Oklahoma Water Resources Board

Lake Thunderbird
Water Quality
2011

for the

Central Oklahoma Master Conservancy District

May 1, 2012

FINAL REPORT

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

Table of Contents

Table of Figures

<u>List of Tables</u>

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 2011, lake water quality monitoring by the Oklahoma Water Resources Board (OWRB) was altered to better monitor the effects of the hypolimnetic oxygenation system which began operation in the same year. The end of 2011 monitoring represents twelve years of continuous monitoring at Lake Thunderbird.

The year of 2011 was marked with below average amounts of precipitation contributing to a dropping pool throughout the summer, and the long hydraulic residence time of 6.03 years. Although strong thermal stratification was never present in the water column during 2011, stratification sufficient to develop anoxia was witnessed from mid-June through the start of September. Total mixing of the water column was first detected in the start of September. Total nitrogen to total phosphorous ratio continues their decline from 2009, indicating a shift away from historically predominant phosphorous limited conditions to more co-limited conditions. Total nitrogen to total phosphorous ratio decline is due to an increase in phosphorous not a decrease in nitrogen.

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. All water samples after the start of June 2011 showed excessive chlorophyll-a values (>20 µg/L). The average trophic state index throughout the monitoring season was 64, indicating hypereutrophic conditions. Taste and odor complaints followed established trends peaking, after lake turnover coinciding with peak chlorophyll-*a* values.

During 2011, the first year of operation of the hypolimnetic oxygenation system at Lake Thunderbird, lacustrine data was marked with significant changes in temperature, dissolved oxygen (DO), and reduction potential from the historical dataset.

The 2011 monitoring data supports the 303 (d) integrated listing of Lake Thunderbird as impaired due to excessive turbidity, low dissolved oxygen and high chlorophyll-*a*. The Oklahoma Department of Environmental Quality Water Quality Division (ODEQ-WQD) currently has Lake Thunderbird prioritized for completion of a Total Maximum Daily Load (TMDL) allocation by the end of 2012.

Active lake and watershed management is required for Lake Thunderbird to meet OWQS for turbidity, dissolved oxygen and chlorophyll-*a* (Chl-*a)*. Lake management goals should focus on lake-wide reduction of algal biomass through nutrient reduction to mitigate low dissolved oxygen and decrease Chl-*a*. Suspended solids control is also necessary in order to meet OWQS for turbidity. Continuation and modification of the active hypolimnetic oxygenation project should provide relief to lakes DO, algal problems, and reduce drinking water taste and odor

complaints. Further recommendations to future lake management of Lake Thunderbird should include the review of watershed evaluations to encourage 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. As a municipal water supply, Lake Thunderbird furnishes raw water for Del City, Midwest City and the City of Norman under the authority of the Central Oklahoma Master Conservancy District (COMCD). The Oklahoma Water Resources Board (OWRB) has provided water quality-based environmental services for the COMCD since 2000. The objective in 2011, in addition to routine monitoring, was to focus on evaluating the performance of Lake Thunderbird's newly implemented Supersaturated Dissolved Oxygen Injection System (SDOX).

Lake Thunderbird is listed as Category 5 (303d list) in the State's 2010 Integrated Report as impaired due to turbidity, and low dissolved oxygen (http://www.deq.state.ok.us/wqdnew/305b_303d/2010_draft_integrated_report.pdf). Because of these impairments, Lake Thunderbird is currently undergoing a Total Maximum Daily Load (TMDL) analysis by the Oklahoma Department of Environmental Quality (ODEQ). As a Sensitive Water Supply (SWS), Lake Thunderbird is also required to meet a 10 μg/L goal for chlorophyll-*a* (Chl-*a*)concentrations. These parameters are evaluated according to the Oklahoma Water Quality Standards (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, and linked to the taste and odor complaints in the finished drinking water. The City of Norman has taken appropriate 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 the SDOX 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, reduction of internal phosphorous load, reduction of dissolved metals, and reduction of peak Chl-*a* events. In 2011, which represented the first year of operation, had a significant impact on the data collected and discussed in this report.

Water Quality Evaluation

Sampling Regime

In 2011, Lake Thunderbird was sampled at the sites indicated in **Figure 1.** Water quality sampling occurred from April 14th to October 11th. 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, dissolved oxygen saturation and concentration, temperature, specific conductance, total dissolved solids and pH. These parameters were measured in approximate one-meter intervals from the lake surface to sediment at each site.

In addition, from April 2011 through October 2011, water quality and nutrient samples were collected at the surface of sites 1, 6, 8 and 11, with samples collected at 4-meter depth intervals at site 1. Analysis performed on these samples included alkalinity, chloride, sulfates, total suspended solids (TSS), dissolved and total iron and manganese, and phosphorus and nitrogen series. Total Organic Carbon (TOC) 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 seven sites (**Table 1**).

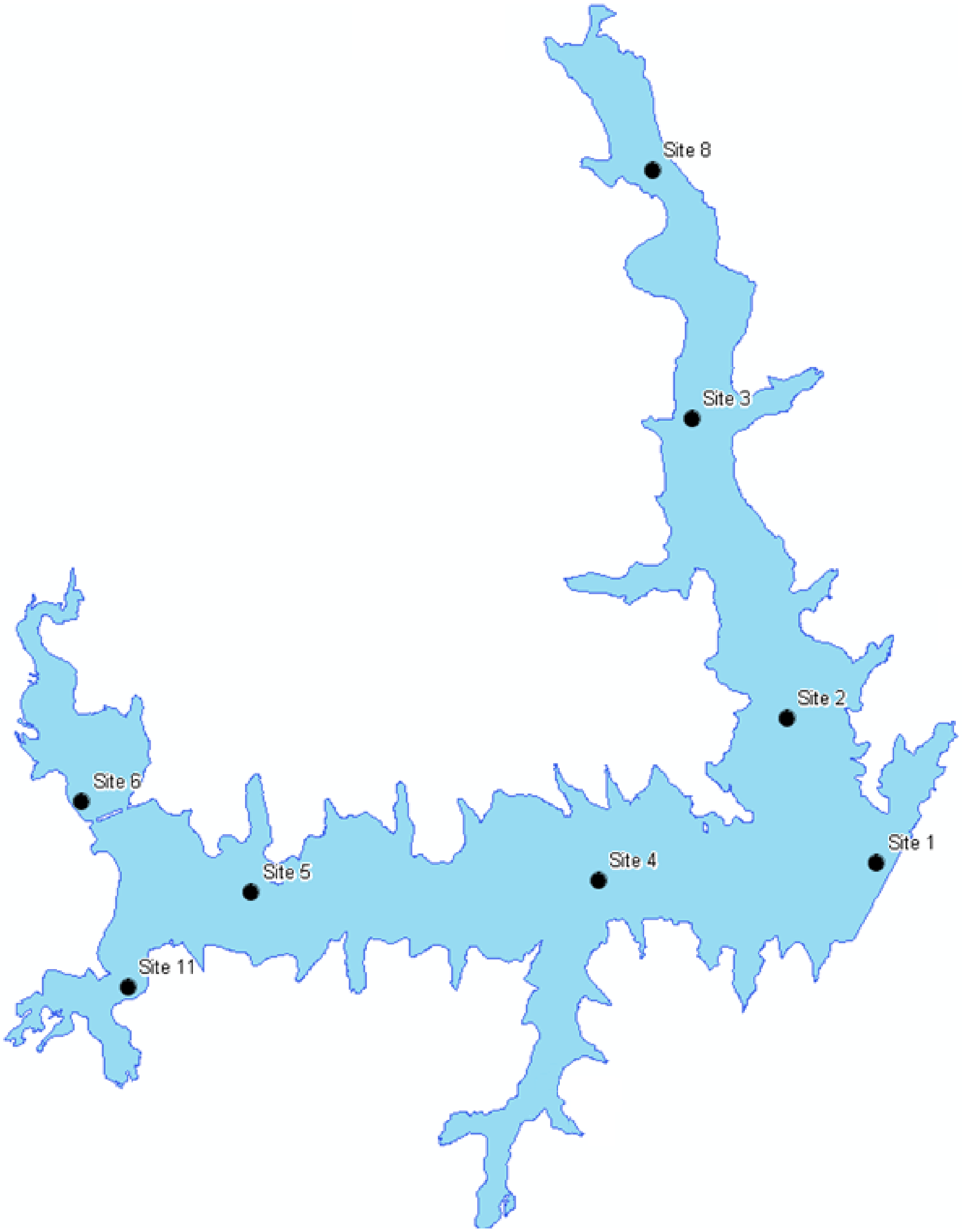


Figure 1. Lake Thunderbird 2011 Sampling Sites

Table 1. 2011 Water Quality Sampling Dates and Parameters Measured.

Date	4/14	5/5	5/18	5/26	6/1	6/15	6/22	6/29	7/7	7/14	7/27	8/3	8/17	8/25	9/1	9/8	9/15	10/11
Hydrolab	X	X	X	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	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	X
Turbidity	X	X	X		X	X		X		X	X		X	X			X	X
Nutrients	X	X	X		X	X		X		X	X		X	X			X	X
Metals						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 2011 sampling season which would compromise the integrity of the dataset.

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

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%. Dissolved and total Iron and Manganese, and suspended solids were the exception showing great variability in the PAD.

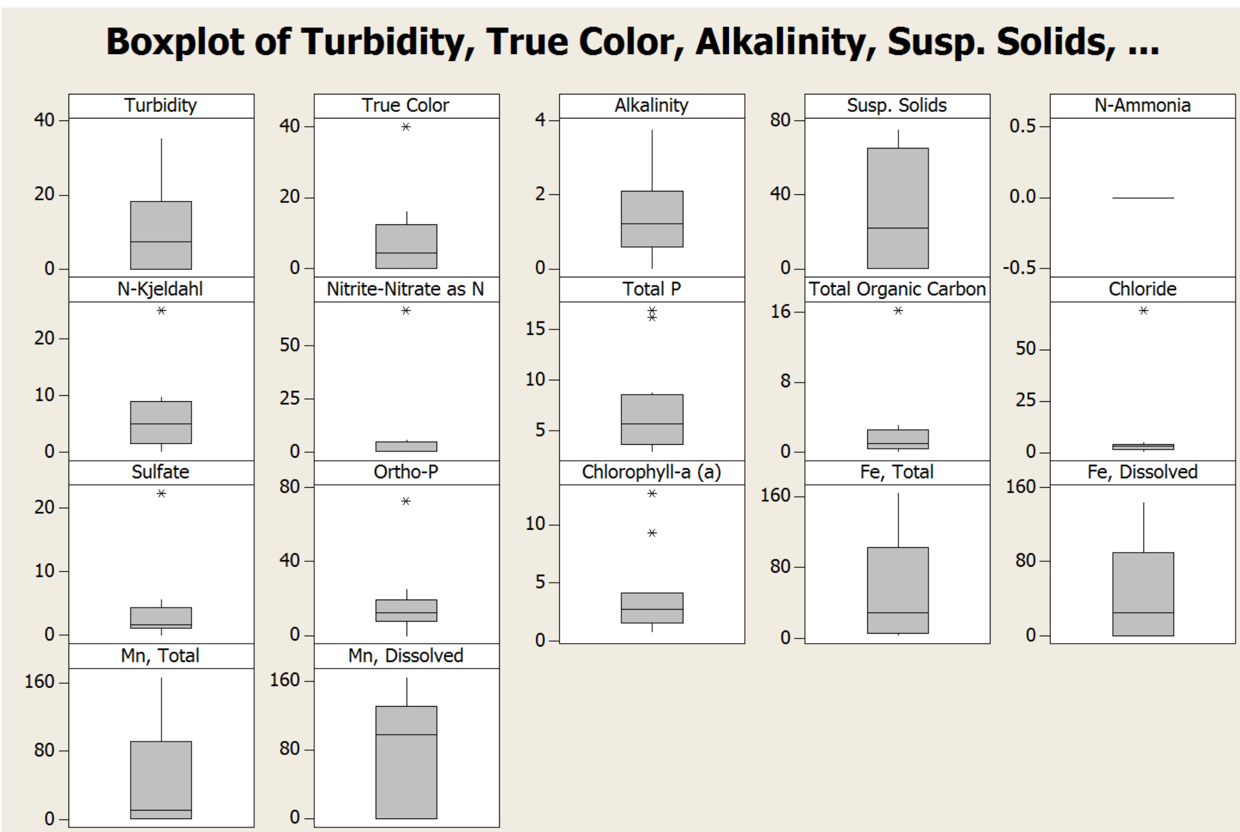


Figure 2. Statistical Summary of Lake Thunderbird Duplicate Samples April 14, 2011- October 11, 2011. (Box represents the middle 50%, the center bar the median value, top and bottom stems the upper and lower 25% quartile and asterisks as outliers**)**

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 chemical and biological characteristics and processes. 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 2011. Annual precipitation at Lake Thunderbird in 2011 totaled at 27.5 inches, *8.3* inches below average. Lake elevations and inflows can vary considerably with rainfall patterns. Pool elevation varied from a high of about 1 feet below conservation pool (1039' MSL) in early-June to around 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 2011 average daily temperature values are illustrated in **Figure 4.** The average daily temperature for the 2011 calendar year was above the historical average by approximately 3°F, but more notably an intense heat wave encompassed the central part of the state from the start of June through early September. This, combined with the intense drought, was linked to the blue-green algae blooms that were documented at many reservoirs throughout the state. Lake Thunderbird had no documented harmful algae bloom events documented.

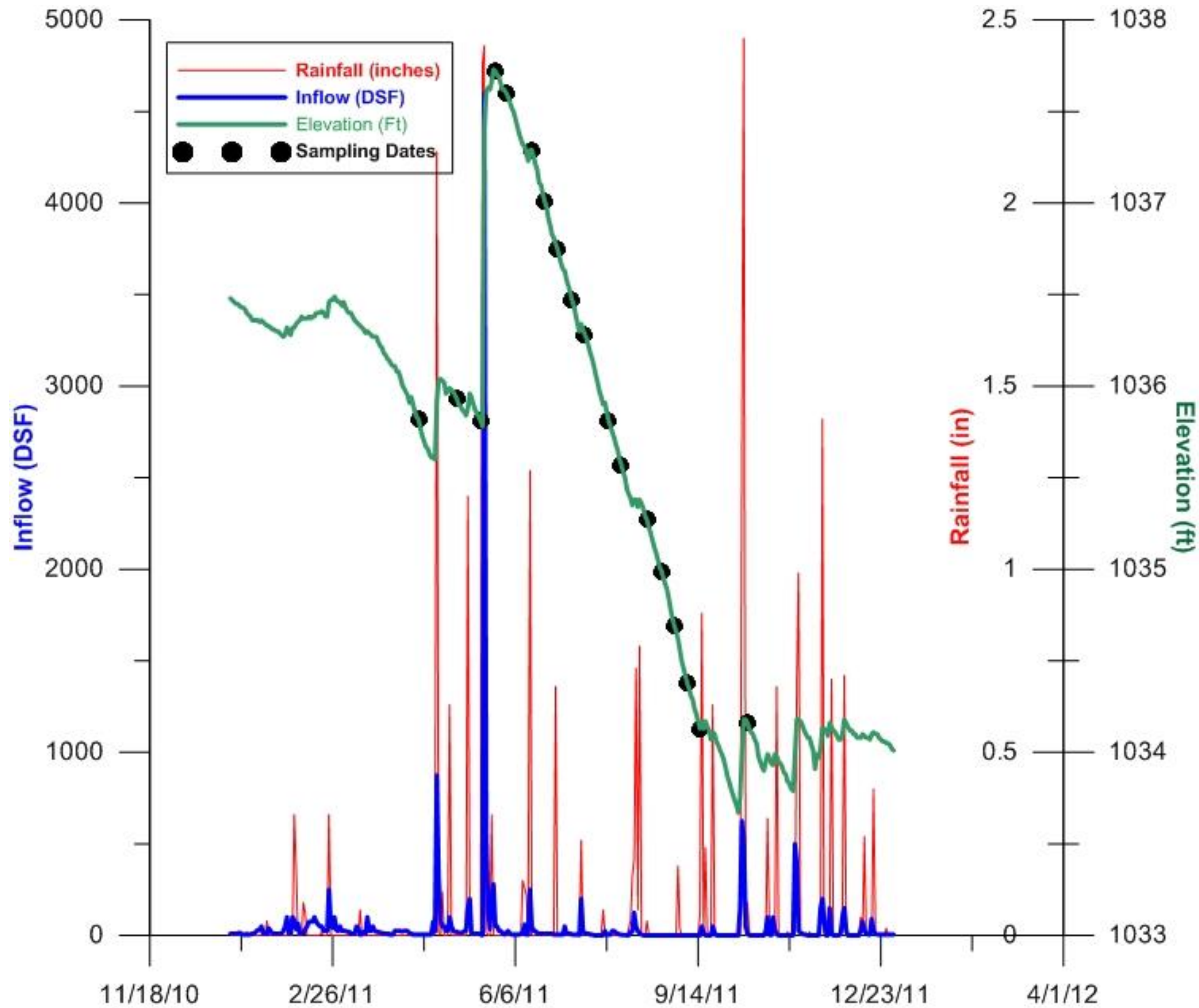


Figure 3.2011 Inflow, Precipitation, and Elevation Data for Lake Thunderbird, with Sample Dates Indicated.

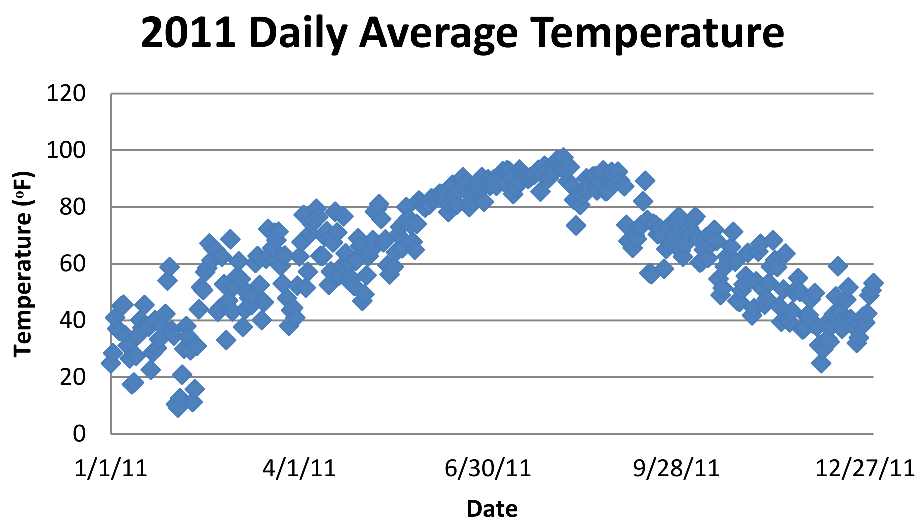


Figure 4. 2011 Average Daily Temperature Values at the Norman Mesonet Station.

