of estimated inflow was accounted for by evaporation.

For the period of 2012, 80% of the inputs into Lake Thunderbird were from inflows, while the outputs were from lake body evaporation, 64%, and water supply 36% (**Figure 5**).



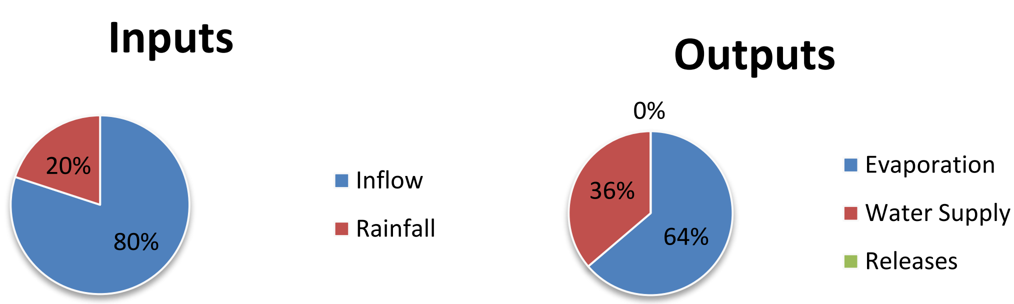


Figure 5. 2012 Lake Thunderbird input and output sources by month and expressed as the percent of totals.

Sources of Error

Although robust, the hydrologic budget does contain error. In the 2012 calendar year, the hydrologic budget contains a cumulative ***annual*** error of 2453 acre-feet, with an average ***monthly*** error of 204 acre-feet in 2012.

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 intake and discharge of the SDOX unit for design and installation purposes. This survey indicates little sediment accumulation in the dead pool of the lake compared to the 2001. Newly deposited sediment is predicted to be mostly in the upper portion of the conservation pool with a loss of approximately 4,800 acre-feet. It should be noted that the method used to calculate capacity in the original design used fewer data points than the 2001 bathymetric survey, and thereby, results 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 to be negligible. This could be verified with field measurements or through a review of the geology in the area.

Of these potential sources of error, the greatest is inflow. Implementing two of the following four actions would reduce uncertainty of inflow estimates:

1. Install a gauge and record instantaneous flow on the main tributary to the lake,
2. Develop modeled estimates of inflow to the lake, and
3. Back calculate inflow volume based on recent bathymetry
4. Check release gate calibration.

It is important to note that 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

As warming of the lake surface progresses through spring, the onset of stratification follows. 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 (**Figure 6**). Because of these differences, thermal resistance to mixing prevents the epilimnion and hypolimnion from coming in contact during stratification. Therefore, when DO is consumed and depleted by the decomposition processes in the hypolimnion, it is not replenished. This process has been documented by the OWRB at Lake Thunderbird for every monitoring year to date (since 2000), and is inevitable without the influence of outside forces.

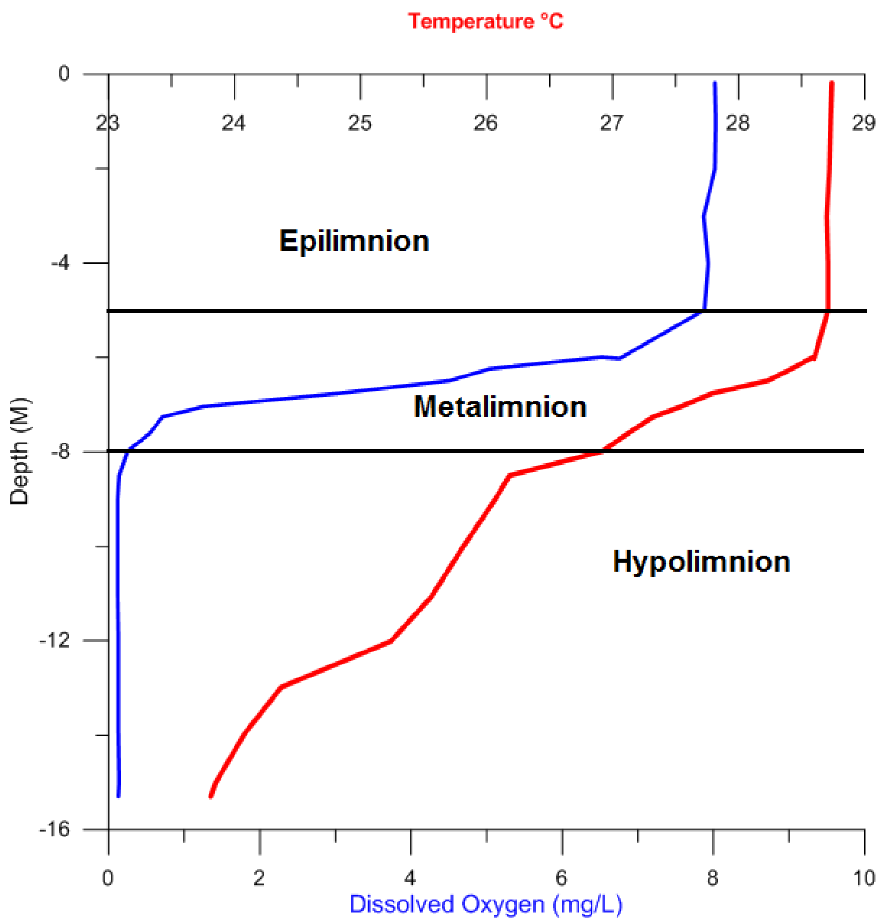


Figure 6. A typical temperature and dissolved oxygen vertical profile for Lake Thunderbird (July 18th, 2012).

Prior to the onset of stratification, the lake has 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, and the thermocline disappears as the epilimnion mixes with the lower layers. This process is referred to as fall mixing or “turnover”.

Lake stratification may have a significant effect on water quality by isolating chemicals in areas of reduced exchanged (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 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 nutrients are then entrained back into the epilimnetic waters in large volumes under 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 nutrients in the hypolimnion are mixed back into the epilimnion.

Lake stratification can also affect drinking water treatment cost and quality. Treatment cost can be affected through rising organic content through the stimulation in algae growth associated with turnover discussed later in this report. Also the quality of drinking water can be affected as hypolimnetically stored algal cells are incompletely decomposed and contents of the algal cells are recirculated into the water column. The City of Norman most commonly receives taste and odor complaints about the drinking water at this time of year, and also has confirmed the presence of algal associated taste and odor compounds MIB and Geosmin.

In 2012, the season began with the lake in an isothermal state. As increased solar radiation and ambient temperatures began to occur, the upper portion of the water column began to heat up while the bottom of the lake stayed cooler, which led to a stratification of the water column. A large portion of the water column experienced anoxia by June 14th 2012 (**Figure 7**). It should be noted that, by the first sampling period in April, the temperature at the bottom of the lake was above 16 degrees centigrade, about 2 degrees higher than normal.

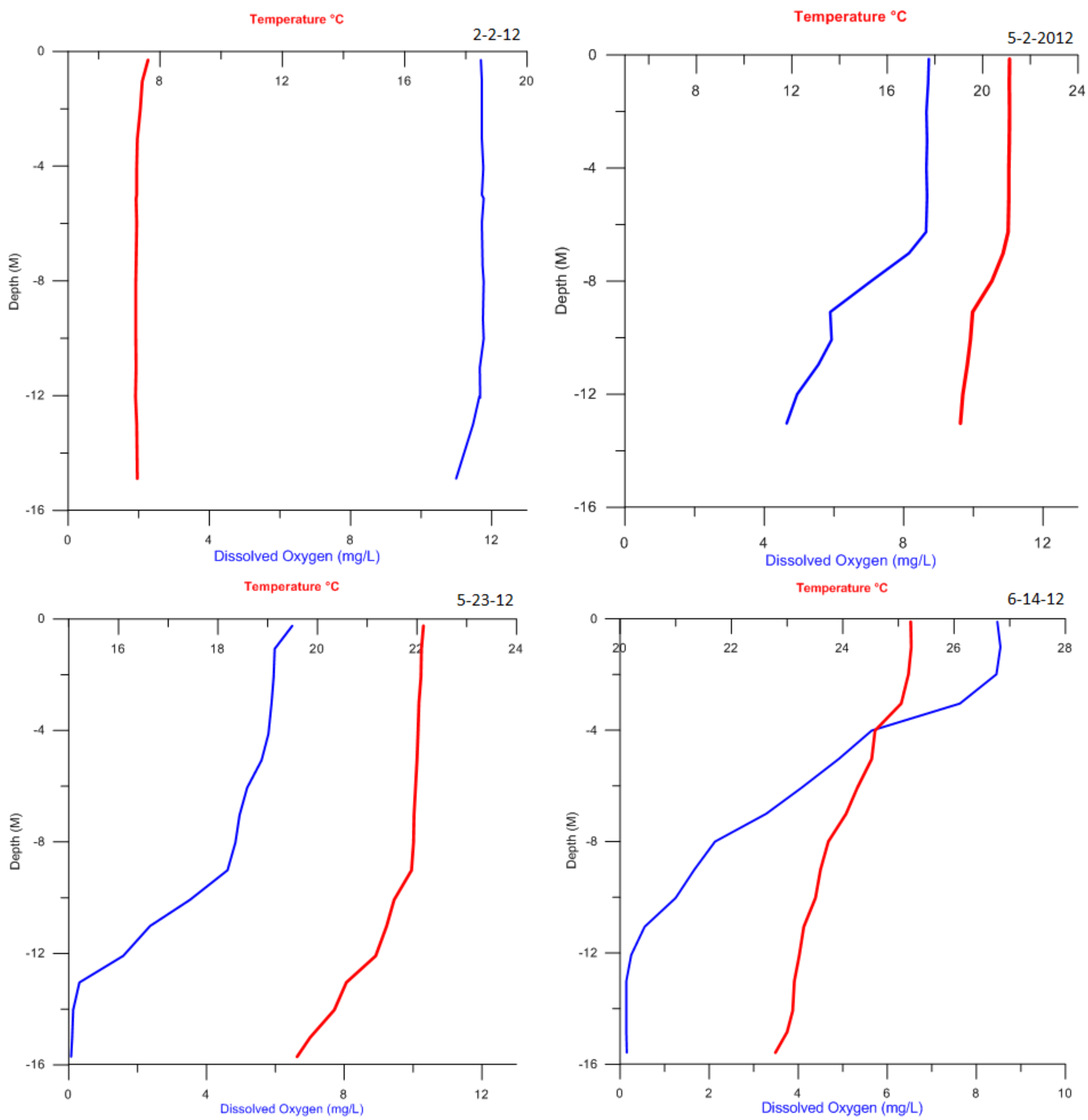


Figure 7. Temperature and Dissolved Oxygen Vertical Profile. Site 1: February 2nd 2012 – June 14, 2012.

As the summer progressed from late June through early August, heating at the surface began to occur much more rapidly than at the lake bottom. This caused thermal stratification to greatly strengthen; anoxia peaked on August 1st, 2012 at ~6 meters **(Figure 8).**

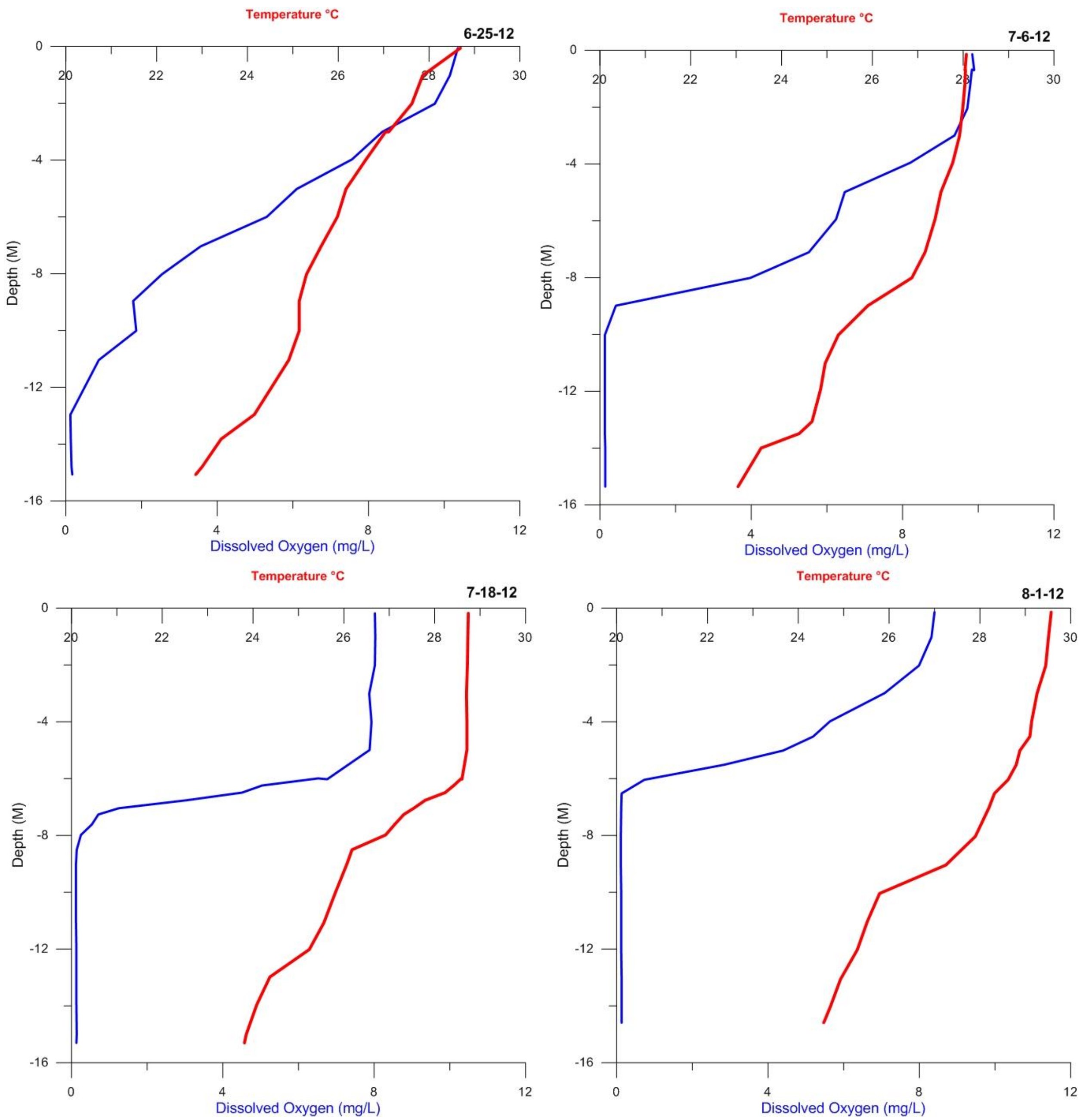


Figure 8. Temperature and Dissolved Oxygen Vertical Profile Site 1: June 25, 2012 – August 1, 2012

As the ambient temperatures cooled from the extreme heat experienced at the end of July, thermal stratification weakened shrinking the hypolimnion from 6 meters to 9 meters. The consequence of mixing this large volume of anoxic water was witnessed as depressed surface DO values during August 15th 2012 (**Figure 9**). By mid-October, sediment oxygen demand was met and a homogenous isothermal water column was observed.

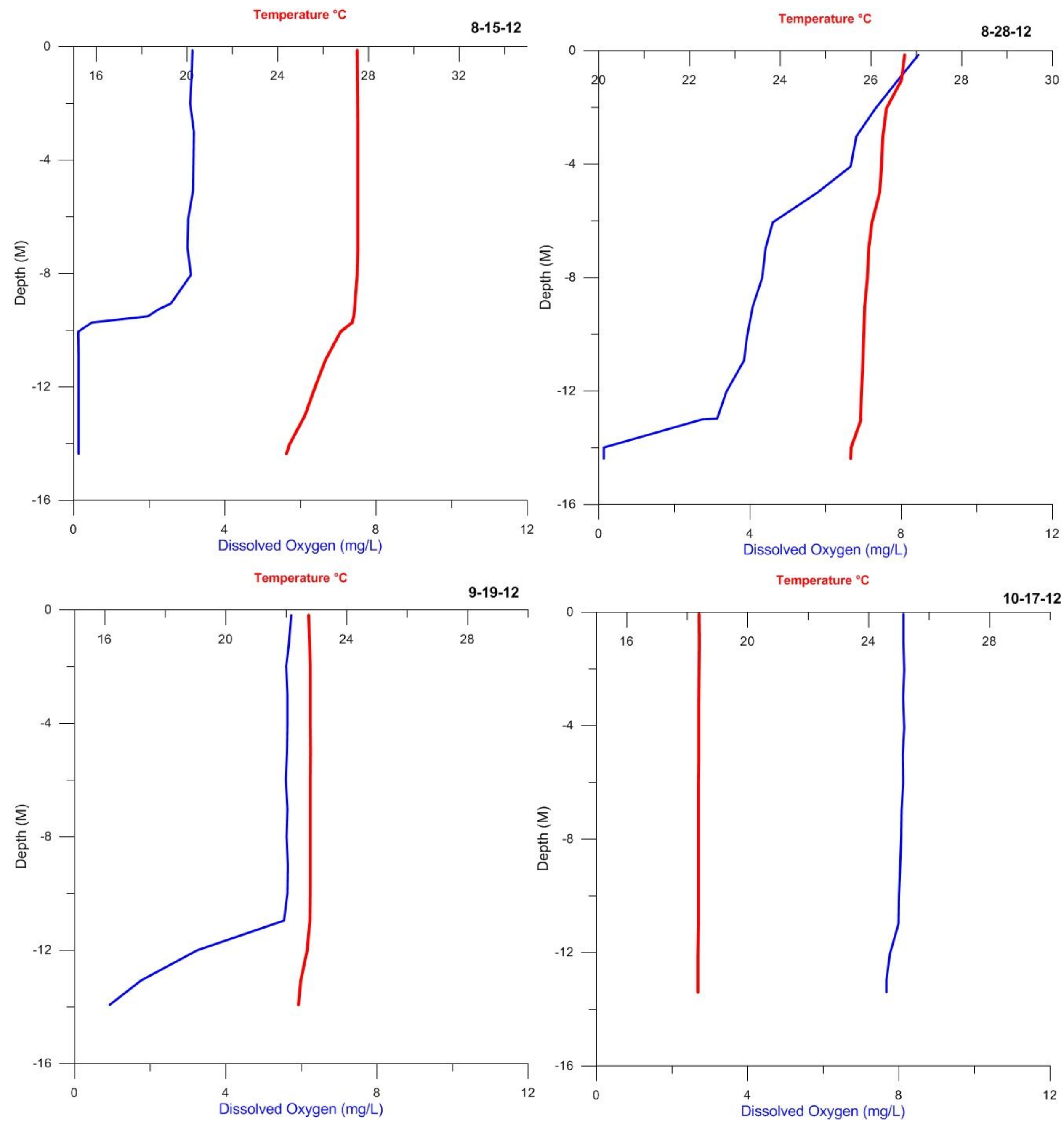


Figure 9. Temperature and Dissolved Oxygen Vertical Profile Site 1: August 1, 2012 – October 17, 2012. Showing complete turnover and recovery of DO (oxidation of reduced compounds formed in the hypolimnion).

