**Oklahoma Water
Resources Board**

Lake Thunderbird
Water Quality
2008

for the

Central Oklahoma Master Conservancy District

June 2009

Draft Final Report

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

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). Oklahoma Water Resources Board lake water quality monitoring in 2008 was designed to meet commitments made by Oklahoma Department of Environmental Quality Water Quality Division (ODEQ) to the Central Oklahoma Master Conservancy District (COMCD) concerning discharges within the watershed of Lake Thunderbird. The close of 2008 monitoring represents nine years of continuous monitoring; COMCD is close to establishing a high quality long-term database.

High amounts of precipitation contributed to larger inflows and an annual hydraulic residence time of 1.29 years. Thermal stratification was first detected in the water column at the beginning of June; concurrent with an anoxic hypolimnion. Total mixing of the water column was first detected in mid-October. Over half of the water samples showed excessive algae growth (>20 µg/L), proportionally larger than any other sample season. The slight increase of taste and odor complaints to the City of Norman is likely due to higher algae levels in 2008. Epilimnetic total nitrogen and phosphorus followed similar trends as in previous years, with a consistent build up of nutrients over the monitoring season, and mid-summer depletion of dissolved nutrients by algal uptake. Oxidation-reduction potentials in the hypolimnion remained low during the summer growing season, providing conditions that allow for the solubilization of metals and sediment-bound phosphorus into the water column.

The 2008 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 ODEQ currently has Lake Thunderbird prioritized for completion of a total maximum daily load (TMDL) allocation.

Active lake management is needed for Lake Thunderbird to meet OWQS for turbidity, color, dissolved oxygen and chlorophyll-*a*. Lake-wide reduction of algal biomass to mitigate low dissolved oxygen and decrease chlorophyll-*a* is needed. Suspended solids control is also necessary in order meet OWQS for turbidity. Both in-lake and watershed activities are needed for water quality standards to be met. Recommendations to further lake management of Lake Thunderbird include:

- Determining the feasibility of oxygenating the hypolimnion (addressing in-lake nutrients, dissolved oxygen, dissolved metals, taste and odor compounds and chlorophyll-*a*)
- Resume routine water quality monitoring of the lake.
- Ensure evaluative processes (TMDL) place watershed nutrient loads in context of in-lake loads using predictive modeling procedures.
- Review watershed evaluations to encourage nutrient reductions in the basin.

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Introduction

Lake Thunderbird is a Bureau of Reclamation impoundment located on the Little River and Hog Creek basins. Construction of the Lake Thunderbird dam began in 1962, with the lake becoming operational in 1966. Flood control, municipal water supply, recreation, and fish and wildlife propagation are the designated uses of the Lake Thunderbird dam and impoundment. The Central Oklahoma Master Conservancy District (COMCD) is the governing body managing Lake Thunderbird. Among the authorities of the COMCD is the supply of raw drinking water for the municipalities of the City of Norman, Midwest City, and Del City. The Oklahoma Water Resources Board (OWRB) has provided water quality monitoring and evaluation services to the COMCD since 2000. The objective in 2008 was a modified (more intensive than previous) environmental monitoring scheme to satisfy ODEQ's agreement with COMCD regarding discharges within the watershed. Lake water quality data collected will be used for TDML development in 2009.

Lake Thunderbird was listed as Category 5 (303d list) in the State's 2006 Integrated Report, citing impairment due to turbidity, low dissolved oxygen, and color (http://www.deq.state.ok.us/wqdnew/305b_303d/2006_integrated_report_appendix_c_303d_list.pdf). As a Sensitive Water Supply (SWS), Lake Thunderbird is also required to meet a 10μg/L goal for chlorophyll-*a* concentrations. These parameters are evaluated according to the Oklahoma Water Quality Standards in this report.

Water Quality Evaluation

Sampling Regime

In 2008, Lake Thunderbird was sampled at the sites indicated in **Figure 1**. Sites 1, 2, and 4 represent the pelagic or lacustrine zones of the lake. Sites 6 and 5 embody the riverine and transition zones of the Little River arm of the lake. The Clear Creek and Hog Creek riverine zones are represented by Sites 7 and 8, respectively. Site 3 represents the transition zone of the Hog Creek arm. Water quality sampling in 2007 began in April and ended in October and consisted of a bi-monthly sampling schedule, with exception of October (**Table 1**). Water quality profiles measured at all sites include oxidation-reduction potential, dissolved oxygen saturation and concentration, temperature, specific conductance, and pH. These parameters were measured in approximate one-meter intervals from the lake surface to bottom at every site when possible. In addition, samples were collected for laboratory analysis of alkalinity, chloride, sulfate, total suspended solids, total organic carbon, and phosphorus and nitrogen series. Secchi disk depth, surface chlorophyll-*a*, and turbidity samples were collected at all seven sites. Water quality and nutrient samples were collected at the surface of Sites 1, 2, and 4, with vertical samples collected at 4-meter depth intervals at Site 1. Total organic carbon was collected at the surface of Sites 1, 2, and 4.

Table 1: 2008 water quality sampling dates and parameters measured

	04-Feb	22-Apr	12-May	16-May	21-May	04-Jun	18-Jun	09-Jul	16-Jul	04-Aug	18-Aug	02-Sep	22-Sep	16-Oct	08-Dec	12-Dec
Hydrolab	X	X		X	X	X	X	X		X	X	X	X	X	X	
Chlorophyll-a		X	X		X	X	X	X		X	X	X	X	X	X	
Water Quality		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	
DOC					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	
Sediment									X							X

Quality Assurance and Quality Control (QA/QC)

Water quality sampling followed the QA/QC procedures described in the "QUALITY ASSURANCE PROJECT PLAN Lake Thunderbird Water Quality Monitoring 2008-2009 Prepared for the Central Oklahoma Master Conservancy District with concurrence from the Oklahoma Department of Environmental Quality" executed May 1, 2008. One failure occurred in the field when the Hydrolab$^{©}$ probe stopped reading dissolved and percent saturation oxygen on May16, 2008. Since this sample event occurred between the routinely scheduled (twice a month) sample events; the loss of the data did not compromise the integrity of the data set.

Laboratory quality control samples included field blanks and duplicates. Field blanks comprised of a sample bottle filled with reagent grade water prior to sampling. These samples then traveled through the field event before delivery to the laboratory for analysis. Duplicate samples were taken at the surface of site 1 and labeled "site 1" and

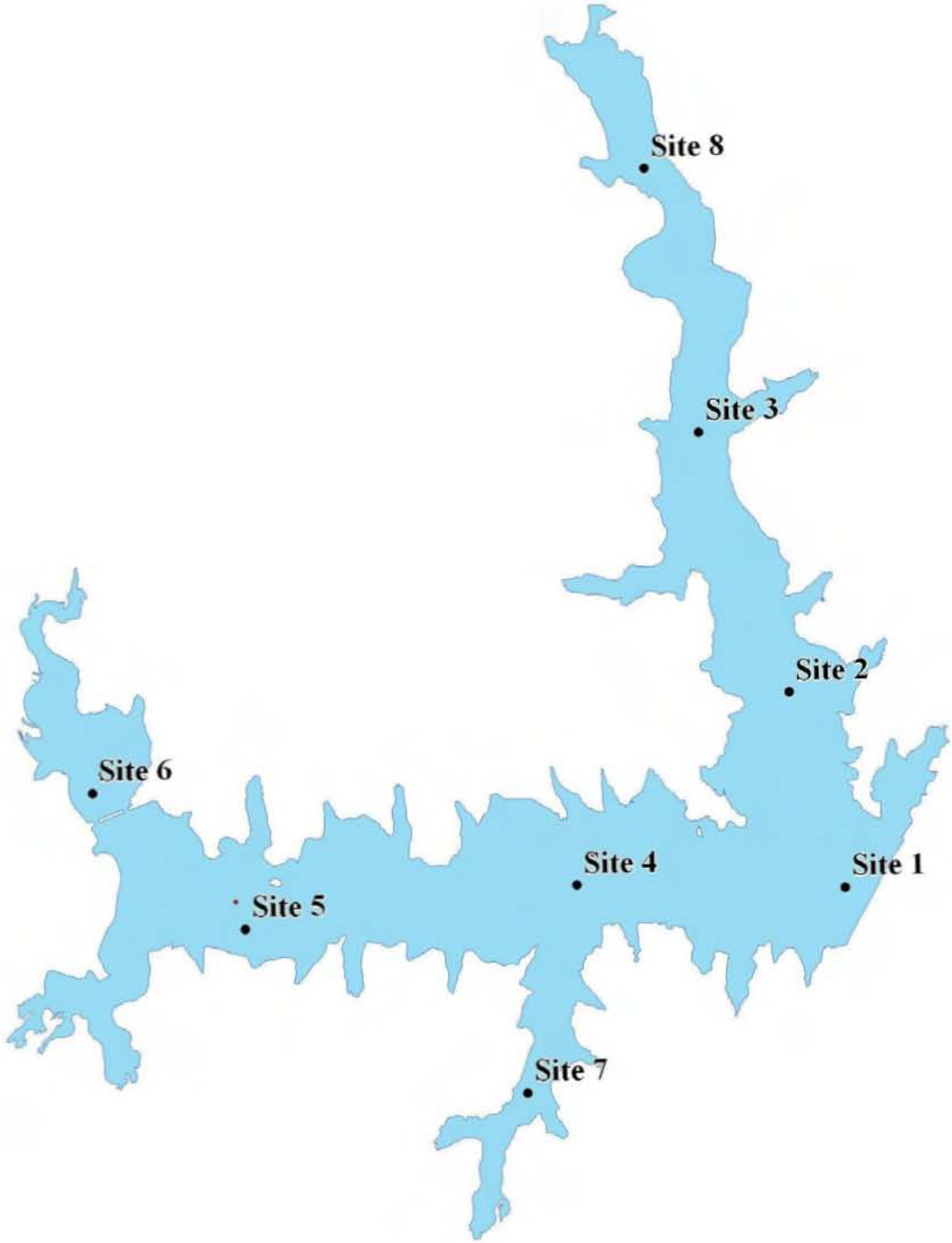


Figure 1: Lake Thunderbird 2007 sampling sites

“site 9” respectively and delivered to the laboratory for analysis. Select 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 blank, replicate and duplicate sampling. Blank, replicate and duplicate sampling occurred on every sample event started on April 22, 2008 with the exception of no replicate samples on December 8, 2008.

Blank Samples

Blank sample results can indicate low-level contamination of the analyte, usually due to introduction into the sample container (preparation handling error) or during laboratory analysis. Detected blank sample reports can be subtracted from the environmental sample value to better estimate the true environmental value. All blank sample reports were below the detection limit. This indicates nominal to no contamination of field samples.

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) Abs. Dif. = $\lvert x_{S1} - x_{S9} \rvert / \quad x * 100$

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 such as secchi depth, turbidity, true color, alkalinity, suspended solids, nitrate nitrogen, Kjeldahl nitrogen, total phosphorous, ortho-phosphorus, total organic carbon, dissolved organic carbon, chloride and sulfate showed relatively good precision with median PAD well below 20%. Chlorophyll-a and pheophytin-a both show relatively low precision with a median PAD of 26 and 63 respectively. Because chlorophyll-a rapidly decays into pheophytin-a with exposure to light, a greater PAD was expected. However, as chlorophyll-a can be transitory and is a key parameter in reservoir diagnostic applications, replicate samples were prepared in addition to the duplicate samples of site 1. This essentially yielded three quality control samples for each sample date and allowed for greater examination of chlorophyll-a. Of thirteen sample dates eleven had triplicate samples and two had duplicate samples.

August 18, 2008 Statistical Anomaly

Laboratory reports were paired off by date and simple statistics calculated. Average standard deviation for chlorophyll-a and pheophytin-a were 4.03 µg/L and 4.88 µg/L respectively. One date, August 18, 2008, had a standard deviation nearly three times that of any other sample date. Examination of the PAD also showed an unusually high value for this date.

When the reported values for chlorophyll-a and pheophytin-a on August 18, 2008 were examined, it appeared that differential decomposition of chlorophyll-a occurred between the duplicate samples. Site 1 b and site 9 report high chlorophyll-a values very close to one another; 40.8 µg/L and 39.1 µg/L respectively. Site 1 a reports chlorophyll-a as 6.76 µg/L. Although it is not clear exactly what caused the differential values for sites 1 a and 1 b, examination of accompanying pheophytin-a values give strong clues.

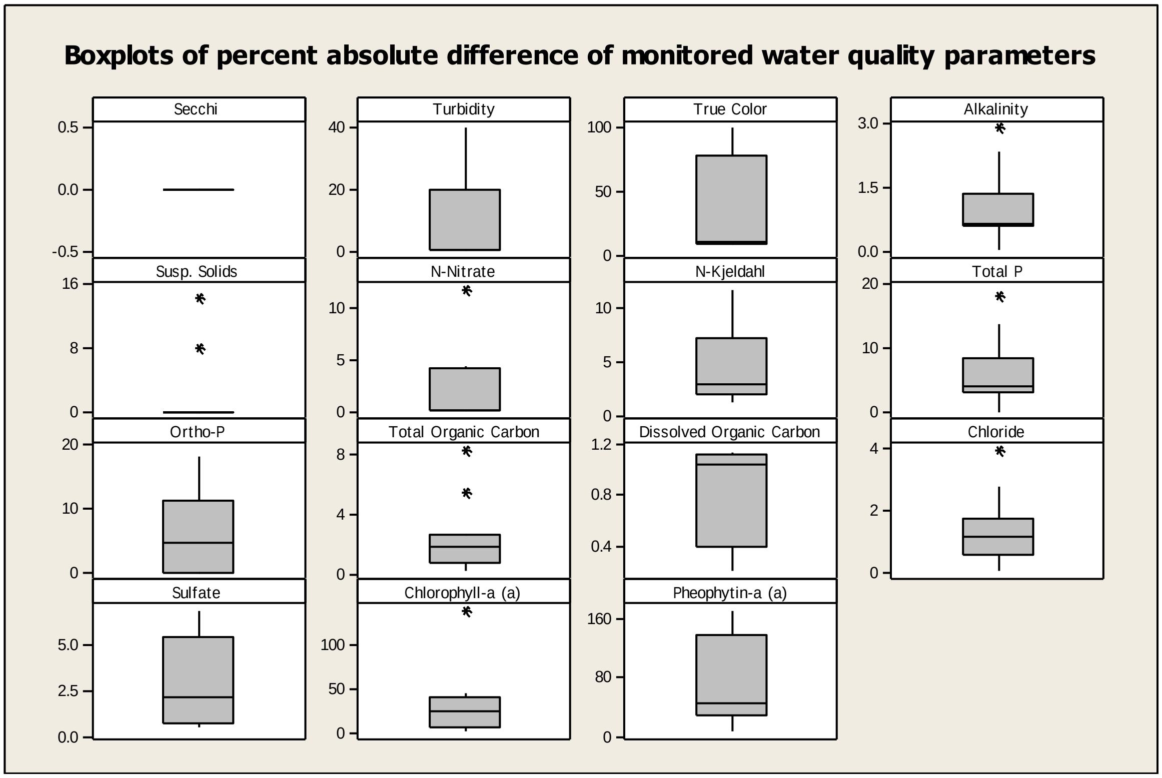


Figure 2: Statistical summary of Lake Thunderbird duplicate samples April 22, 2008- December 8, 2008. Box represents the middle 50%, the center bar the median reported value, top and bottom stems the upper and lower 25% quartile and asterisks as outliers

Site 9 reports 39.1 µg/L chlorophyll-a and <0.10 pheophytin-a, Site 1 b reports 30.8 µg/L chlorophyll-a and <0.10 pheophytin-a while site 1 a reports 6.76 µg/L chlorophyll-a and 50.7 pheophytin-a. The lopsided mismatch (low chlorophyll-a and high pheophytin-a) of site 1 a clearly indicates that the chlorophyll-a sample for site 1 had partially degraded to pheophytin-a. It is likely that sampler error due to brief light exposure during OWRB post processed caused the differential reports for the August 18, 2008 samples. No other pair of chlorophyll-samples showed evidence of differential degradation so clearly. Because it is clear that differential degradation occurred the site 1 a report will be discarded in favor of using site 1 b report to represent chlorophyll-a at site 1 on August 18, 2008.