Hydrologic Budget

A hydrologic 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:

$$dV/dt = Q_{in} - Q + PA_s - E_vA_s - W_S$$

where V = lake volume [L3],

As = lake surface area [L2],

Qin and Q [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,

Ev [L/T] is the lake evaporation,

WS is the water exported for water supply use.

In other words, the rate of change in storage of the volume of water 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:

$$\mathbf{Q_P = P * A_s}$$

where P [L/T] is rainfall amount and 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.

$$\mathbf{Q_E = E_v * A_s}$$

where E_v [L/T] is the evaporation rate and 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

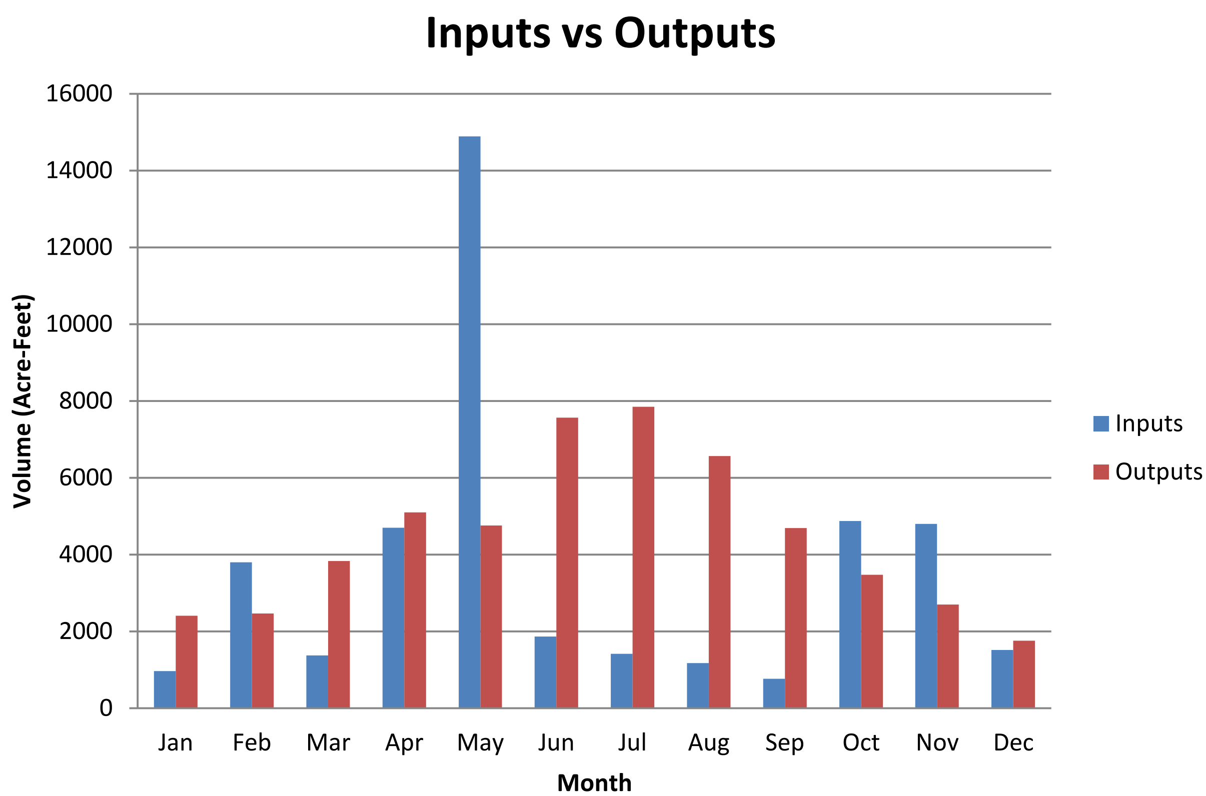
Water budget calculations were summarized on a monthly basis for Lake Thunderbird as described previously **(Table 2).** Total input is the sum of all the flows into the lake. Total output is the sum of all the outflows from the lake. From equation 1, the difference between the inputs and the outputs 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 2011 Water Budget Calculations Expressed in Acre-Feet.

	INPUTS			OUTPUTS				RESULTS		
Month	Inflow	Rainfall	**Total Inputs**	Evaporation	Water Supply	Releases	**Total Outputs**	I-O	ΔV	Error
Jan	950	17	967	1344	1059	0	2403	-1436	-1132	-304
Feb	3223	576	3799	1524	942	0	2466	1333	669	664
Mar	1369	8	1377	2640	1191	0	3830	-2453	-1801	-653
Apr	3560	1142	4702	3588	1513	0	5101	-399	-823	424
May	13281	1608	14889	3279	1473	0	4752	10137	8489	1647
Jun	1240	628	1868	5692	1875	0	7567	-5700	-4682	-1018
Jul	962	449	1411	5653	2194	0	7848	-6436	-5946	-490
Aug	561	615	1176	4508	2059	0	6567	-5391	-3705	-1686
Sep	258	510	768	2987	1703	0	4690	-3922	-4066	144
Oct	3243	1626	4869	2095	1381	0	3476	1393	0	1393
Nov	3074	1726	4800	1590	1108	0	2698	2102	990	1112
Dec	1200	315	1515	724	1034	0	1758	-243	0	-243
Total	32922	9219	42141	35624	17533	0	53157	-11016	-12007	990

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 6.03 years for 2011 and an average hydrologic residence time of 4.07 years since 2001 (including 2011 data). The relatively high 2011 residence time reflects the sustained drought experienced in 2011 that prevented in any water releases from occurring. The only outflow of water during 2011 was from COMCD water withdrawals for water supply purposes.

For the period of calendar year 2011, 78% of the inputs into Lake Thunderbird were from inflows, while the outputs were from lake body evaporation, 67%, and water supply 33% (**Figure 5**).



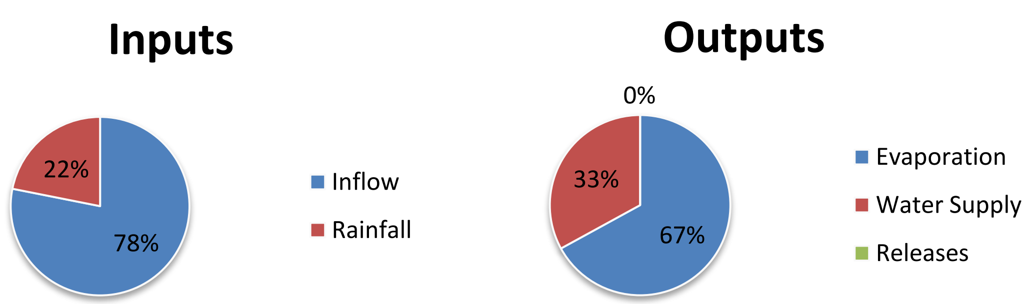


Figure 5. 2011 Lake Thunderbird Input and Output Sources By Month and Expressed as the Percent of Totals.

Sources of Error

Although robust, the hydrologic budget does contain error. In the 2011 calendar year the hydrologic budget contains a cumulative ***annual*** error of 990 acre-feet, with an average ***monthly*** error of 83 acre-feet in 2011. This was perhaps the most accurate budget yet. Drought conditions likely contributed to the accuracy.

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 4,000 acre-feet. It should be noted that the method used to calculate capacity in the original design used less 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 source of uncertainty in the budget is inflow. Implementing two of the following three 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 dissolved oxygen (DO) is consumed and depleted by the decomposition processes in the hypolimnion, it is not replenished. This process has been documented at Lake Thunderbird for every monitoring year to date, and is inevitable without the influence of outside forces.

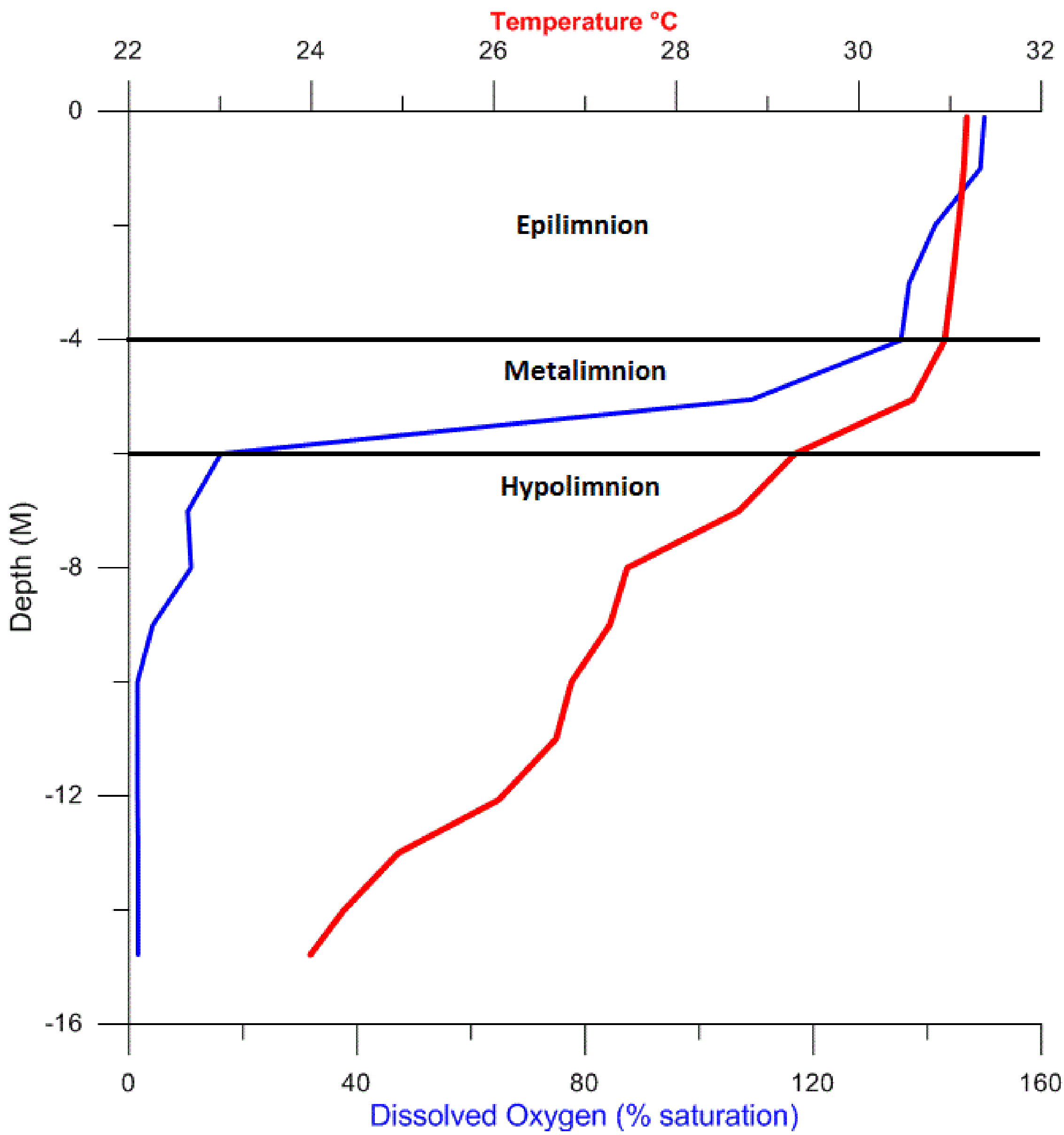


Figure 6. A Typical Temperature and Dissolved Oxygen Vertical Profile for Lake Thunderbird (Period of Greatest Thermal Stratification in 2010).

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 both isolating nutrients or chemicals in areas of reduced exchange and water interaction (hypolimnion) and increased loading of nutrients in the anoxic hypolimnion as inorganic phosphorous and ammonia are reduced out of the sediment under anaerobic conditions. 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.

In a normal season conditions begin isothermal, but as increased solar radiation and ambient temperatures occur with the start of summer, the upper portion of the water column rapidly heats while the bottom of the lake stays cool leading to a well defined stratification pattern in the water column as the water in the bottom of the lake. In 2011, the onset of ambient temperatures did not lead to a strongly stratified system by June 1st, nor did anoxia become present in a significant portion of the water column (**Figure 7**).

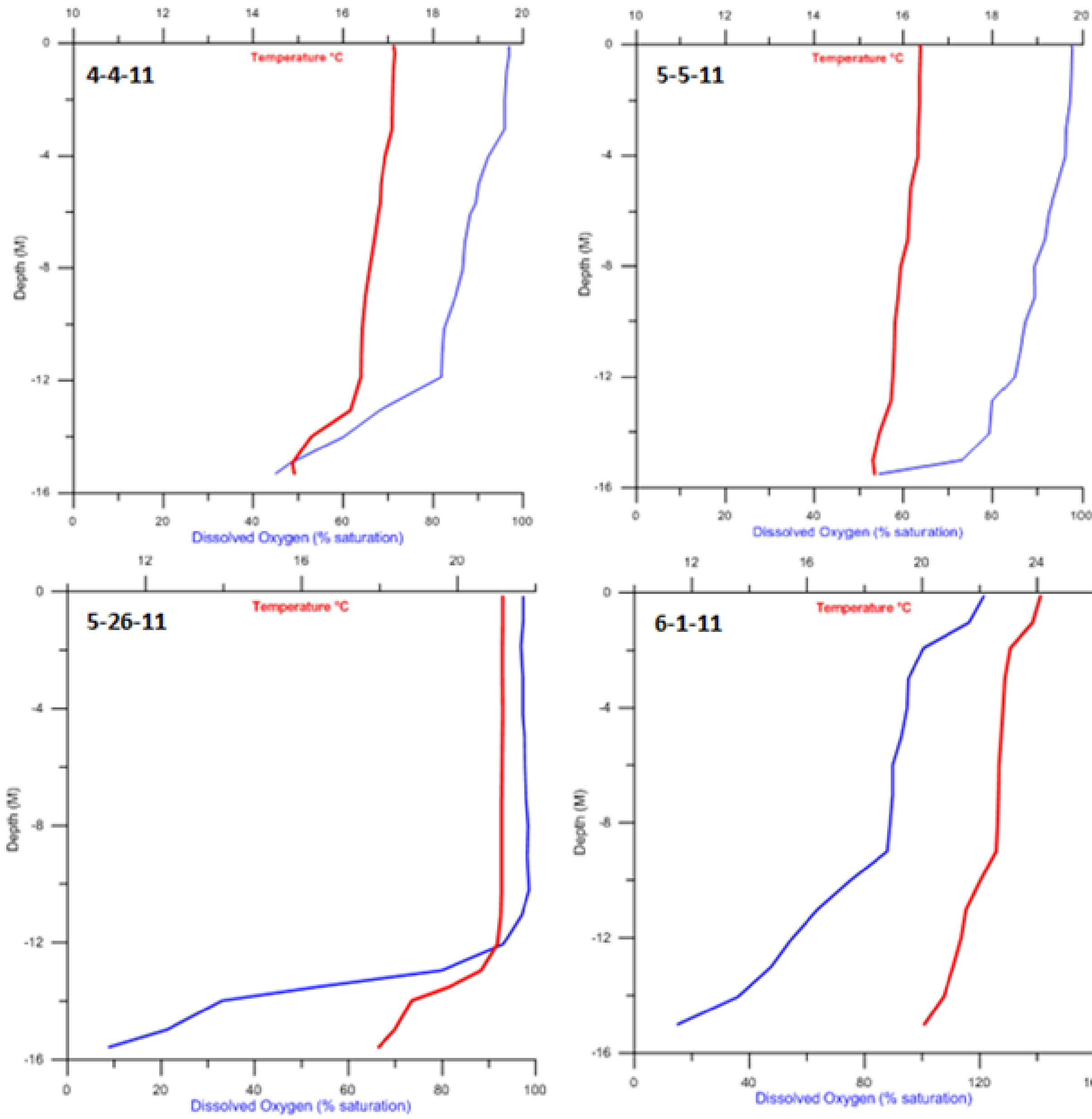


Figure 7: Temperature and Dissolved Oxygen Vertical Profile. Site 1: April 4, 2011 – June 1, 2011.