An alternate method for illustrating physical lake data is by using an isopleth. These 3 dimensional plots show variation in physical parameters over depth and time. The following isopleths show the same temperature and DO data for Site 1 in a summarized form (**Figure 10**). Site 1 is largely representative of seasonal dynamics and 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, warmer temperatures are colored red, graduating to blue as temperature decreases, while on the DO plot, low DO values are colored red, graduating to blue as DO increases.

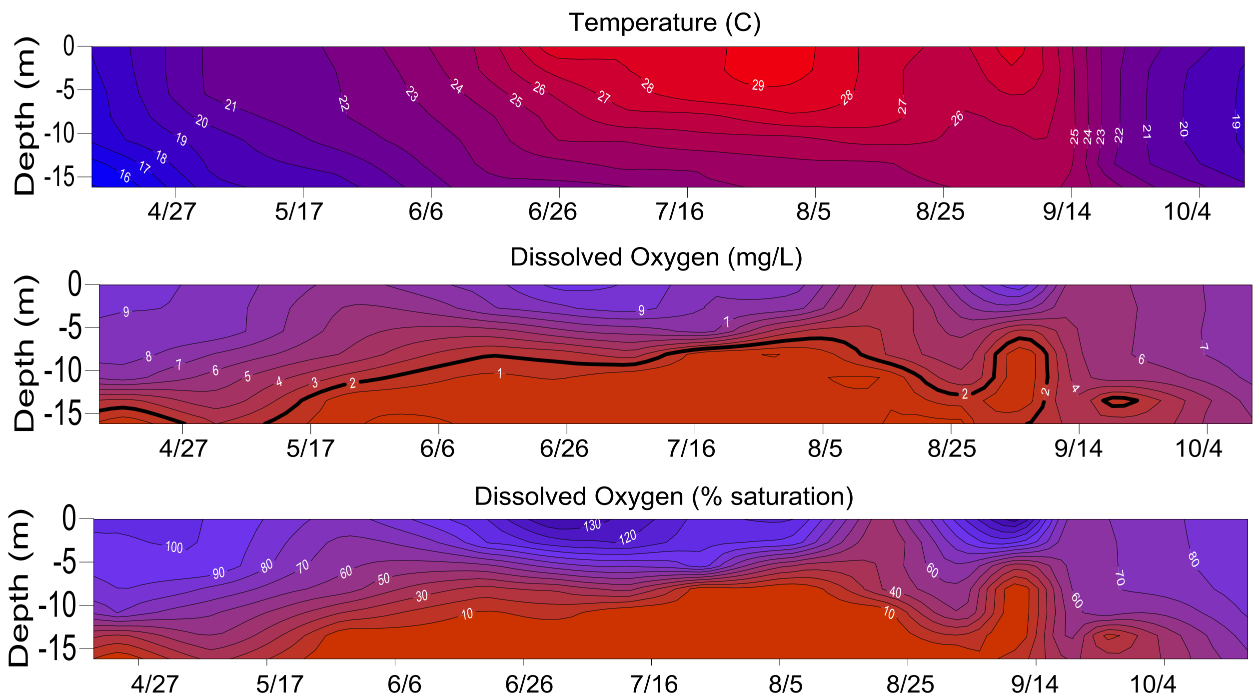


Figure 10. Lake Thunderbird isopleths showing temperature (C), and dissolved oxygen (mg/L) with depth at Site 1, by date for 2012

During 2012, thermal stratification patterns changed significantly throughout the monitoring season. During May and most of June, the entire water column warmed up at a uniform rate. As the summer progressed, 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 mid-July and can be observed on the isopleth as the tightening of contour lines that run parallel with the x axis. While strong thermal stratification did not arrive until mid-July, stratification significant enough to isolate a hypolimnion void of DO, became present much earlier.

Anoxia is generally defined as less than 2 mg/L of DO. While a well defined thermal stratification pattern was not present until July, anoxia appeared in May. In the hypolimnion, bacterial respiration and consumption of dead algae generally depletes oxygen trapped in the hypolimnion due to the lack of mixing with the upper water layer. When 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 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 blue area (higher oxygen content) pushes down into the red area (lower oxygen content).

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 blue at the surface in **Figure 10** represent oxygen production by excess algae growth with epilimnetic (surface) dissolved oxygen percent of saturation well above 100%. Supersaturation as the epilimnetic water warms is evidence of high algae productivity; epilimnetic waters below the saturation point indicate the decomposition of detrital material, which has built up during the previous five months, requires more oxygen than is available from the mixed epilimnion and/or diffusion with 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, fish kills, hypoxic/anoxic conditions, harmful algal blooms, taste and odor problems in finished drinking water, and public health concerns related to recreation and increased organic content of drinking water sources.

Nutrient samples were collected twelve times during the 2012 sampling season. Winter environmental conditions are represented by samples taken in February, samples taken in April and May represent spring conditions, while samples from June, July, August, and September represent summer conditions, and samples from October represent fall conditions.

Several measures of N and P were made, 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 limited 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. Blue-green algae are the only type of algae that may have heterocysts, and are generally implicated for producing harmful toxins and chemicals that can 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.

In regard to nutrient limitation, P, as the limiting nutrient, is desired for most freshwater systems. Under P limiting conditions, desirable green algae will typically be present, as opposed to the less desirable nitrogen-fixing blue-green algae. A recent study by Dzialowski *et al.* (2005) has broken the molecular ratio into three ranges, wherein a TN to TP ratio, TN:TP, 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. The molecular ratios correspond to TN:TP concentrations of less than 7 being nitrogen-limited, 8-18 being co-limited, and greater than 26 being phosphorus-limited, with gaps in classification between co-limitation and either nutrient. 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 in the 20's to 30's over the years, indicating the lake was phosphorus–limited and co-limited. Since the low in 2006, when all sample dates in the lake fell within a co-limitation range of N and P, the ratio has generally trended upward (**Figure 11**). In 2012, for all but the fall sampling date, data indicated strong phosphorous limiting conditions, with an average TN:TP ratio of 68 (**Figure 12**). Examination of TN:TP constituents shows the high ratio in 2012 is due to both a large rise in N and a drop in P. 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 be held in low concentration throughout the monitoring period. The 2012 dataset exhibited very low concentrations of Ortho-P throughout much of the growing season (average 0.007), and inorganic N levels below detection limit. While TN:TP ratios strongly suggest P limitation, a closer look at inorganic nutrients suggest that N may be the limiting nutrient.

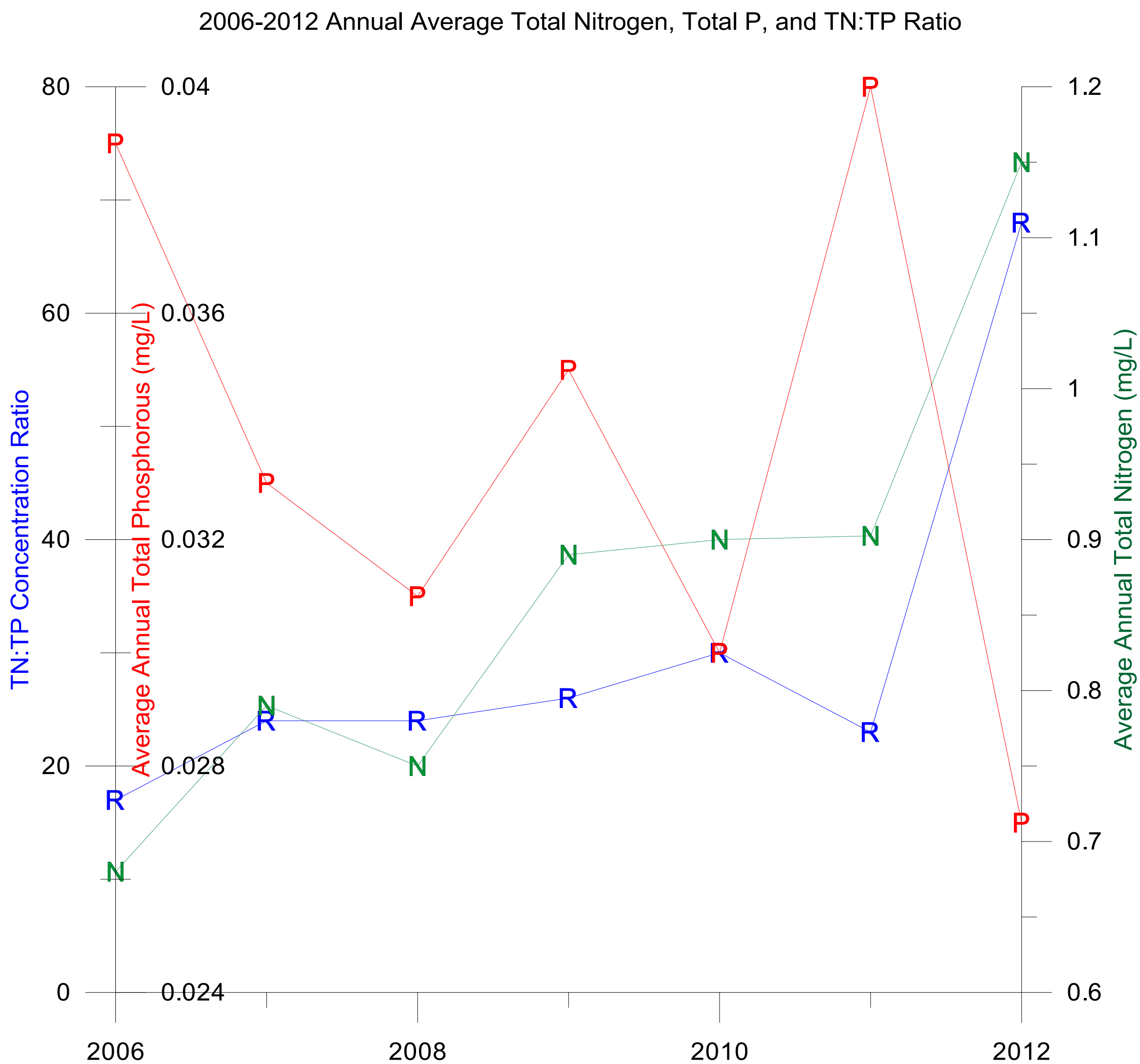


Figure 11. Annual average Total N, Total P, and TN:TP ratio for 2006 through 2012

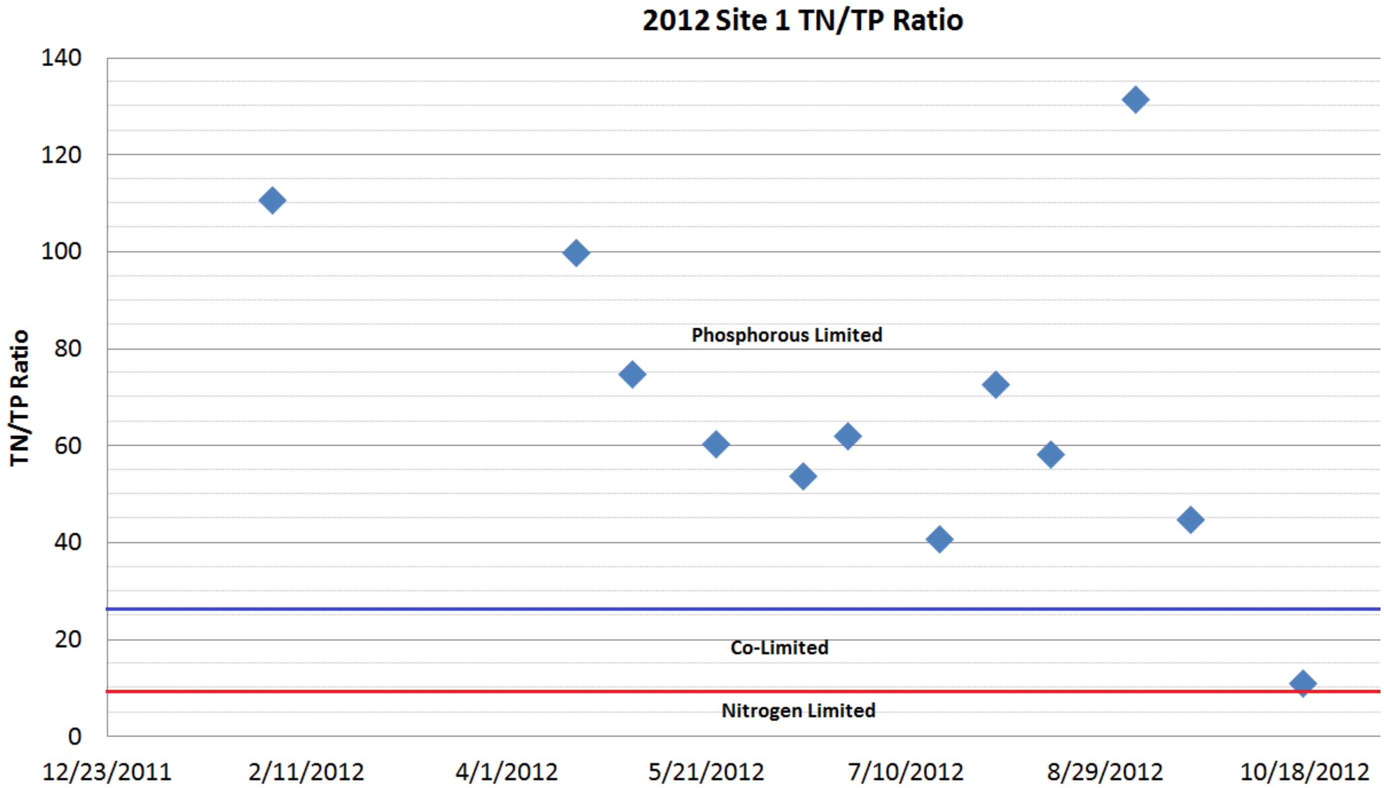
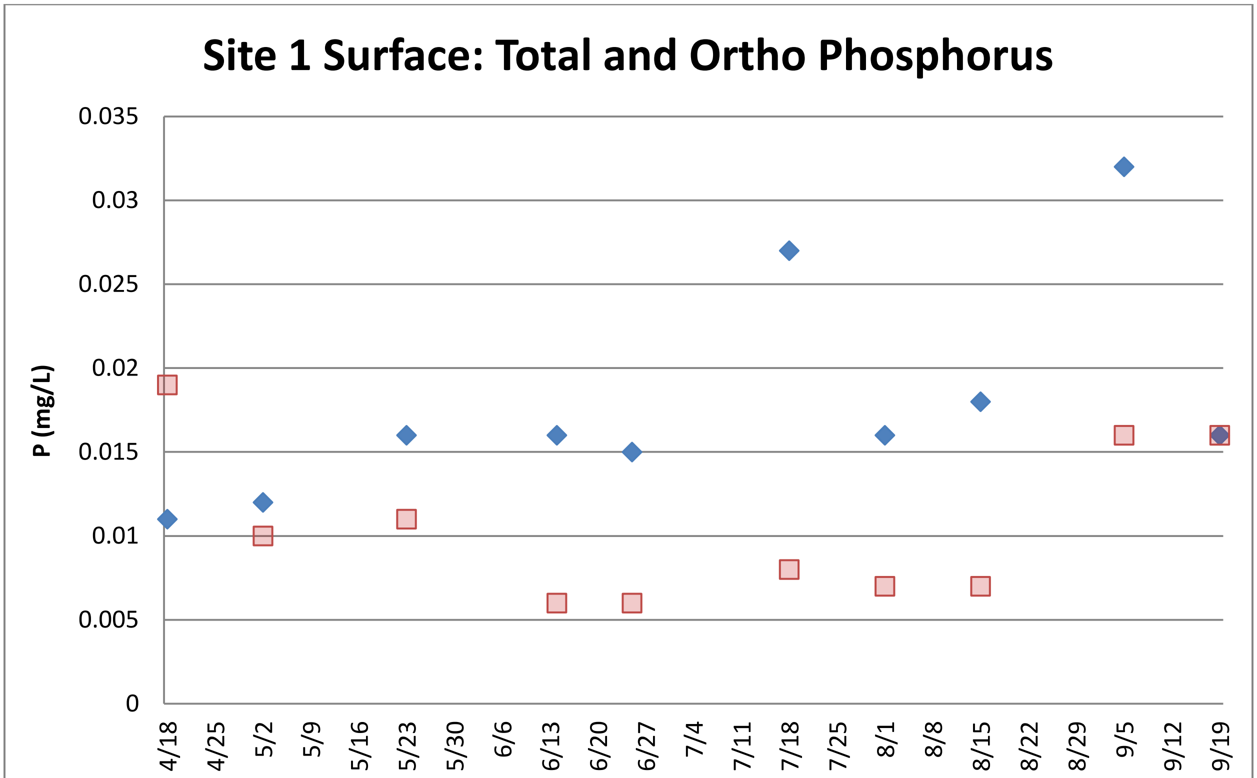


Figure 12. 2012 Site 1 surface TN:TP concentration ratio

Phosphorus – P

Total phosphorus and Ortho-P concentrations produced patterns typical of seasonal ecological cycles in lakes (**Figure 13**). Ortho-P was detected in every sample taken at Site 1 in 2012 with surface Ortho-P initially decreasing until reaching a relatively stable level near 0.006 mg/L. Surface Ortho-P averaged 0.015 mg/L. 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 14**). Rise in surface Ortho-P in late 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.

The highest surface TP was noted at the end of the monitoring season; on October 17th TP peaked at .155 mg/L (nearly 9 times that of any other site 1 surface sample). In 2012, the average surface TP concentration at the surface of site 1 was 0.027 mg/L, 20% less than the 0.034 average from the 2006-2011 historical dataset.



	4/18	5/2	5/23	6/14	6/25	7/18	8/1	8/15	9/5	9/19
Total-P	0.011	0.012	0.016	0.016	0.015	0.027	0.016	0.018	0.032	0.016
Ortho-P	0.019	0.010	0.011	0.006	0.006	0.008	0.007	0.007	0.016	0.016

Figure 13. 2012 Lake Thunderbird surface Ortho-P and TP, by date, at Site 1.