Climate

Knowledge of potential climatologic influences is essential when assessing the water quality of a water body. The hydrology of a given lake, including dynamic inflows and elevations, can have significant impacts on internal chemical and biological characteristics and processes. Storm water inflows can increase nutrient and sediment loading into the lake, resuspend 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 increased solubility of phosphorus and metals from the sediments.

Figure 2 provides a graphical representation of Lake Thunderbird's rainfall, elevation, inflow, and sampling dates for calendar year 2008. Lake elevations and inflows can vary considerably with rainfall patterns. Pool elevation varied from about 3½' above conservation pool (1039 MSL) in April to around ½' below conservation pool in August, November and December. Calendar year 2008 marked central Oklahoma as relatively normal in regards to temperature and precipitation with an annual average temperature of 59.8°F, 0.3°F below average and annual precipitation total of 37.8", just 0.2' below average. Seasonal variation was noted with the fall season much cooler than average and higher than average rainfall in the spring and summer. The fall of 2008 recorded some 5.28" short (half) the seasonal average rainfall.

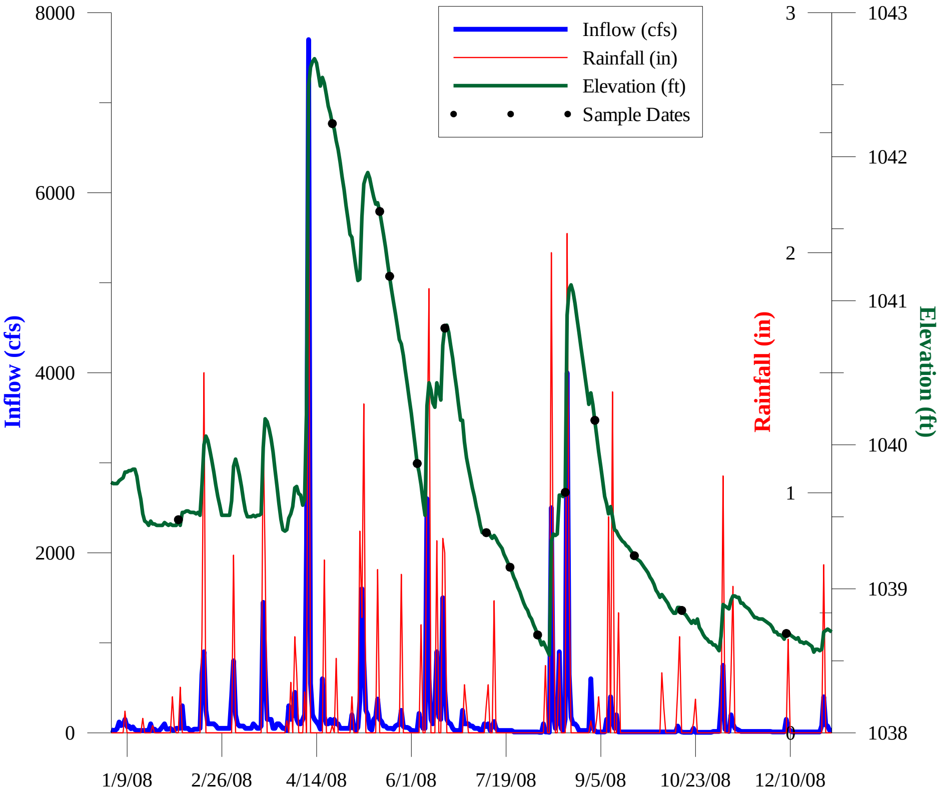


Figure 2: 2008 Inflow, precipitation, and elevation data for Lake Thunderbird, with sample dates indicated

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 water body such as a lake is given by:

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

where V = lake volume [L^3],

A_s = lake surface area [L^2],

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

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

E_v [L/T] is the lake evaporation,

W_S is the water exported for water supply use.

In other words, the rate of change in 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 are precipitation or rainfall and inflow from the tributaries, which includes all surface runoff in the basin. The outputs are evaporation, dam releases (spilled), and water supply. 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 released from Lake Thunderbird includes 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 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.

Table 2: Lake Thunderbird 2008 water budget calculations

Month	**INPUTS**			**OUTPUTS**				**RESULTS**		
	Inflow	Rainfall	**Total Inputs**	Evaporation	Water Supply	Releases	**Total Outputs**	I-O	ΔV	Error
Jan	3,134	83	3,217	1,832	1,311	2,200	5,343	-2,125	-1,544	582
Feb	6,863	1,049	7,912	1,706	1,290	3,822	6,818	1,094	360	-734
Mar	11,355	1,287	12,642	2,705	1,327	8,077	12,108	534	-412	-946
Apr	28,324	2,251	30,575	4,177	1,360	10,338	15,875	14,701	10,805	-3,896
May	11,355	2,043	13,398	4,498	1,673	14,164	20,335	-6,937	-5,814	1,123
Jun	16,909	2,852	19,761	5,966	1,812	13,392	21,170	-1,409	-2,007	-597
Jul	2,350	395	2,745	5,811	2,196	1,698	9,705	-6,960	-5,042	1,917
Aug	19,864	2,712	22,576	3,846	2,052	5,159	11,057	11,519	7,923	-3,596
Sep	2,479	1,399	3,878	2,964	1,649	6,468	11,081	-7,203	-6,328	874
Oct	714	501	1,215	2,377	1,502	0	3,879	-2,664	-2,264	400
Nov	3,660	870	4,529	2,045	1,308	0	3,353	1,177	720	-457
Dec	2,251	489	2,740	1,592	1,279	0	2,871	-131	-206	-75
Total	**109,259**	**15,932**	**125,191**	**39,518**	**18,759**	**65,318**	**123,595**	**1,596**	**-3,807**	**-5,404**

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 1.26 years for 2008 and an annual average hydrologic residence time of 4.72 years since 2001 (including 2008 data). The relatively short 2008 residence time reflects the increased inflows due to high rainfall amounts in April, June and August (**Figure**). Interestingly enough, input roughly equaled output, 125,191 acre-feet vs. 123,595 acre-feet respectively. Only in October, November and December was no water spilled through the dam.

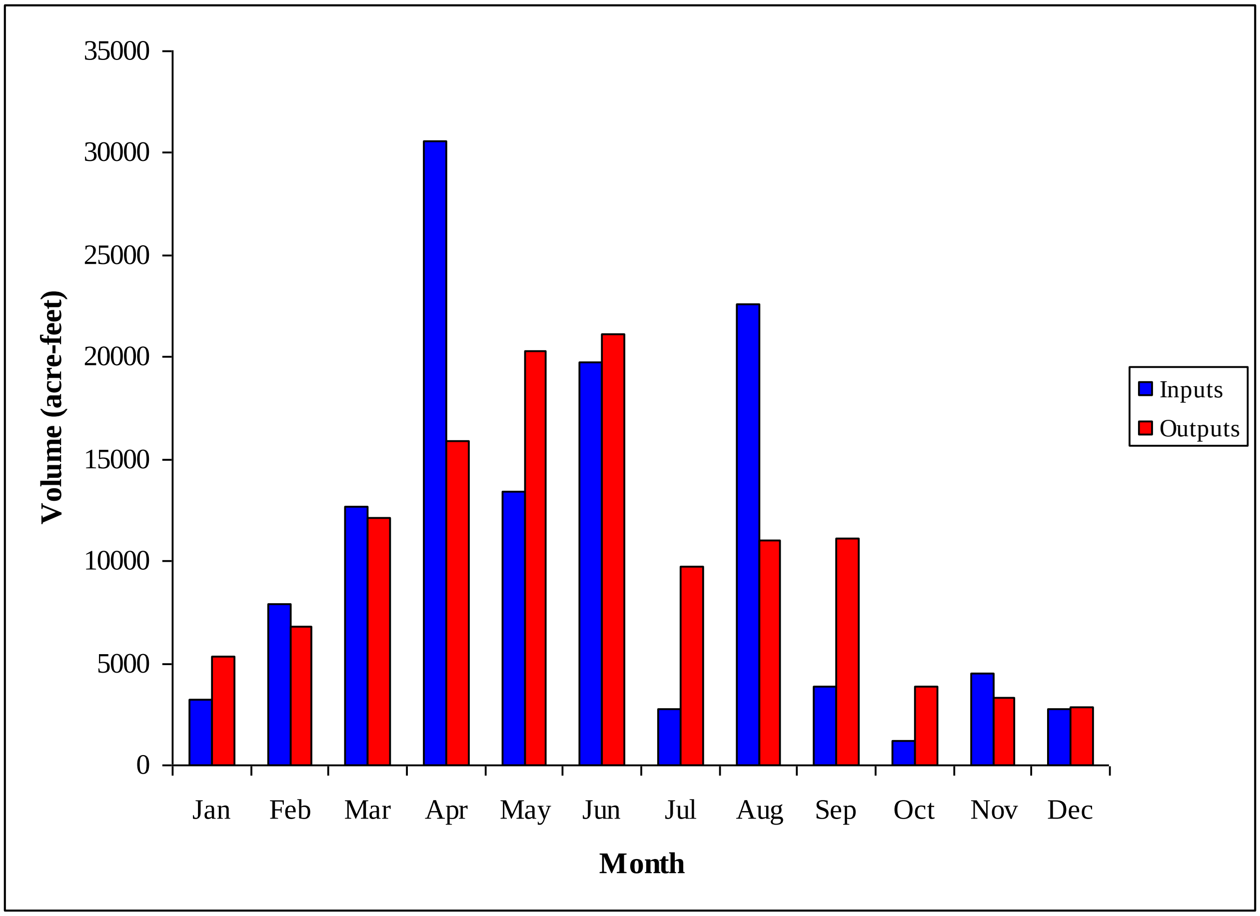
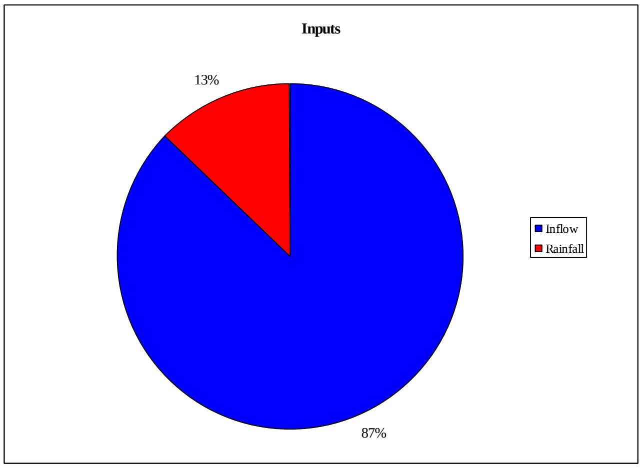


Figure 4 2008 Lake Thunderbird inflows and outflows by month

For the period of calendar year 2008, 87% of the inputs into Lake Thunderbird were from inflows, while the majority of outputs were from gated dam releases (**Figure**). This approximates the percentage in 2007, a very wet year for Lake Thunderbird. Outputs were dominated by spillway releases, 53% of the total, while water supply (15%) was less than half what was lost by evaporation (OWRB, 2008).



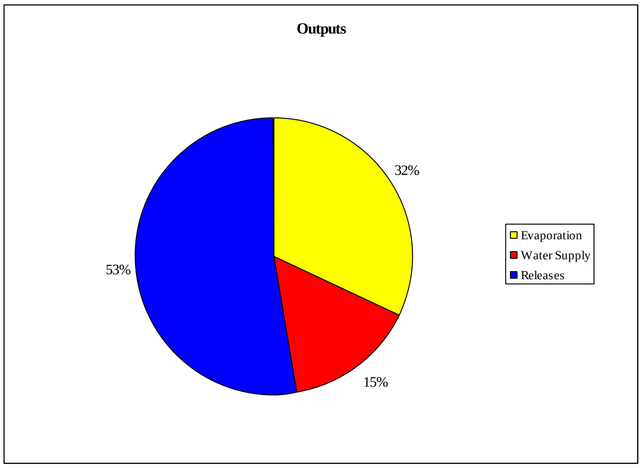


Figure 5: 2008 Lake Thunderbird input and output sources expressed as the percent of totals

Sources of error

Although robust, the hydrologic budget does contain error. However, of the annual water budgets prepared, 2008 reflects perhaps the least error with a cumulative ***annual*** error of -5,404 acre-feet. This is only a few time greater than the average ***monthly*** error, -2,042 acre-feet, in 2008. Additionally the two measures of monthly change in capacity (I-O, and ΔV) match in sign (either negative or positive) for every month but March. These suggest error is small. The greatest error noted was with the month of highest lake inputs: April and August. Based on the simplifying assumptions made in calculating some of the parameters, the following potential sources of error have been identified.

- Evaporation rates used for water losses due to evaporation were calculated rather than measured.

- Inflow from the tributaries was estimated by the USACE based on changes in lake volume using the original lake bathymetry. The 2001 survey showed significant sedimentation of the lake, which could greatly influence the calculation of inflows.

- Transpiration through plants and seepage through the dam were assumed to be negligible.

- 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 three actions would reduce uncertainty of inflow estimates: install a gauge and record instantaneous flow on the main tributary to the lake, develop modeled estimates of inflow to the lake, and back calculate inflow volume based on recent bathymetry. It is important to note that the hydrologic budget is robust enough to support lake nutrient budget development.

Temperature and dissolved oxygen

As warming of the lake surface progresses through spring, so does the onset of stratification. Thermal stratification occurs when an upper, less dense layer of water (epilimnion) forms over a cooler, more dense layer (hypolimnion). The metalimnion, or thermocline, is the region of greatest temperature and density differences and is located at the depth interval 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, dissolved oxygen is consumed and depleted by decomposition processes in the hypolimnion.