As the summer progressed from mid-June through July the temperature throughout the entire water column continued to increase at a rate that prevented a strong stratification pattern to become present. While the water column was not strongly stratified throughout much of this time period, atmospheric diffusion of oxygen became sufficiently restricted for anoxia to develop. By the end of July this anoxia had encompassed the water column from 7 meters and below **(Figure 8).**

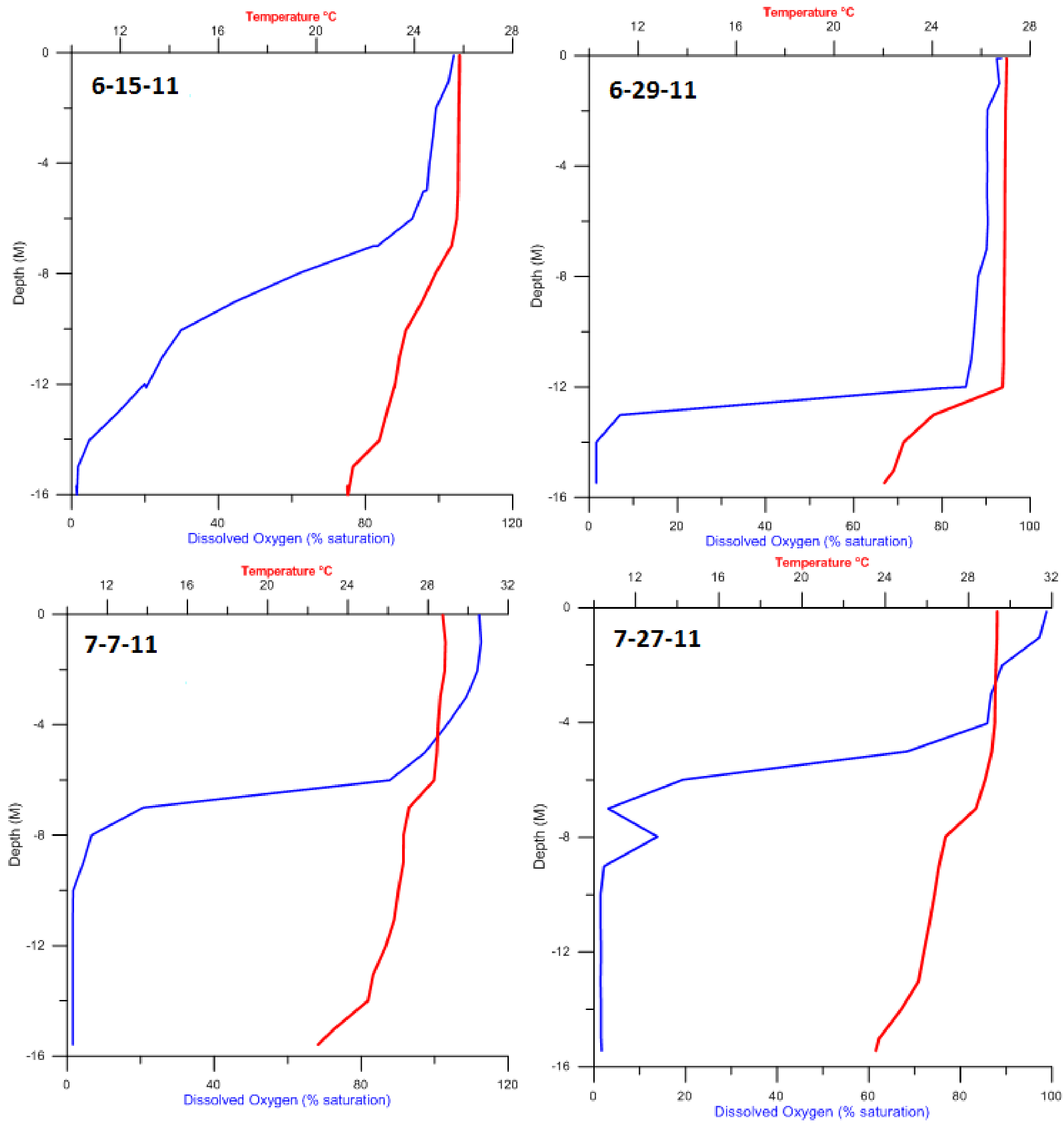


Figure 8. Temperature and Dissolved Oxygen Vertical Profile Site 1: June 15, 2011 – July 27, 2011

Anoxia reached its apparent peak on August 3rd 2011, with anoxia present in waters 6 meters and below. The temperature at the lake bottom continued its unusual pattern of heating up, leading to an exceptionally early turnover event that began around mid-August and was complete by early September. The reduced surface DO values throughout this time period, illustrate the consequence of mixing the large volume of anoxic hypolimnetic waters with the epilimnion (**Figure 9**).

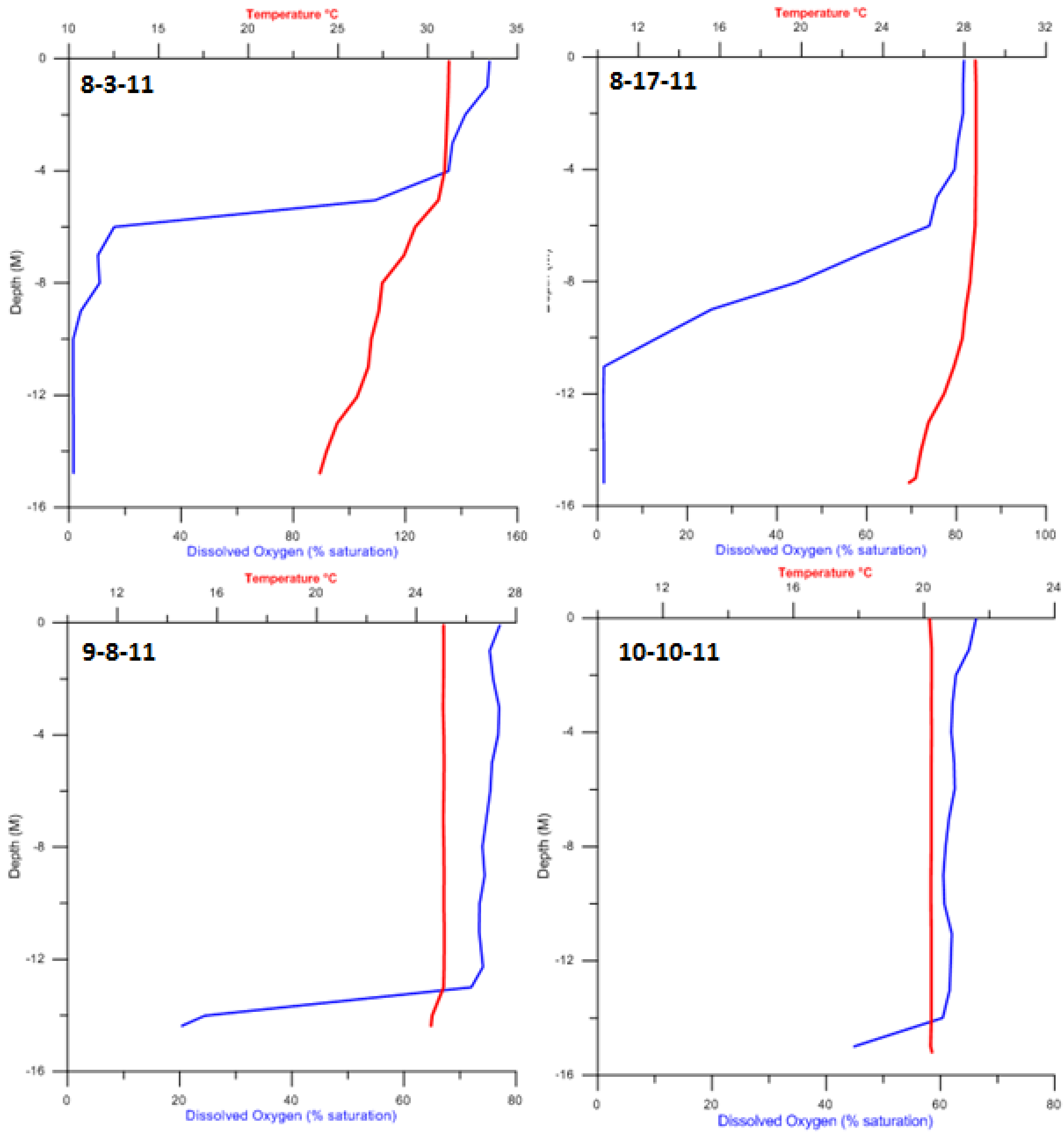


Figure 9.Temperature and Dissolved Oxygen Vertical Profile Site 1: August 3, 2011 – October 10, 2011. Showing Complete Turnover and Recovery of DO (Oxidation of reduced compounds formed in the hypolimnion).

An alternate method for illustrating physical lake data is by using 3-dimensional isopleths, which 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 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 temperature plot warmer temperatures are colored red, graduating to blue as temperature decreases, while on the DO plots, low DO values are colored red, graduating to blue as dissolved oxygen increases.

Strong thermal stratification was never present during the 2011 sampling season, which can be seen on the isopleths as spacing generally greater than 1 meter required to change temperature by one degree Celsius. While strong stratification was never present, stratification was significant enough to isolate a hypolimnion relatively void of dissolved oxygen. Stratification reached an apparent peak in mid to late July and decreased in size until complete lake turnover was noted at the start of September. The temperature isopleths also makes evident the continual warming that occurred at the lake bottom throughout the summer as temperatures rose from 16 to 25 degrees Celsius during the summer; this also indicates that the hypolimnion was not completely isolated through the summer as in strongly stratified systems little to no change in temperature occurs after stratification becomes present.

Anoxia is generally defined as less than 2 mg/L of DO. While a well defined thermal stratification pattern is never evident in 2011, anoxia is witnessed in the lower half of the water column from July through August. 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 algae 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 intense blue 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 while instances of below saturation epilimnetic waters is evidence of the decomposition of the large amount of detrital material built up during the previous five months requiring more oxygen than is available in the mixed epilimnion and that diffusion with the atmosphere can provide.

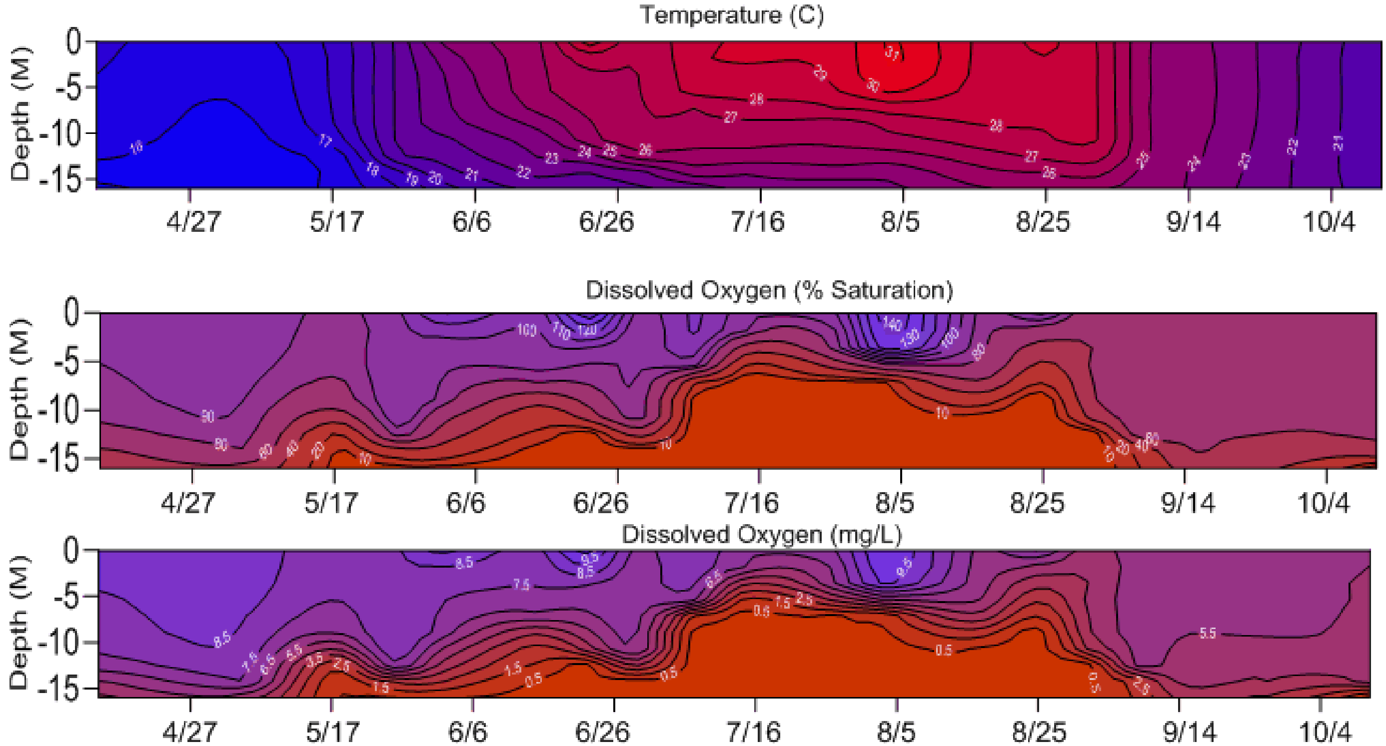


Figure 10.Lake Thunderbird Isopleths Showing Temperature (C), Dissolved Oxygen (% Saturation) and Dissolved Oxygen (mg/L) with Depth at Site 1, by date for 2011

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 and phosphorus lead to significant water quality problems including reduced spawning grounds and nursery habitats, fish kills, hypoxic/anoxic conditions, harmful algal blooms, and public health concerns related to increased organic content of drinking water sources.

Nutrient samples were collected twelve times during the 2011 sampling season. Spring environmental conditions are represented by samples taken in April and May, while samples from June, July, August, and September represent summer conditions and samples from October represent fall conditions.

Several measures of nitrogen (N) and phosphorus (P) were made, including dissolved and total forms. Dissolved nutrient concentrations consist of nutrients that are available for algal growth, such as ortho-phosphorus (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 are available for future algal growth.

Nitrogen and phosphorus concentrations in the epilimnion can also indicate what may be limiting algal growth. Generally, when both nitrogen and phosphorus are readily available, neither is a limiting nutrient to algal growth, and excessive Chl-*a* values are expected. When high phosphorus concentrations are readily available in comparison to very low nitrogen concentrations, algal growth may be nitrogen 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 nitrogen, certain blue-greens have the ability to convert atmospheric nitrogen into a usable form by way of specialized cells called heterocysts. Blue-green algae are the only type of algae that have heterocysts, and are generally implicated for producing harmful toxins and chemicals that can cause taste and odor problems in public water supplies. While no blue-green algae events were documented at Lake Thunderbird during the summer of 2011, many large reservoirs within the state experienced blue-green algae blooms with measurable amounts of cyanotoxins found in the waters.

In regard to nutrient limitation, phosphorus, as the limiting nutrient, is desired for most freshwater systems. Under phosphorus limiting conditions, typically desirable green algae will 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, where the total nitrogen to total phosphorus, TN:TP of less than or equal to 18 indicates a nitrogen-limited waterbody, 20-46 is a co-limitation of nitrogen and phosphorous, and greater than 65 regarded as phosphorus-limited. The molecular ratios corresponds to TN:TP concentrations of less than 7 being nitrogen-limited, 8-18 co-limited, and greater than 26 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 had molecular 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 nitrogen and phosphorus, the ratio has trended upward until 2011. An average TN:TP concentration ratio of 23 at the surface of site 1 was observed in 2011 predicting a system which is co-limited under much of the growing season (**Figure 11**). Examination of TN:TP constituents shows the ratio increases when TN increases and TP decreases and the ratio decreases as TP increases and TN decreases. Under phosphorus or nitrogen limiting conditions, one would expect that the limiting nutrient would be significantly decreased in concentration, particularly the biologically available inorganic phosphorus, or nitrogen. The aforementioned ratio suggested inorganic phosphorus, or inorganic nitrogen and phosphorus would be held in low concentration throughout the monitoring period. The 2011 nutrient dataset exhibited inorganic dissolved nitrogen data below detection limit from late-June until mid September, while inorganic phosphorus was detected in some amount throughout the entire year. This suggests that nitrogen is playing a role in limiting phytoplankton growth during the summer when productivity peaks. This is further discussed in the **Nitrogen** section of this report.

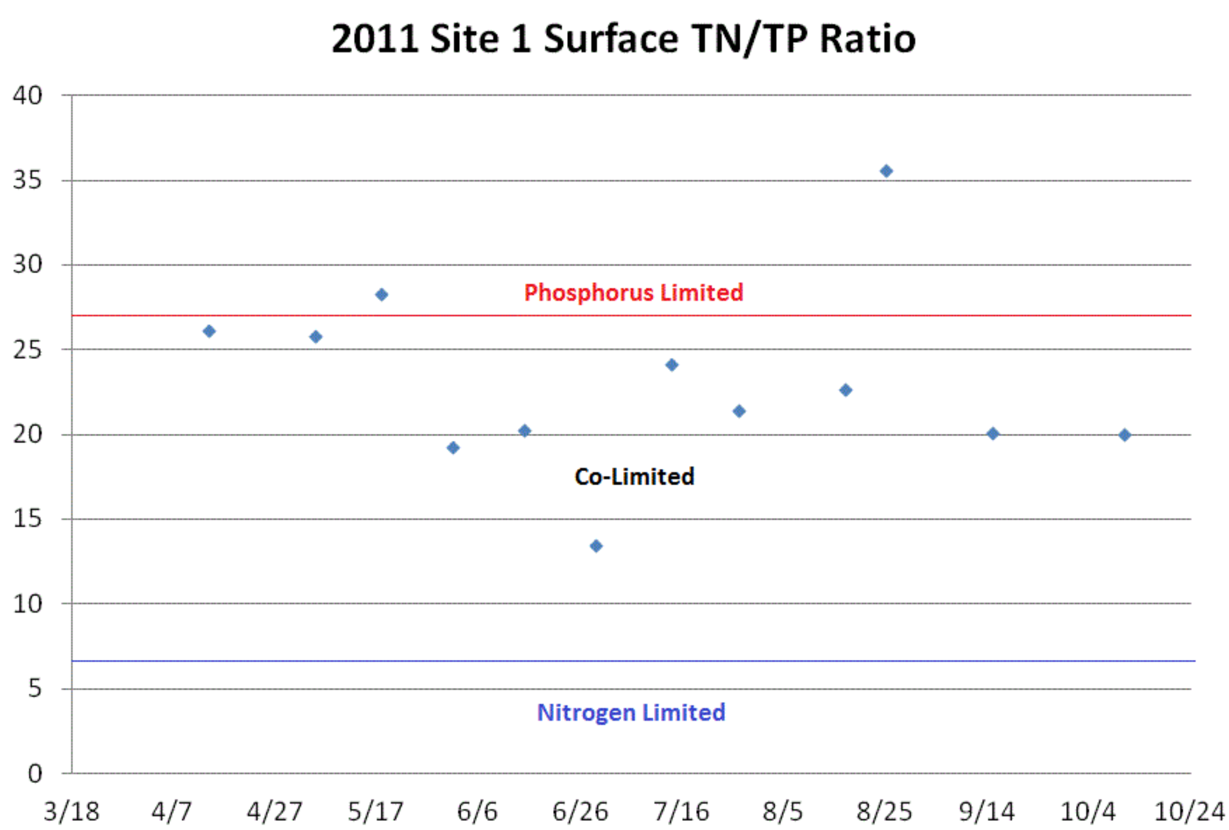
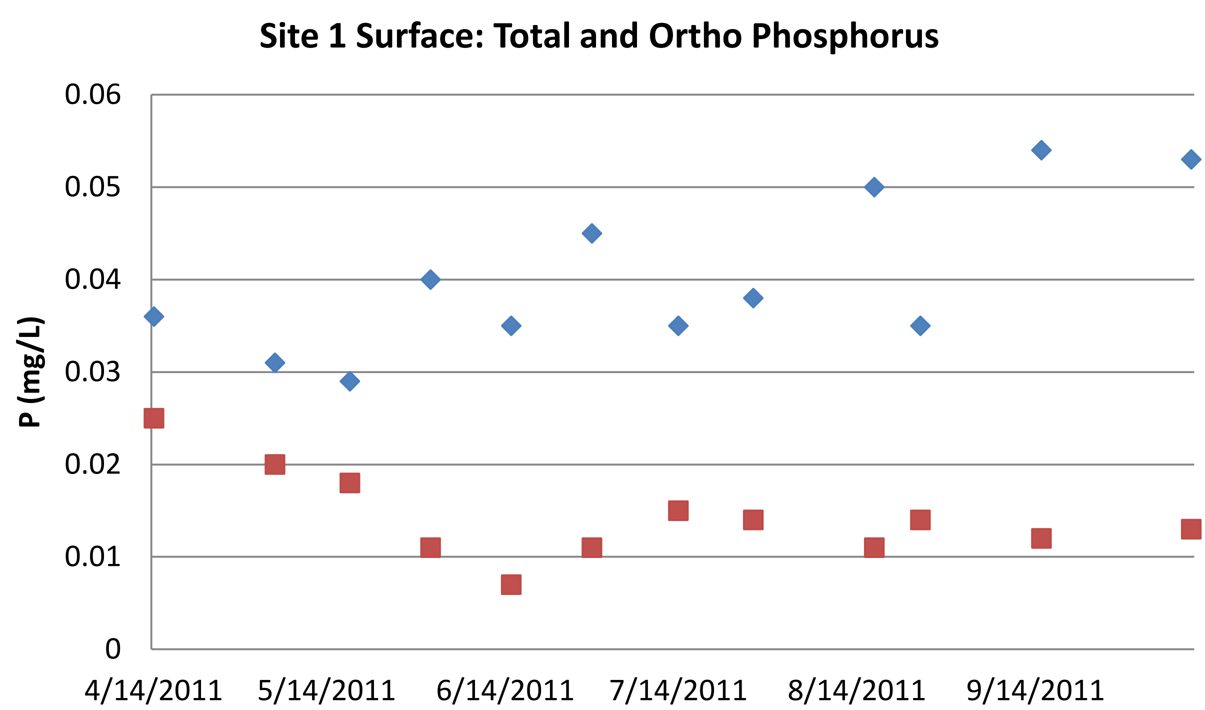