Note data from 10/17 has been omitted from the graph due to the excessive TP value. This excessive value made observation of seasonal trend difficult. 10/17/2012 Ortho-P=0.03 mg/L Total P=0.155 mg/L

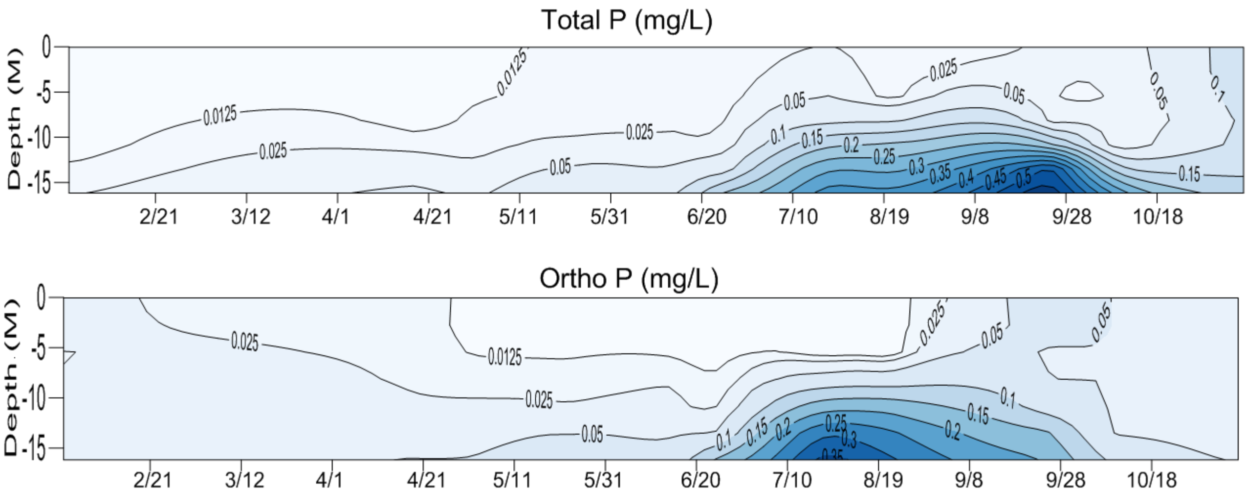


Figure 14. 2012 Lake Thunderbird total phosphorus and ortho-phosphorous Contours with depth, by date, at Site 1.

Nitrogen – N

Total nitrogen and DO concentrations also produced patterns somewhat typical of seasonal ecological cycles in lakes (
Figure 15). Surface total kjeldahl nitrogen showed a pattern of a general increase over the summer while dissolved forms of N fell below detection at the surface through most of the summer. As stratification deepened, nitrate-nitrite data spiked at the surface, which was followed by an increase in ammonia as hypolimnetic ammonia, finally reaching the lake's surface.

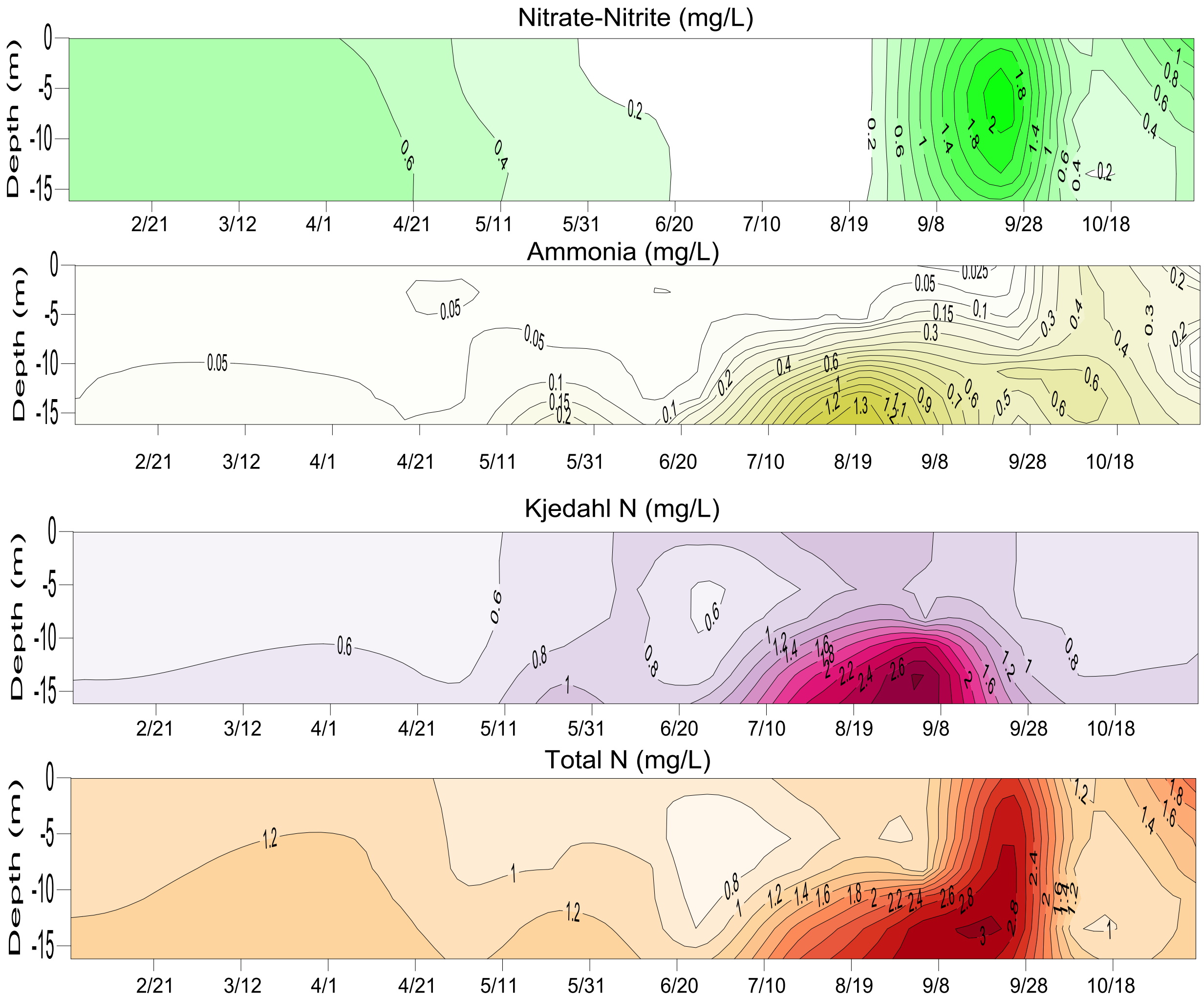
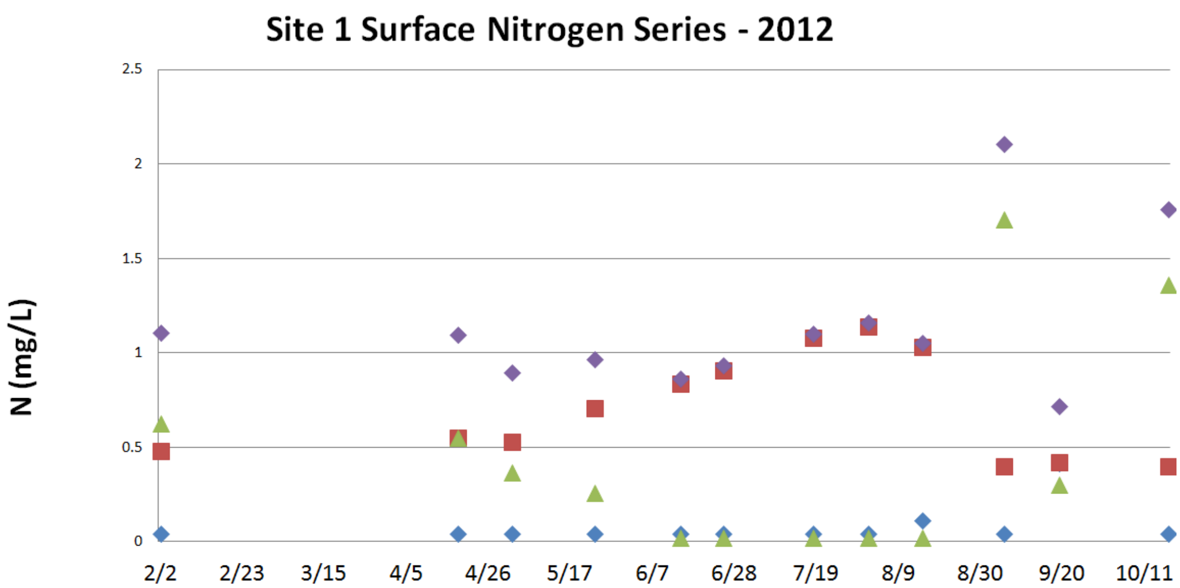


Figure 15. 2012 Lake Thunderbird NO2-NO3, Ammonia, Total Kjedahl N, and Total N contours with Depth, by date, at Site 1

The two most likely forces driving the surface N dynamics seen in the dataset are epilimnetic algae growth (uptake) and hypolimnetic sediment release of ammonia. These two forces were seen operating in 2012, as dissolved inorganic N plunged with rising Chl-*a*, and the large amount of ammonia released was then converted to nitrite-nitrate through nitrification in oxygenated conditions. Examination of dissolved N, ammonia and nitrate distribution with depth and over time, illustrates these points. In the hypolimnion, nitrate does not serve as a macronutrient, but as an electron source for anaerobic (bacterial) metabolism. A plot of ammonia details the reason for the high levels of dissolved N noted in the hypolimnion as ammonia was released from the sediment under anoxic conditions. Ammonia also results from the decomposition product of senescent algae cells in the epi- and metalimnion.

Dissolved inorganic N (NO3-NO2 + NH3) decreased to below detection limits in the epilimnion from mid-June through mid-August. The primary form of dissolved N in the epilimnion was nitrate (**Figure 16**). Nitrate is an algal macronutrient second only to ammonia for preferential uptake. Depletion by algal uptake can indicate nitrogen-limiting conditions. In 2012, biologically available Ortho-P remains above the detection limit throughout most of the summer while inorganic N is held below the detection limit. This gives strong evidence that N is limiting algae growth.



	2/2	4/18	5/2	5/23	6/14	6/25	7/18	8/1	8/15	9/5	9/19	10/17
◆ N-Ammonia	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.12	BDL	0.42	BDL
■ N-Kjeldahl	0.48	0.55	0.53	0.71	0.84	0.91	1.08	1.14	1.03	0.4	0.42	0.4
▲ Nitrate-Nitrite	0.63	0.55	0.37	0.26	BDL	BDL	BDL	BDL	BDL	1.708	0.301	1.36
◆ Total N	1.11	1.1	0.9	0.97	0.865	0.935	1.105	1.165	1.055	2.108	0.721	1.76

Figure 16. 2012 Site 1 Surface NO2-NO3, N-Ammonia and Total Kjedahl N, by date, at Site 1.

Nutrient Budget

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 bathymetric survey data to partition TP reports in one meter intervals between epilimnetic, metalimnetic and hypolimnetic layers (**Table 3**). The cumulative summation of these layers allows the massing of P for each sample date. Once the lake mass was established, the distribution within the lake and losses were estimated using USACE water quantity reports and OWRB water quality reports. Missing from this lake nutrient budget are estimates of phosphorus inflow, dry deposition and sediment flux.

Table 3. 2012 Lake Thunderbird Site 1 Phosphorus Mass (kg) at Depth Intervals by Sample Date. (Gold cells represent anoxic accumulation of phosphorus).

Depth (m)	2-Feb	18-Apr	2-May	23-May	14-Jun	25-Jun	18-Jul	1-Aug	15-Aug	5-Sep	19-Sep
0 - 1	171	213	237	308	322	281	488	283	302	545	534
1 - 2	132	171	196	280	236	262	558	247	265	507	471
2 - 3	100	135	160	215	219	224	592	203	221	395	414
3 - 4	73	106	139	205	171	210	672	189	194	506	445
4 - 5	51	113	162	214	176	211	611	156	167	301	301
5 - 6	38	61	108	153	141	176	492	156	168	235	235
6 - 7	27	44	96	129	125	151	331	150	167	193	193
7 - 8	19	33	87	113	115	161	221	140	158	160	209
8 - 9	11	25	80	100	137	128	131	120	135	121	119
9 - 10	13	41	67	120	97	108	182	211	238	380	77
10 - 11	12	64	75	103	75	82	175	216	248	237	46
11 - 12	8	32	31	57	52	56	136	169	184	160	22
12 - 13	5	19	16	32	28	30	80	100	110	89	10
13 - 14	4	10	8	16	15	28	52	55	55	31	10
14 - 15	0	3	2	4	5	15	24	19	15	14	0
15 - 16		2	1	1	2	0	1	0	0	0	
16+		0	0	0	0	0	0		0		
x											
Total	663	1074	1466	2049	1915	2123	4747	2413	2627	3875	3086
Hypolimnetic Mass			133	433	177	211	468	559			
Hypo % of Total Water Column			9%	21%	9%	10%	10%	23%			

The constructed budget demonstrates pre-stratification lake P mass in 2012 of approximately 1,074 kg. This is the lowest pre-stratification TP mass ever detected (2009:3600 kg, 2010:3700 kg, 2011:4100 kg). Drought conditions likely contributed to the drop. The spring of 2007, which followed the severe drought of 2006, had the second lowest pre-stratification mass on record of 1,920 kg. July 18th marked the highest (4747 kg) mass lake TP.

Lastly, it is worthwhile mentioning that reduction in extent and duration of anoxia (areal anoxia) within the water column in 2012, when compared to the 2005-2009 average, should correspond to a reduction in anaerobically mediated sediment P release. Using calculations based on Nurnberg (2005), and specifically developed for Lake Thunderbird by OWRB, it was calculated that anaerobically mediated sediment P release was reduced by 17%, equivalent to 4% of the average annual TP load (OWRB 2011).

Chlorophyll-*a* – Chl-*a*

Chlorophyll-*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 2012; Chl-*a* peaked in mid-August. In 2012, 88% of samples were considered eutrophic based on a 7.2 g/L division between mesotrophy (Wetzel 2001). This appears to be a reversal of the steady increase witnessed since 2007, (2011:98%, 2010:95%, 2009:91%, 2008:87%, 2007:80%). For the lacustrine sites (1, 2, 4), Chl-*a* followed a typical seasonal progression of early stability followed by marked increase until fall turnover **(Figure 17**). For the riverine sites of Hog Creek and Dave Blue Creek (8 and 11), Chl-*a* followed a pattern similar to that of the lacustrine sites. The Little River (Site 6) was the exception, starting off the year at very high levels and maintaining these high levels of Chl-*a* through much of the year (**Figure 18)**. This is not surprising as it has been documented in previous reports that the Little River is the major contributor of nutrients to the reservoir and it maintains the highest nutrient concentrations of the riverine sites (**Figure 19**) and well above that of the lake average.

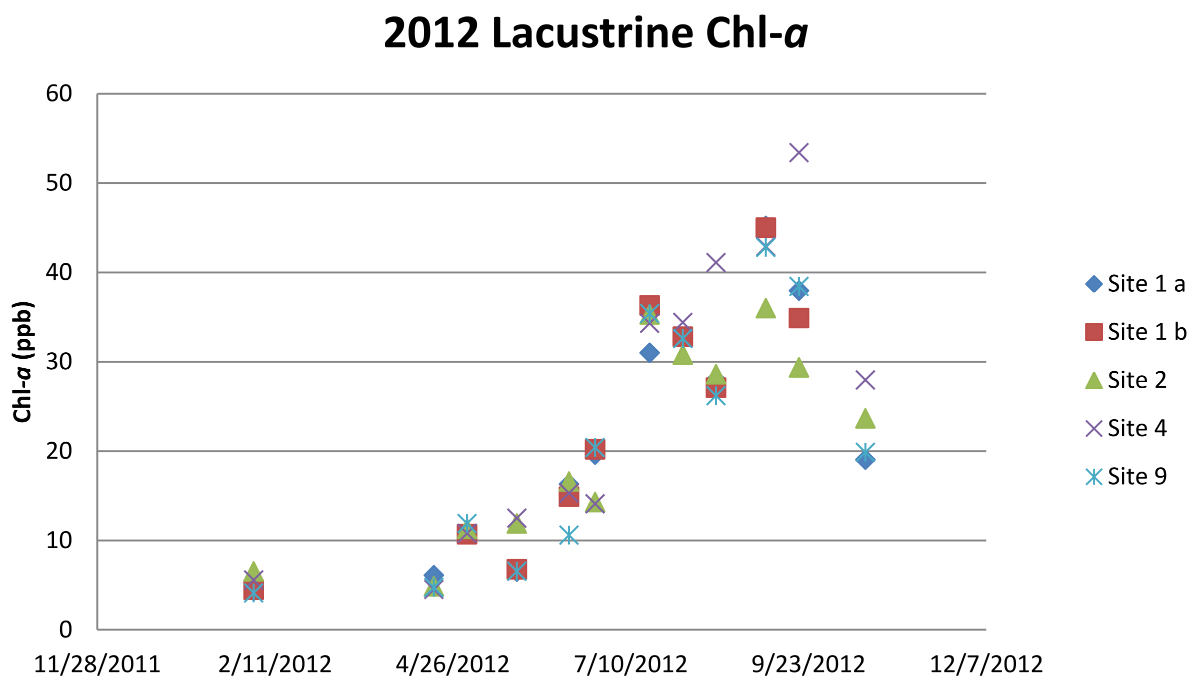


Figure 17. Lake Thunderbird lacustrine surface Chl-*a* (g/L) by site; February through October 2012