Prior to the onset of stratification, the lake has isothermal conditions throughout the water column. As stratification sets in and strengthens, the epilimnion stays 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 “trapping” nutrients or chemicals in areas of reduced exchange and water interaction (hypolimnion). This key feature has implications for epilimnetic water quality.

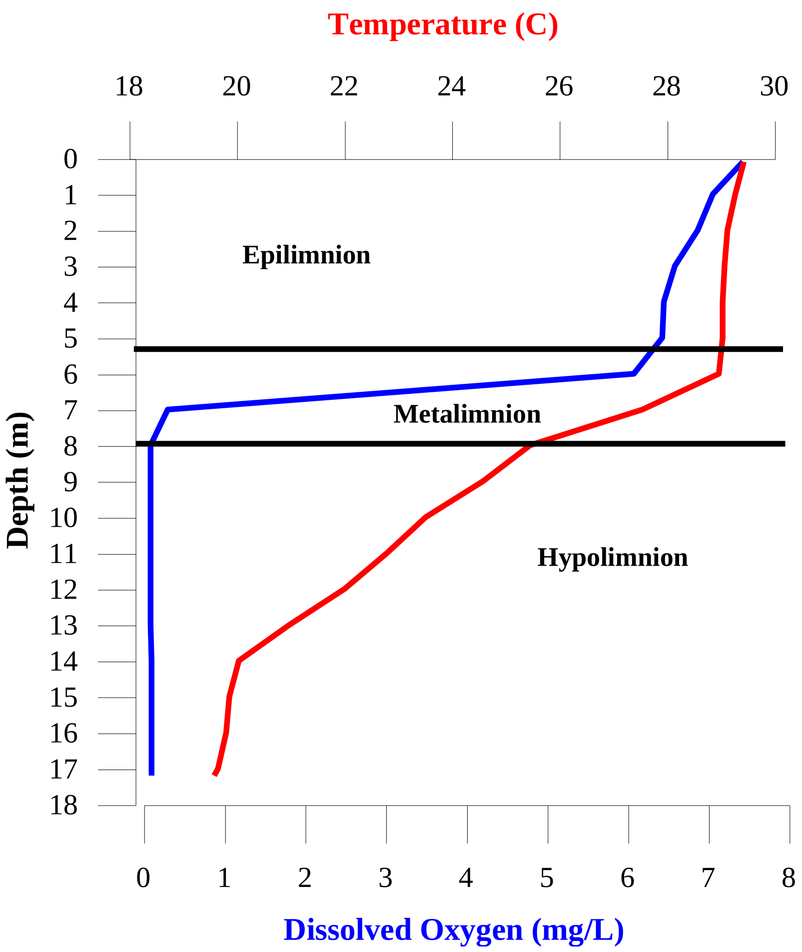


Figure 6: Temperature and dissolved oxygen vertical profile for Lake Thunderbird at its period of greatest thermal stratification

At the beginning of 2008 sampling, conditions were relatively isothermal at site 1, with fairly constant dissolved oxygen (DO) levels throughout the water column (**Figure 7**). By May 6, 2008 the lake had warmed up about 3°C without thermal stratification. Thermal stratification had set in by June 4, 2008 with an isothermal epilimnetic layer present from the surface to 10 meter depth. Within a little over two weeks thermal stratification had set in and oxygen trapped in the hypolimnion had been consumed. Between June 4 and 18, 2008 high winds (5 days with maximum wind speed above 50 mph) and two rainfall events (3.11" on June 9 and 1.35' on June 17, 2008) combined to mix the epilimnion from a depth of 8 meters on June 4 to 10.5 meter on June 18, 2008. The increase of dissolved oxygen at 12 meters suggests a deep mixing event.

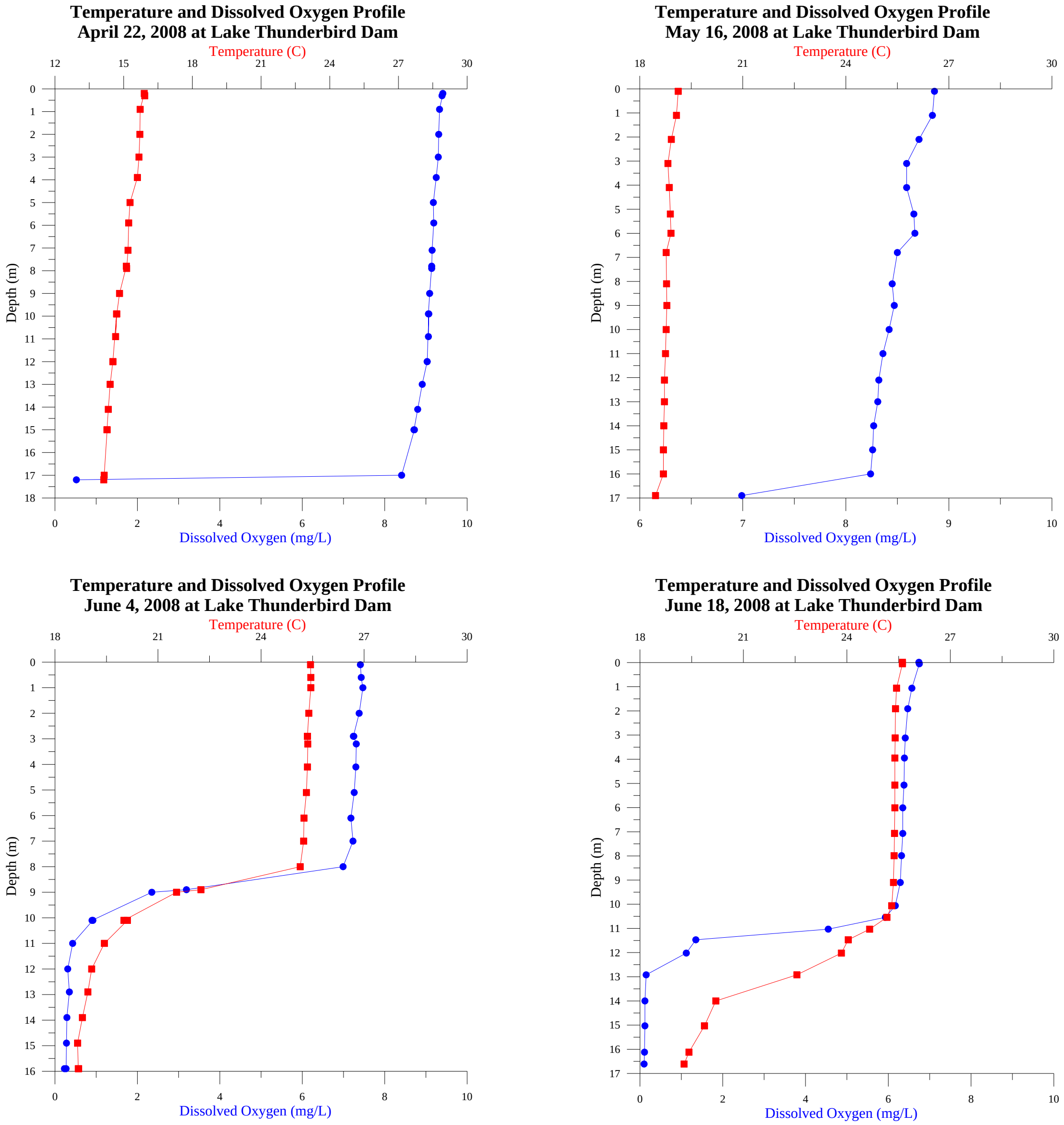


Figure 3: Temperature and dissolved oxygen vertical profile Site 1: April 22, 2008 – June 18, 2008. Showing the strengthening of thermal stratification and onset of hypolimnetic anoxia

As the summer progressed and the epilimnion warmed, the largest volume of anaerobic water was noted on August 4, 2008 (**Figure 8**). On this date the epilimnion measured 4 meters in depth while just one meter down (5 meters depth) dissolved oxygen fell below 2 mg/L. High rainfall and wind (maximum of 44 mph recorded on August 14, 2008) combined again to push the epilimnion from 4 meter depth to 8.5 meters. Mixing of anaerobic bottom waters into the epilimnion lowered dissolved oxygen an average of 3.6 mg/L between August 4 and 18, 2008.

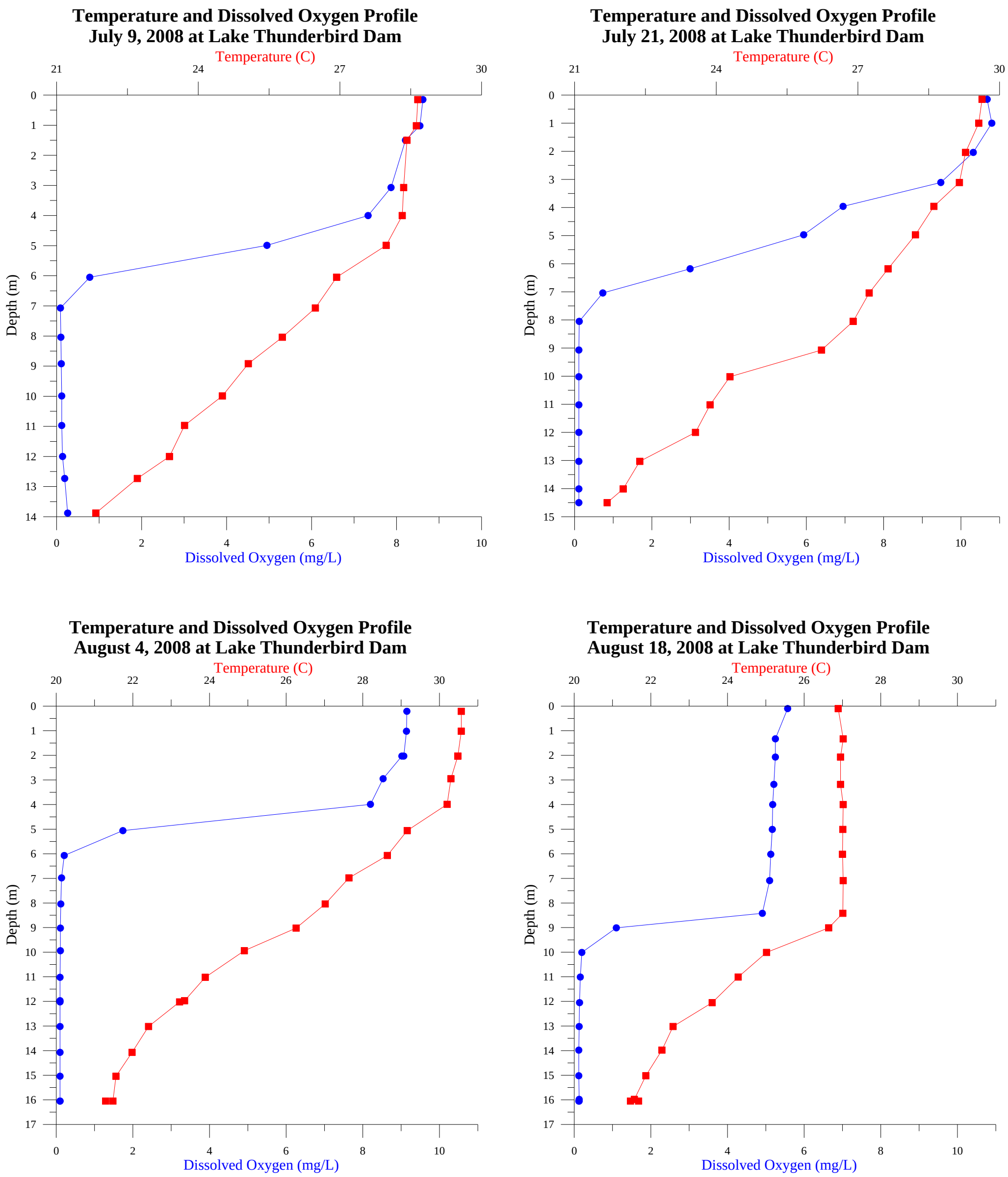


Figure 4: **Temperature and dissolved oxygen vertical profile Site 1: July 9, 2008 – August 18, 2008. Showing the deepening of the epilimnion. The mixing of hypolimnetic waters into the epilimnion explains the relatively low dissolved oxygen record August 18, 2008**

Between August 18 and September 2, 2008 the epilimnion warmed, slightly strengthening the intensity of stratification and again decreasing epilimnetic depth to approximately 5 meters (**Figure 9**). Ten days of cooler weather (daytime highs below 80°F) cooled the epilimnion sufficiently to virtually mix the water column by September 22, 2008. It is notable that on this day anaerobic water was noted from 12 meter depth and below. By October 16, 2008 complete mixis had occurred while dissolved oxygen was still depressed (near 70% saturation). This indicates incomplete oxidation of the mixed anaerobic hypolimnetic waters. On December 8, 2008 the lake had oxidized with dissolved oxygen near 10mg/L and percent saturation near 85%.