Figure 11. 2011 Site 1 Surface TN:TP Ratio

Phosphorus

Total phosphorus (TP) and ortho-phosphorus (ortho-P) concentrations produced patterns typical of seasonal ecological cycles in lakes (**Figure 12**). Ortho-P was detected in every sample taken at Site 1 in 2011 with surface ortho-phosphorus initially decreasing until reaching a relatively stable level near .01 mg/L. Surface ortho-P averaged 0.014 mg/L, and never fell below 0.010 mg/L in the peak of summer as it consistently has in the past, suggesting the lake may of shifted to a more co-limited system during the summer of 2011 suggesting a luxuriant amount of phosphorous available for algae growth. The buildup of hypolimnetic ortho-phosphorus is evidence of the settling of decomposing algae from the epi- and metalimnion, in addition to active release from the anoxic sediment (**Figure 13**).

Interestingly in 2011 absent was a large rise in surface ortho-P noted in the turnover timeframe; The large "bulge" in ortho-P noted after late-August is due to portions of the nutrient rich hypolimnion mixing into the less nutrient rich surface waters. This mixing coincides with the depression of DO and dissolved oxygen percent saturation. Total phosphorus shows a similar pattern to ortho-P with the exception of higher values. The highest surface TP were noted at the end of the monitoring season, with September 15th total phosphorous peak at 0.054 mg/L. In 2011, the average surface TP concentration at the surface of site 1 was .048 mg/L 20% greater than the .04 seen on average in the 2005-2009 historical dataset.



	4/14	5/5	5/18	6/1	6/15	6/29	7/14	7/27	8/17	8/25	9/15	10/11
◆ TP	0.036	0.031	0.029	0.04	0.035	0.045	0.035	0.038	0.05	0.035	0.054	0.053
■ Ortho-P	0.025	0.02	0.018	0.011	0.007	0.011	0.015	0.014	0.011	0.014	0.012	0.013

Figure 12. 2011 Lake Thunderbird Ortho-Phosphorus and TP Surface, by Date, at Site 1.

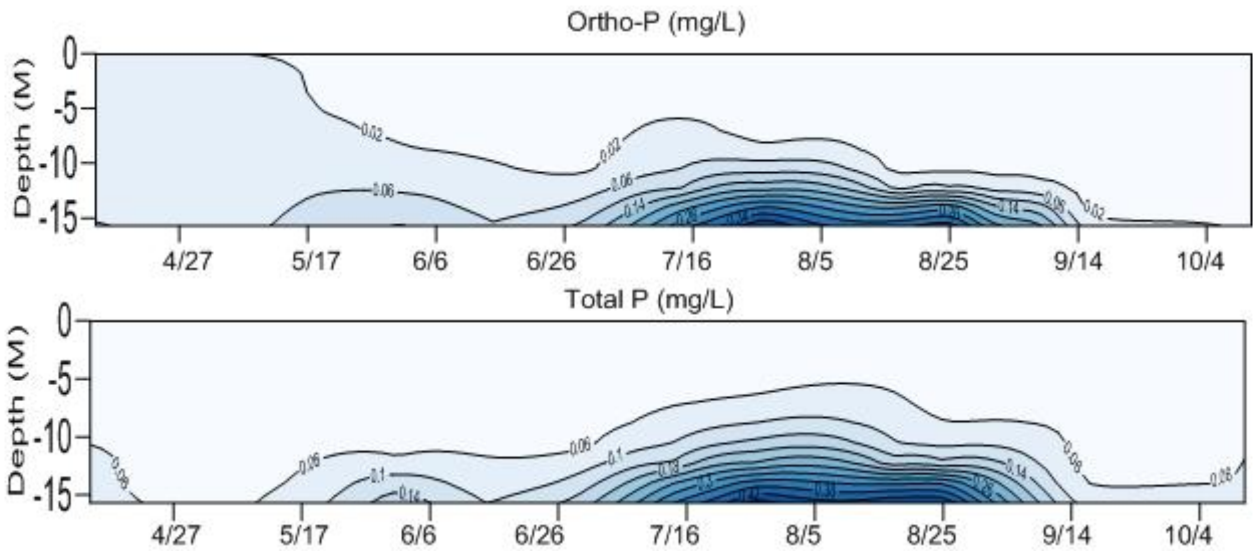


Figure 13. 2011 Lake Thunderbird Ortho-Phosphorus and TP Contours with Depth, by Date, at Site 1.

Nitrogen

Total nitrogen (TN) and dissolved nitrogen concentrations also produced patterns typical of seasonal ecological cycles in lakes (**Figure 14**). Surface total kjeldahl nitrogen showed a pattern of a general increase over the summer while dissolved forms of nitrogen fell below detection through the summer until stratification deepened, mixing ammonia, a dissolved form of nitrogen back into the epilimnion. The annual or seasonal pattern observed warrants potential explanations.

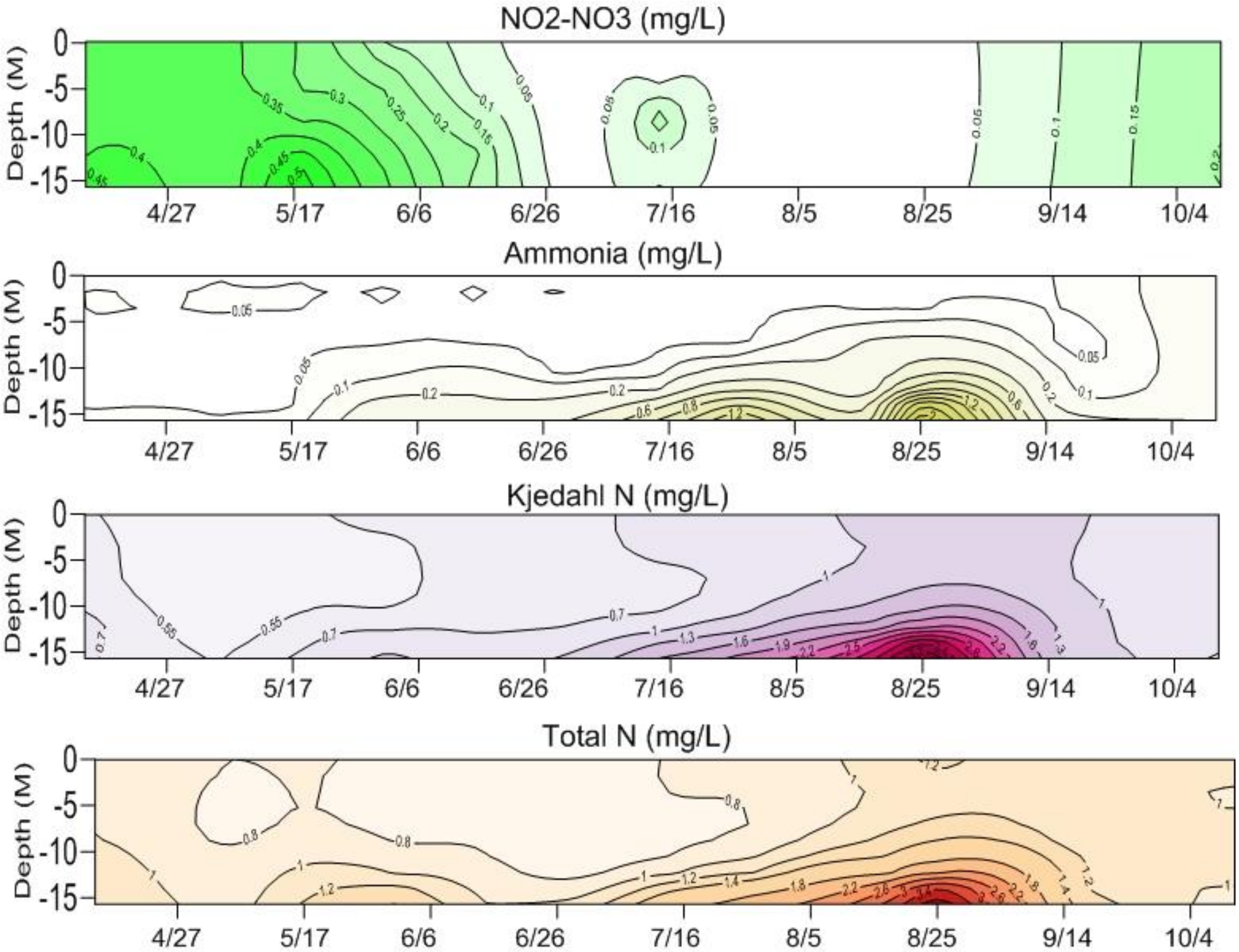
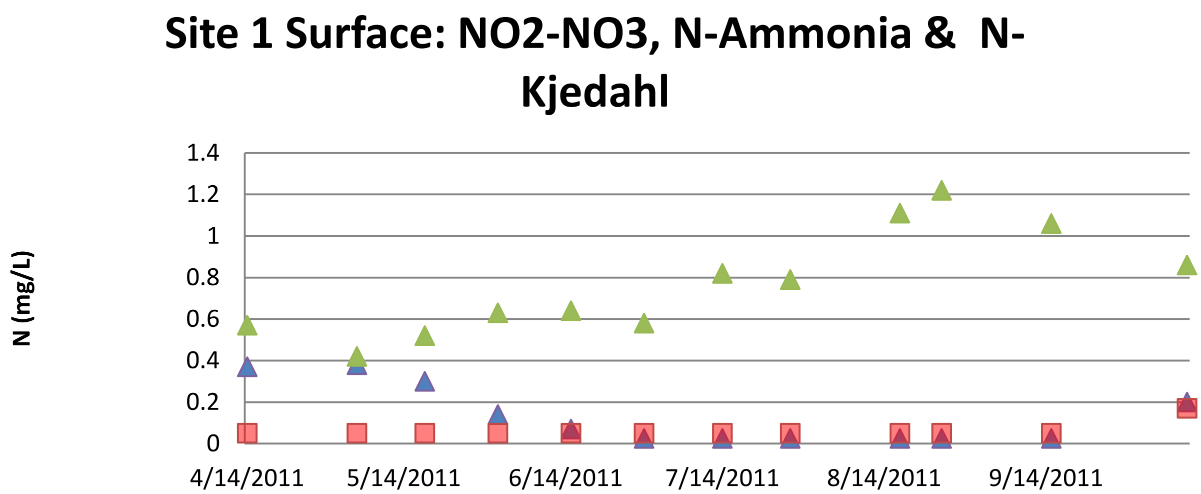


Figure 14. 2011 Lake Thunderbird NO2-NO3, Ammonia, Total Kjedahl N, and Total N contours with Depth, by Date, at Site 1

The two most likely forces driving the surface dynamics seen in the last few years are due to epilimnetic algae growth (uptake) and hypolimnetic sediment release of ammonia. Examination of dissolved nitrogen, 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 nitrogen 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 from the epi- and metalimnion.

Dissolved inorganic nitrogen (NO3-NO2 + NH3) decreased to below detection limits in the epilimnion from late June through the end of August. The primary form of dissolved nitrogen in the epilimnion was nitrate (**Figure 15**). Nitrate is an algal macronutrient second only to ammonia for preferential uptake. Depletion by algal uptake, generally indicates nitrogen-limiting conditions. This idea is furthered by the fact that a measurable amount of inorganic phosphorous was detected throughout the entire summer. This represents the second consecutive year in which epilimnetic inorganic nitrogen sources were held below detection limit, but measurable amounts of inorganic phosphorous was available for algal uptake.



	4/14/2011	5/5/2011	5/18/2011	6/1/2011	6/15/2011	6/29/2011	7/14/2011	7/27/2011	8/17/2011	8/25/2011	9/15/2011	10/11/2011
Nitrite-Nitrate as N	0.37	0.38	0.3	0.14	0.07	0.025	0.025	0.025	0.025	0.025	0.025	0.2
N-Ammonia	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.17
N-Kjeldahl	0.57	0.42	0.52	0.63	0.64	0.58	0.82	0.79	1.11	1.22	1.06	0.86

Figure 15. 2011 Site 1 Surface NO2-NO3, N-Ammonia and Total Kjedahl N , by Date, at Site 1.

While extended depletion of dissolved inorganic nitrogen is not unique to the Lake Thunderbird historical dataset (occurrences in 2007, 2008, 2010), previous instances of dissolved nitrogen depletion coincided with ortho-P depletion, indicating co-limited conditions. The 2011 (and 2010) monitoring year was distinctively different from the historical dataset in that depletion of dissolved nitrogen occurred while ortho-phosphorous remained in measurable amounts in epilimnetic waters. It is important to note that while the system seems to be shifting more towards nitrogen limitation than in the past, nutrient data suggests that this is due to a disproportionate increase in phosphorous rather than a decrease in nitrogen.

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. 2011 Lake Thunderbird Site 1 Phosphorus Mass (kg) at Depth Intervals by Sample Date. (Blue cells represent anoxic accumulation of phosphorus).

Depth (m)	14-Apr	5-May	18-May	1-Jun	15-Jun	29-Jun	14-Jul	27-Jul	17-Aug	25-Aug	15-Sep	11-Oct
0 - 1	425	573	472	750	652	990	577	576	765	585	841	962
1 - 2	612	518	493	574	556	702	577	689	791	519	819	753
2 - 3	497	409	388	669	520	755	524	509	719	505	681	727
3 - 4	448	400	373	524	471	515	459	489	612	407	655	670
4 - 5	379	388	306	488	407	619	557	401	509	370	809	616
5 - 6	373	285	294	404	532	404	489	498	573	434	223	483
6 - 7	292	270	258	345	154	314	424	480	500	337	396	460
7 - 8	257	230	223	289	284	253	498	451	448	298	326	336
8 - 9	200	200	192	236	281	288	482	443	403	259	248	289
9 - 10	210	131	162	212	168	173	377	461	347	265	168	181
10 - 11	114	92	113	155	132	117	269	347	244	196	108	118
11 - 12	85	56	73	104	138	73	191	236	155	124	78	64
12 - 13	49	28	40	65	86	37	136	142	84	78	8	30
13 - 14	20	13	19	50	22	25	78	88	66	59	14	13
14 - 15	7	5	8	26	4	8	25	37	28	32	3	4
15 - 16	1	0	1	12	5	6		5	5			
16+	1	0										
x												
Total	3972	3595	3415	4902	4413	5280	5662	5851	6249	4468	5376	5704
Hypolimnetic Mass					1121	980	2479	1759	2853	2081		
Hypo % of Total Water Column					25.4%	18.6%	43.8%	30.1%	45.7%	46.6%		

To complete the massing of Lake Thunderbird phosphorus, sample dates were averaged to yield monthly amounts. The constructed budget demonstrates pre-stratification lake phosphorus mass in 2011 of approximately 4,900 kg or less. May 18th marked the lowest observed phosphorus mass (3,415 kg) while August 17th marked the highest (6,249 kg) mass of lake TP.

Monthly phosphorus masses demonstrate a general trend of baseline levels occurring in winter under mixed conditions, then steady increases progressing to a late-summer peak as the thermocline begins to break up. After destratification 2011's phosphorous mass followed an unseen trend in that phosphorous mass initially decreased but then began increasing until the final sampling date on October 11th 2011. In previous years, destratification was followed with a decrease of total phosphorous throughout the water column.