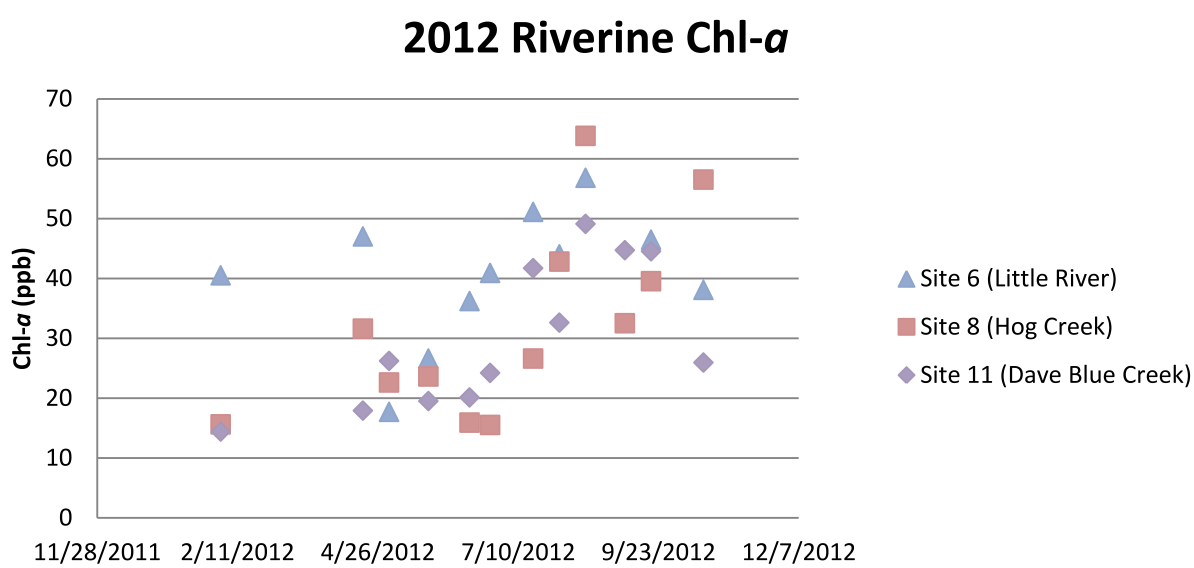


Figure 18. Lake Thunderbird riverine surface Chl-*a* (g/L) by site; February through October

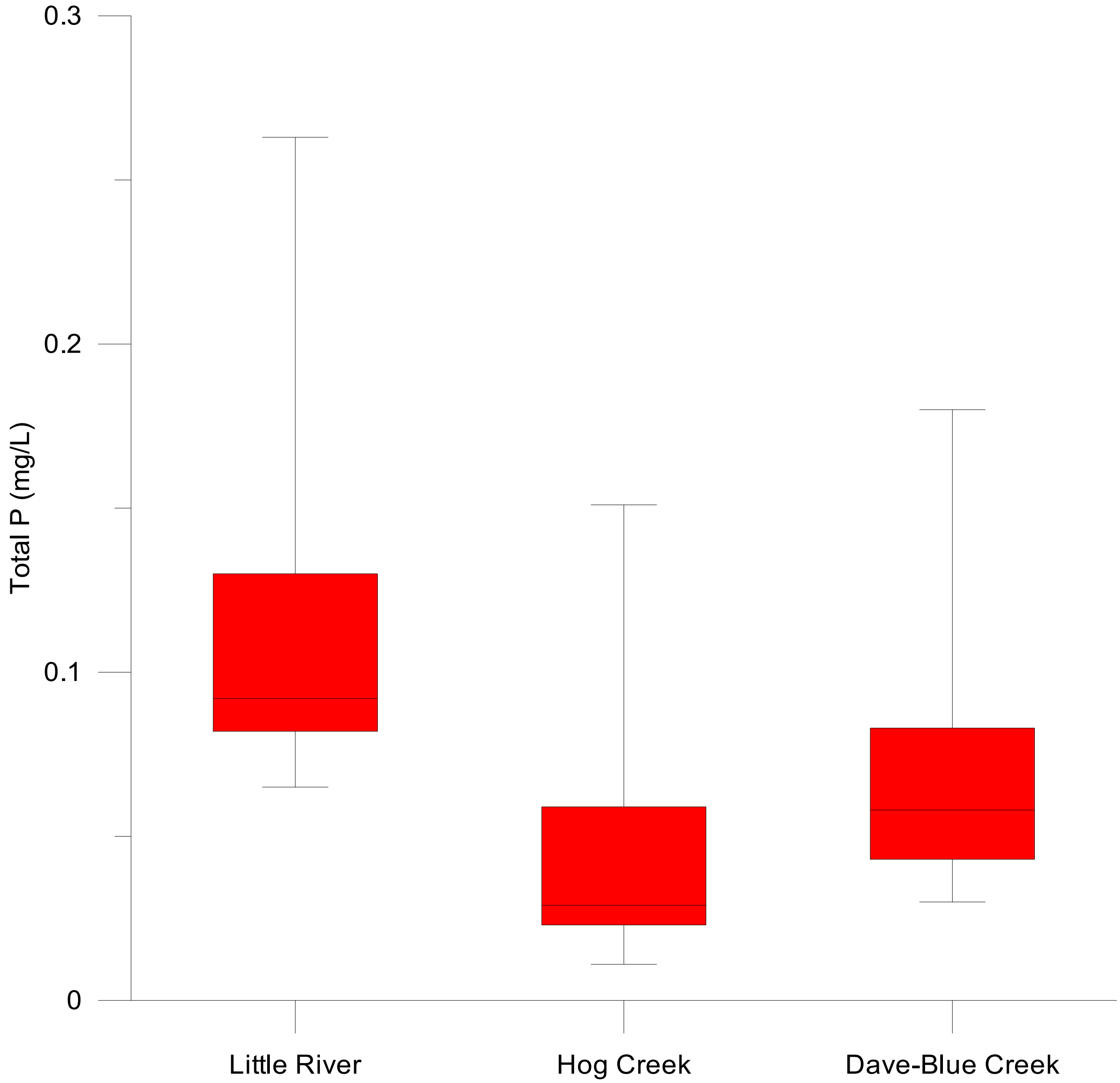


Figure 19. Box plot of TP values from riverine sites in 2012.

For the 2012 sampling season, the lake wide average Chl-*a* at Lake Thunderbird was 24.6 µg/L which represents a large reduction from the lake wide average of 36 from 2011 and the 2005-2009 historical average of 30.6. Observed peak Chl-*a* was also greatly reduced from the previous few years with the Site 1 maximum of 45 ug/L representing the lowest peak at Site 1 since 2007 (**Figure 20**).

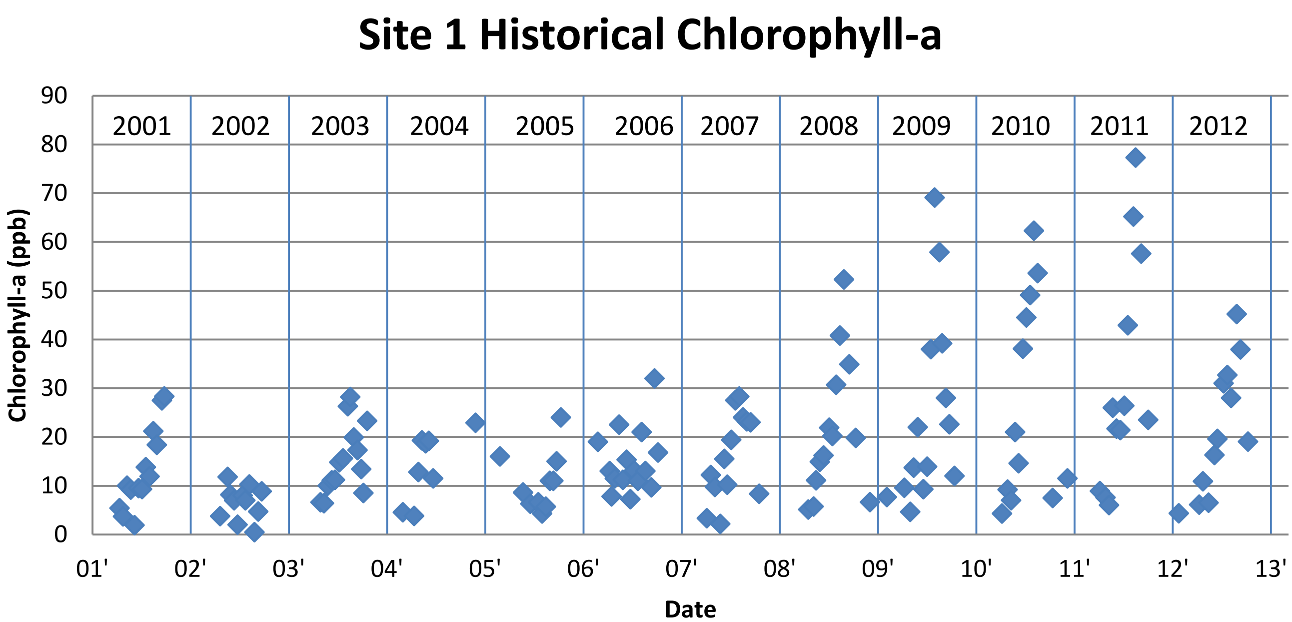


Figure 20. 2001-2012 Lake Thunderbird surface Chl-*a* (ppb) at Site 1

General Water Quality

Total Organic Carbon - TOC

Total organic carbon is an additional measure of organic content and productivity. Total organic carbon samples were collected at the surface of one of the lacustrine sites and three riverine sites within the 2012 calendar year.

Lacustrine TOC concentrations increased from the end of May through mid-September, with peak concentrations occurring in mid-September (**Figure 21**). Concentrations declined significantly after this large peak event. This trend is consistent with another proxy of primary production, Chl-*a* (**Figure 17**).

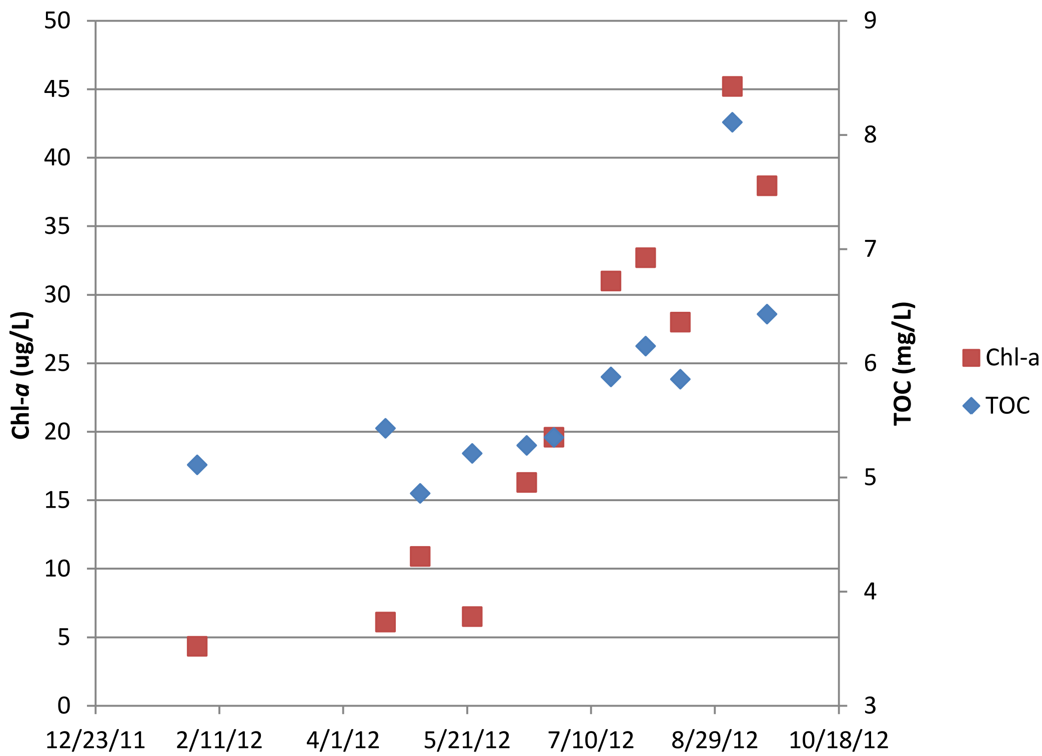


Figure 21. TOC concentrations and Chl-*a* at Site 1 surface on Lake Thunderbird during the 2012 sampling season

Statistical regression as seen in **Figure 22**, suggested that 75% of the variability in reported TOC could be explained by Chl-*a*. 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). 2012 represented the fourth consecutive year of TOC sampling; each season of sampling has shown a correlation coefficient of 0.5 or better. Regression suggests 4.6 ppm TOC is the lowest TOC that could be expected without any algae growth, the regression also indicates that there is approximately a 0.5 ppm change in TOC per 10ug/L Chl-*a*.

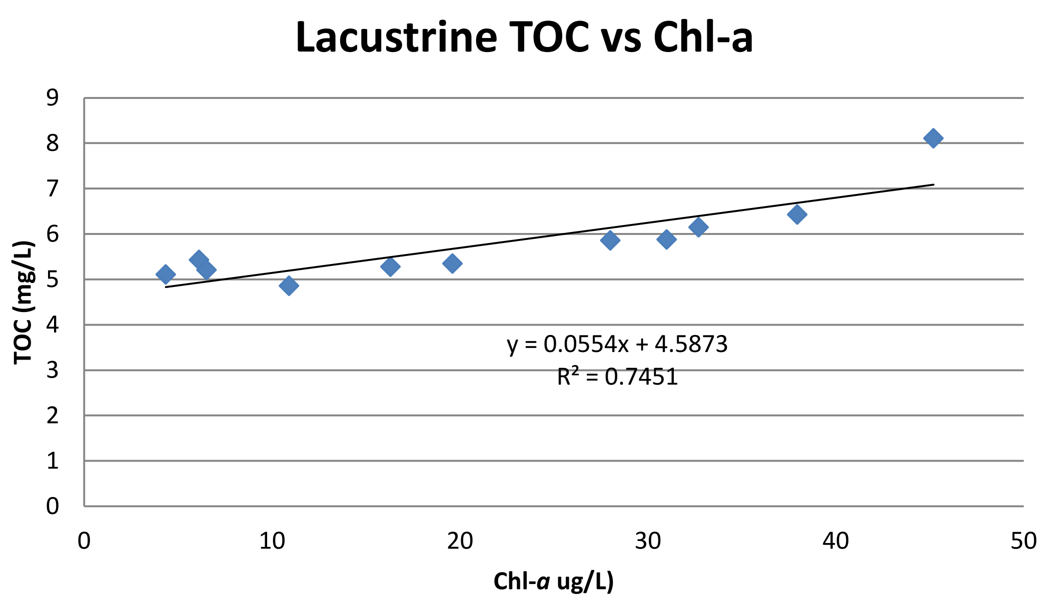


Figure 22. 2012 Lake Thunderbird TOC vs Chl- *a* for raw water samples

Trophic State Index - TSI

Trophic state is defined as the total algal biomass in a water body at a specific time and location. For lakes and reservoirs the Ttrophic State Index (TSI) of Carlson (1977) is the most common measure of algal biomass and is used as the trophic index by the United States Environmental Protection Agency. Three surface variables, Chl-*a*, Secchi depth, and TP can be used independently to estimate algal biomass. Of these three, chlorophyll yields the most accurate measure, as it is the most direct measure of algal biomass. Secchi depth is probably 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.

Lake Thunderbird's TSI values for the three variables can be seen, in **Figure 23**, to range from 37-76 throughout the year. Lake Thunderbird starts the year in mesotrophic conditions (TSI 30-50), then as the TP concentration rises, so does Chl- *a*. This brings the lake through periods of eutrophic conditions (50-60) and hypereutrophic conditions (60+). Secchi disk TSI starts the year high and remains relatively high throughout the year.

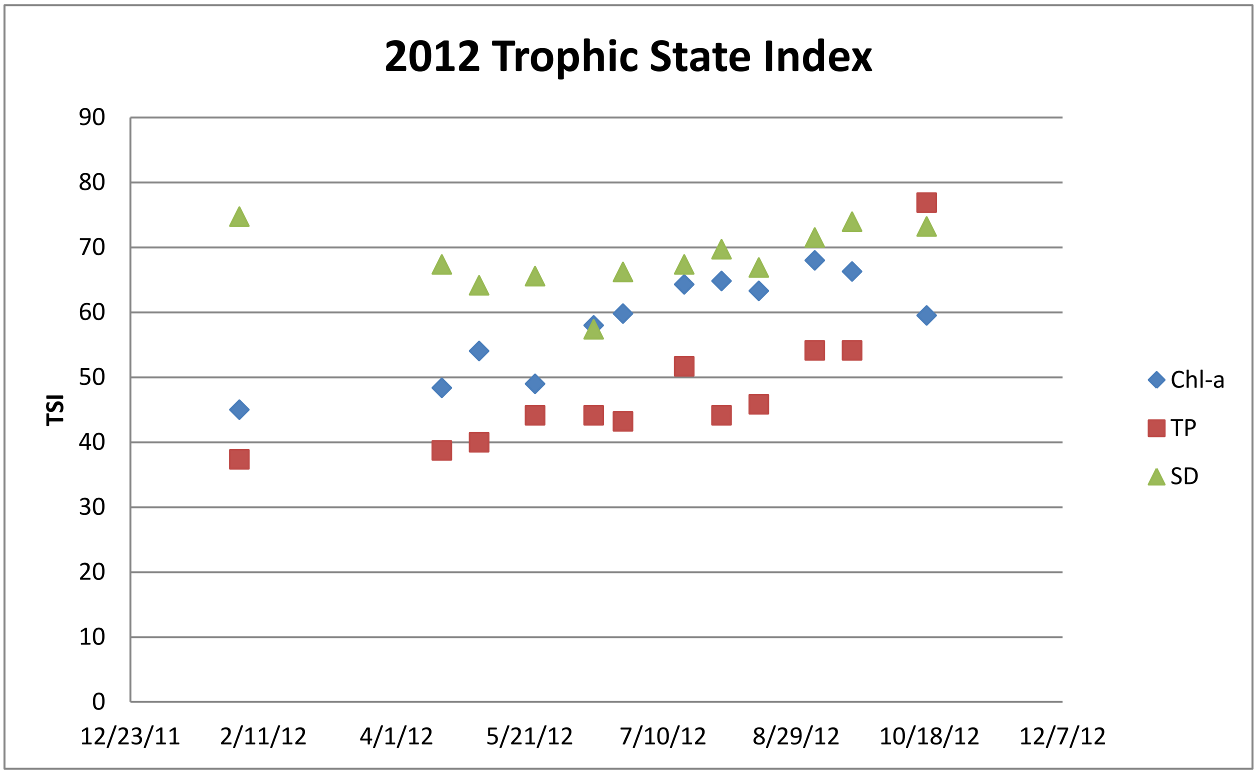


Figure 23. Carlson's Trophic State Index values for Lake Thunderbird 2012 at Site 1.