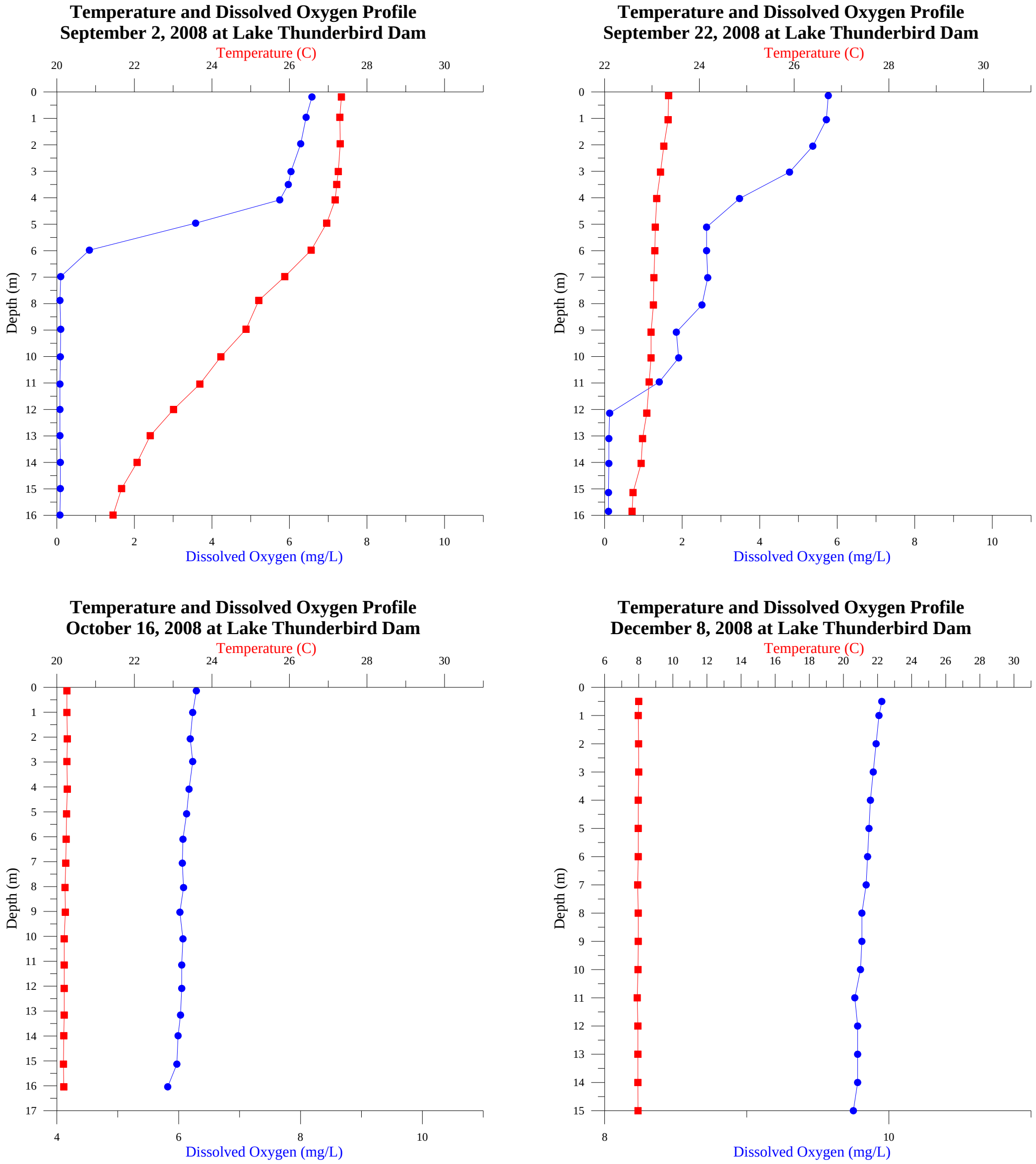
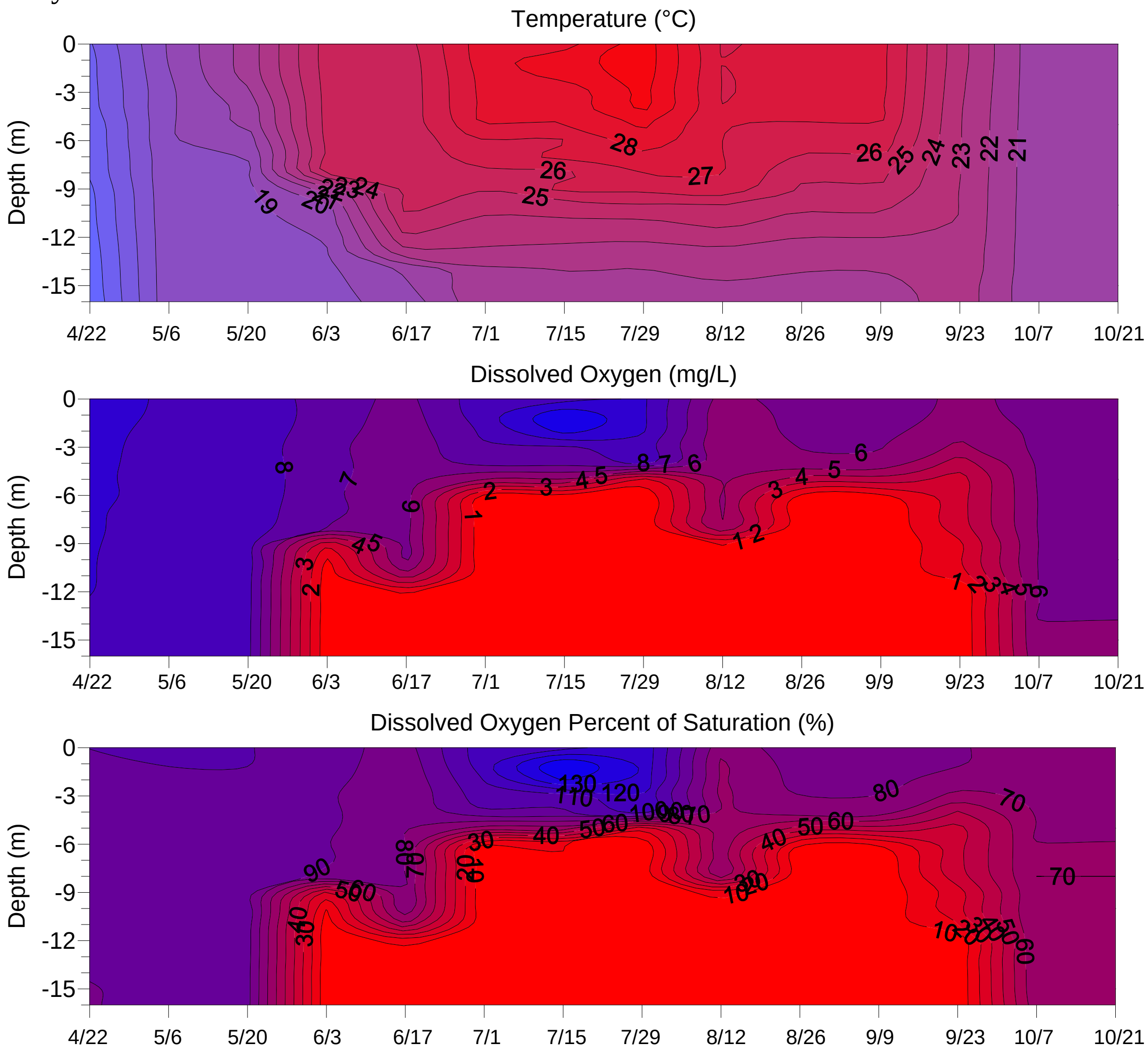


Figure 5: Temperature and dissolved oxygen vertical profile Site 1: September 2, 2008 – December 8, 2008. Showing complete turnover and recovery of dissolved oxygen (Oxidation of reduced compounds formed in the hypolimnion)

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 dissolved oxygen 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. Also, warmer temperatures are colored red, graduating to blue as temperature decreases. On the DO plots, low DO values are colored red, graduating to blue as dissolved oxygen increases.

Thermal stratification began to develop at the beginning of May, with strong stratification patterns observed by early June (**Figure 10**). Stratification peaked in early-August, with partial mixing events occurring in mid-June and mid-August. Complete lake turnover was noted by late September. 2008 appears to have been an abbreviated year with respect to stratification patterns in that stratification set in a bit late and broke up a bit early.


Temperature (°C)

Dissolved Oxygen (mg/L)

Dissolved Oxygen Percent of Saturation (%)

Figure 6: 2008 Lake Thunderbird temperature (°C) , dissolved oxygen (mg/L) and dissolved oxygen percent saturation (%DO) with depth at site 1, April 22, 2007 – October 16, 2008

Anoxia in the hypolimnion, defined as less than 2 mg/L of dissolved oxygen, followed the thermal stratification pattern (**Figure 10**). Dissolved oxygen is lowered in the epilimnion by high plant and animal respiration rates, but is offset by high photosynthetic rates and physical mixing of atmospheric oxygen into the water. The areas of intense blue in **Figure 10** represent oxygen production by excess algae growth with dissolved oxygen percent of saturation above 130% mid-July (**Figure 10**). 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 water. When mixing events occur, these released nutrients can further stimulate algae growth. The partial mixing events are more evident when examining the oxygen isopleths as the blue area (higher oxygen content) pushes down into the red area (lower oxygen content). In Lake Thunderbird, dissolved oxygen depletion below the photic zone occurs so rapidly that any partitioning of water layers is followed by immediate depletion of dissolved oxygen. There is typically no lag time between onset of stratification and dissolved oxygen depletion in highly eutrophic systems.

Water Quality Standards

Implementation protocols of Oklahoma's Water Quality Standards (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 D.O. 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 to be not supporting its Fish and Wildlife Propagation beneficial use.

The first date the DO criteria failed was on July 9 when at site 1, anoxic (less than 2 mg/L of dissolved oxygen) conditions started at 6 meters depth and persisted to the bottom. Although anoxia began developing in May, July 9 was the first date this site did not meet the water column beneficial use requirement of no more than 50% anoxic. Anoxia of greater than 50% of the water column by depth persisted for the sample dates of July 21 and August 4 until anoxia receded past 8.5 meters depth on August 18 and the lake again met the dissolved oxygen criteria.

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 average of 17 centimeters at site 6 to 70 centimeters at site 1 (**Figure 11**). The lacustrine sites (1, 2, and 4) had the greatest Secchi depths, while the upper arms (riverine zone) sites had the least clear water. This pattern of high clarity at lacustrine site and lower clarity at riverine sites is typical of reservoirs, indicating settling of solids as water progresses from site 6 to site 5 to site 4, and finally to site 1 for the Little River arm and from sites 8 to site 3 to site 2 and finally to site 1 for the Hog Creek arm respectively.

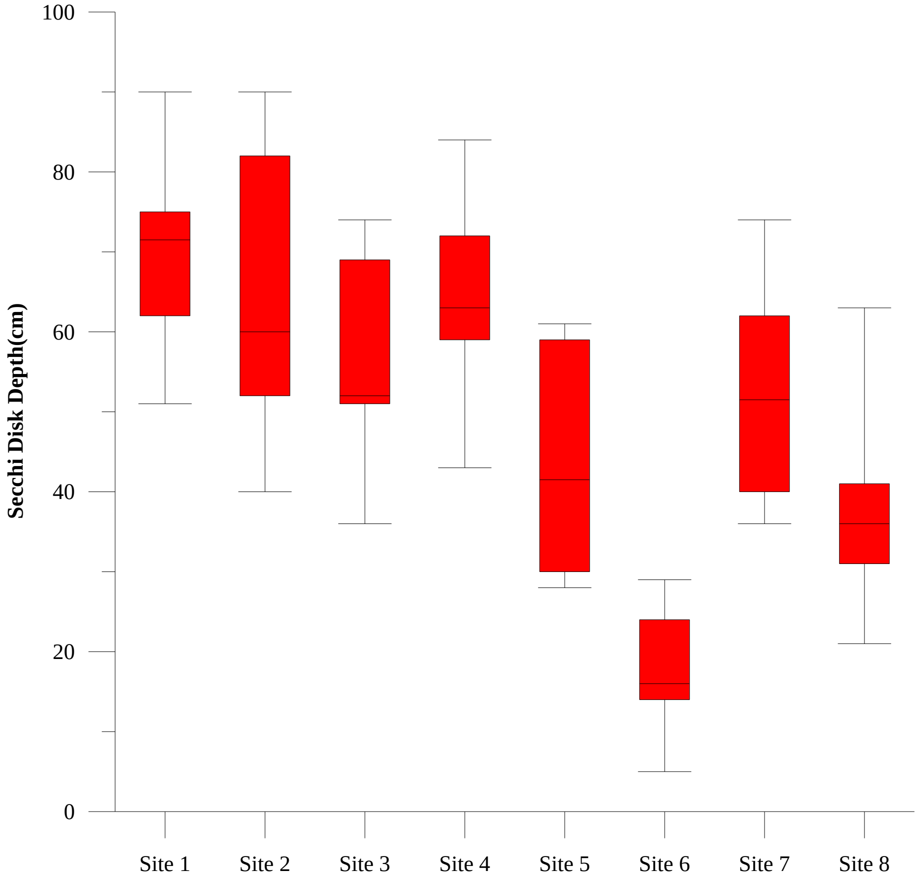


Figure 7: Box and whisker plot of Lake Thunderbird Secchi disk depth, in centimeters, by site. Boxes represent 25% of the data distribution above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution

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 to be not supporting its beneficial use, and is thus impaired for turbidity. In 2008, 22% of Lake Thunderbird samples exceeded the 25 NTU criteria. Sites 5, 6, 7 and 8 had the highest turbidity values (**Figure 12**). Site 6 was significantly different from all other sites in that all samples exceeded 25 NTU. Fifty eight percent (7 of 13) samples exceeded 25 NTU at site 8 while one sample (of 13) exceeded 25 NTU at sites 5 and 6. This data supports the same scheme of solids settling out of the water column (and turbidity dropping) as water progresses toward the lacustrine zone.

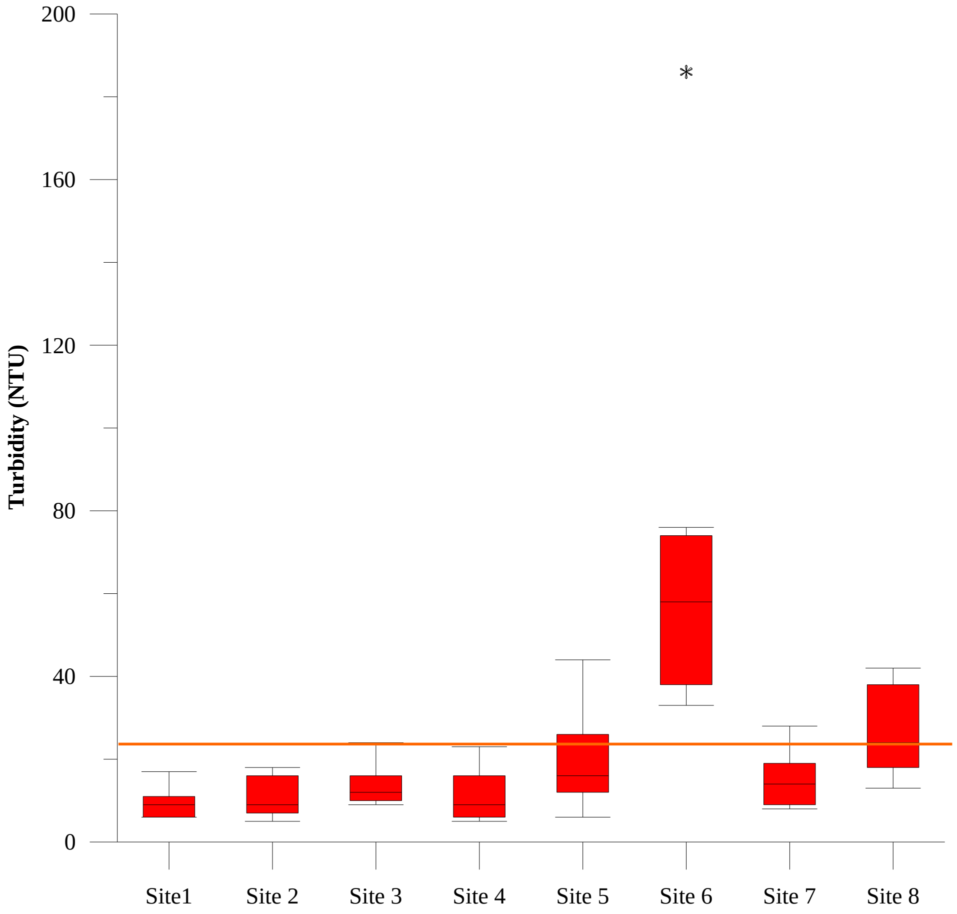


Figure 8: Box and whisker plot of Lake Thunderbird turbidity, in NTU's, by site. The orange line along the x-axis represents the 25 NTU turbidity criteria. Symbols (*) represent outliers in the dataset

Nutrients

Nutrient samples were collected twelve times during the 2008 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 and phosphorus were made, including dissolved and total forms. Dissolved nutrient concentrations consist of nutrients that are available for algal growth, such as ortho-phosphorus, 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 chlorophyll-*a* is 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 blue-green algae (cyanobacteria). In the absence of adequate dissolved nitrogen, cyanobacteria have the ability to convert atmospheric nitrogen into a usable form by way of specialized cells called heterocysts. Cyanobacteria are the only type of algae that have heterocysts, and are major producers of harmful toxins and chemicals that can cause taste and odor problems in public water supplies.