Lastly it is worthwhile mentioning that reduction in extent and duration of anoxia within the water column in 2011 when compared to the 2005-2009 average should correspond to a reduction in anaerobically mediated sediment phosphorous release. Using calculations based on Nurnberg (2005), and specifically developed for Lake Thunderbird in OWRB (2011); calculated anaerobically mediated sediment phosphorous release was reduced by 29%, equivalent to 5% of the average total phosphorous load (OWRB 2011).

Chlorophyll-*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 2011. Chlorophyll-*a* peaked in late August (**Figure 16**). In 2011, 98% of samples were considered eutrophic based on a 7.2 g/L division between mesotrophy (Wetzel 2001). This appears to be a continuation of the steady increase witnessed since 2007, (2010:95%, 2009:91%, 2008:87%, 2007:80%, **Figure 17**). For the lacustrine sites (1, 2, 4) Chl-*a* followed a typical seasonal progression of early (relative) stability followed by marked increase until fall turnover. For the riverine sites of the Little River and Dave Blue Creek (6, 11) Chl-*a* started the growing season off at an unusually high level and this season and was maintained throughout the season.

Goal setting by the COMCD in previous years set a maximum Chl-*a* of 20 g/L. During the 2011 sampling season 79% of samples exceeded this upper limit. This number represents a significant increase from the previous 3 years (2010:56%, 2009:58%, 2008:53%). The large number of hypereutrophic samples is likely due to the excessive nutrient inputs documented in this report.

Because Lake Thunderbird is designated a Sensitive Public and Private Water Supply (SWS); currently used as water supply reservoirs, it is required to meet a long term average Chl-*a* criterion of 10 g/L (OAC 785:45-5-10 (7)). In 2011 89% of the samples were above this limit. Significant abatement of nutrient inputs into the watershed is necessary to significantly reduce Chl-*a* concentrations on a long-term basis. The ODEQ will draft a TMDL to address necessary nutrient reductions needed to meet WQS set for SWS reservoirs.

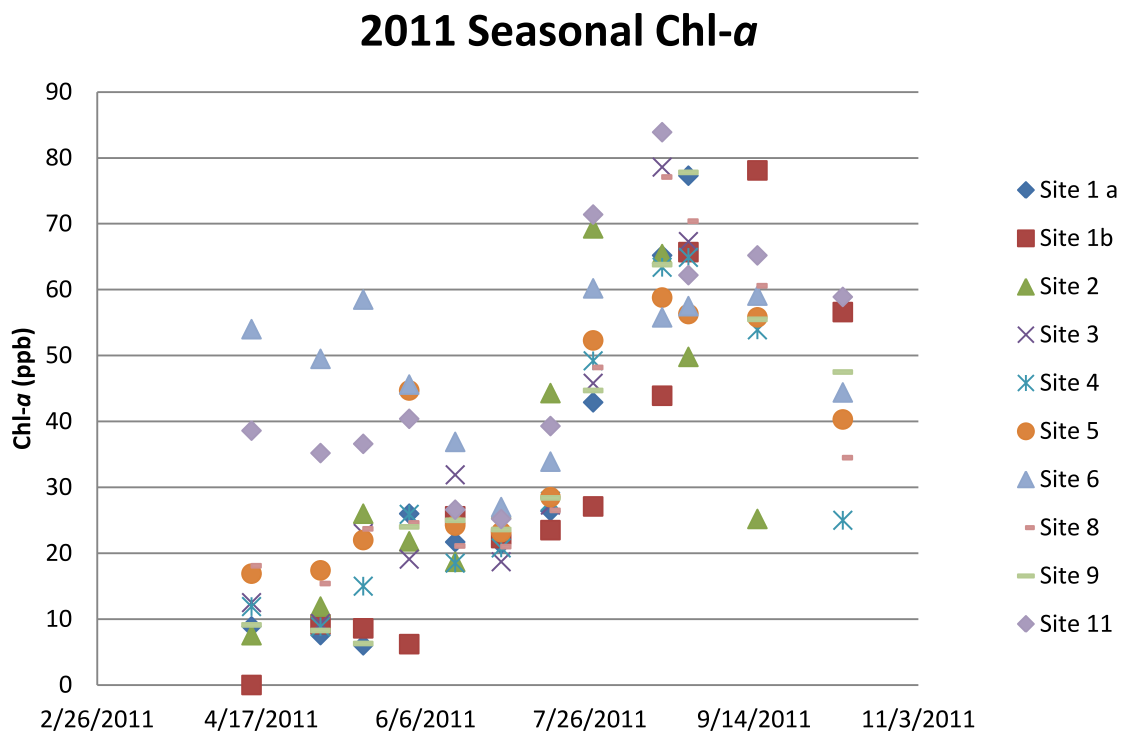


Figure 16. Lake Thunderbird Surface Chl-*a* (g/L) by Site; April through October 2011

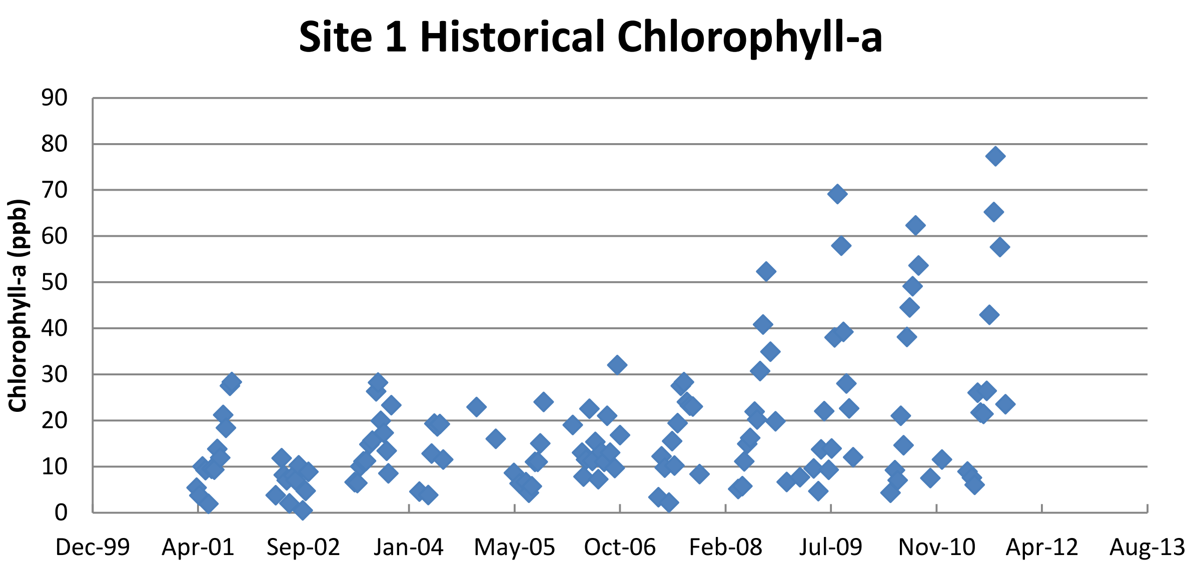


Figure 17. 2001-2011 Lake Thunderbird Surface Chl-*a* (ppb) at Site 1

General Water Quality

Total Organic Carbon - TOC

Total organic carbon (TOC) 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 2011 calendar year.

In general, lacustrine TOC concentrations increased during spring and early summer, with peak concentrations occurring in late August (**Figure 18**). Concentrations consistently declined after this peak date. This trend is consistent with other proxies of primary production, such as Chl-*a* (**Figure 16**) and pH (**Figure 21**).

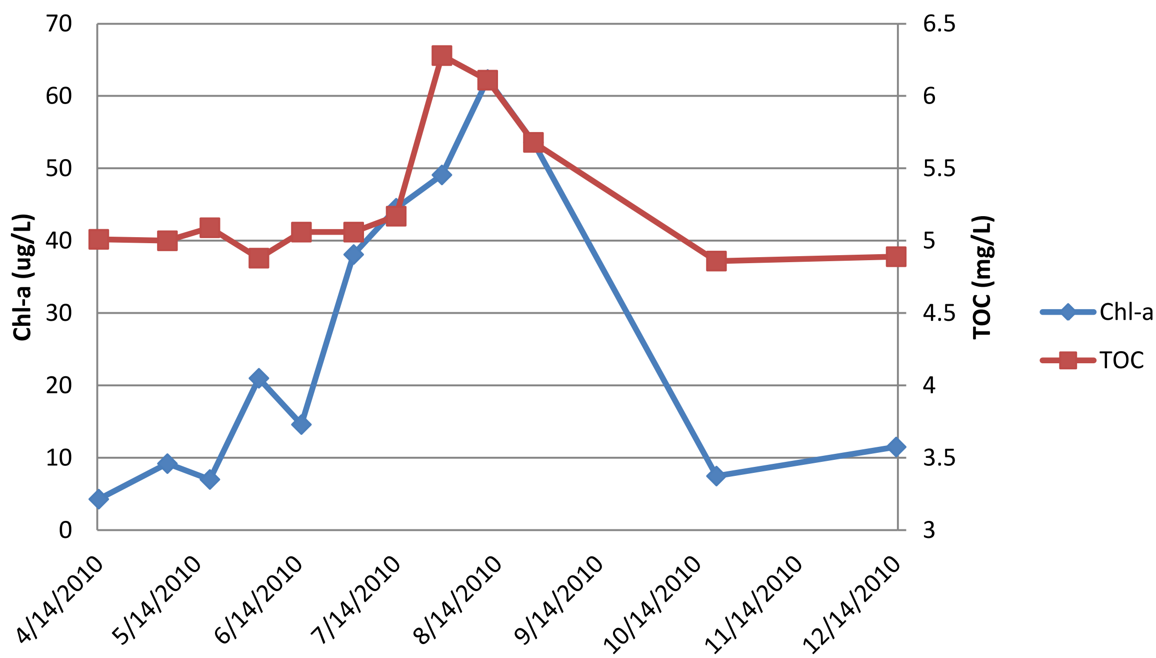


Figure 18. TOC Concentrations and Chl-*a* at Site 1 Surface on Lake Thunderbird during the 2011 Sampling Season

Statistical regression as seen in **Figure 19**, suggested that 49% 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). 2011 represented the third consecutive year of TOC sampling, each season of sampling has shown a correlation coefficient of 0.6 of better.

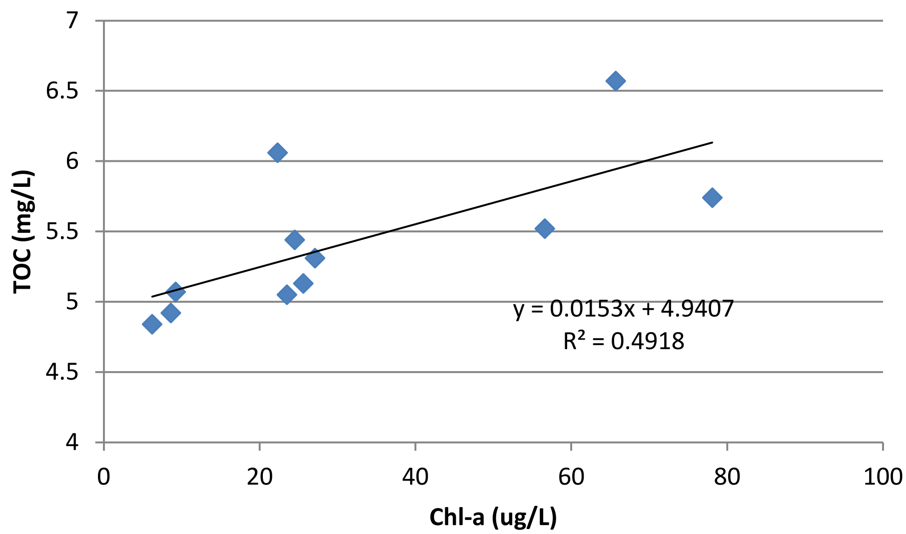


Figure 19. 2011 Lake Thunderbird TOC vs Chl-*a* for Raw Water Samples

Trophic State Index

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

Lake Thunderbird's TSI values for the three variables can be seen in **Figure 20,** and ranges from 48-73 throughout the year. These values place Lake Thunderbird in the hypereutrophic category (TSI 60+) with periods of eutrophic conditions TSI (50-60).

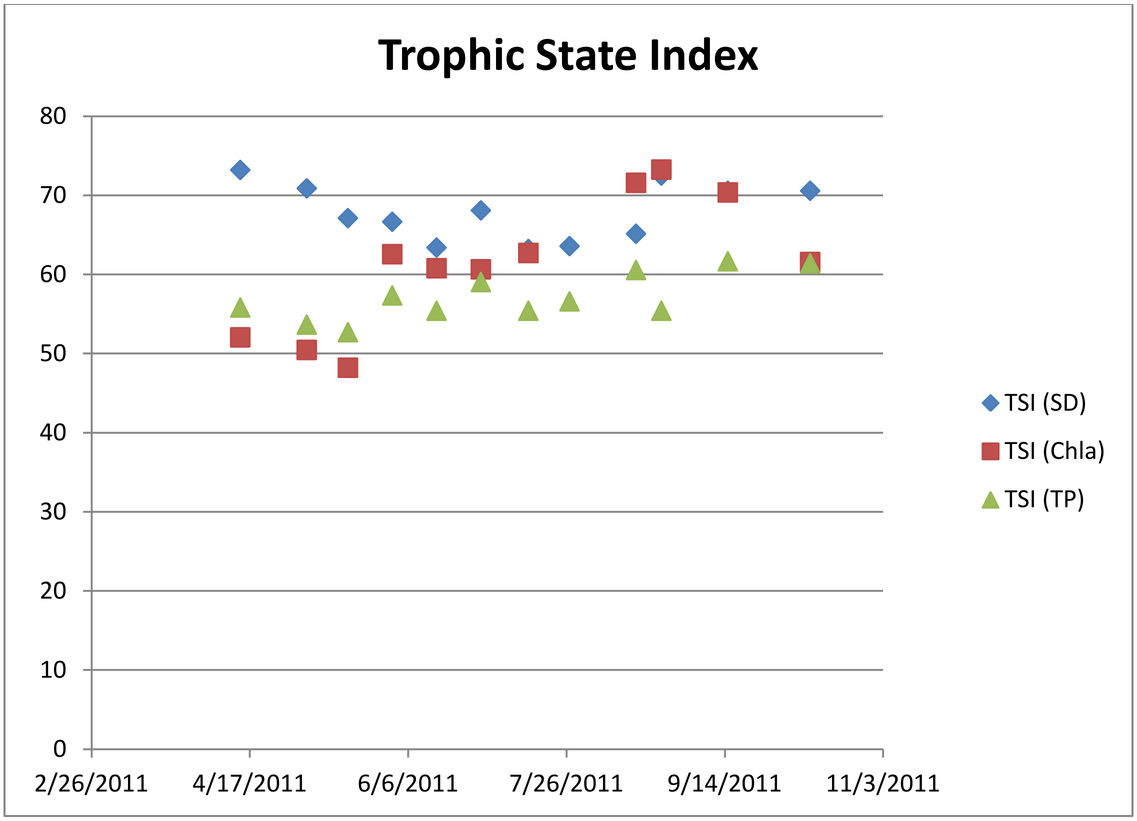


Figure 20. Carlson's Trophic State Index Values for Lake Thunderbird 2011 at Site 1.

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 2011 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 where decomposition processes within hypolimnion depressed the pH to below 7 (**Figure 21**). The riverine sites operated differently than the lacustrine sites, where Chl-a and pH started off unusually high and remained that way through the duration of the summer, indicative of hypereutrophic conditions. 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 8.89 and the lowest recorded pH value was 6.85. While Lake Thunderbird currently falls within water quality standards, it should be noted that peak pH has been observed incrementally increasing over the years and that if Chl-*a* continues to increase; algal biomass will likely lead to pH impairments in the near future.

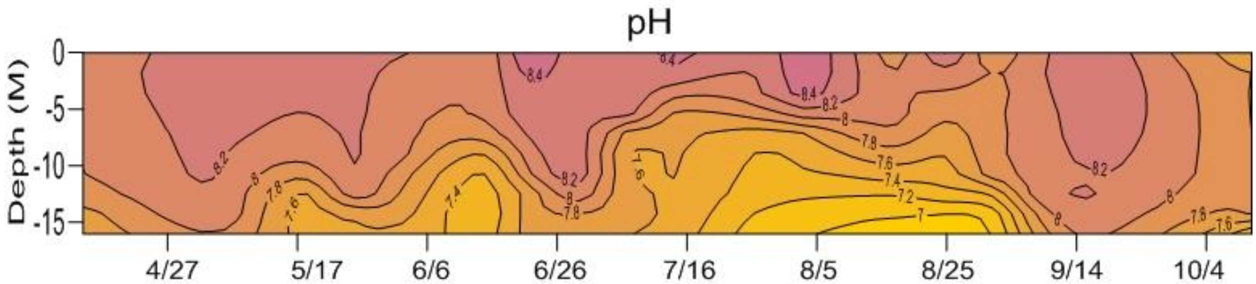


Figure 21. 2011 Lake Thunderbird pH (S.U.) versus Depth Over Time: Site 1

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 positive (300-500 mV). Normally as oxygen concentrations approach zero, redox potential begins to drop in proportion to anaerobic metabolism. Initially in 2011 the oxygenated conditions that were present throughout the water column and redox potentials remained high throughout the water column. As anoxia set in the lake bottom at the start of June, redox potentials remained high. In late June 2011, redox values began to drop into strong reducing conditions, but still occupied a significantly smaller volume of water than anoxia occupied (**Figure 22** and **Figure 23**). This led to a significant reduction in both duration and extent of sub-100 mV ORP values from previous years.