The three TSI measures change throughout the year due to changes in nutrient availability and levels of non-algal turbidity. In **Figure 24,** the TSI comparison plot indicates that the system is most often a P limited system, with one instance of potential light limitation seen on Oct 17th, 2012 following complete mixing. This observation is corroborated due to the fact that in all but 1 instance TSI (Chl-*a)* is larger than TSI (*TP)*, and TSI (Chl-*a)* is normally less than TSI (SD).

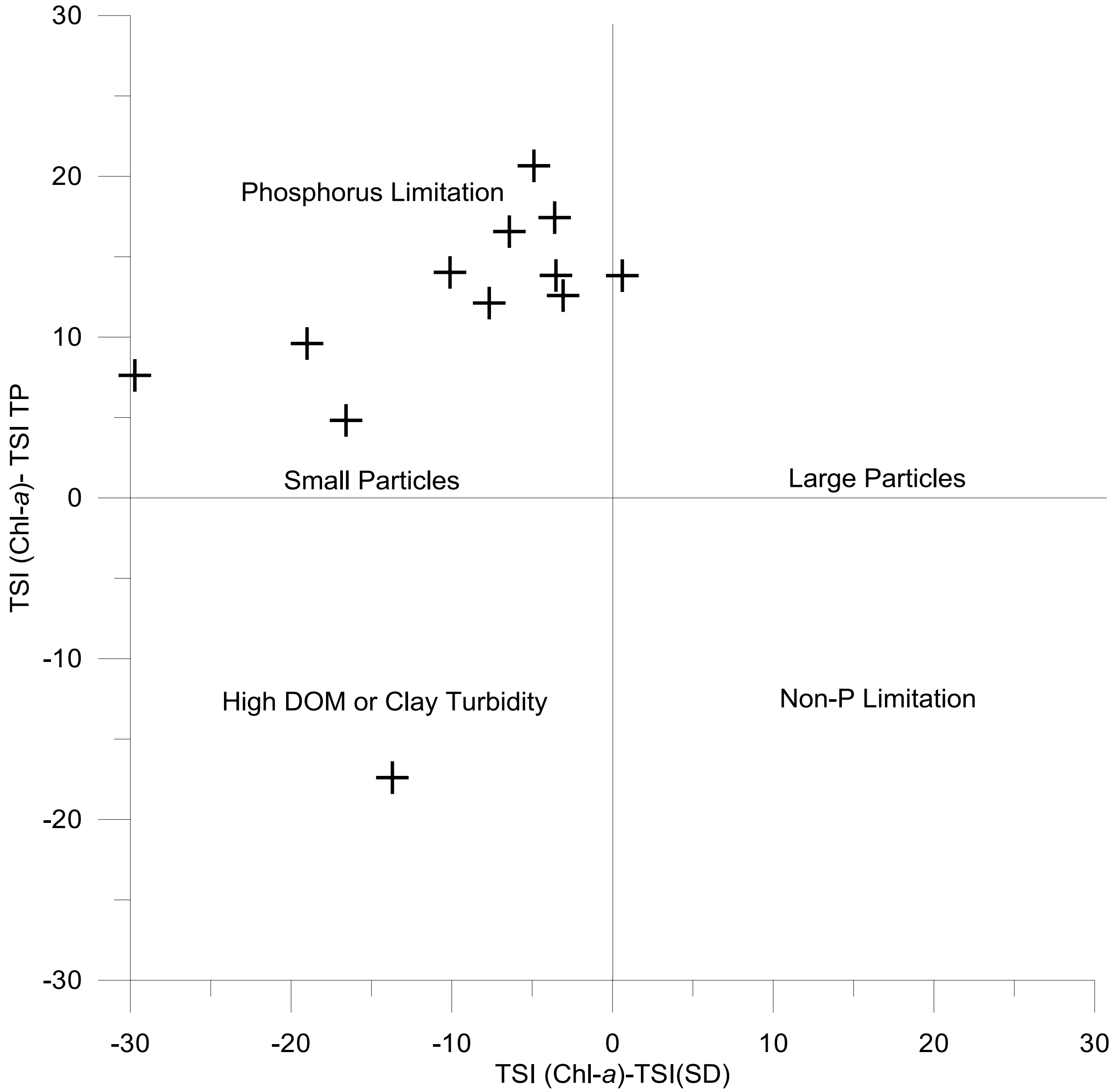


Figure 24. Potential nutrient limited and nonnutrient-limited causes for the deviation of biomass-based trophic state index.

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. It is the sinking organic matter in the summer months (due to high algal production) that stimulates decomposition processes in the hypolimnion. High and low pH corresponds to peak algae productivity. High rates of photosynthesis will temporarily elevate pH as carbon dioxide is stripped from the water column in the epilimnion, while catabolism of the settling algae depresses pH in the hypolimnion.

Lake Thunderbird followed a typical eutrophic pattern of pH in 2012 in lacustrine sites (1,2,3 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 7) due to decomposition processes within hypolimnion (**Figure 25**). The riverine sites operated differently Chl- *a* and pH started off high and remained that way through the duration of the summer, indicative of hypereutrophic conditions. All riverine pH samples collected exceeded a value of 8. Oklahoma's WQS state that "pH values shall be between 6.5 and 9.0 in waters designated for fish and wildlife propagation". The maximum pH value recorded was 8.8 and the lowest recorded pH value was 6.8.

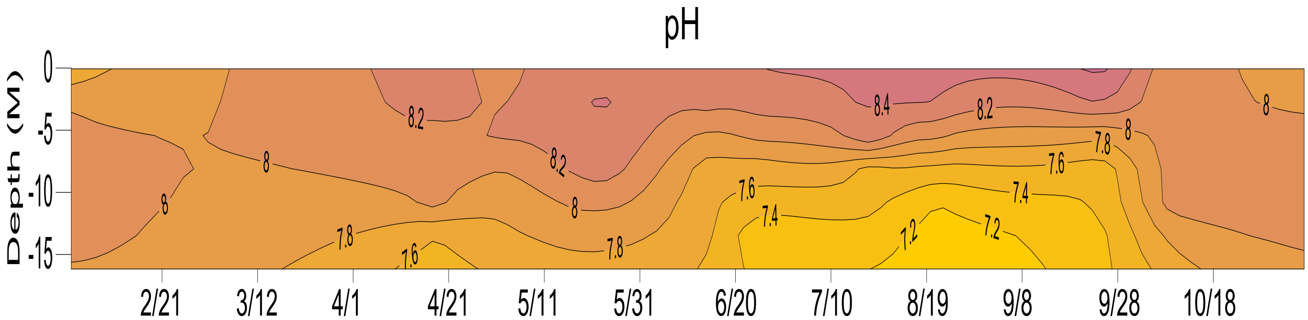


Figure 25. 2012 Lake Thunderbird pH (S.U.) versus Depth Over Time: Site 1

The biogeochemical cycling of inorganic nutrients is regulated to a large extent by changes in oxidation-reduction (redox) states and 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 begins to drop in proportion to anaerobic metabolism. In early 2012, oxygenated conditions were present throughout the water column and redox potentials remained high. As thermal stratification began to divide the water column, anoxia ensued. However, oxidation-reduction potential (ORP) values remained high. While anoxia was first noted in mid-May 2012, strong reducing conditions did not appear until July 2012. Oxidation-reduction potential data observed in 2012, like 2011, displayed a significant reduction in both the duration and extent of strong reducing conditions (<100 mV) from what was witnessed in the historical dataset (
Figure 26). It is important to note that literature sources state that sediment bound phosphorus and common metals, such as iron and manganese, will desorb as redox potential falls below 100 mV (Lerman 1978). Low redox potential is also associated with the production of sulfide and methane, as electron acceptors for anaerobic metabolism become scarce. Therefore, the reduction in the duration and extent of strong reducing conditions should result in a reduction of the desorption of these compounds as well.

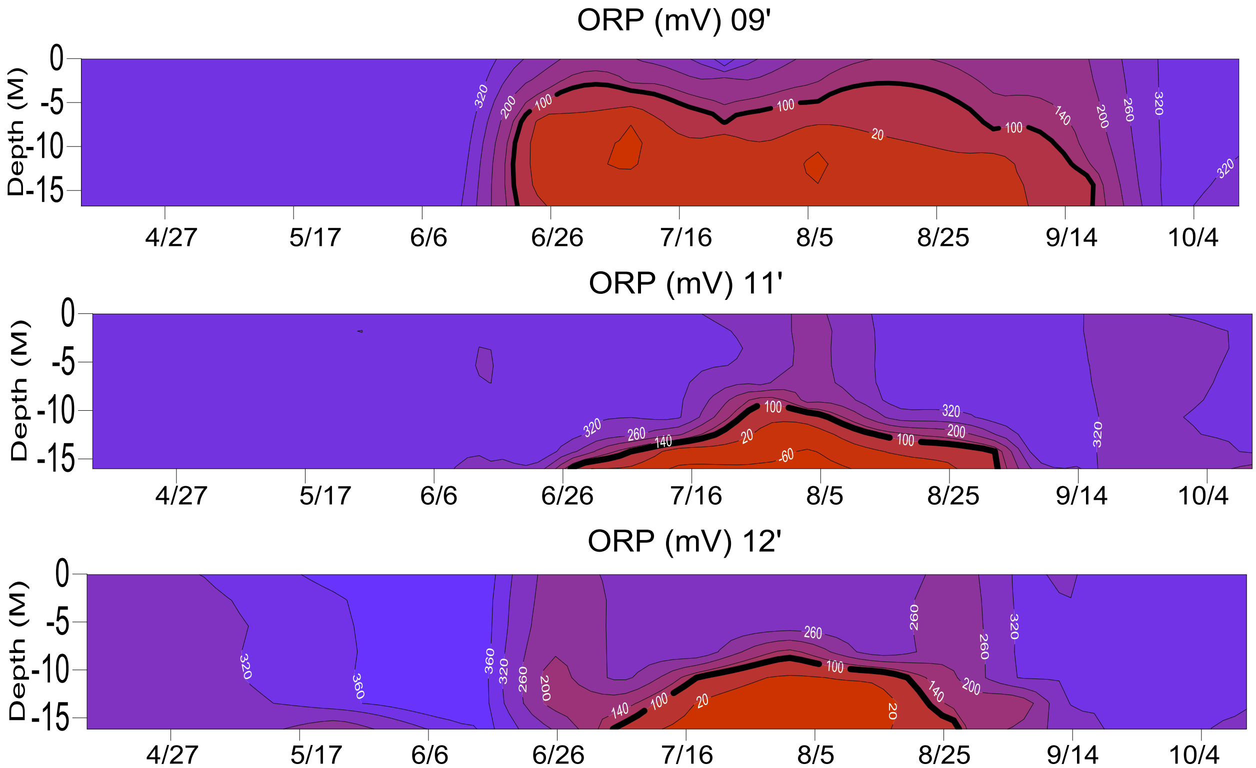


Figure 26. 2009, 2011, and 2012 Lake Thunderbird oxidation-reduction potential (mV) versus depth (M) over time: Site 1. Area below thick black line represents the strong reducing conditions responsible for reduction of sediment bound phosphorous.

Taste and Odor Complaints

The City of Norman provided data on the number of taste and odor complaints from their customers in 2012. 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 (~5-10 ng/L) (Graham et al 2008). The majority of these compounds are by-products of high algal productivity. The most commonly known taste and odor compounds, geosmin and 2-methylisoborneol (MIB), are produced primarily by cyanobacteria and were detected during the taste and odor event in September of 2012. In response to taste and odor event that began in late August of this year, the City of Norman added an additional treatment measure, particulate activated carbon (PAC), to the drinking water treatment process. The PAC process is known for its ability to remove taste and odor compounds from finished drinking water, and most likely was able to reduce the number of taste and odor complaints for the 2012 calendar year.

The month with the highest number of complaints was September with 5 (**Figure 27**). This pattern is similar to previous years, where a hypolimnetic mixing event in late summer or early fall, causes a spike in the number of complaints (**Figure 28**).

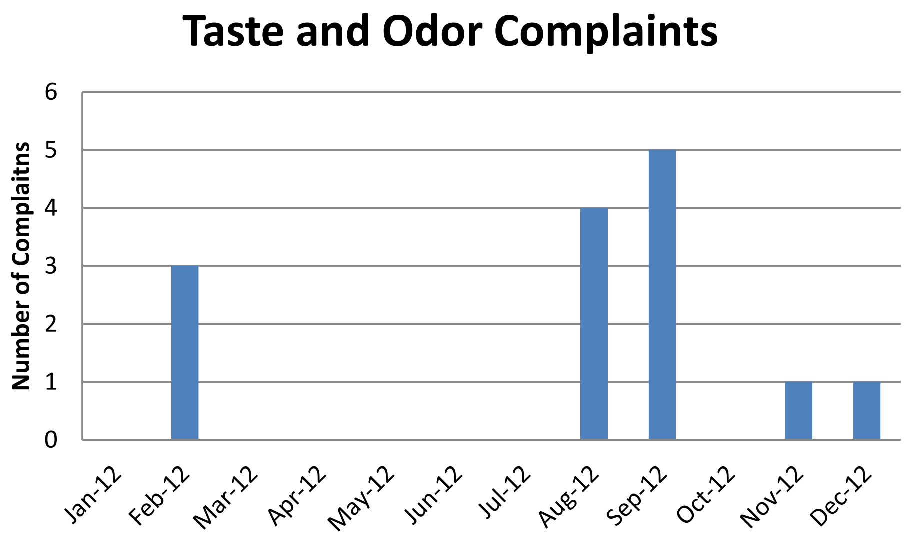


Figure 27. Taste and odor complaints to the City of Norman during 2012

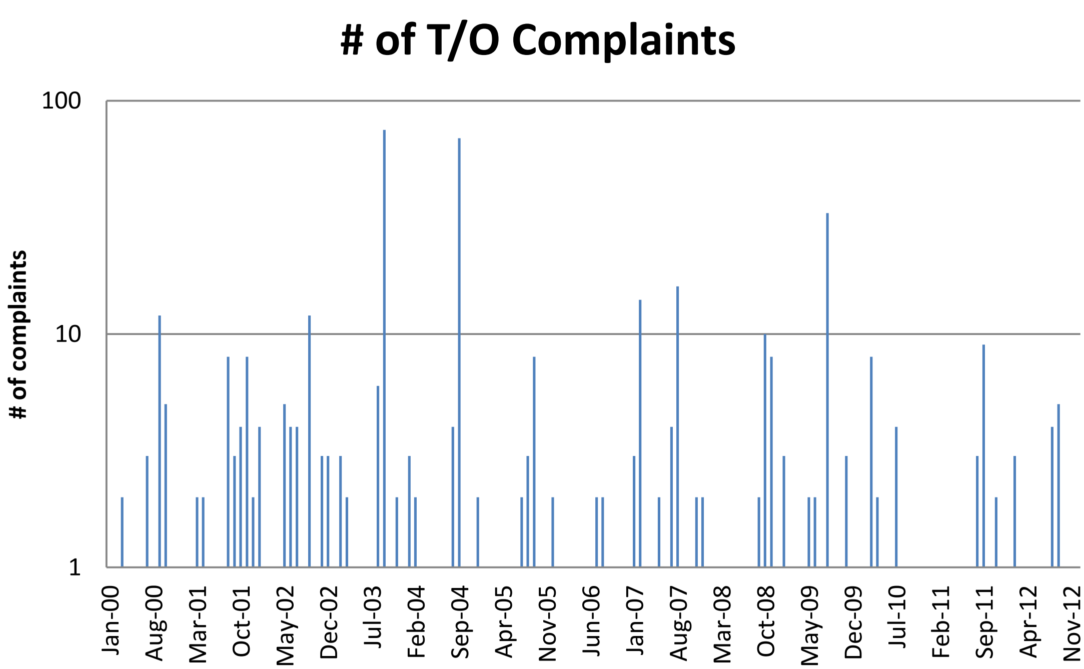


Figure 28. Taste and odor complaints to the City of Norman from 2000 through 2012

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 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 are 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 waterbody's beneficial uses are being 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.

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 (OAC 785:46-15-5).

Lake Thunderbird fully supports both its surface and water column criteria for the monitoring period in 2012. It must be noted that the lake did have moments of heightened anoxia. In respect to the surface DO criteria, on August 15th 2012, epilimnetic DO averaged at 3.1 mg/L, violating the surface criteria of 5 mg/L that applies during that timeframe. This single violation does not exceed the surface water DO criteria for 2012. Maximum water column anoxia peaked at 24.92% of the lake volume on August 1st 2012, bringing the lake well under the 50% volumetric threshold for anoxia.

Chlorophyll-*a* – Chl-*a*

Oklahoma surface drinking water supplies are extremely sensitive and vulnerable to pollution. 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 Chl-*a* concentration criterion of 10 ug/L at a depth of 0.5 meters. For the 2012 sampling season the lake wide average Chl-*a* at Lake Thunderbird was 24.6 µg/L, exceeding the SWS Chl-*a* criterion, but drastically reduced from the lake wide average of 36 in 2011 and the five year historical average of 30.6.

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 2012 mean of 19 centimeters at Site 6 to a mean of 64 centimeters at site 1. The lacustrine Sites (1, 2, and 4) had the greatest Secchi depths, while the riverine or transition zone sites had the lowest water clarity (
Figure 29). When a site had a Secchi depth greater than 40 cm, turbidities were within WQS 95% of the time.