In regards 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 cyanobacteria. A recent study by Dzialowski *et al.* (2005) has broken the (molecular) ratio of total nitrogen to total phosphorus (TN/TP) into three ranges, where a TN/TP of less than or equal to 18 indicates a nitrogen-limited waterbody, 20-46 is a co-limitation of nitrogen and phosphorus, and greater than 65 is defined as phosphorus-limited. This 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 and co-limited. Since the low in 2006, when all sample dates fell within a co-limitation range of nitrogen and phosphorus, the ratio has trended upward with TN/TP splitting between the co- and phosphorus–limitation (**Figure 13**). Average TN/TP ratio for the lacustrine zone of Lake Thunderbird averaged 24.5 in 2008. Riverine sites average TN/TP for site 6, the Little River arm, and site 8, the Hog Creek arm, were 19.7 and 11.0 respectively. Although both riverine sites fall within the co-limitation range, the much lower ratio for the Little River site (6) suggests either potential for higher phosphorus input or lower nitrogen input than Hog Creek. Each constituent of the TN/TP nutrient ratio needs examination to better understand the impact of nutrients on lake water quality.

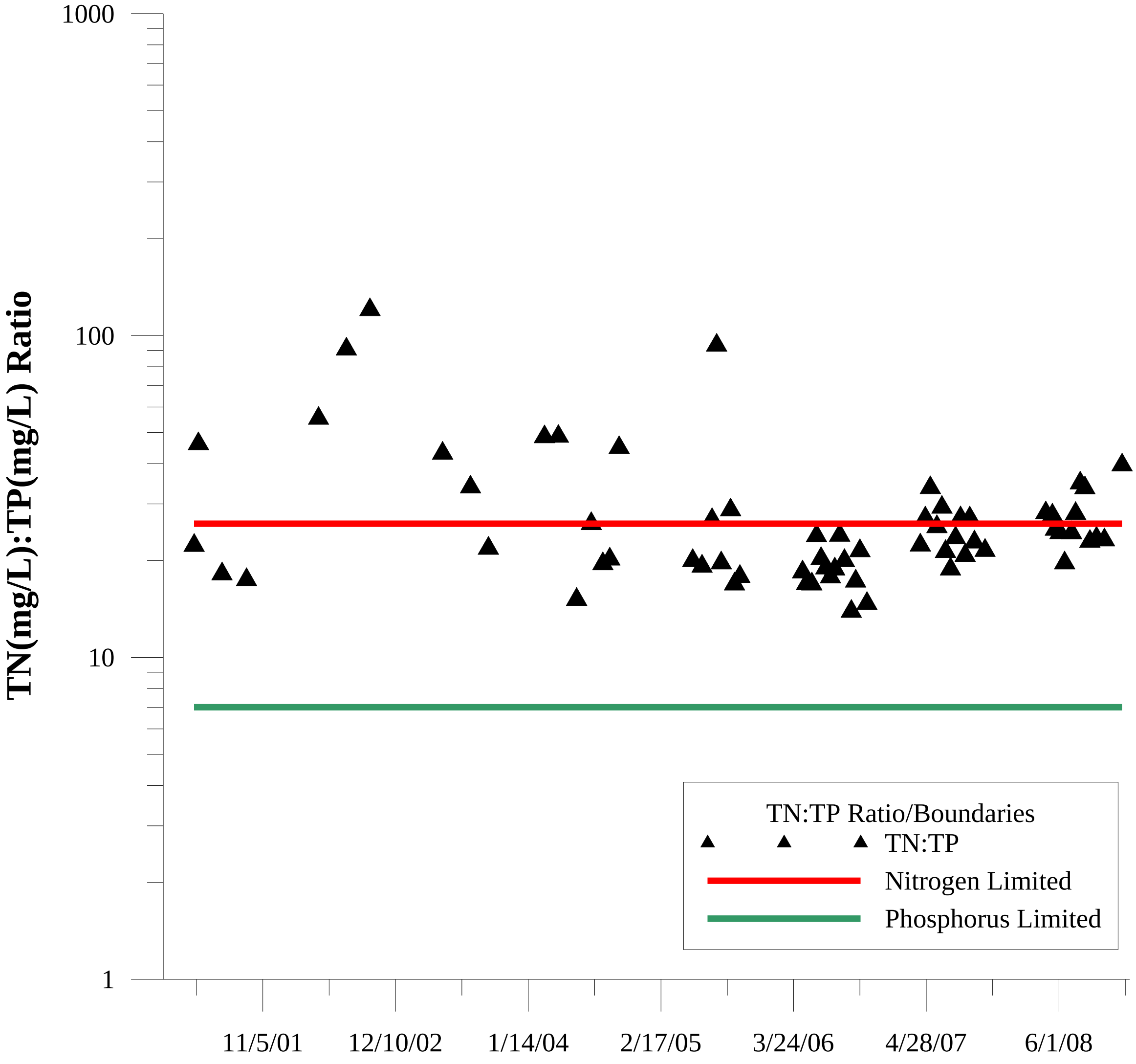


Figure 9: Surface Total Nitrogen and Total Phosphorus Ratio at Site 1, 2001-2008

Nitrogen

Surface nitrogen showed a pattern of a general increase over the summer for total nitrogen while dissolved forms of nitrogen fell below detection through the summer period (**Figure 14**). The amount of detected dissolved nitrogen seems to have increased from the low seen in 2005 towards that seen in 2001 and 2003. The reason for this pattern is not easily discerned. However, the annual or seasonal pattern observed does suggest potential explanations.

The two most likely forces driving the surface dynamics seen in the last 2 years are due to algae growth (uptake) and sediment release of ammonia. Examination of dissolved nitrogen, ammonia and nitrate distribution with depth and over time illustrates.

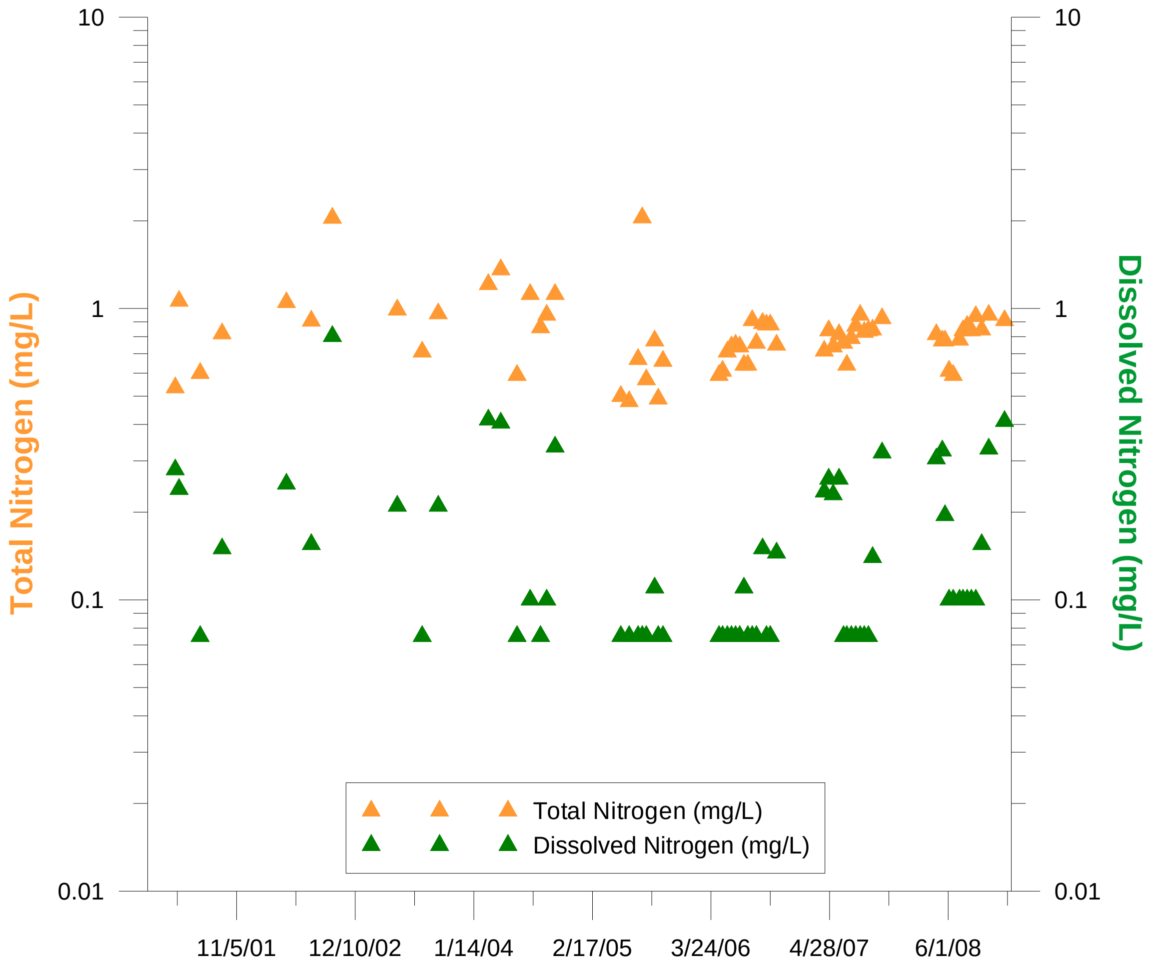


Figure 10: Surface Comparison of Total Nitrogen and Dissolved Nitrogen Species Concentrations at Site1, 2001-2008

Dissolved nitrogen decreased below detection limits in the epilimnion from June into early September (**Figure 15**). The primary dissolved nutrient in the epilimnion was in the form of nitrate (**Figure 16**). Nitrate is an algal macronutrient second only to ammonia for preferential uptake. Depletion by algal uptake, generally indicating nitrogen-limiting conditions, explains the epilimnetic below detection limit reports observed. It is interesting to note that while there was no nitrate in the epilimnion past May 21, 2008, nitrate was detected in the hypolimnion on June 18, 2008 (**Figure 16**). In the hypolimnion, nitrate does not serve as a macronutrient but as an electron source for anaerobic (bacterial) metabolism. It was not until the nitrate trapped in the hypolimnion had been consumed as an oxidant source that by the end of June nitrate was below detection in the water column. A plot of ammonia details the reason for the high levels of dissolved nitrogen noted in the hypolimnion.

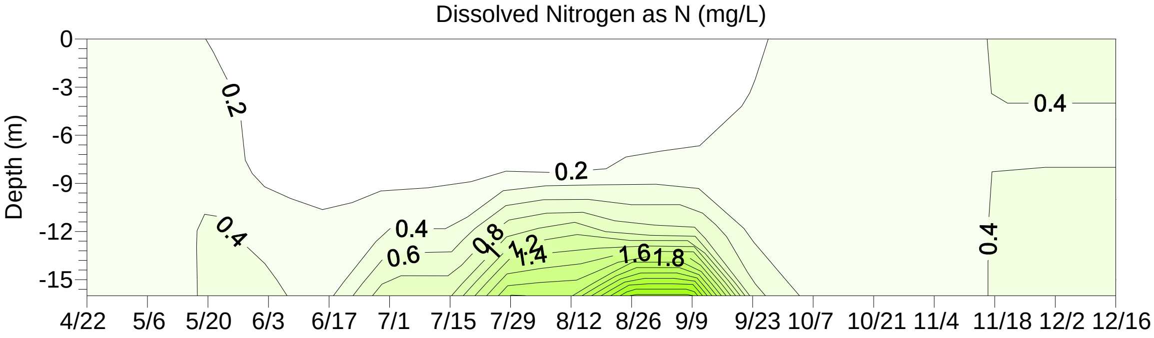


Figure 11: Lake Thunderbird total and dissolved nitrogen (mg/L as N) versus depth over time Site 1 April 22, 2008 - December 8, 2008

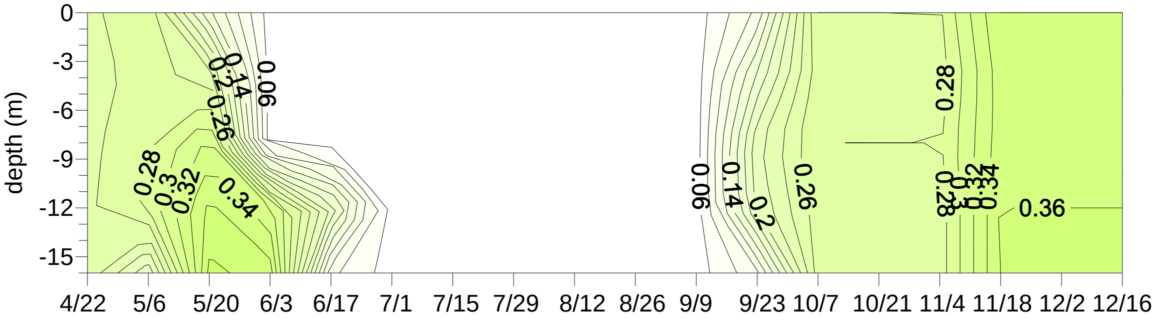


Figure 12: Plot of NO2-NO3 as N (mg/L) as N) versus depth over time Site 1 April 22, 2008 - December 8, 2008

It is not until the nitrate is consumed in the hypolimnion that ammonia accumulates (**Figure 17**). Simply put, ammonia is released from the sediment (the sediment absorptive capacity falls) as the oxidation-reduction potential falls in the hypolimnion. **Figure 18** illustrates how the onset of sediment mediated release of ammonia coincides with the July peak negative oxidation-reduction potential. This reservoir of dissolved nutrient (ammonia requires the least energy for uptake) is made available for algae growth as partial mixing events starting in August.