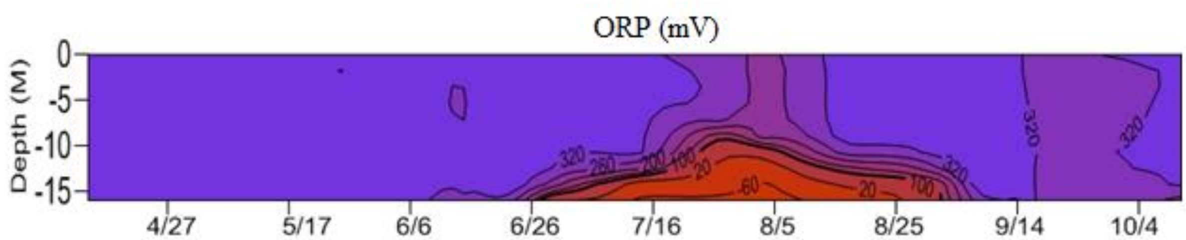


Figure 22. 2011 Lake Thunderbird Oxidation-Reduction Potential (mV) versus Depth (M) Over Time: Site 1. Area Below thick black line represents strong reducing conditions responsible for reduction of sediment bound phosphorous.

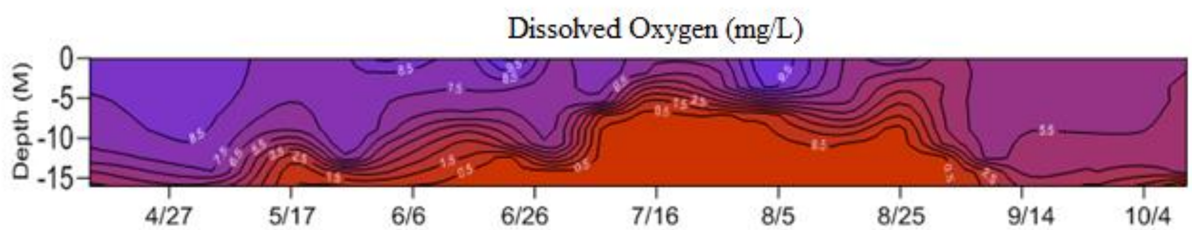


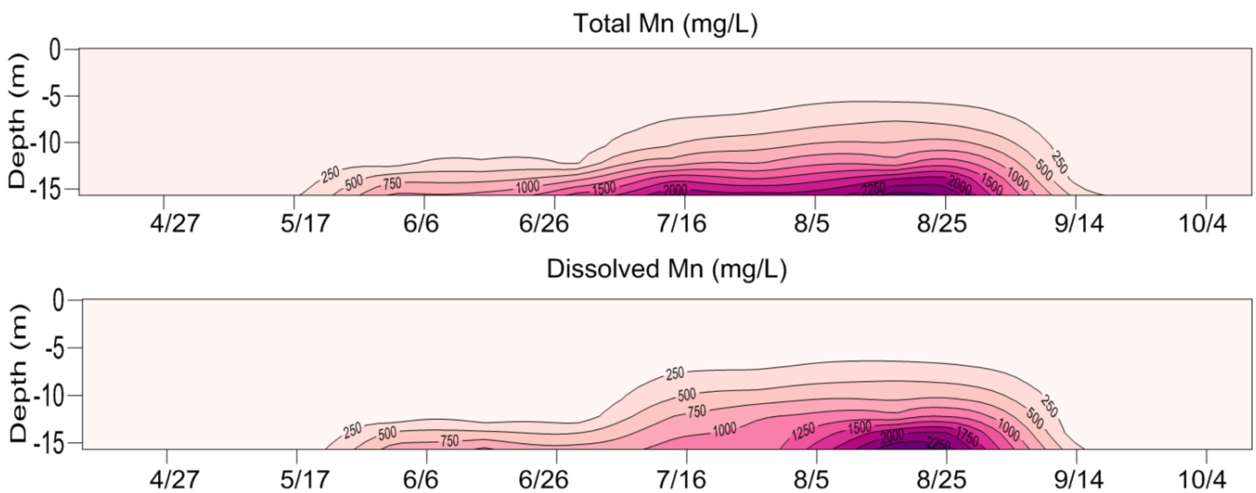
Figure 23. Lake Thunderbird Dissolved Oxygen (mg/L) versus Depth (m) Over Time: Site 1.

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.

Total and dissolved forms of iron and manganese were sampled at 4 meter intervals at Site 1, and displayed dissimilar temporal patterns of build up. Initially under aerobic oxidative conditions dissolved and total manganese were below detection limits. As anoxia and reducing conditions set in dissolved manganese began building up and represented the majority of total manganese in the water column. As anoxia subsided and oxidative conditions resumed dissolved and total manganese returned to very low levels.

Total and dissolved iron data displayed a strikingly different pattern of build up, where a large rapid buildup was seen in late spring, and then rapidly dropped off (**Figure 24**). One potential explanation of this was that dissolved Fe present in the hypolimnion was eliminated through the formation of very insoluble FeS with sulfide also formed under reducing conditions that would return to the sediment bed (Wetzel 2001). Manganous sulfide on the other hand is much more soluble and would have little effect on dissolved Mn concentrations.

2011 represented the first full season of collection dissolved and total Fe and Mn. With a more continuous dataset a more definitive conclusion can be made.



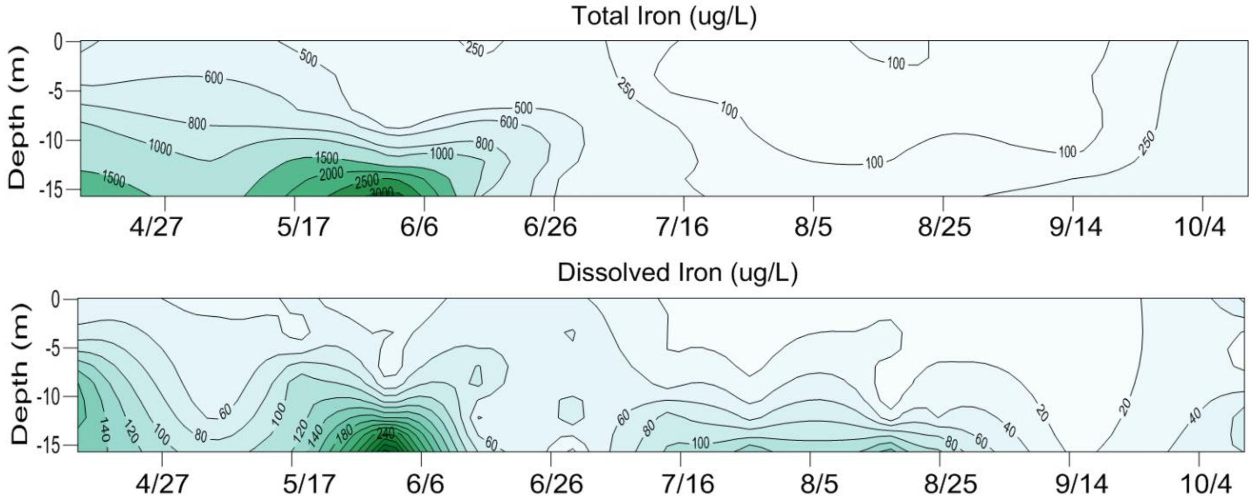


Figure 24. 2011 Site 1 Total and Dissolved Manganese and Iron concentrations by depth over time.

Taste and Odor Complaints

The City of Norman provided data on the number of taste and odor complaints from their customers in 2011 and previous years. 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 in treated waters in past years. Eutrophication results in cyanobacteria dominance of algal communities in lakes, and therefore corresponds to excessive nutrient concentrations.

In 2011, the City of Norman received very few taste and odor complaints. The month with the highest number of complaints was September with 9 (**Figure 25**). 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 26**).

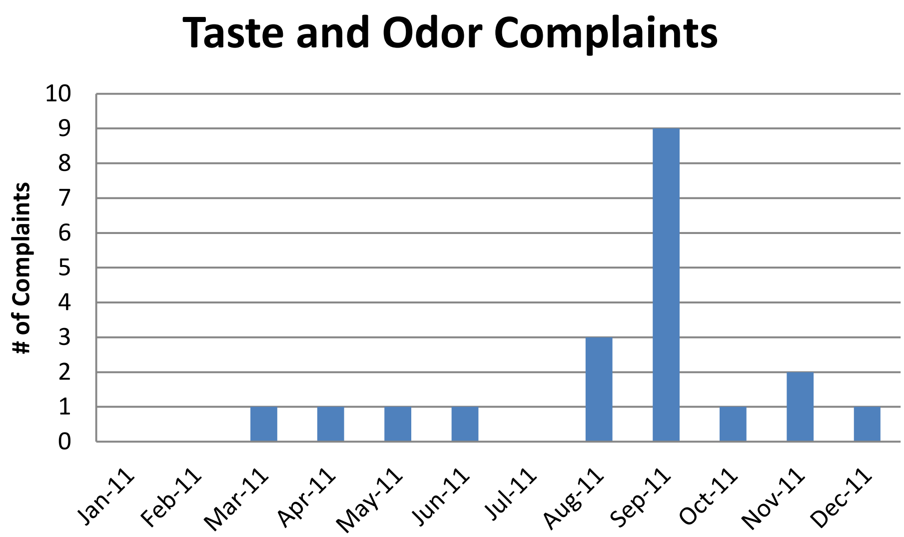


Figure 25. Taste and Odor Complaints to the City of Norman during 2011

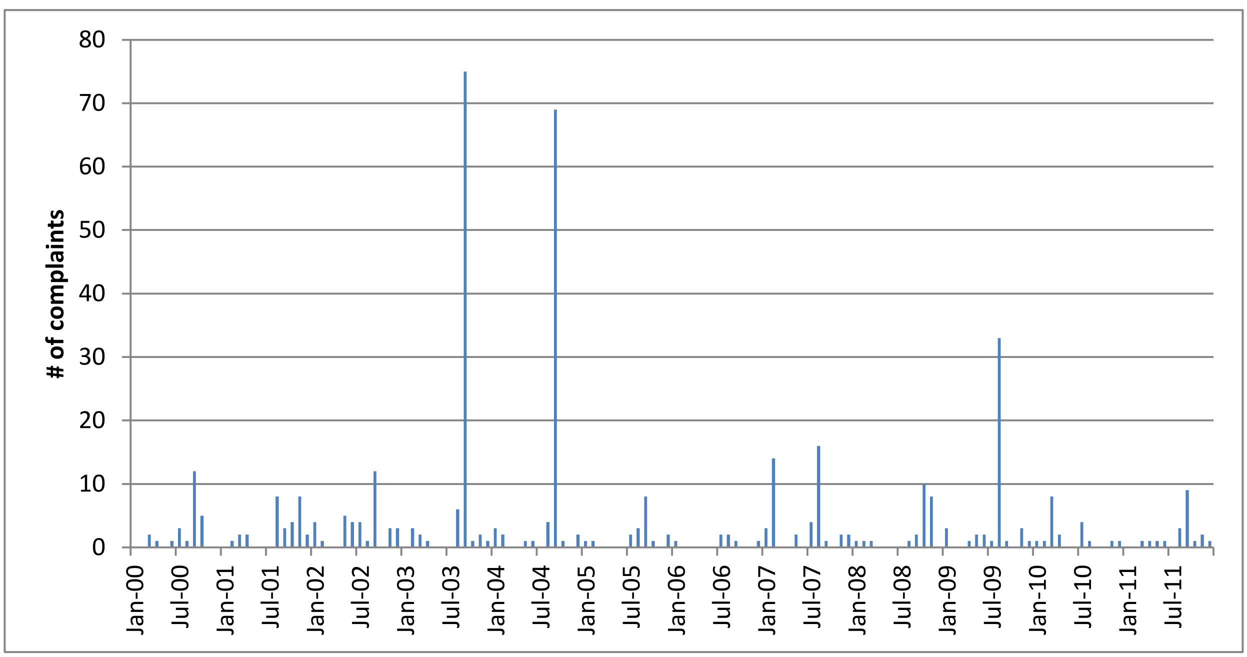


Figure 26. Taste and Odor Complaints to the City of Norman from 2000 through 2011

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 a 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 water bodies. 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

Implementation protocols of OWQS (OAC 785:46-15-5) provide assessment methodologies for the beneficial use of Fish and Wildlife Propagation. This beneficial use is deemed not supported if more than 50% of the water column at any given sample site has DO concentrations less than 2 mg/L. A designation of not supporting requires an impaired listing in Oklahoma's Water Quality Assessment Integrated Report. Upon assessment, Lake Thunderbird was found not supporting its Fish and Wildlife Propagation beneficial use.

Anoxia (less than 2 mg/L of dissolved oxygen) was first noted on June 1st, 2011 at the bottom sample of site 1. Just greater than 50% of the water column was anoxic on July 14th 2011 at site 1; this was maintained at site 1until August 3rd. This 19 day period of violation of WQS represents the shortest duration of violation on record.

Chlorophyll-*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. 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 g/L at a depth of 0.5 meters. For the 2011 sampling season the lake wide average Chl-*a* at Lake Thunderbird was 36 µg/L, exceeding the SWS Chl-*a* criterion.

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 of less than one meter. In Lake Thunderbird, Secchi disk depths ranged from a 2011 median of 16 centimeters at Site 6 to a median of 60 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 27**). When a site had a Secchi depth greater than 40 cm, turbidities were within WQS 90% of the time.

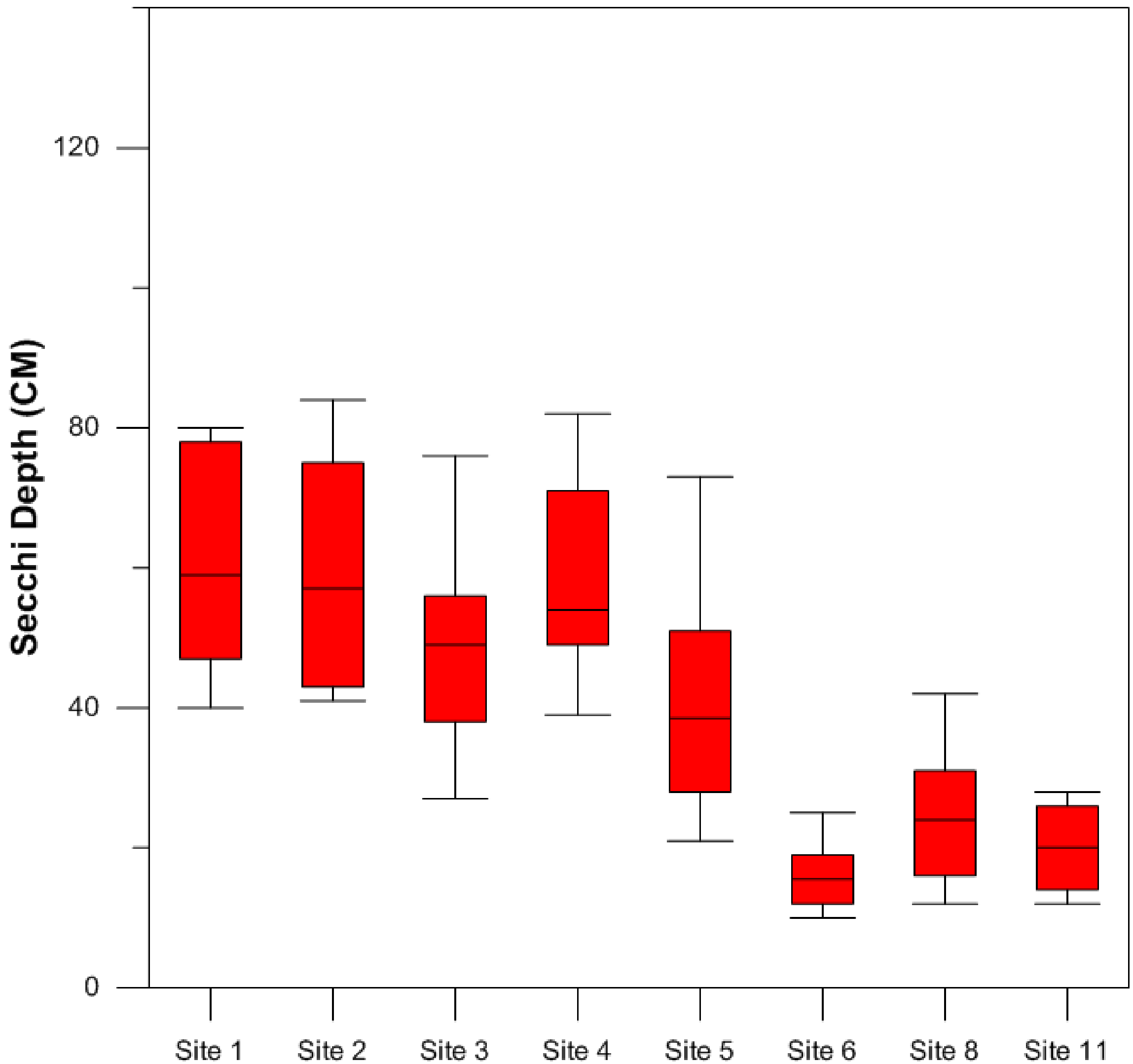


Figure 27. 2011 Lake Thunderbird Secchi Disk Depth (in centimeters) by Site, where Boxes represent 25% of the Data Distribution Above and Below the Median (horizontal black line), and Lines (or whiskers) represent the Other 50% of the Data Distribution.

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 2011, 51% of Lake Thunderbird samples exceeded the 25 NTU criteria (**Figure 28**). This is greater than the previous 3 years (2010:30%, 2009:46%, 2008:22%). All sites had at least one sample that violated the 25 NTU criterion. As witnessed consistently in the past, Site 6 had the highest average turbidity indicating that the Little River arm of Lake Thunderbird is contributing more turbidity to the lake body than either the Hog Creek (Site 8) or Dave Blue Creek (Site 11) arms.