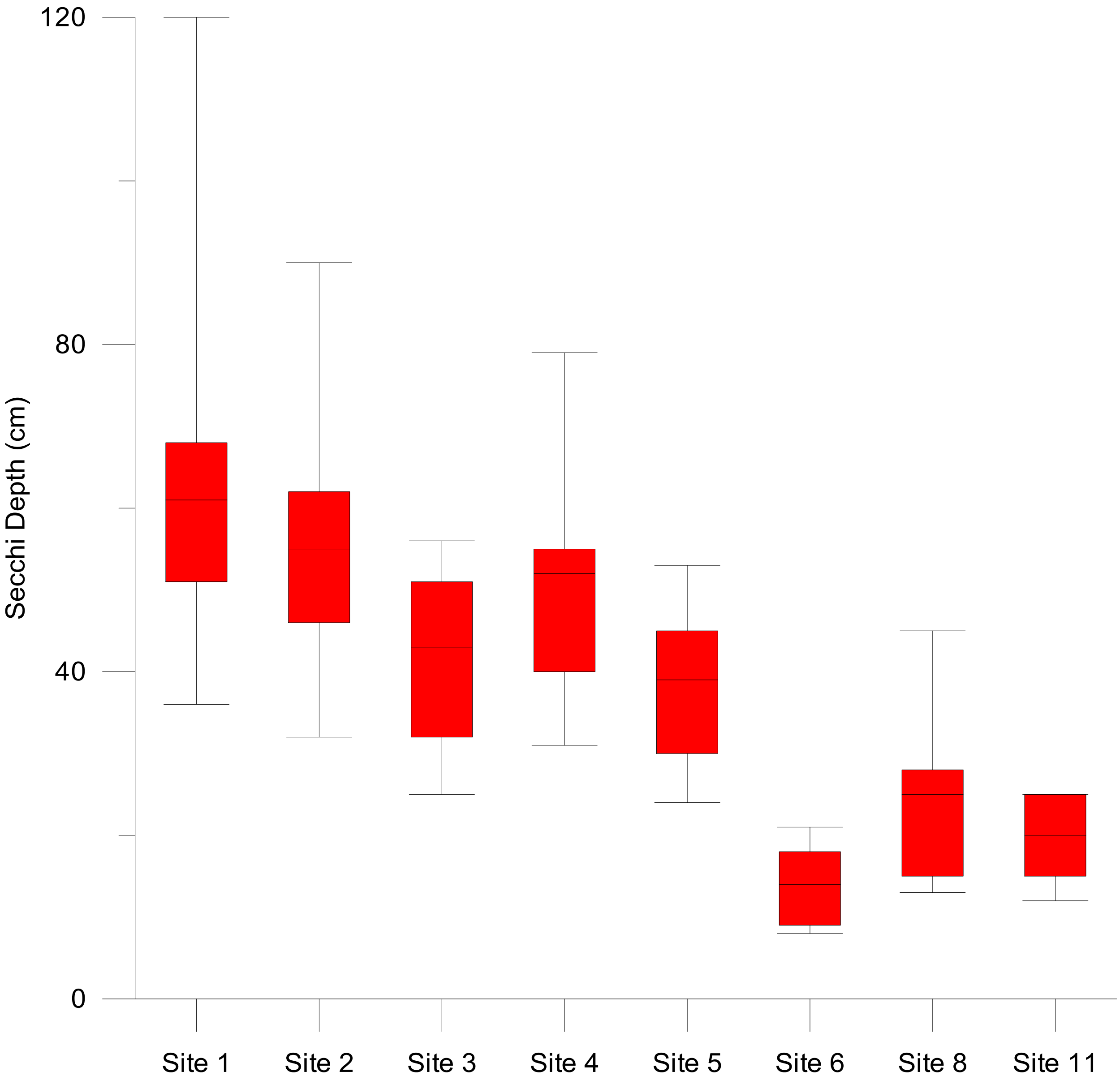


Figure 29. 2012 Lake Thunderbird Secchi disk depth (in centimeters) by site, where boxes represent 25% of the data distribution above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution.

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, the lake is deemed not supporting its beneficial use, and is thus impaired for turbidity. In 2012, 38% of Lake Thunderbird samples exceeded the 25 NTU criteria (
Figure 30). This is similar to the average of the previous three years (2011:51%, 2010:30%, 2009:46%). The lacustrine sites 1, 2, and 4 did not have any samples that exceeded the 25 NTU criterion. Riverine mixing zones (sites 3 and 5) had periods of time when turbidity rose above 25

NTU. This was likely due to inflow events early in the sampling season and wind mixing with low water levels in the later part of the summer. The riverine sites 6, 8, and 11 usually exceeded the criterion, with the entire Little River arm (Site 6) and Dave Blue Creek arm (Site 11) samples greatly exceeding 25 NTU.

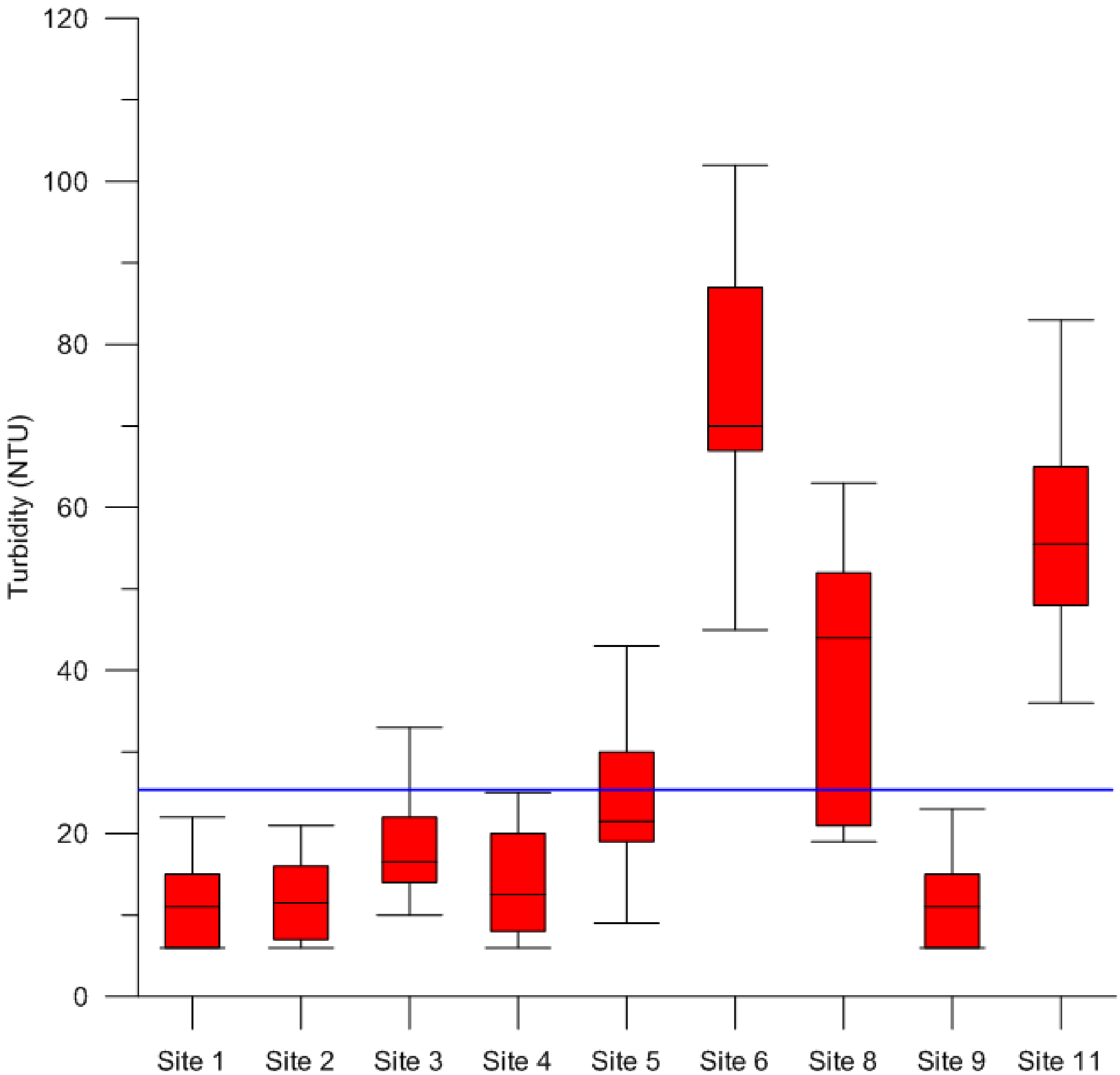


Figure 30. 2012 Lake Thunderbird turbidity (NTU), by site, where boxes represent 25% of the data distribution above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution (horizontal blue line represents state water quality standard).

Supersaturated Dissolved Oxygen Injection System (SDOX)

The summer of 2012 marked the second season of operation for the supersaturated dissolved oxygen injection system (SDOX) installed at Lake Thunderbird in 2010. In operation from mid-May until turnover in early September, the system was designed to oxygenate 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 deep, supersaturating this water under pressurized conditions, and then re-injecting it in two separate locations that are at 12 meters water depth, relative to the conservation pool. 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, and encompassing 480 acres of nutrient rich sediment. In 2012, 82% of the designed oxygen output was met (**Figure 33)**. Reduction of dissolved oxygen output was due to the low lake level, which requires the SDOX system to be run at a reduced capacity to compensate for the increased hydraulic lift. Another factor that contributed to reduced seasonal operating capacity was the few instances where the system needed to be shut down for maintenance.

When oxygen is present, it is used as the terminal electron acceptor in respiration, allowing the redox potential in the hypolimnion to be spared from the drop that is witnessed when other compounds are reduced through anaerobic respiration. The drop in 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.

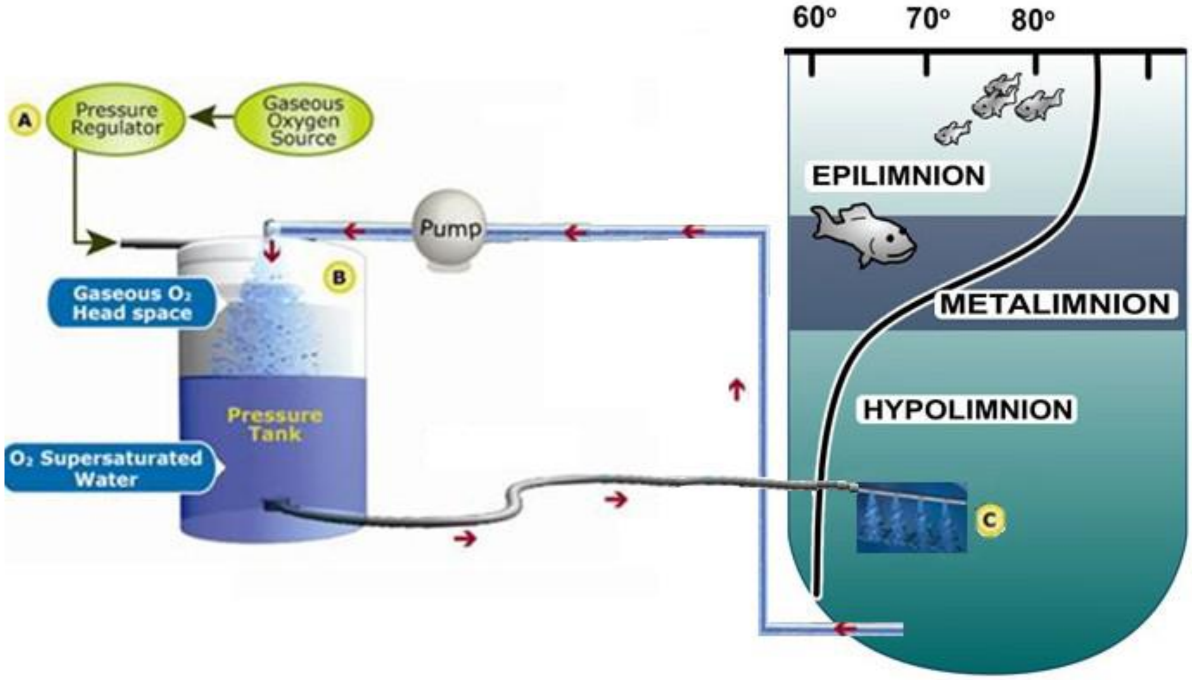


Figure 31. Conceptual Illustration of the SDOX System at Lake Thunderbird

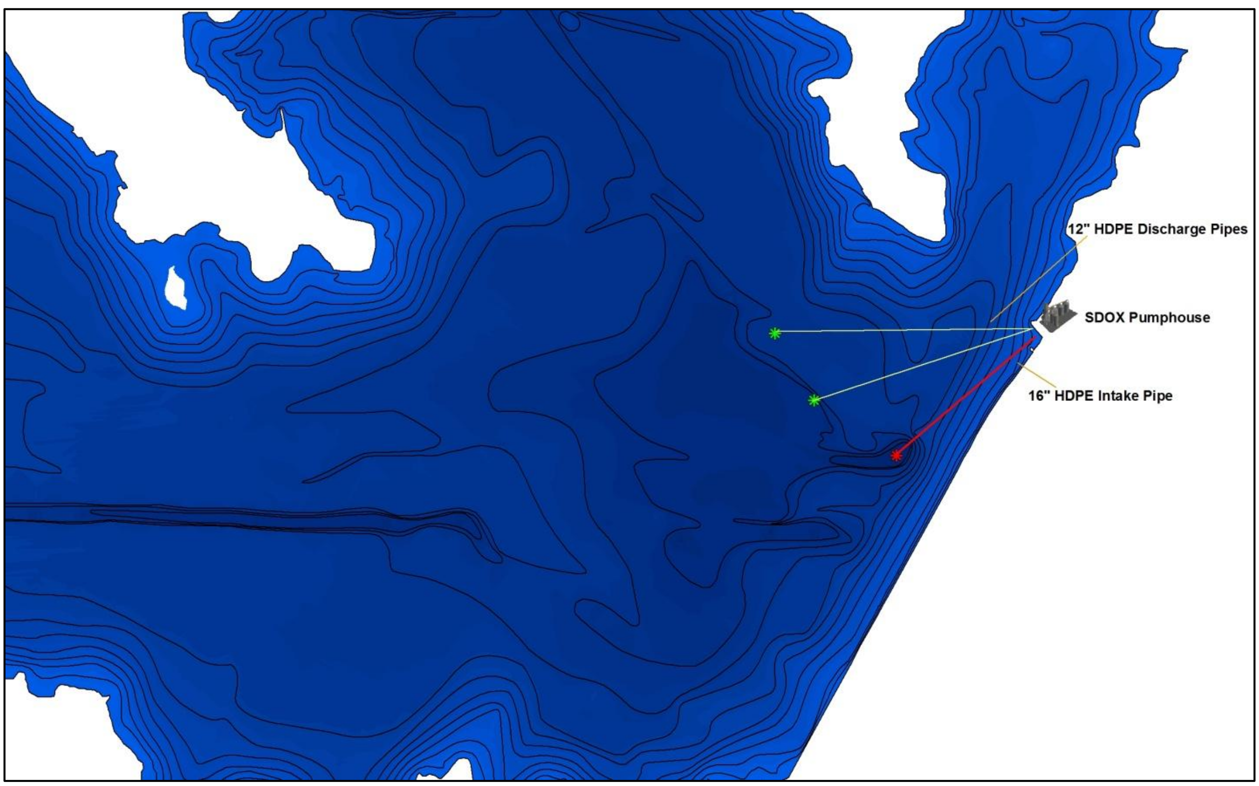


Figure 32. Map of SDOX location

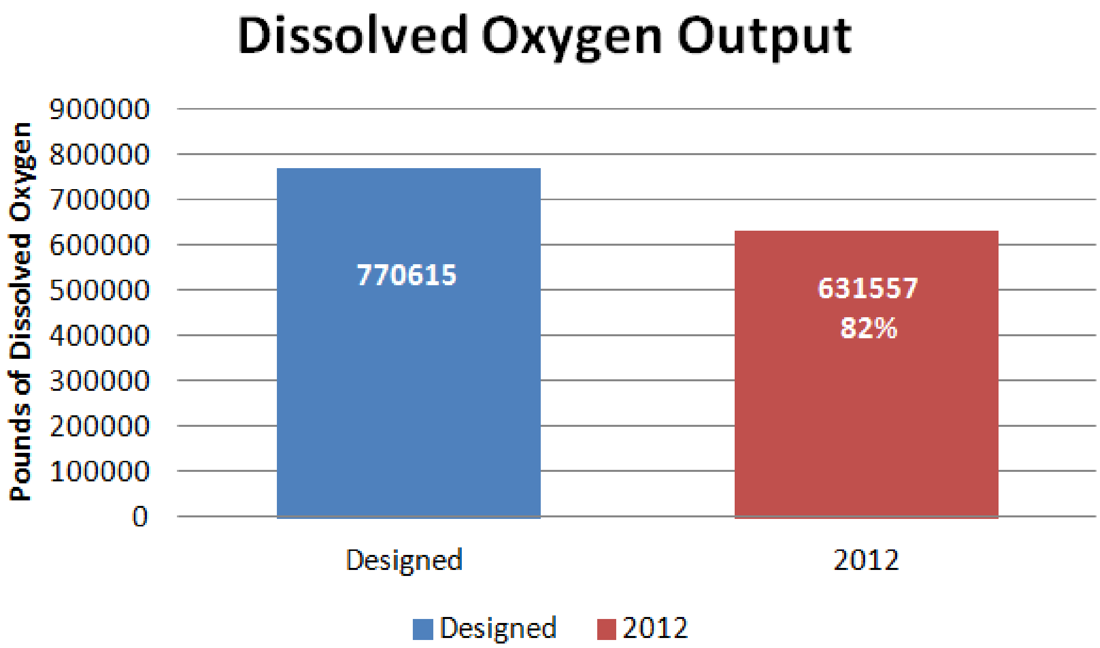


Figure 33. SDOX Dissolved Oxygen output.

System Modification

Data collected in the first year of operation suggested that the system was inducing vertical mixing within the water column (OWRB 2012). After reviewing all options with the system operator, COMCD, and system manufacturer, BlueNGreen, it was decided to modify the system to potentially reduce metalimnetic disruption. Proposed modifications included moving the nozzle discharge locations to a deeper location and changing the nozzle to help diffuse the force from one opening to many openings.

Over the winter in 2012, the SDOX lines were moved to bring them closer to the rapid slope that leads to the deep pocket of water. While the nozzles were only moved a short distance, the change in location for the south nozzle allowed it to be in a location much closer to the drop off and about one meter deeper. The replacement nozzle was installed at the start of July 2012 (**Figure 34**). During this installation, it was noticed by the BlueNGreen engineers that the north line had a large break in it near the shoreline. After this date, the system ran solely off of the modified south nozzle.

In the previous sections of this report, the 2012 dataset was interpreted largely without regard to the effects of the SDOX system. In this section, the SDOX unit's performance and effect on collected data will be discussed.