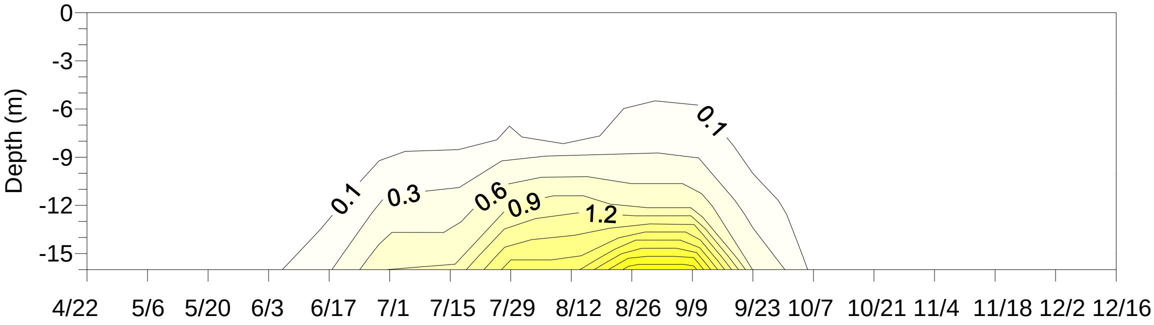


Figure 13: Plot of ammonia (mg/L as N) versus depth over time Site 1 April 22, 2008 - December 8, 2008

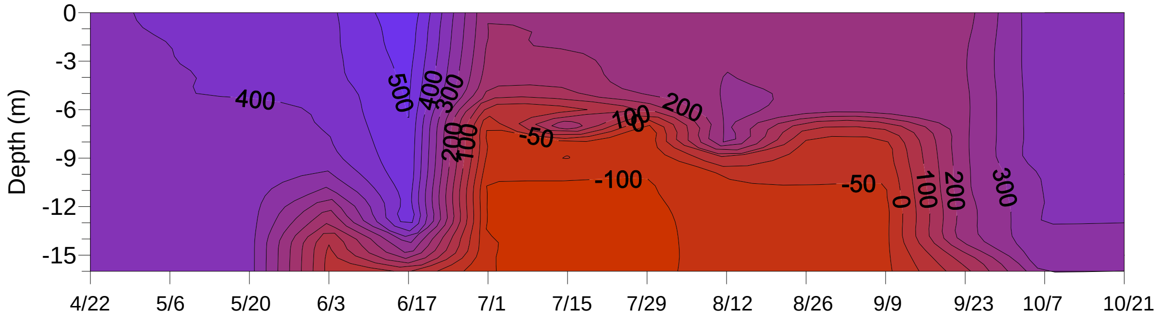


Figure 14: Lake Thunderbird oxidation-reduction potential versus depth over time Site 1 April 22, 2008 - December 8, 2008

Phosphorus

Evaluating the 2008 ortho-phosphorous data in the context of preceding years data, a typical seasonal pattern for ortho-phosphorus was observed in 2008 (**Figure 19**), with surface ortho-phosphorus initially decreasing then recovering by the end of the sample season. This shows the utilization of easily available phosphorus in early summer and the regeneration of ortho-phosphorus by late summer. The dip in ortho-phosphorus indicates a period when phosphorus could have been limiting algae growth. This, in combination with the low surface dissolved nitrogen, supports a conclusion of co-limitation of algae growth by both nitrogen and phosphorus. It is interesting to note that spring (April into May) ortho-phosphorus concentration in 2007 and 2008 were much higher than previous years. It may be that these two years of significantly higher inflow yielded higher than previous amounts of ortho-phosphorus in the lake.

Total phosphorus showed a seasonal increase representing an accumulation of epilimnetic phosphorus. In 2008 the most likely source for epilimnetic accumulation of phosphorus is from the hypolimnion and stormwater inflow (**Figure 20**). Ortho-phosphorus from the anoxic hypolimnion reaches the epilimnion through two different processes: following the diffusion gradient across the metalimnion and direct mixing as the epilimnion cools and deepens by partial mixing events. The ortho-phosphorus "bubble" seen mid-depth at the end of August could be the result of a partial mixing event mid-August, inflow of ortho-phosphorus rich storm waters or some mixture of both.

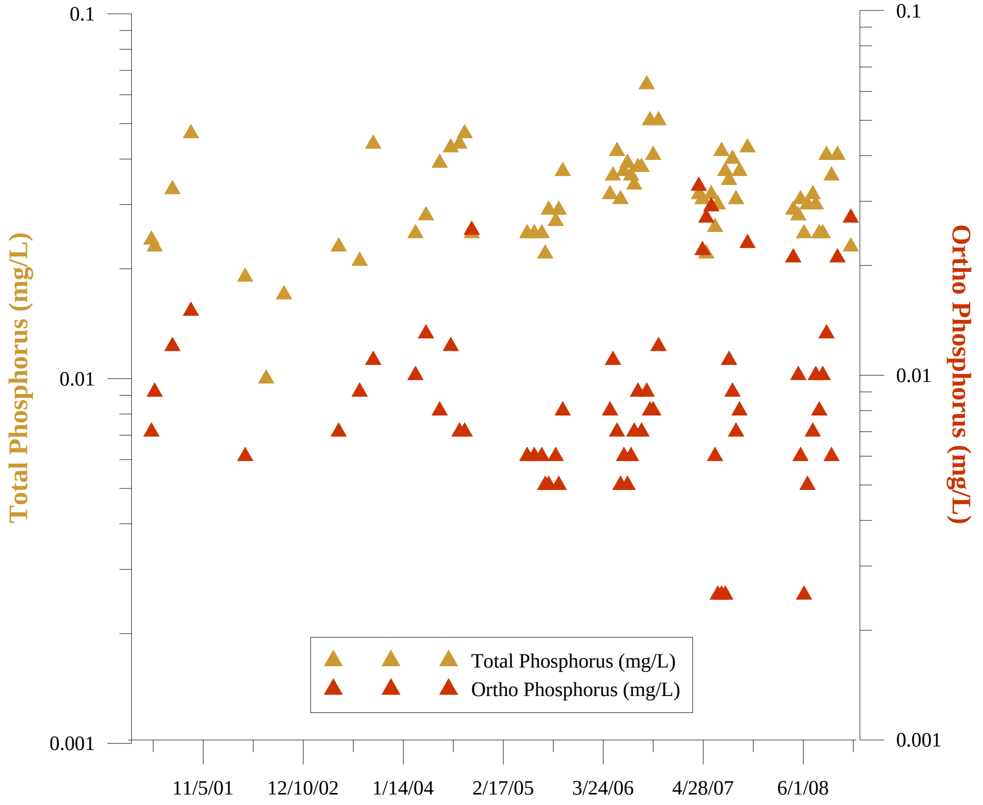


Figure 15: Surface Total Phosphorus and Ortho (dissolved) Phosphorus at Site 1: 2001-2008

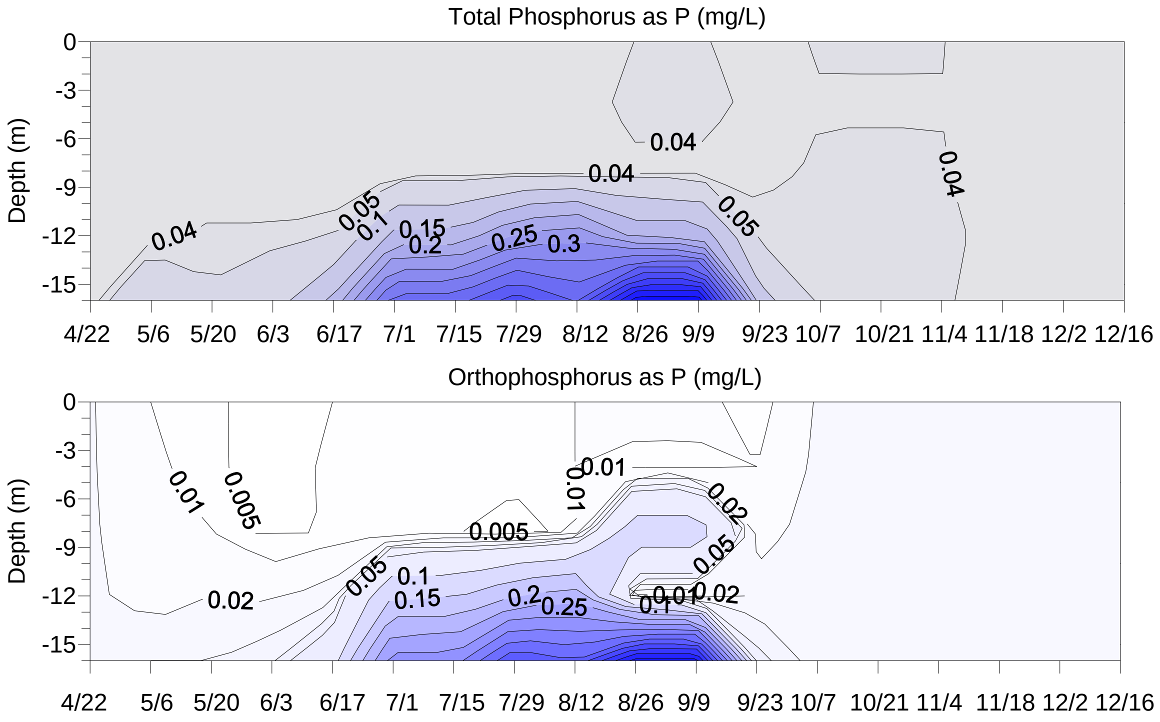


Figure 16: Lake Thunderbird site 1 total and orthophosphrous (P) versus depth April 22, 2008 - December 8, 2008

2008 monitoring also allowed for comparison of surface phosphorus between the lacustrine and two riverine sites in Lake Thunderbird. The average total phosphorus and ortho-phosphorus of the lacustrine sites (1, 2 & 4) were 0.032 mg/L and 0.012 mg/L respectively. Average total and ortho-phosphorus of site 8, riverine zone of Hog Creek, was 0.041 mg/L and 0.014 mg/L respectively. Total phosphorus was higher while ortho-phosphorus was about the same. Average total and ortho-phosphorus of site 6, riverine zone of the Little River, was 0.087 mg/L and 0.036 mg/L respectively. Here total phosphorus was twice and ortho-phosphorus nearly three time that seen at Hog Creek. Although speculative, it is likely the higher degree of urban development in the Little River drainage basin compared to the Hog Creek drainage basin that is largely responsible for the large disparity between the two lacustrine sites (COMCD, 2006).

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 used to partition total phosphorus reports between epilimnetic, metalimnetic and hypolimnetic layers. The cumulative summation of these layers allows the massing of phosphorus for each sample date (**Table 3**). Once the lake mass was established, the distribution within the lake and losses were estimated using COE water quantity reports and OWRB water quality reports. Missing from this lake nutrient budget are estimates of phosphorus inflow, dry deposition and sediment flux. To complete the massing of Lake Thunderbird phosphorus, sample dates were averaged to yield monthly amounts (**Table 4**). The constructed budget demonstrates pre-stratification lake phosphorus mass in 2008 of approximately 4,000 kg. April and December marked the lowest observed phosphorus mass while September marked the highest (5,971 kg) mass of lake total phosphorus.

Monthly phosphorus masses demonstrate a general trend of baseline levels occurring in winter under mixed conditions, then steady increases progressing to a mid-summer peak (coinciding with stratification peak) followed by a decline as stratification breaks up. The phosphorus mass in October, following fall turnover, is about 1,500 kilograms greater than the pre-stratification mass. It is important to note that even though there were significant inflow events during monitoring, the hypolimnion still accumulated phosphorus. Accumulation of dying algae (settling) from the epilimnion, release of ortho-phosphorus from the sediment and stormwater inflow are the primary contributors.

This preliminary budget has set the foundation for understanding lake nutrient dynamics and placing external (runoff) and internal (sediment mediated release) factors in context of water quality based goals. Enhancements to increase the accuracy of the nutrient budget include assessing dry deposition and estimates of inflow load. It will not be until water quality data is available for the tributaries to the lake that sediment influence can be put in context of the phosphorus mass from runoff and total phosphorus inputs.

Table 3: 2007 Lake Thunderbird 2008 phosphorus mass by depth interval and date, site 1. Red cells in table represent the hypolimnetic water

Depth (m)	22-Apr	12-May	21-May	04-Jun	18-Jun	09-Jul	21-Jul	04-Aug	18-Aug	02-Sep	22-Sep	16-Oct	08-Dec
0 - 1	416	657	645	522	611	638	599	542	819	820	781	892	556
1 - 2	510	589	627	485	477	545	559	461	588	798	658	819	477
2 - 3	408	506	455	368	564	561	478	371	542	738	558	616	406
3 - 4	325	449	400	449	343	389	366	373	313	646	511	648	371
4 - 5	348	420	331	343	427	355	350	339	395	471	487	535	343
5 - 6	243	273	332	322	294	360	333	288	359	648	364	450	269
6 - 7	296	245	270	244	414	282	269	242	273	385	335	387	252
7 - 8	180	346	257	191	100	221	227	256	213	169	283	301	203
8 - 9	185	215	183	151	270	181	200	205	175	380	248	276	169
9 - 10	138	186	198	202	138	412	144	405	189	385	190	234	133
10 - 11	118	150	173	138	95	360	278	569	426	512	150	163	92
11 - 12	86	107	143	104	116	312	290	421	481	465	108	79	59
12 - 13	52	71	86	62	90	234	239	367	410	266	61	58	34
13 - 14	33	60	45	37	106	250	175	197	225	223	42	21	16
14 - 15	13	38	28	19	60	180	142	108	109	137	25	13	7
15 - 16	9	26	12	6	37			44	35	54	9	4	3
16+	0	8	5	3	7			6	15	33	4	1	
Total	3359	4346	4191	3646	4152	5280	4647	5192	5566	7130	4813	5498	3391

Table 4: Monthly summary of lake mass with itemized gains and losses for 2008

Month	Lake	Runoff	Sediment	Rainfall	Releases	Water Supply
January	NA	NA	NA	0.1	NA	NA
February	NA	NA	NA	1.3	NA	NA
March	NA	NA	NA	1.6	NA	NA
April	3359	NA	NA	2.8	283	37
May	4268	NA	NA	2.5	502	56
June	3899	NA	NA	3.5	439	60
July	4963	NA	NA	0.5	61	79
August	5379	NA	NA	3.3	173	75
September	5971	NA	NA	1.7	306	78
October	5498	NA	NA	0.6	0	79
November	NA	NA	NA	1.1	0	0
December	3391	NA	NA	0.6	0	42

Chlorophyll-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 at each sampling event during 2008. Chlorophyll concentrations reached their peak in early September (**Figure 21**). In 2008, 87% of samples were considered eutrophic based on a 7.2 µg/L division between mesotrophy (Wetzel 2001). This is slightly higher than the 80% seen in 2007 and almost equal to the 86% in 2006. Perhaps the most notable item of the 2008 seasonal chlorophyll-a was a large mid-August jump. Between August 4 and 18, 2008 lake wide chlorophyll-a increased an average of 19 µg/L. The August 18, 2008 sample event followed a partial mixing of the hypolimnion. Usually these mixing events result in a depression of chlorophyll-a. Apparently, nutrient stimulation of algae growth was greater than the depression caused by an increased mixing depth. Also notable was that the chlorophyll-a reports following the mid-august jump were among the highest reported during the OWRB’s monitoring of Lake Thunderbird. Open water, lacustrine zone, chlorophyll-a appears to have increased over the years since a low in 2005 (**Figure 22**).