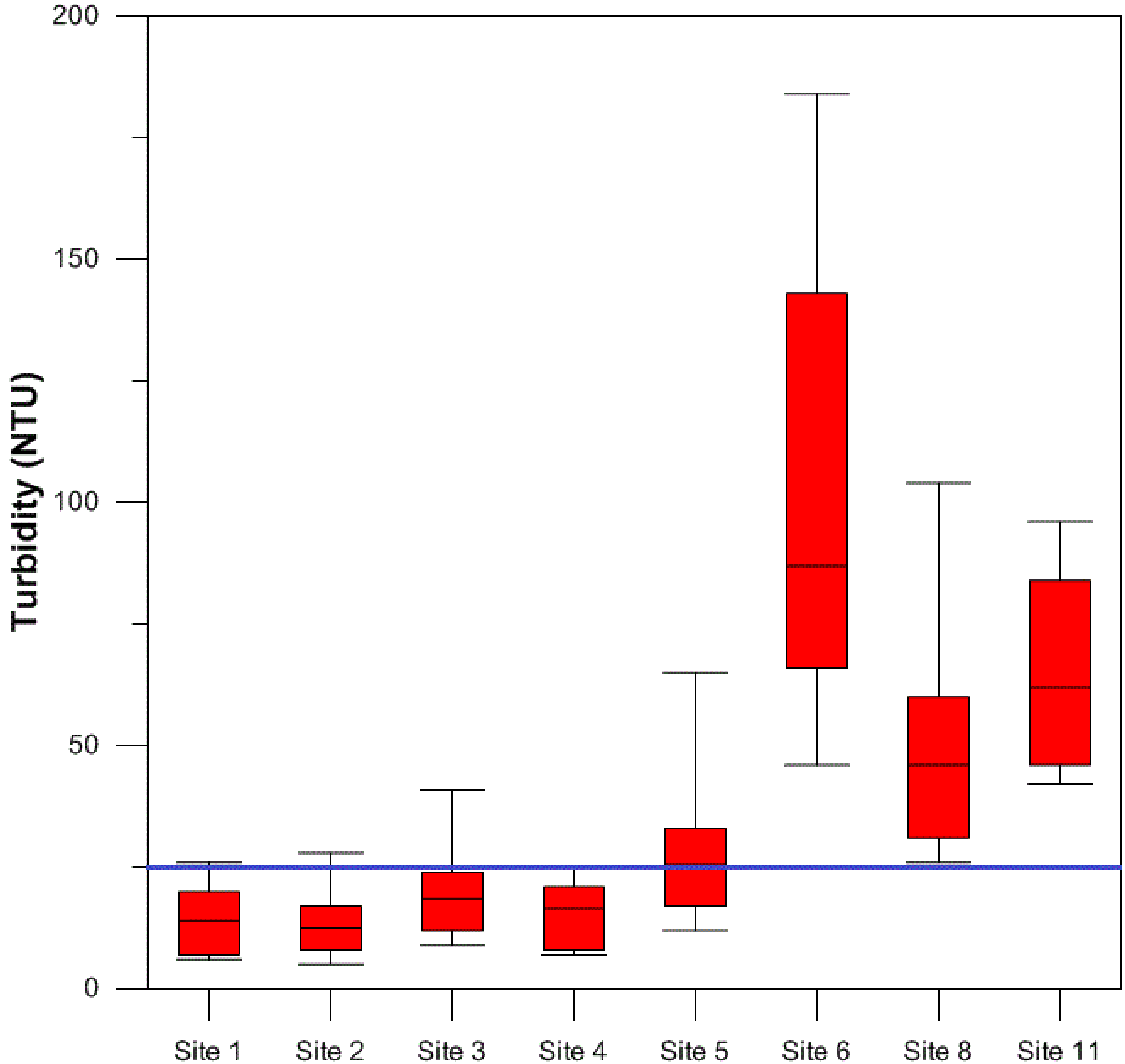


Figure 28. 2011 Lake Thunderbird Turbidity(NTU), by Site, where Boxes Represent 25% of the Data Distribution Above and Below the Median (horizontal black line), and Lines (or whiskers) Represent the Other 50% of the Data Distribution (horizontal blue line represents state water quality standard).

Supersaturated Dissolved Oxygen Injection System

The summer of 2011 marked the first season of operation for the supersaturated dissolved oxygen injection system installed at Lake Thunderbird in 2010. In operation from mid-May until turnover in early September, the system is designed to oxygenate the lower five meters of the lake with disrupting thermal stratification (**Figure 29** and **Figure 30**). 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 reinjecting it in two separate locations at 12 meters water depth relative to the conservation pool. At full capacity this system is capable of treating 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.

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 of redox potentials 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 reduce dissolved metals, such as iron and manganese, in the water column.

In the previous sections of this report the 2011 dataset was interpreted 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.

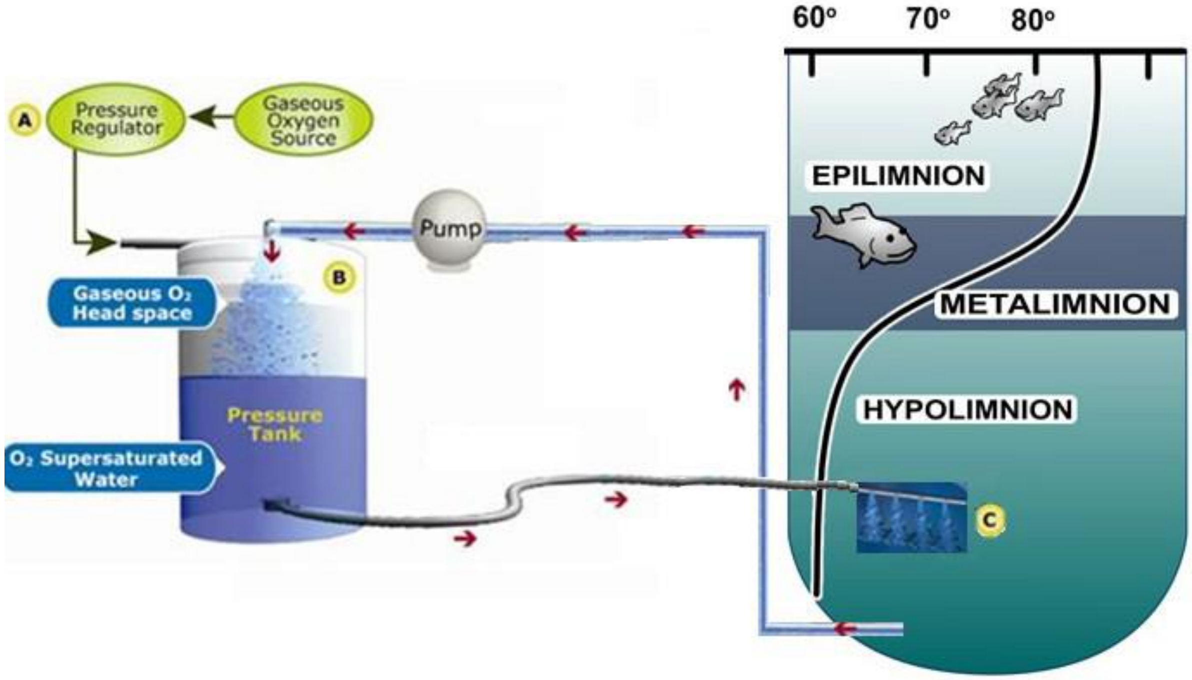


Figure 29. Conceptual Illustration of the SDOX System at Lake Thunderbird

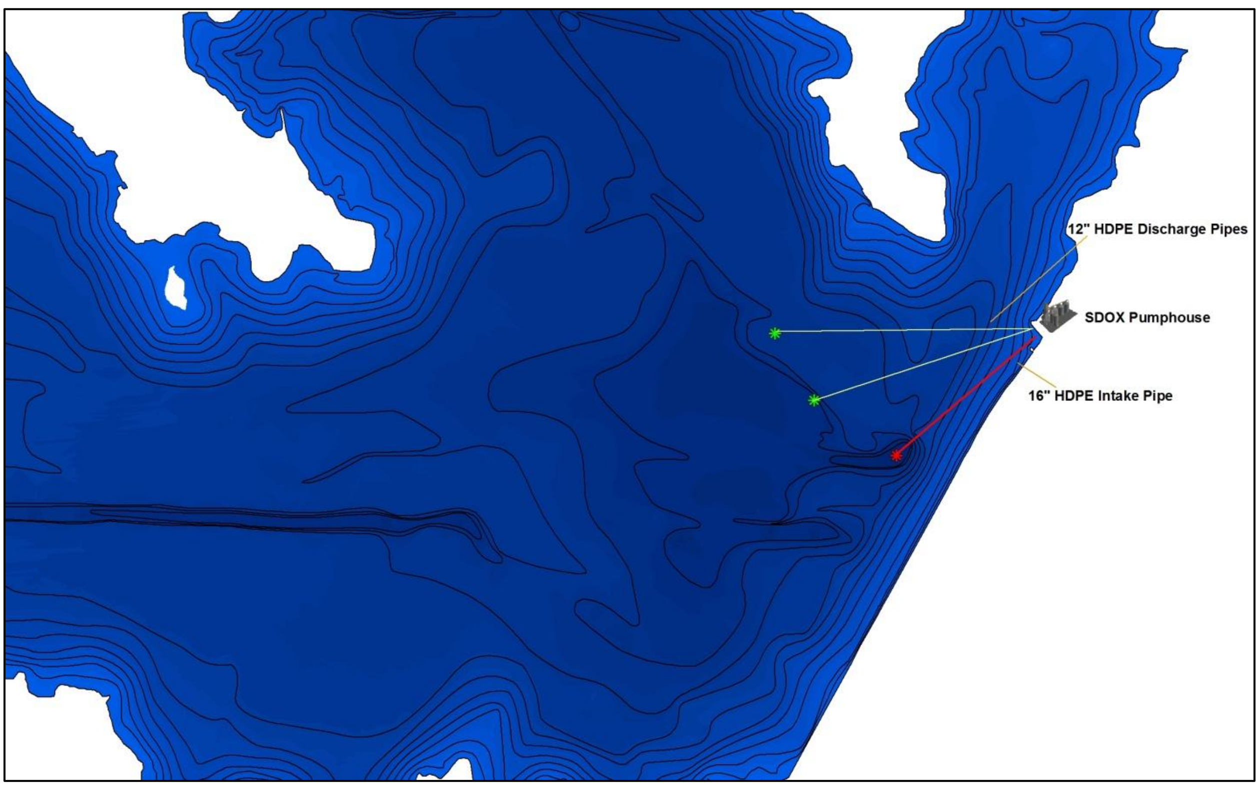


Figure 30. Map of SDOX location

SDOX effect on Dissolved Oxygen

The main goal of the SDOX system was to provide an oxygenated hypolimnion through much of the summer. While it was not designed to prevent anoxia (>2mg/L DO) over the entire summer, it was expected to raise dissolved oxygen levels noticeably throughout a large period of the summer. Previously in this report it was documented that dissolved oxygen was reduced in duration and extent when compared to the average from the historical dataset, but anoxia does occur in 2011 and extends to a large portion of the water column in mid-July. The decreased height of anoxia in 2011 represents a substantial increase of oxygenated water. For example from June 26 the 2 mg/L mark was at 13 meters in 2011 and 7 meters in 2010. This represents an additional 22,000 acre-feet of oxygenated water in 2011 at that date. Comparison isopleths from 2011 and 2010 are provided in **Figure 31** and **Figure 32**, which helps differentiate the 2011 dataset from a season without SDOX operation (2010). While the combination of drought and intense heat in 2011 would almost certainly of made anoxia worse without operation SDOX, it is apparent that the SDOX system was unsuccessful in oxygenating the water column throughout most of the summer.

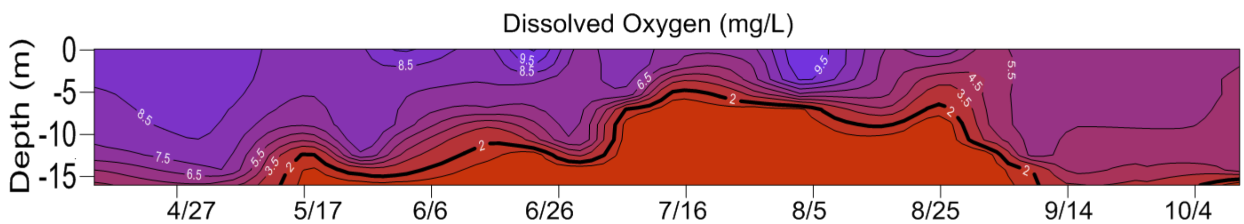


Figure 31. 2011 Lake Thunderbird Dissolved Oxygen Isopleth, Site 1.

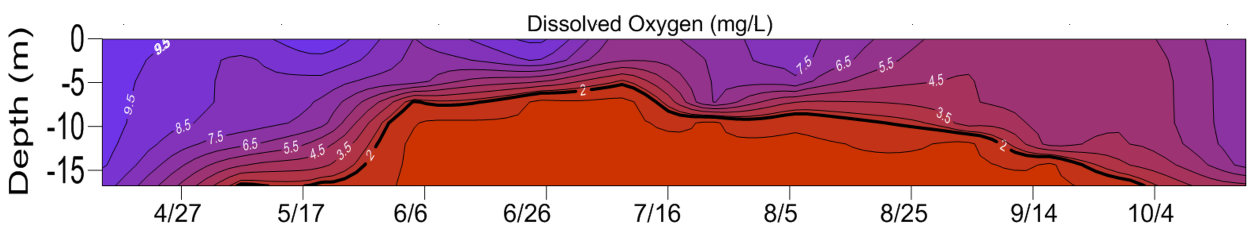


Figure 32.2010 Lake Thunderbird Dissolved Oxygen Isopleth, Site 1.

SDOX effect on Thermal Stratification

One of the advertised advantages of SDOX is oxygenation without disruption of thermal stratification. In 2011, data illustrates that the thermal gradient was greatly reduced from the historical dataset. In **Figure 33** and **34**, this can be seen as increased distance between horizontal contours. To help illustrate the SDOX systems effect on heat distribution throughout the water column and thermal stratification, a comparison of relative thermal resistance has also been provided for selected dates (**Figure 35** and **Figure 36**). In these two figures it is apparent that the water-column temperatures in 2011 are much more uniform from a typical year, which translates to greatly reduced thermal resistance to mixing. Here it is evident that instead of the cold released oxygenated water sinking toward its density depth (approximately 16 meters) the released water mixed upwards into the water column reaching approximately 8 meters in depth. It is also worth pointing out that the temperature on the lake bottom in 2011 continually increased throughout the entire summer, leading to an earlier turnover period in 2011 than witnessed in the historical dataset. Clearly, the SDOX unit was unable operate without disruption of thermal stratification; reasons for this are discussed later in this section.

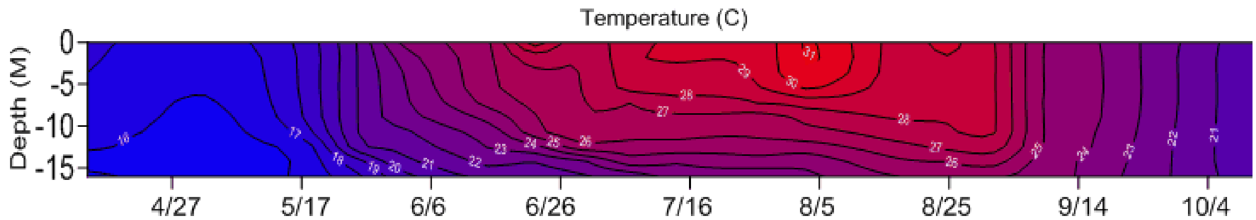


Figure 33. Lake Thunderbird 2011 Temperature Isopleth, Site 1.

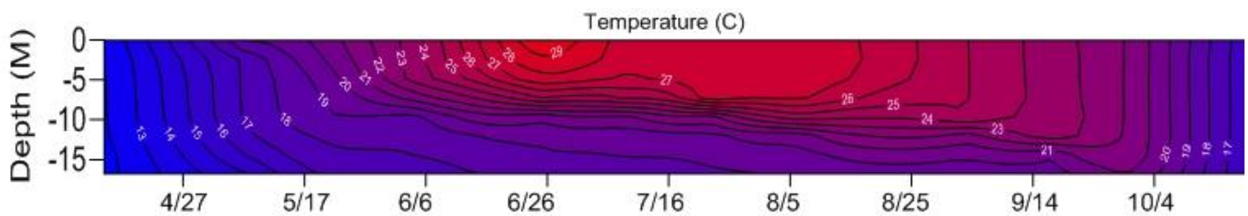


Figure 34. Lake Thunderbird 2010 Temperature Isopleth, Site 1.