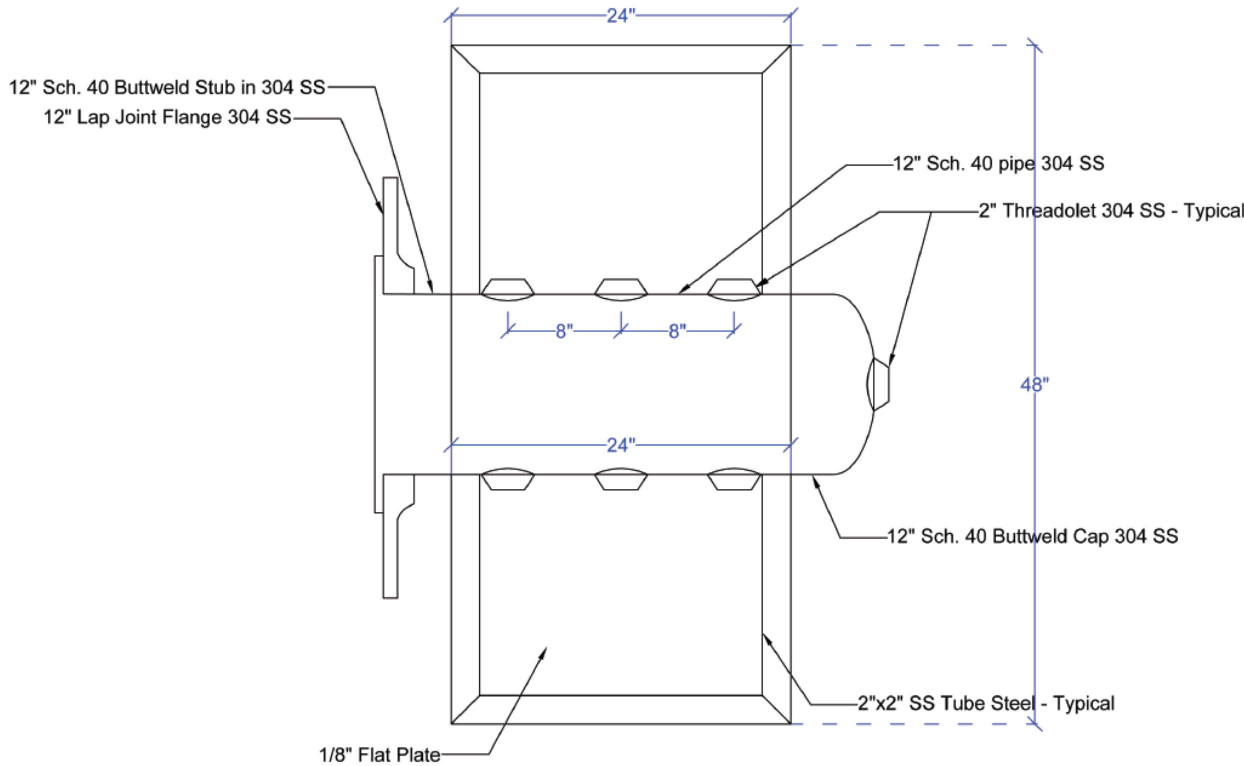


Figure 34. Schematic of the modified nozzle

SDOX Effect on Dissolved Oxygen

The main goal of the SDOX system was to provide a section of oxygenated hypolimnion through much of the summer. While it was not designed to prevent anoxia (>2mg/L DO) in the entire hypolimnion, it was expected to raise DO levels in the deepest 2000 acre-feet of the lake. Previously in this report, it was documented that dissolved oxygen followed a pattern that mimicked thermal stratification throughout much of the summer. Unlike typical summers, there were instances of hypolimnetic oxygenation in the late summer time-frame. The effect from the SDOX unit can be witnessed within Site 1 data through the observation of the breakup of anoxia in lake August-early July (**Figure 35**).

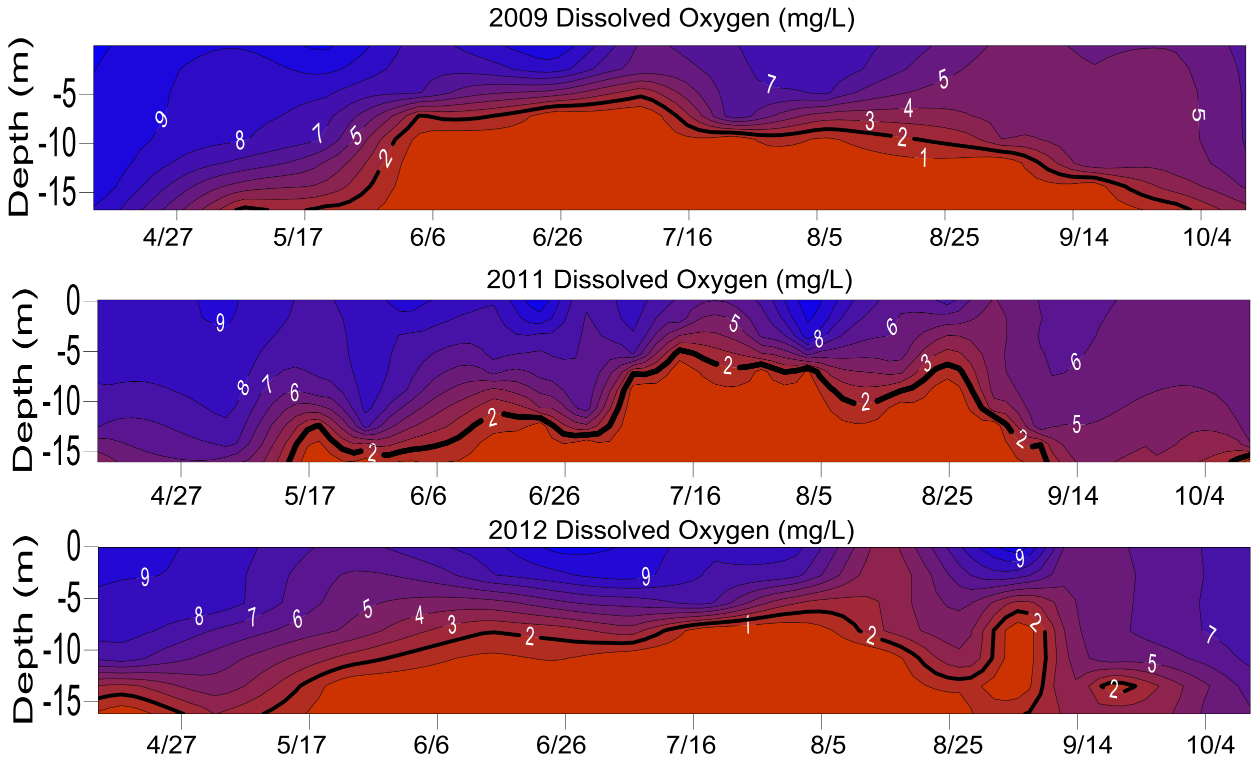


Figure 35. 2009, 2011, 2012 Seasonal Dissolved Oxygen Plot for Site 1.

Site 1, which is located in an isolated pocket of the lakes deepest area, is not always representative of the lakes large hypolimnetic pool, which is more directly treated by the SDOX unit. On August 28th, 2012, water quality profile data was collected in a linear fashion from the SDOX south nozzle. The results showed that supersaturated conditions existed within a localized area around the nozzle, with oxygenated conditions present in most of the area within the lakes largest volume of hypolimnetic waters (**Figure 36**).

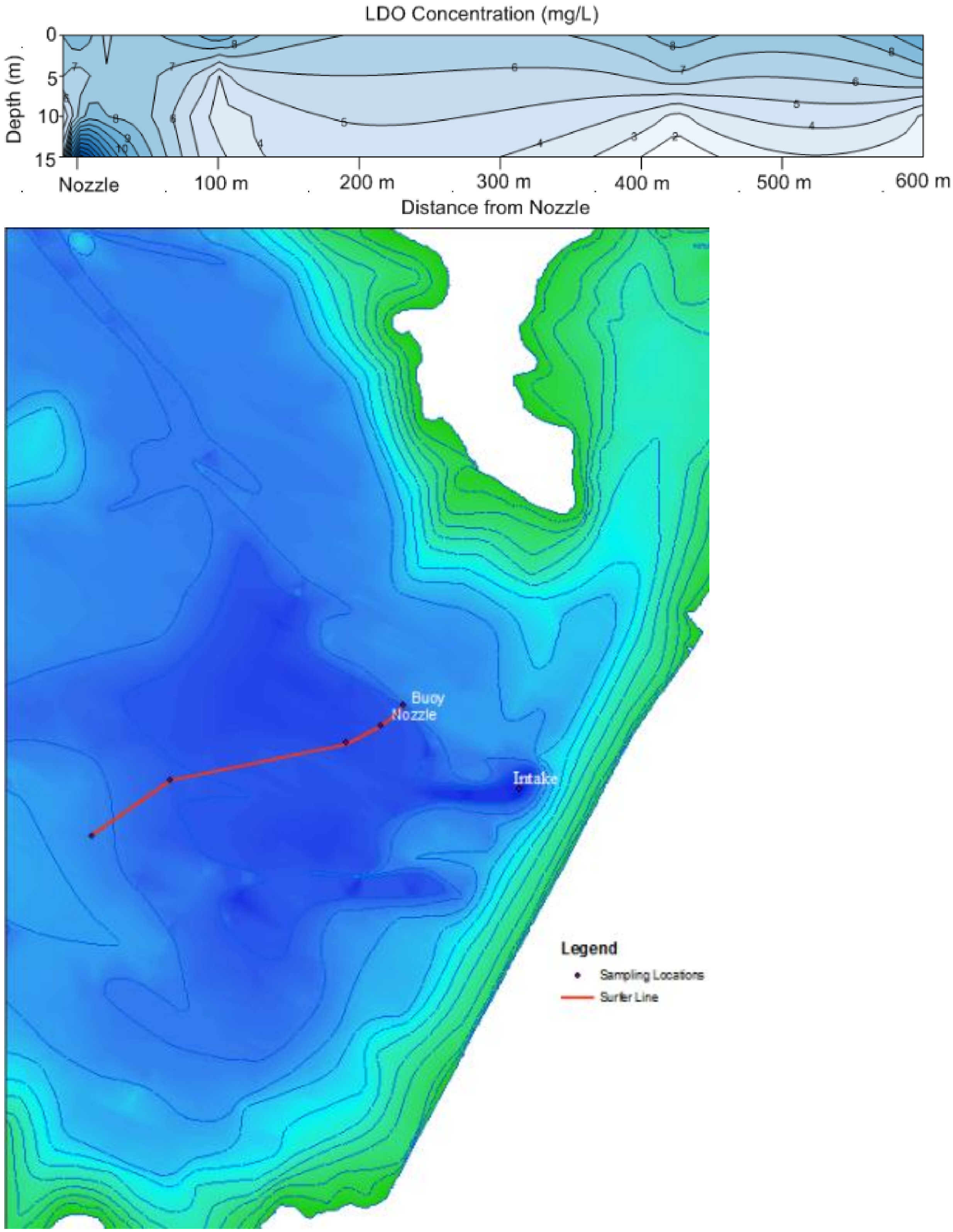


Figure 36. LDO data by distance from nozzle on August 28th, 2012.

SDOX Effect on Thermal Stratification

One of the advertised advantages of SDOX is oxygenation 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 12'{July 6th, 2012-August 28th 2012}, 0.085 C°/day 11'{July 7th 2011- August 25th 2011}). To help illustrate the SDOX systems effect on heat distribution throughout the water column, a comparison of relative thermal resistance has also been provided for similar dates.

In **Figure 37,** it is apparent that the water-column temperatures in 2011 and 2012 are much more uniform from a typical year (represented by 2009), which translates to greatly reduced thermal resistance to mixing. In 2011, instead of the cold re-injected water sinking toward its density depth, the released water mixed upwards into the water column reaching approximately 8 meters in depth. In 2012, similar data was observed in the beginning of the year. However, after the system modifications occurred in early July, the mixing layer dropped two meters to 10 meters, getting the system much closer to treating the sub-12 meter volume of water and area of sediment that the system was designed to treat (**Figure 38** and **Figure 39**). This is evident from the shift in depth of the relative thermal resistance peak to 9 meters.

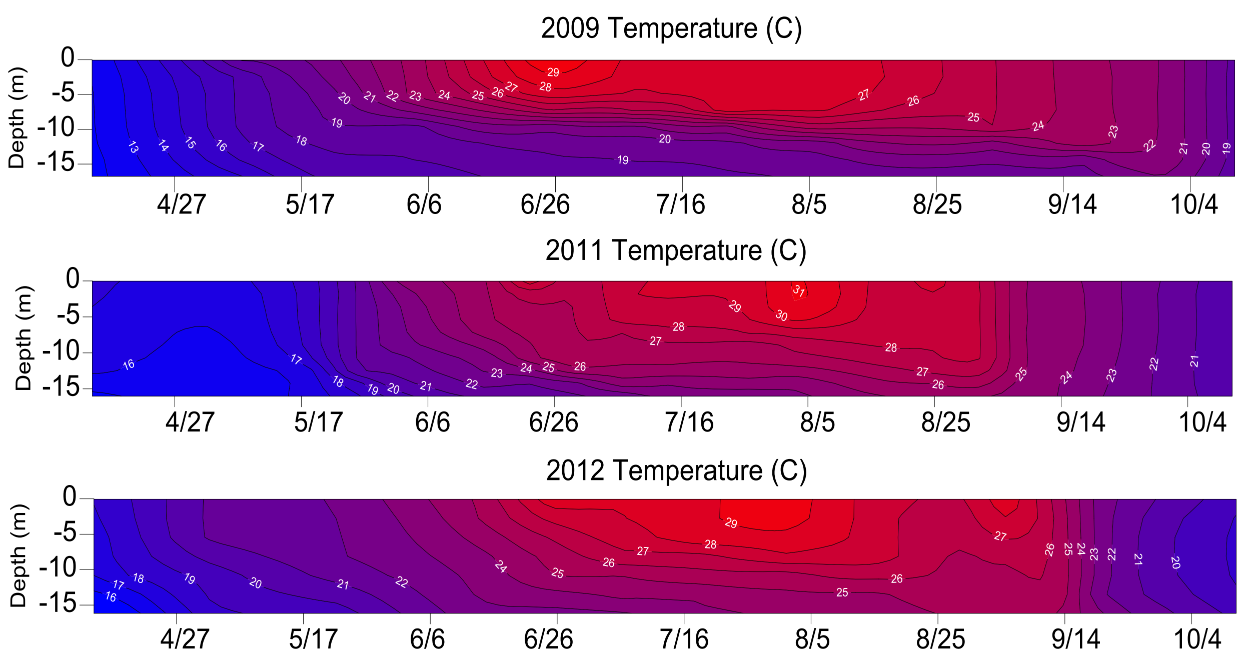


Figure 37. 2009, 2011, and 2012 seasonal temperature plots for Site 1.

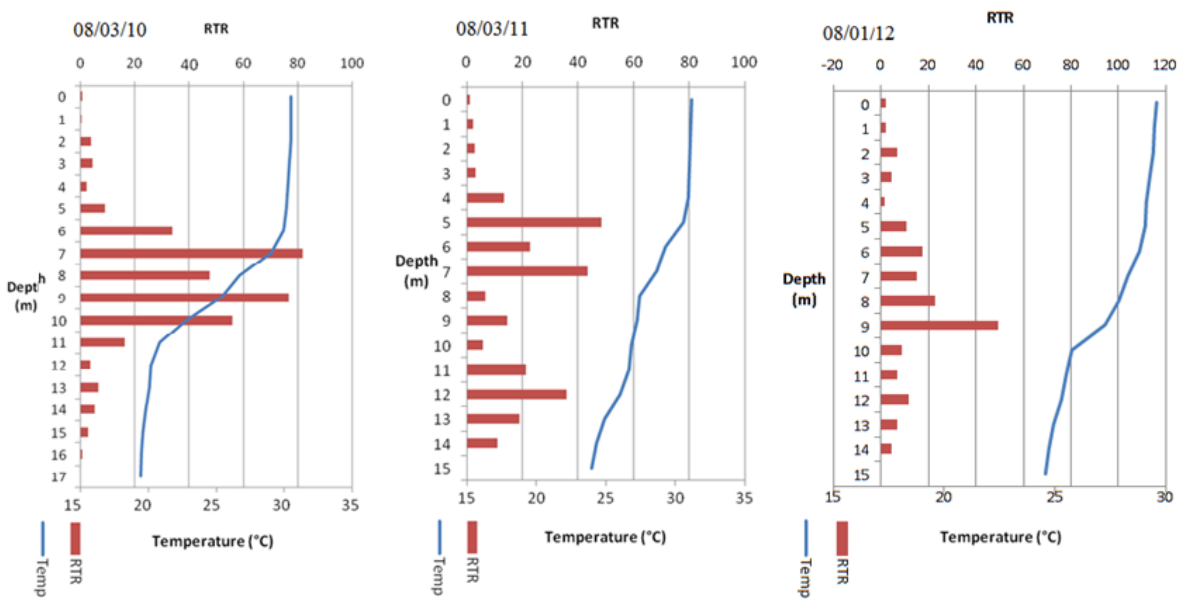


Figure 38. Relative thermal resistance data comparison for August 2010, 2011, and 2012 from Site 1.

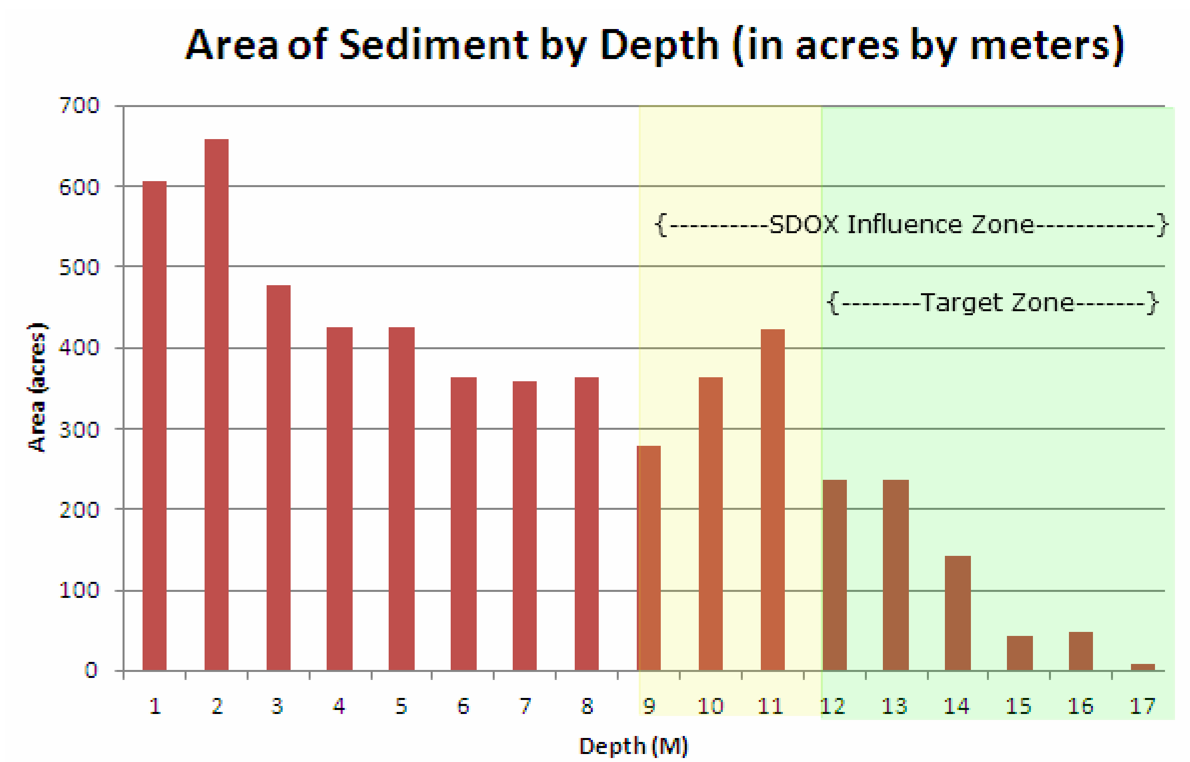


Figure 39. Area of sediment by depth. Graphics display engineered target zone, and zone of influence.