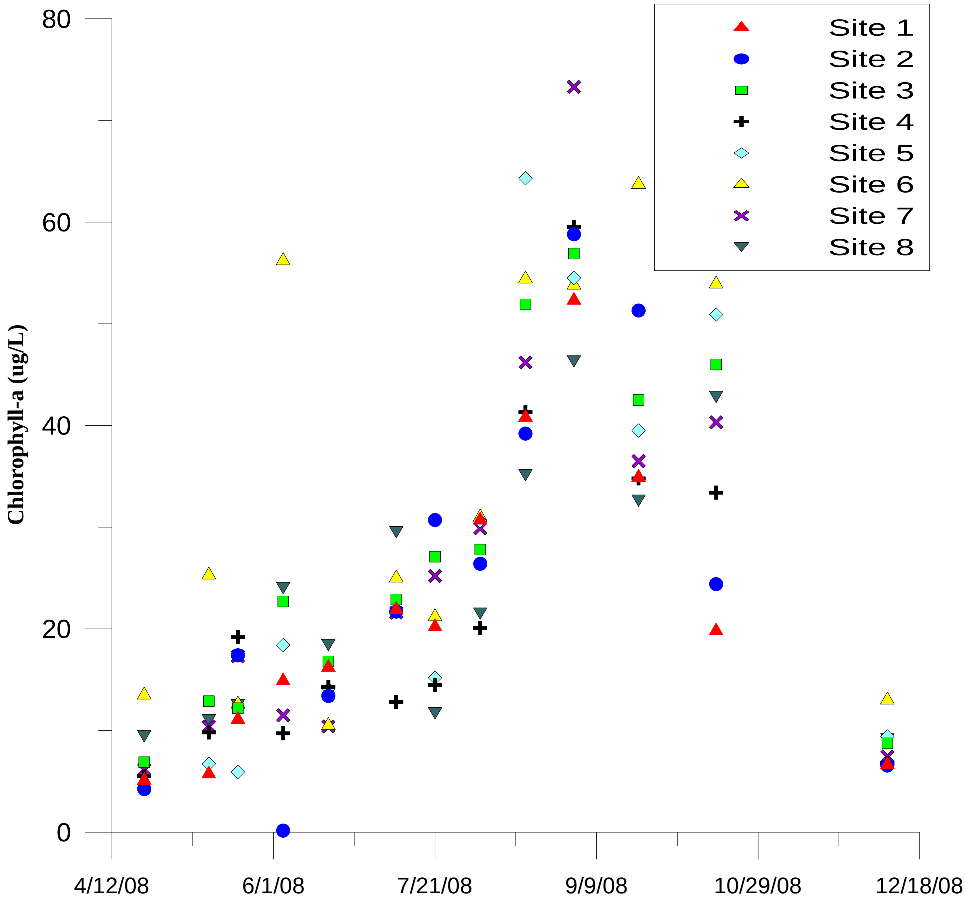


Figure 17: Lake Thunderbird surface chlorophyll-*a* (μg/L) by site April 22, 2008 through December 8, 2008

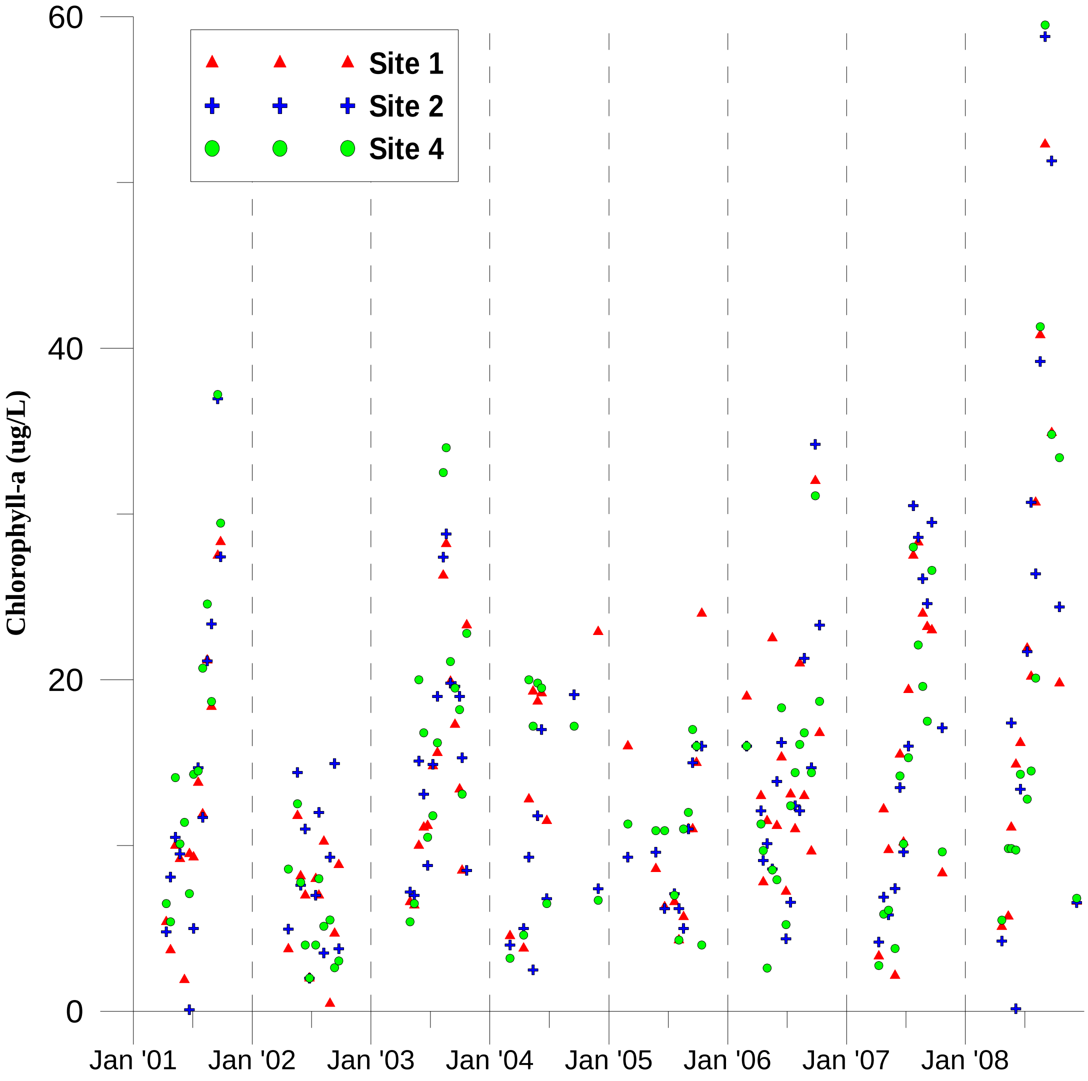


Figure 18: 2001-2008 Lake Thunderbird surface chlorophyll-*a* (µg/L) by site

Goal setting by the COMCD in previous years set a maximum chlorophyll-*a* of 20 µg/L. During the 2008 sampling season, 53% of chlorophyll-*a* samples exceeded this upper limit (**Figure 23**). This number is higher than the 38% in 2007 and 14% in 2006. It could be due to excessive nutrient inputs from run-off events in this wet year and partial mixing of nutrients from the hypolimnion in June and August.

Because Lake Thunderbird is a designated Sensitive Water Supply, it is required to meet a chlorophyll-*a* standard of 10 µg/L (OAC 785:45-5-10 (7)). 21 % of the 2008 samples were below this concentration, less than the 31% and 29% seen in 2007 and 2006 respectively. Although this standard is obtainable for Lake Thunderbird, abatement of nutrient inputs into the watershed is necessary to significantly reduce chlorophyll concentrations on a long-term basis. The Oklahoma Department of Environmental Quality will draft a watershed management plan to address specific recommendations in regards to thwarting nutrient pollution.

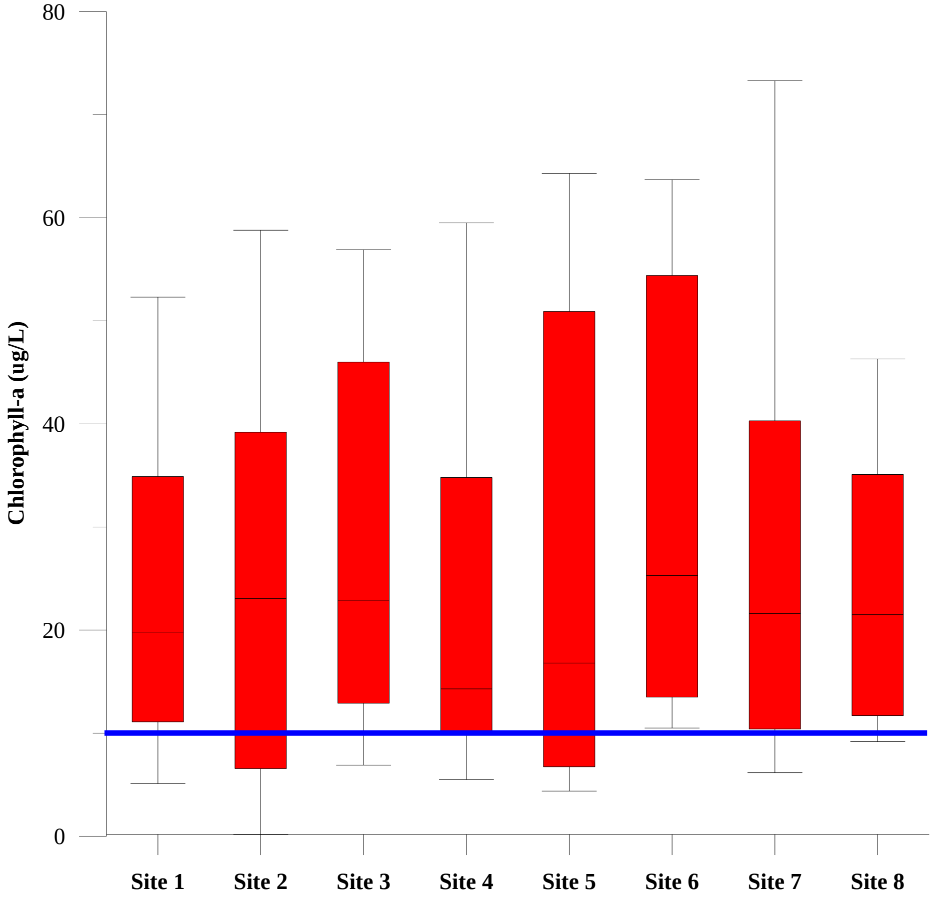


Figure 19: 2008 Lake Thunderbird chlorophyll-*a* (μg/L) averages by site. The blue line at 10 μg/L indicates the water quality standard for sensitive water supplies (SWS)

Taste and Odor Complaints

The City of Norman provided data on the number of taste and odor complaints from their customers in 2007 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 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 by cyanobacteria. Eutrophication results in cyanobacteria dominance of algal communities in lakes, and therefore corresponds to excessive nutrient concentrations.

In 2007, the City of Norman received the majority of taste and odor complaints in October (10) and November (8) (**Figure 24**). This pattern is similar to previous years, where a hypolimnetic mixing event in late summer or early fall, usually in September, causes a spike in the number of complaints (**Figure 25)**.

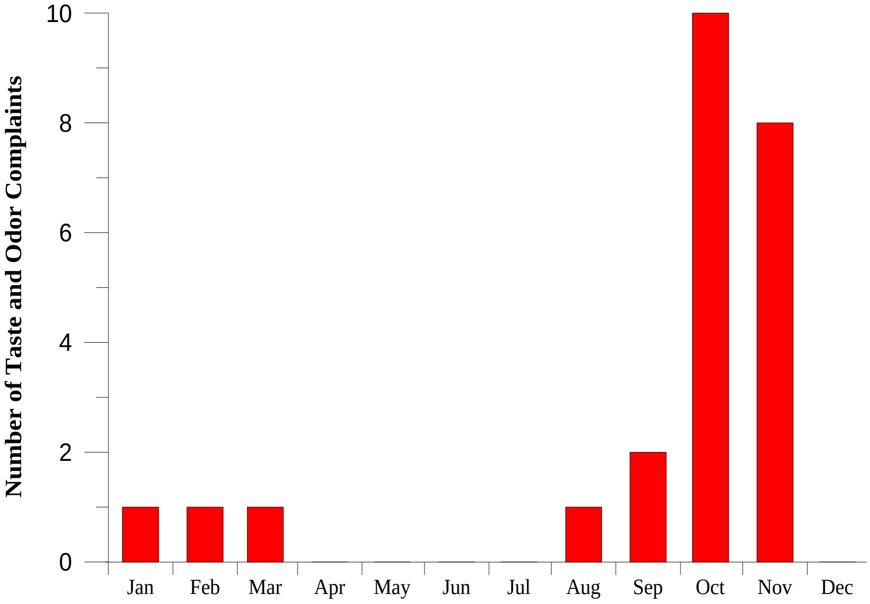


Figure 20: Taste and odor complaints to the City of Norman during 2008

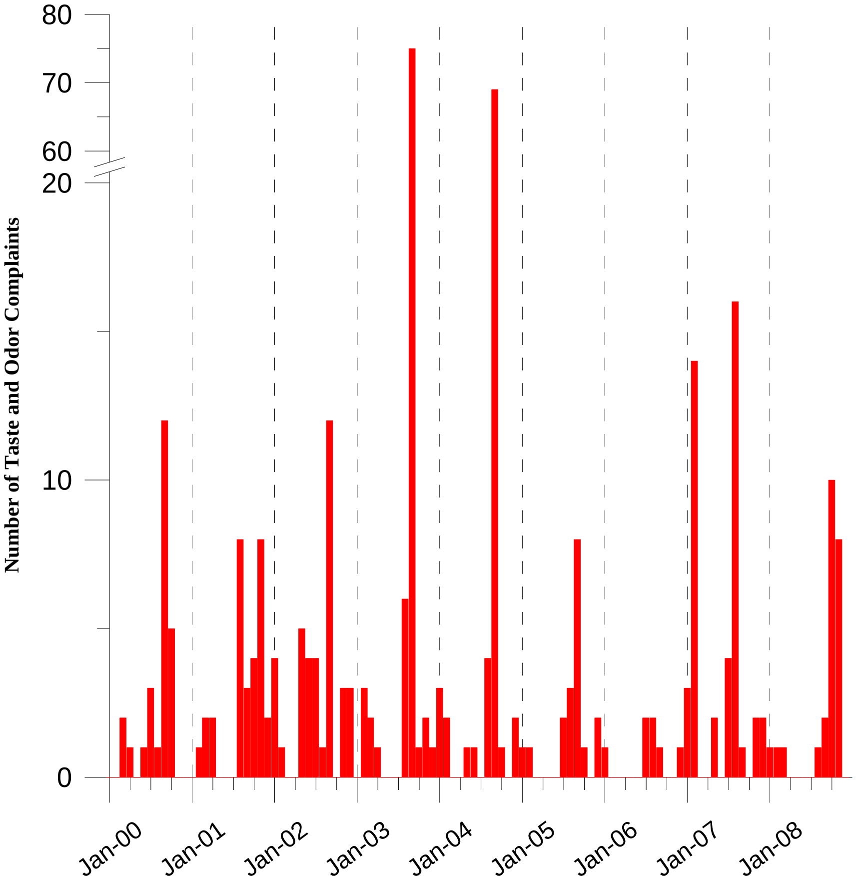


Figure 21: Taste and odor complaints to the City of Norman from 2000 through 2008

General Water Quality

Total organic carbon (TOC) is an additional measure of organic content and productivity. TOC samples were collected at the surface of the three lacustrine sites (1, 2, and 4) at each sample event and also with depth (4 meter intervals) during 2008. In general, TOC concentrations increased during spring and early summer, with peak concentrations occurring in late July (**Figure 26**). Concentrations consistently declined after this peak date. This plot bears a striking resemblance to the seasonal plot of chlorophyll-a (**Figure 21**) with the exception that TOC trending appears to precede chlorophyll-a by two weeks. This trend is consistent with other proxies of primary production, such as chlorophyll-*a* (**Figure 21**) and pH (**Figure 27**). While statistical regression suggested that only 30% of the variability in reported chlorophyll-a could be explained by TOC, it is evident that TOC and chlorophyll-a are intimately related parameters. Increased sampling in 2008 allowed for a view of TOC with depth and time (**Figure 28**). The epilimnetic maximum seen at the beginning of August follows the period of dissolved oxygen supersaturation (excessive algae growth) from July into August (**Figure 10**). The hypolimnetic buildup of TOC matches the hypolimnetic buildup of ammonia and orthophosphorus (**Figures 17** and **20**, respectively).