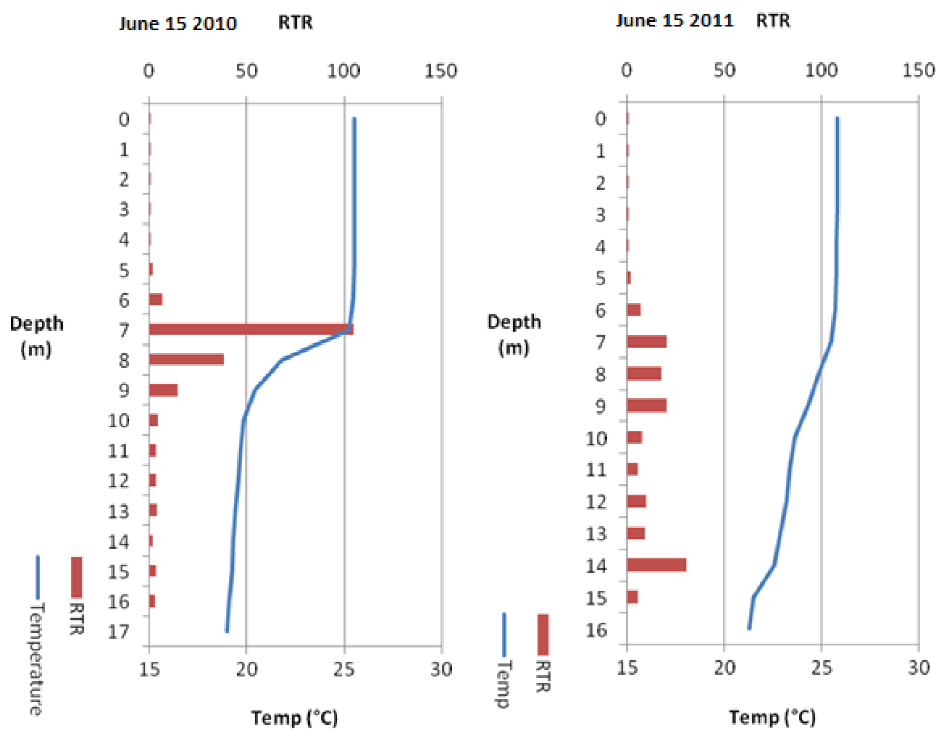


Figure 35. Relative thermal resistance data comparison for June 15 2010, and June 15 2011

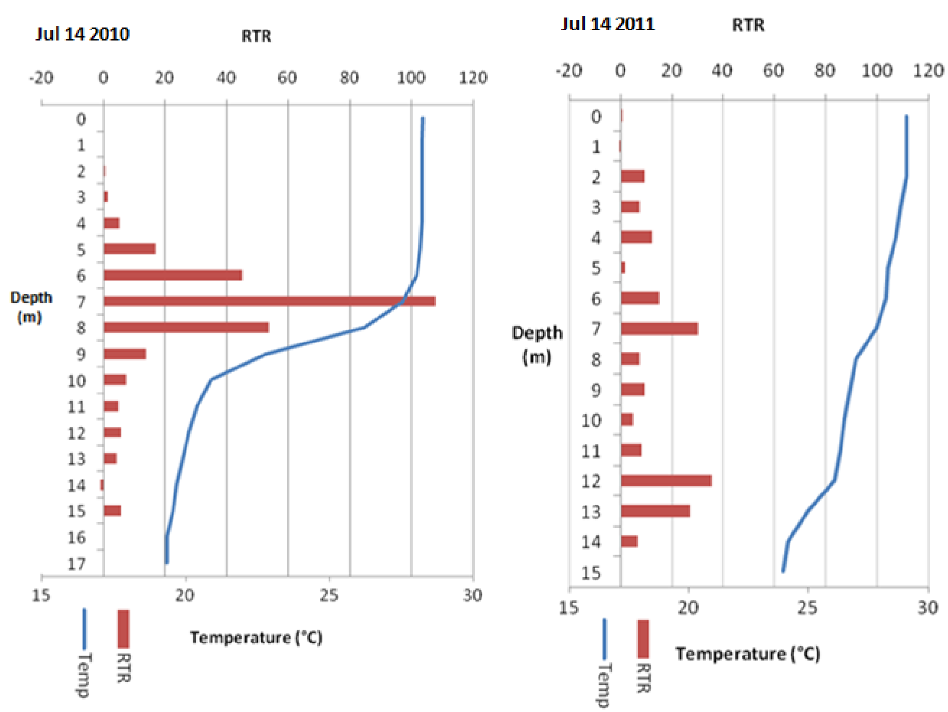


Figure 36. Relative thermal resistance data comparison for July 14 2010, and June 14 2011. SDOX effect on Oxidation-Reduction Potential

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. In 2011, strong reducing conditions were largely eliminated throughout the water column during much of the summer. **Figure 37** and **Figure 38** allow for a comparison of oxidation reduction potential (ORP) data from 2011, and 2010 which is representative of the historical dataset. In 2011, ORP data also disconnected with historical data, and traditional knowledge when correlated 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 this was no longer the case, first observation of strong reducing conditions took nearly an entire month from the first observation of anoxia, also the extent of strong reducing conditions often only occupied about a half of the water column that anoxia occupied (**Figure 39**).

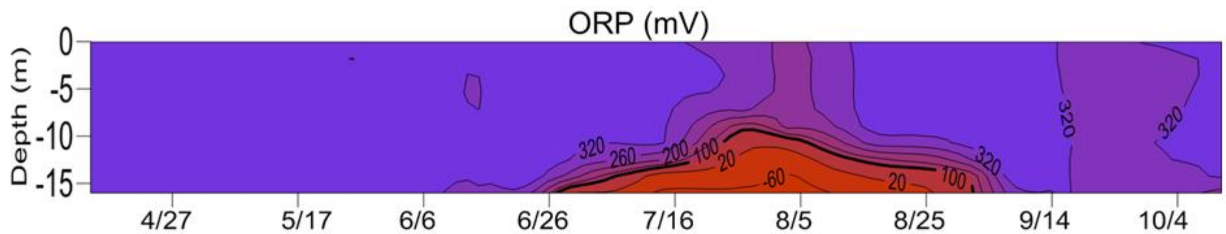


Figure 37.Lake Thunderbird 2011 Oxidation-Reduction Potential Isopleth

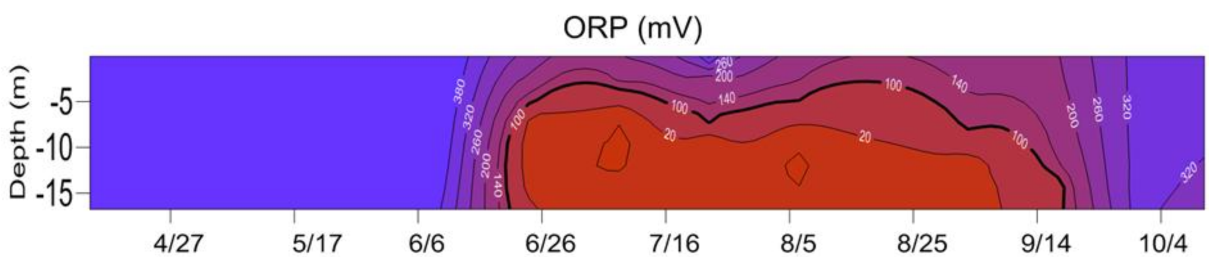


Figure 38. Lake Thunderbird 2010 Oxidation-Reduction Potential Isopleth.

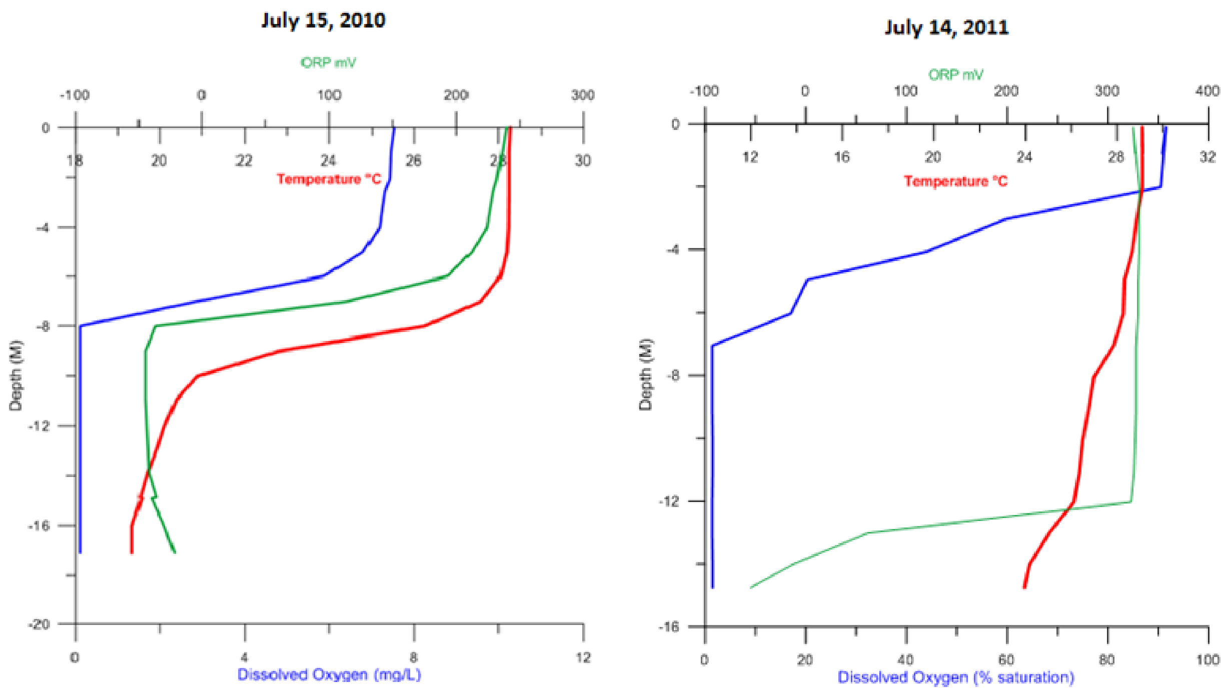


Figure 39. Temperature, Oxidation-Reduction Potential, and Dissolved Oxygen by Depth: July 15, 2010 and July 14, 2011

SDOX Discussion

The 2011 calendar year marked the first 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 suggests that the convectional force of the system was great enough to induce mixing of waters in the area of the water column that typically defines the upper hypolimnion and lower metalimnion. The system was designed and intended to oxygenate lake waters from 12 meter depth to the bottom, approximately 2,000 acre-feet of volume encompassing approximately 480 acres. Instead, the convection force of re-injection distributed the oxygenated waters mostly between 7 and 13 meters in the water column, representing 5 to 10 times the initial target volume. In addition, the induced mixing likely caused for at least a portion of the oxygen designed to reach the hypolimnion to escape the target area. Induced mixing also likely caused the significant 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 clearly shows that the extent and duration of anoxia and low-to-negative ORP was reduced. This corresponded to a calculated reduction of anaerobically mediated phosphorous release of 29% from the 2005-2009 average calculated anaerobically mediated phosphorous release, equivalent to a 5% reduction of the average total phosphorous load to Lake Thunderbird. Should the unit not induce mixing above the 12 meter depth, significant efficiencies of phosphorous reduction are expected.

Data collected in 2011 shows that while the SDOX unit made an impact to the reservoir, it was unsuccessful in several of the designed performance measures. Some of the issues may be partly blamed on the extreme heat and drought in 2011. The climatic conditions in 2011 would typically 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 1 to 2 meters the water column lost throughout the summer. Lastly the lowered pool directly reduced the capacity of the SDOX system to operate. It was engineered to lift the water from the conservation pool to the pump-house. As the pool dropped, necessary hydraulic lift increased requiring the system to reduce the flow rate to compensate for the increased lift. The lowered pool thus reduced the capacity of the SDOX unit to treat hypolimnetic waters as the net flow rate was reduced by approximately 25%.

While some of the shortcomings of the system could be blamed on weather, others likely had to do with the design and location of the system. 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. Small changes in the discharge locations occurred in the winter of 2011, the result of the movement placed the discharge nozzles in waters approximately 1 meter deeper than last year, and closer to the target area. These changes may help reduce mixing as the zone of influence should move proportionately deeper with the nozzles. The OWRB is currently attempting to work with the SDOX design company to modify the discharge nozzles in a way that would help reduce mixing and improve the efficiency at which the injected oxygen is delivered to the target area.

Lastly while some effects were witnessed in the first year of SDOX operation, it is logical to believe that the full impact of the installed system will not be witnessed for subsequent years as the large amount of settled organic matter that currently exists in the lake must be broken down before oxygen demand can be met. Improvement of the design of the SDOX unit through deepening of discharge locations should also improve its effectiveness.

Discussion

Water Quality

Consequences of cultural eutrophication were observed in Lake Thunderbird in 2011. These included high Chl-*a*, elevated TOC, elevated pH, super-saturation of DO, lowered Secchi depth, and increased turbidity, all occurring at the water's surface during the summer growing season. Trophic state indices indicated 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 2011, clearly helped reduce the extent and duration of both anoxia and low to negative oxidation-reduction potentials, as well as reduced anaerobically mediated sediment phosphorous 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. 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 continually higher peak Chl-*a* in since 2004 indicates risks of recreation exposure to blue-green algae toxins are increasing.

State Water Quality Standards

In 2010, 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 2011 were analyzed for beneficial use impairments in accordance with the Use Support Assessment Protocols (USAP) (OAC 785:46-15) of the OWQS. In 2011 Lake Thunderbird was found to be not supporting its Fish and Wildlife Propagation beneficial use in regard to DO and turbidity, and therefore should remain listed as impaired for these uses. In addition, Lake Thunderbird was not meeting the 10 μg/L Chl-*a* requirement for SWS. Lastly, WQS state that waterbodies used for fish and wildlife propagation should maintain a pH of 6.5-9.0; while Lake Thunderbird remained within these parameters, a peak pH of 8.89 was witnessed on May 5th, 2011 at Site 6. If increased peak algae growth continues as witnessed through increasing peak Chl-*a* values, Lake Thunderbird may surpass this 9.0 impairment threshold.

Closing Remarks

During the past year (2011) significant achievements have been made modeling Lake Thunderbird's watershed and internal phosphorus load, allowing for better understanding of the phosphorous 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 2011 calendar year represented the highest peak Chl-*a* on record, and continued the trend of increasing peak Chl-*a* that has been witnessed nearly every year since 2004. Significant nutrient reduction from the surrounding watershed, particularly in the Little River area, are critical to bring Chl-*a* within Oklahoma Water Quality Standards.

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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**
4/14/2011	8.9	9.22	9.12	9.08	0.16
5/5/2011	7.57	8.6	8.27	8.15	0.53
5/18/2011	6.02	6.2	6.3	6.174	0.14
6/1/2011	26	25.6	24	25.2	1.06
6/15/2011	21.7	22.3	25	23	1.76
6/29/2011	21.4	23.5	23.6	22.83	1.24
7/14/2011	26.4	27.1	28.4	27.3	1.01
8/17/2011	65.2	65.7	63.8	64.9	0.99
8/25/2011	77.3	78.1	77.8	77.73	0.40
9/15/2011	57.6	56.6	55.5	56.56	1.05
10/11/2011	23.5	24.5	47.5	31.83	13.58
				AVG SD	1.99
				Min	0.14
				Max	13.58

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

NOTE: less than symbol represents below detection limit report

Date	Site	Turbidity	True Color	Alkalinity	Susp. Solids	N-Ammonia	N-Kjeldahl	Nitrite-Nitrate as N	Total P	Total Organic Carbon	Chloride	Sulfate	Ortho-P	Chlorophyll-a (a)	Pheophytin-a (a)	Fe, Total	Fe, Dissolved	Mn, Total	Mn, Dissolved
4/14/2011	1	26	62	166	13	<0.10	0.57	0.37	0.036	5.07	27.9	23.6	0.025	8.9	2.31	628	42	35.8	<5.0
5/5/2011	1	23	56	171	<10	<0.10	0.42	0.38	0.031	4.92	28.2	19.5	0.02	7.57	4.46	576	31.3	28.5	<5.0
5/18/2011	1	20	34	172	11	<0.10	0.52	0.3	0.029	4.84	24	19.3	0.018	6.02	6.97		50.7		<5.0
6/1/2011	1	13	33	166	11	<0.10	0.63	0.14	0.04	5.13	23.3	20.7	0.011	26	2.35	334	25.5	27.9	<5.0
6/15/2011	1	10	25	168	10	<0.10	0.64	0.07	0.035	6.06	23.3	19.6	0.007	21.7	3.95	232	53.1	37.1	7.3
6/29/2011	1	15	29	171	14	<0.10	0.58	<0.05	0.045	5.05	26.8	19.4	0.011	21.4	4.77	323	42.2	66.5	10.5
7/14/2011	1		18	161	<10	<0.10	0.82	<0.05	0.035	5.31	26.9	19.1	0.015	26.4	4.04	91.3	20.3	34.4	5.3
7/27/2011	1	6	9	161	11	<0.10	0.79	<0.05	0.038	5.24	27	14.7	0.014			70.3	<20	58.2	<5.0
8/17/2011	1	7	18	157	<10	<0.10	1.11	<0.05	<0.10	6.57	57.5	20.1	0.011	65.2	4.2	123	<20	89.7	9.4
8/25/2011	1	10	18	157	<10	<0.10	1.22	<0.05	0.035	5.74	29.4	16.9	0.014	77.3	4.86	91.4	<20	66.6	<5.0
9/15/2011	1	19	20	167	10	<0.10	1.06	<0.05	0.054	5.52	28.9	16.7	0.012	57.6	8.67	38.9	<20	22.9	<5.0
10/11/2011	1	17	23	165	11	0.17	0.86	0.2	0.053	5.44	28.7	19	0.013	23.5	13.8	398	66	88.1	20.9

Date		Turbidity	True Color	Alkalinity	Susp. Solids	N-Ammonia	N-Kjeldahl	Nitrite-Nitrate as N	Total P	Total Organic Carbon	Chloride	Sulfate	Ortho-P	Chlorophyll-a (a)	Pheophytin-a (a)	Fe, Total	Fe, Dissolved	Mn, Total	Mn, Dissolved
4/14/2011	9	28	56	170	18	<0.10	0.6	0.36	0.033	5.02	29	24	0.021	9.12	1.56	652	94.8	37.8	12.8
5/5/2011	9	24	56	171	<10	<0.10	0.45	0.36	0.032	4.92	29	19.7	0.017	8.27	2.5	628	190	31.8	11.3
5/18/2011	9	24	36	173	11	<0.10	0.51	0.29	0.028	4.85	25.1	19.6	0.019	6.3	2.56	513	30.5	33.9	<5.0
6/1/2011	9	13	34	171	<10	<0.10	0.49	0.14	0.034	5.24	24.1	20.7	0.009	24	2.12	33.6	113	<5.0	26
6/15/2011	9	10	25	169	13	<0.10	0.64	0.07	0.037	5.15	23.8	19.3	0.009	25	4.54	174	26	37.6	2.5
6/29/2011	9	13	33	172	14	<0.10	0.58	<0.05	0.038	5.01	27	19.2	0.01	23.6	5.39				
7/14/2011	9		27	163	11	<0.10	0.81	<0.05	0.034	5.45	27	19.3	0.007	28.4	4.48				
7/27/2011	9	5	9	163	10	<0.10	0.87	0.05	0.035	5.16	28	18.4	0.012						
8/17/2011	9	6	20	159	<10	<0.10	1.01	<0.05	0.047	6.58	28	20.6	0.011	63.8	4.69	80.7	<20	79.8	<5.0
8/25/2011	9	7	18	163	11	<0.10	1.15	<0.05	0.037	5.71	28.5	16.1	0.013	77.8	5.89	86.3	<20	65.6	<5.0
9/15/2011	9	20	20	166	12	<0.10	1.11	<0.05	0.051	5.55	28.3	15.8	0.011	55.5	9.37	124	<20	56.7	<5.0
10/11/2011	9	17	27	163	16	0.17	0.88	0.19	0.055	5.28	28.5	18.5	0.012	47.5	25.9	426	42.2	89.2	12.2