Another direct consequence of providing oxygen to the hypolimnion would be a rise in oxidation-reduction potential. Raising the redox potential in the hypolimnion will decrease the solubility of nutrients and metals from the sediment (Lerman 1978). In 2011 and 2012, strong reducing conditions were largely eliminated throughout the water column during much of the summer. **Figure 40** allows for a comparison of oxidation reduction potential (ORP) data from 2009, 2011, and 2012. In 2011 and 2012, ORP data is also disconnected with historical data and traditional knowledge of ORP's correlation with dissolved oxygen. It is observed and expected, for instances when dissolved oxygen concentration approach zero, for ORP values to drop to values indicating strong reducing conditions (<100 mV). With the operation of the SDOX unit in 2011 and 2012, this was no longer the case. In 2012, first observations of strong reducing conditions took well over an entire month from the first observation of anoxia. The extent of strong reducing conditions often only occupied about a half of the water column and significantly less volume than anoxia occupied in 2009 (
Figure 41).

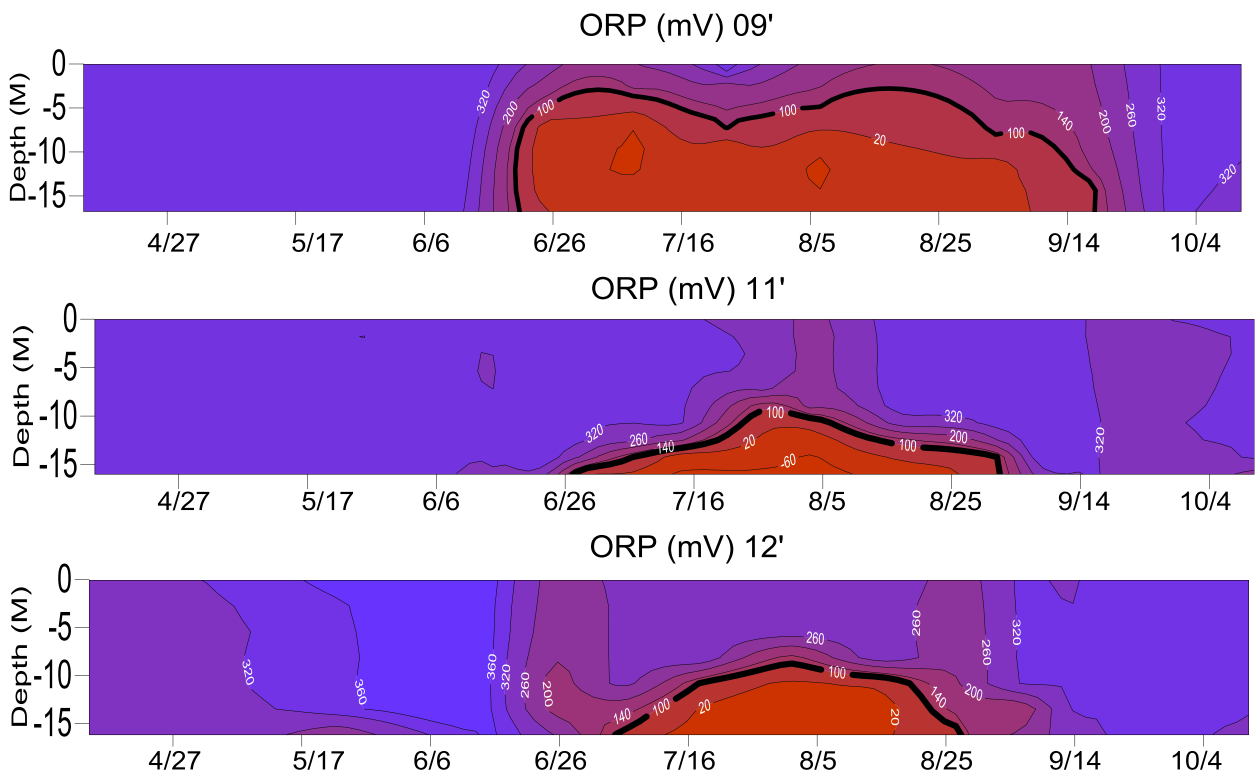


Figure 40. Lake Thunderbird 2010, 2011, and 2012 oxidation-reduction potential isopleth

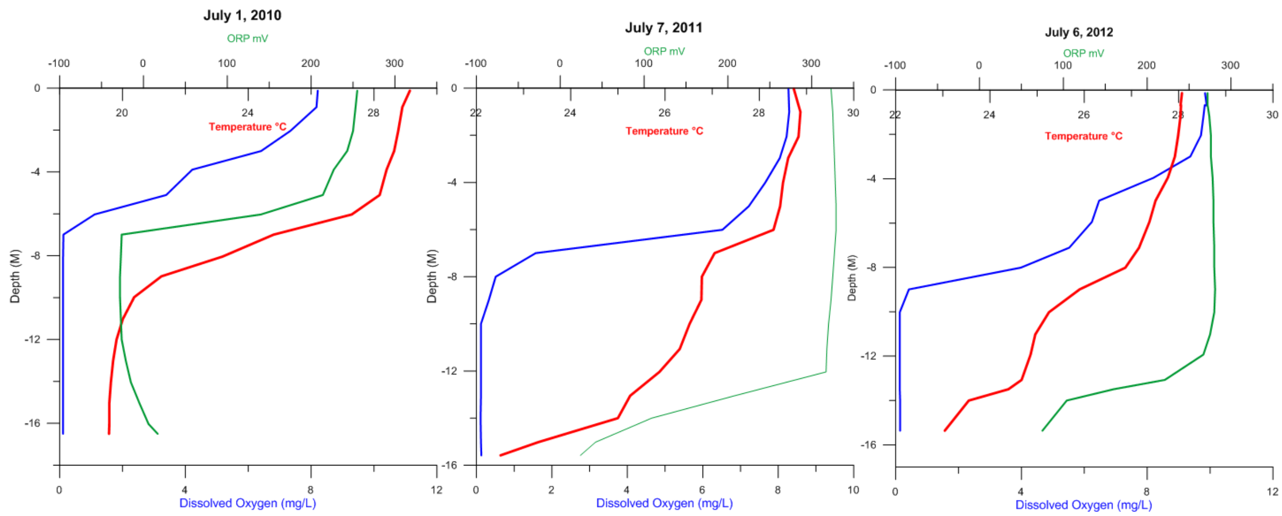


Figure 41. Temperature, Oxidation-Reduction Potential, and Dissolved Oxygen by depth: July 1 2010, July 7 2011, and July 6 2012.

SDOX Discussion

The 2012 calendar year marked the second season of operation for the supersaturated DO system that is designed to oxygenate water throughout the lakes anoxic hypolimnion while leaving thermal stratification intact. Data in 2012, before the system modification, suggests that the convectional force of the system was great enough to induce mixing of waters in the area of the water column that is typically occupied by the metalimnion. Data observed after the system modification displays significant lowering of the mixing zone, and instances of hypolimnetic oxygenation. The system was designed and intended to oxygenate lake waters and sediment from 12 meters of depth to the bottom, approximately 2,000 acre-feet of volume encompassing approximately 480 acres. In 2011, the mixing zone distributed re-injected waters to about 7 meters, representing a volume 10 times that of the design capacity. In 2012, the mixing zone was lowered to 10 meters. This represented a volume that is still over 3 times the volume (7,041 acre-feet) as well as over 3 times the sediment area of the 12 meter design capacity.

Induced mixing is also the likely cause of heat transfer from epilimnetic waters to hypolimnetic waters, as made evident in the thermal stratification section of this report. While the system did not entirely operate inside the framework that it was designed, data shows that the extent and duration of low-to-negative ORP and anoxia was reduced. As discussed earlier, when applying a common way of estimating sediment phosphorus release to the 2012 dataset, a 17% reduction in anaerobically mediated sediment phosphorus release was observed when compared to the 2005-2009 datatset (Nurnberg 2005).

Data collected in 2012 shows that while the SDOX unit improved on its performance measures from 2011, it was still unsuccessful in several of the designed performance measures. Some of the issues may be clouded by the extreme heat and drought in 2011 and 2012. The climatic conditions in 2012 would typically have created a larger hypolimnion than average from the intense heat and increased solar radiation. The drought also meant thermal stratification would have been pushed down the corresponding 2 to 3 meters that the water column lost throughout the summer. The lower pool elevation also could have accelerated heating of the lakes deeper waters. Lastly, the lowered pool directly reduced the capacity of the SDOX system to operate. It was engineered to lift water from the conservation pool to the pump-house. As the pool dropped, the SDOX units operational capacity had to be reduce to compensate for the increased lift, thus the amount of oxygen being put into the system was also reduced.

While some of the shortcomings of the system could be partly blamed on climate, others likely had to do with the design and location of the system. Modifications made during the summer of 2012 helped focus the SDOX treated waters to a more discreet volume, but it still operated outside its designed area and more importantly outside the density seeking principal it was engineered upon. SDOX operation in 2013 is scheduled to operate in a fashion consistent with the latter half of the summer of 2012, operating strictly out of the deeper, modified south nozzle.

In hindsight, it appears that it would have been beneficial to locate these discharge locations as deep as possible to constrain induced mixing to the deepest part of the water column possible. While there are no scheduled changes or modifications to the system for the 2013 operating season, OWRB will continue to work with the system manufacturer, BlueNGreen, and COMCD to meet performance criteria.

Lastly, while some effects were witnessed in the first two year of SDOX operation, it is logical to believe that the full impact of the installed system will not be witnessed until the large amount of settled organic matter that currently exists in the lake is broken down. Sources also suggest that oxygenation systems will decrease hypolimnetic oxygen demand over time as there will be less “carry over” of latent demand from one year to the next (Gantzer 2008).

Discussion

Water Quality

Consequences of cultural eutrophication were observed in Lake Thunderbird in 2012. These included high Chl-*a*, elevated TOC, elevated pH, and super-saturation of DO all occurring at the water's surface during the summer growing season. Trophic State Indices indicated eutrophic to hypereutrophic conditions. Anoxia occurred during the summer months as well, coinciding with low to negative ORP. During this time, phosphorous and metals were released back into the water column and entrained during fall turnover. The infusion of hypolimnetic waters with external oxygen by the SDOX system, installed in 2010 and operating in 2012, clearly helped reduce the extent and duration of low to negative ORP, likely anoxia, as well as anaerobically mediated sediment P release.

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 2012. 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 contaminated water sources. As cultural eutrophication remains unabated, risks of harmful algal blooms and their associated consequences continue to increase. The significant lowering of peak and average Chl-*a* in 2012 indicates the lake may have begun to move in the right direction.

State Water Quality Standards

In 2012, Lake Thunderbird was listed on Oklahoma's 303(d) list of the Water Quality Integrated Report as impaired due to low DO and turbidity, with the causes of these impairments unknown. Data collected in 2012 were analyzed for beneficial use impairments in accordance with the USAP (OAC 785:46-15) of the OWQS. In 2012 Lake Thunderbird was found to be supporting its Fish and Wildlife Propagation beneficial use in regard to DO. USAP assessments are done on the most recent 10 year dataset. Therefore, this single year of meeting WQS will not remove Lake Thunderbird from the 303(d) list for DO. Lake Thunderbird was found not supporting its Fish and Wildlife Propagation beneficial use in regard to turbidity. In addition, Lake Thunderbird was not meeting the 10 μg/L Chl-*a* requirement for SWS.

Closing Remarks

During the past few years, significant achievements have been made in modeling Lake Thunderbird's watershed and internal P load, allowing for better understanding of the P mass-balance for Lake Thunderbird. Regression analysis with Lake Thunderbird water quality data and City of Norman drinking water treatment data, indicates that organic enrichment through increased algal biomass is increasing TOC within the reservoir. The 2012 calendar year represents the first year since 2007 that peak Chl-*a* has been reduced. Lacustrine Chl-*a* averaged at 22 ug/L in 2012, reduced 32% from 2011. Significant nutrient reduction from the surrounding watershed, particularly in the Little River area (OWRB 2011), are critical to bring Chl-*a* within Oklahoma Water Quality Standards of 10 ug/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

	Chlorophyll-a			Paired	
Date	Site 1 a	Site 1 b	Site 9	Average	SD
2/2/2012	4.3	4.5	4.1	4.3	0.2
4/18/2012	6.1		4.7	5.4	1.0
5/2/2012	10.9	10.7	11.9	11.2	0.6
5/23/2012	6.5	6.8	6.6	6.6	0.1
6/14/2012	16.3	14.9	10.6	13.9	3.0
6/25/2012	19.6	20.2	20.4	20.1	0.4
7/18/2012	31.0	36.3	35.4	34.2	2.8
8/1/2012	32.7	32.8	32.6	32.7	0.1
8/15/2012	28.0	27.1	26.2	27.1	0.9
9/5/2012	45.2	45.0	42.8	44.3	1.3
9/19/2012	38.0	34.9	38.4	37.1	1.9
10/17/20112	19.0		19.9	19.5	0.6
				AVG SD	1.08
				Min	0.1
				Max	2.97

Laboratory Results of Duplicate Samples for COMCD Lake Thunderbird Water Quality Sampling April 14, 2011 – October 11, 2011

Site 1

Date	Fe, Total	Fe, Dissolved	Mn, Total	Mn, Dissolved	Turbidity	True Color	Alkalinity	Susp. Solids	N-Ammonia	N-Kjeldahl	Nitrite-Nitrate as N	Total P	TOC	Chloride	Sulfate	Ortho-P
	ug/l	ug/l	ug/l	ug/l	NTU	units	mg/L	mg/L	mg/L	mg/L	mg/l	mg/L	mg/L	mg/L	mg/L	mg/L
2/2/2012	452	53.3	31.4	6.3	22	49	160	12	0.05	0.48	0.63	0.01	5.11	29.5	20.3	0.031
4/18/2012	550	153	16.9	22.8	15	60	155	5	0.05	0.55	0.55	0.011	5.43	26.8	25.7	0.019
5/2/2012	344	59.9	17.7	2.5	13	38	160	10	0.05	0.53	0.37	0.008	4.86	23.6	20.3	0.01
5/23/2012	437	82.4	27.5	2.5	15	45	162	5	0.05	0.71	0.26	0.016	5.21	25.1	21	0.011
6/14/2012	115	19.5	28.4	2.82	6	20	164	5	0.05	0.84	0.025	0.016	5.28	24.7	19.9	0.006
6/25/2012	207	9.26	59.5	5.54	10	23	163	13	0.05	0.91	0.025	0.015	5.35	26.9	21.9	0.006
7/18/2012	69.6	15.3	33.2	2.5	8	20	154	5	0.05	1.08	0.025	0.027	5.88	26.5	8.3	0.008
8/1/2012	416	10	30.4	26.2	8	16	153	10	0.05	1.14	0.025	0.016	6.15	29	19.9	0.007
8/15/2012					6	14	158	5	0.12	1.03	0.025	0.018	5.86	28.2	19.4	0.007
9/5/2012	67	10	29	10	6	81	148	9.2	0.05	0.8	1.708	0.032	8.11	29.95	7.5	0.025
9/19/2012	112	1	86	1	12	94	160	10	0.42	0.8	0.301	0.032	6.43	33.01	4.04	0.025
10/17/2012	0.145	0.05	0.078	0.014	16	100	156	9.6	0.05	0.8	1.36		10.2	24.5	8.04	0.03

Duplicate

Date	Fe, Total	Fe, Dissolved	Mn, Total	Mn, Dissolved	Turbidity	True Color	Alkalinity	Susp. Solids	N-Ammonia	N-Kjeldahl	Nitrite-Nitrate as N	Total P	TOC	Chloride	Sulfate	Ortho-P
	ug/l	ug/l	ug/l	ug/l	NTU	units	mg/L	mg/L	mg/L	mg/L	mg/l	mg/L	mg/L	mg/L	mg/L	mg/L
2/2/2012	437	55.6	31.2	7.9	23	53	162	13	0.05	0.7	0.65	0.005	5.18	30.3	22.2	0.029
4/18/2012	488	163	16.5	26.1	15	55	153	5	0.05	0.47	0.55	0.015	5.38	26.3	25.8	0.019
5/2/2012	343	55.4	17.8	2.5	12	11	161	5	0.05	0.57	0.37	0.008	5.02	23.7	20.6	0.01
5/23/2012	431	106	28.6	2.5	15	42	164	12	0.05	0.71	0.25	0.02	5.13	25.3	20.8	0.012
6/14/2012	114	10.9	28.4	1.3	6	14	165	5	0.05	0.93	0.025	0.012		25.7	19.8	0.009
6/25/2012	203	16.9	61.7	10.4	10	27	163	11	0.05	0.66	0.025	0.017	5.37	26.6	21.5	0.01
7/18/2012	95.4	16.4	58.6	8.27	9	23	155	5	0.05	1.02	0.025	0.027	5.74	26.5	18.9	0.007
8/1/2012	71	10	29.7	26.6	8	20	153	10	0.05	1.18	0.025	0.016	6.13	28.9	20.5	0.007
8/15/2012					6	18	159	5	0.12	1.14	0.025	0.021	5.94	28	18.9	0.007
9/5/2012	44	9	29	9	7	104	158	9.2	0.1	0.8	1.693	0.016	6.94	39.48	7.5	0.025
9/15/2012	109	1	89	1	16	132	156	10.8	0.42	0.8	0.384	0.136	5.6	28.88	9.05	0.01
10/17/2012	0.134	0.009	0.073	0.001	14	100	156	9.6	0.2	0.8	0.81	0.155	5.82	24.5	8.04	0.03