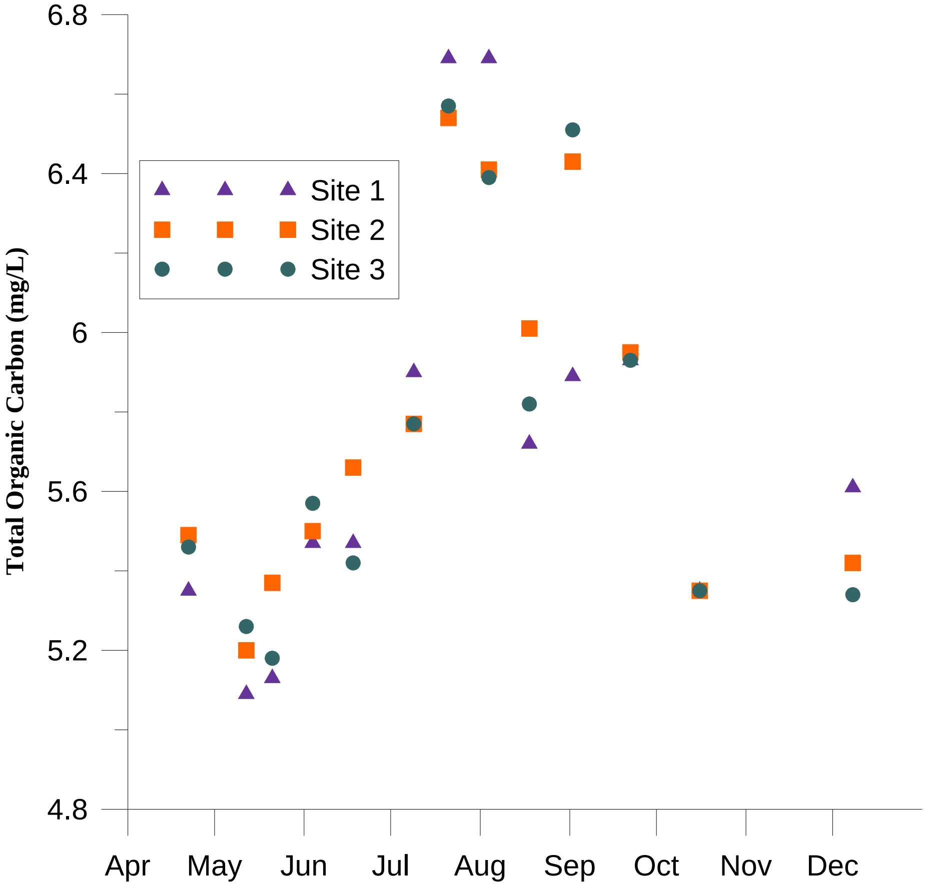


Figure 22: Total organic carbon concentrations at the surface of the three lacustrine sites on Lake Thunderbird during the 2008 sampling season

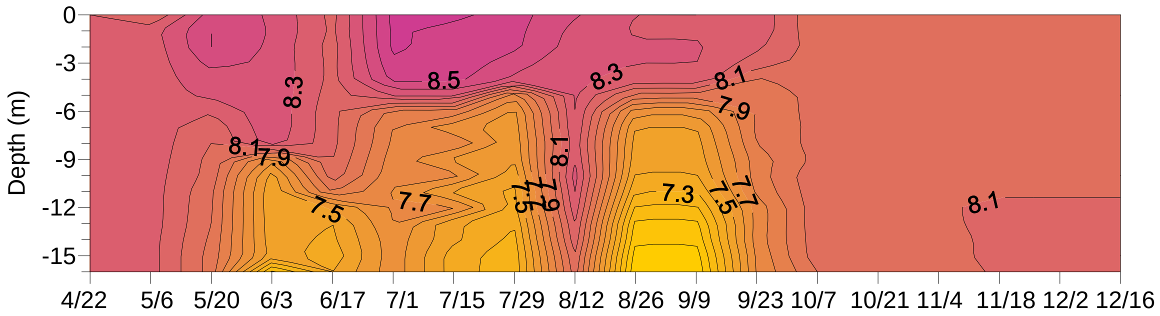


Figure 23: Lake Thunderbird pH (S.U.) versus depth over time Site 1 April 22, 2008 - December 8, 2008

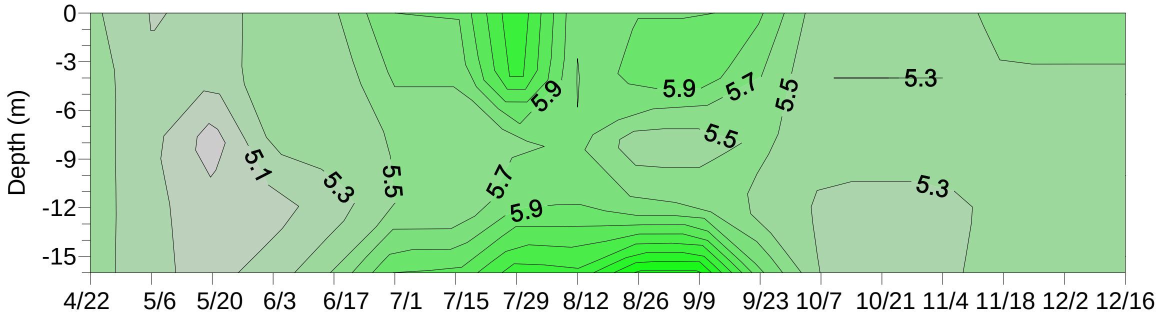


Figure 24: 2008 Lake Thunderbird TOC (mg/L) versus depth over time Site 1 April 22, 2008 - December 8, 2008

High algae growth affects other basic water quality parameters. 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.

Hypolimnetic oxidation reduction (redox) potential in Lake Thunderbird approached 100 mV beginning in June 2007 (**Figure 18**). Negative redox potential occurred from this time throughout the growing season, until fall turnover when hypolimnetic waters were mixed. Sediment bound phosphorus and common metals such as iron will desorb as redox potential falls below 100 mV. Low redox potential associated with anaerobic conditions is also associated with the production of sulfide and methane (**Figure 18**).

Initially, oxygen is used as a terminal electron acceptor. As oxygen is depleted, other compounds are reduced reflected by a decreasing hypolimnetic redox potential. For example, ferric iron is reduced to ferrous iron when the redox potential (Eh) approaches 100mV. This results in the release of ortho-phosphorus that was chemically bound to ferric iron in the sediment. When this phosphorus reaches the epilimnion it can contribute to additional algae production. Other metals are reduced to soluble forms when the redox falls below 100mV. Dissolved metals such as iron and manganese should be expected in the water column with low redox potential.

Summary and Discussion

Water Quality

Nutrients such as nitrogen and phosphorus are essential components of aquatic food webs, as they are utilized by primary producers (i.e. algae) for growth. Algae then serve as food sources for zooplankton, which are consumed by planktivorous and juvenile fish. In a healthy ecosystem, these trophic levels interact and together form a balanced food web. Excessive nutrients inputs into lakes such as Thunderbird can cause algal growth to increase past the ability of primary consumers to utilize and will cause imbalances that are easily identifiable. The most notable of these imbalances are reflected as overabundant algal populations, algal blooms and surface scums. Consequences of these occurrences include high chlorophyll-*a*, high total organic carbon, elevated pH, super-saturation of dissolved oxygen, lowered Secchi depth, and increased color and turbidity at the water's surface. In addition, lower dissolved oxygen concentrations will occur at hypolimnetic depths and oxidation-reduction potentials will decrease; releasing sediment bound phosphorus and metals such as iron and manganese. This process of elevated algal growth and ensuing consequences is known as cultural eutrophication, where anthropogenic point and non-point sources are almost always the cause of excess nutrients in aquatic environments, where in-lake dynamics will exacerbate associated problems.

Consequences of cultural eutrophication were observed in Lake Thunderbird in 2008. These included high chlorophyll-*a*, elevated total organic carbon, elevated pH, super-saturation of dissolved oxygen, lowered Secchi depth, and increased color and turbidity at the water's surface during the summer growing season. Anoxia occurred during the summer months as well, coinciding with low to negative oxidation-reduction potentials. During this time, phosphorus and metals were released back into the water column and entrained during fall turnover.

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 blue-green algae 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 lysis, or senesce 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 annually receives 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 higher chlorophyll-a in 2008 represents a greater recreational risk than previous years.

Oxidizing the hypolimnion

Maintaining an oxidized hypolimnion will allow for the oxidation of nutrients, metals and taste and odor-causing compounds prior to mixing while increasing the retention of sediment-bound nutrients. Several avenues exist to lessen the reducing properties of Lake Thunderbird's hypolimnion. Direct oxidations using a pneumatic device such as selective layer or hypolimnetic aeration treats the symptoms, providing immediate relief. Injection of an oxidant, such as nitrate or sulfate, could also potentially minimize the impact of an anaerobic hypolimnion. Unfortunately, these compounds also serve as nutrients for algae growth. Nutrient reductions in the overlying surface water to minimize algal growth, and thereby reducing oxygen demand, are a direct avenue. To date, no projections are available of what algal (or chlorophyll-*a*) concentrations are needed to maintain some semblance of oxidation in the hypolimnion. Whole lake mixing, whether by pneumatic or mechanical device, is another alternative to ensure oxidized water at the sediment-water interface. The concept design for a pneumatic device using technology from the early 1980s proved too energy intensive to be implemented. It is likely that some active intervention, such as nutrient inactivation or pneumatic oxidation, will be more cost effective as opposed to whole-lake mixing. Providing an oxidized hypolimnion is one step towards reducing surface chlorophyll-*a* concentration. Reducing overlying algae content will reduce the demand of oxidant in the hypolimnion. In this way, reduced algae serves as a feedback mechanism to minimize the need for oxygen.

Reducing runoff of nutrients from the watershed into the lake is the other step towards reducing chlorophyll-a. The extensive evaluation of the Lake Thunderbird watershed should identify land use practices most likely to contribute nutrients to the lake. It may be that these results could be leveraged by the COMCD to encourage incorporation of best land use practices (BMP)s throughout the watershed of Lake Thunderbird.

State Water Quality Standards

In 2006, Lake Thunderbird was listed on Oklahoma's 303(d) list as impaired due to color, low dissolved oxygen and turbidity, with the causes of these impairments unknown. Data collected in 2008 were analyzed for beneficial use impairments in accordance with the Use Support Assessment Protocols (OAC 785:46-15) of the Oklahoma Water Quality Standards (OWQS). Lake Thunderbird was found to be not supporting its Fish and Wildlife Propagation beneficial use in regards to dissolved oxygen and turbidity, and therefore should remain listed as impaired for these uses. 2008 data was insufficient to make an aesthetic use support determination for true color. In addition, Lake Thunderbird was not meeting the 10 μg/L chlorophyll-*a* requirement for sensitive water supplies.

Recommendations

Determine the feasibility of oxygenating the hypolimnion of Lake Thunderbird

Oxygenation of the hypolimnion would aid in achieving the 10 μg/L chlorophyll-*a* standard (reducing algae growth), reduce fall taste and odor reports and eliminate dissolved metals in raw water. Maintaining an oxidized hypolimnion reduces algae growth by slowing the movement of nutrients from the lake bottom into the epilimnion. Oxygenation would also eliminate the role of lake sediments in the gradual increase of surface nutrients during the summer.

Continued nutrient sampling

The current sample scheme allows effective accounting of phosphorus in Lake Thunderbird. With the completion of ODEQ required monitoring, a less intensive monitoring scheme could be adopted to characterize Lake Thunderbird.

Additional evaluations

Data sufficient to predict a phosphorus level equivalent to 10 μg/L of chlorophyll-a has been collected. This work, in conjunction with an estimate of watershed phosphorus loading and land use assessment would provide concrete goals and suggest the first steps toward Lake Thunderbird meeting the 10 μg/L chlorophyll-a standard. Predictive modeling by ODEQ to achieve this goal should also include the role lake sediments play on water quality.

The goal of compiling a comprehensive long term data set is being realized. The OWRB has collected and reported data for the COMCD since 2000. While the specific parameters and duration of monitoring has changed over the years there is enough data to start looking for deterministic parameters of water quality and the effect of varying water quality over time. Statistical trend detection of long term water quality data is most useful when combined with a clear understanding of watershed land use changes and lake management changes over time.

COMCD should look forward toward the results of the non-point source pollution program (319) watershed evaluation and seek ways to encourage adoption of best land management practices (BMP) s throughout the watershed. Targeting practices that reduce nutrient and sediment in runoff to the lake would be an investment in the quality and longevity of the raw water supply.

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Appendix A: Quality Control Data

Laboratory Results of Blank Samples Taken for COMCD Lake Thunderbird Water Quality Sampling April 22, 2008 – December 8, 2008.

NOTE: less than symbol represents a below detection limit report

Date	Site	True Color	Alkalinity	Susp. Solids	Chloride	Sulfate	Ammonia as N	Nitrite as N	Nitrate as N	Nitrite-Nitrate as N	Kjeldahl Nitrogen as N	Ortho-P as P	Total P as P	Total Organic Carbon	Dissolved Organic Carbon
04/22/2008	10		<10.0	<10.0	<10.0	<10.0	<.10	<.05	<.05		<0.10	<0.005	<0.005	<0.50	
05/12/2008	10	<1.00	<10.0	<10.0	<10.0	<10.0	<0.10	<0.05	<0.05		<0.10	<0.005	<0.005	<0.50	
05/21/2008	10	<1.00	<10.0	<10.0	<10.0	<10.0	<0.10	<0.05	<0.05		<0.10	<0.005	<0.005	<0.50	
06/04/2008	10	<1.00	<10.0	<10.0	<10.0	<10.0	<0.10	<0.05	<0.05		<0.10	<0.005	<0.005	<0.50	
06/18/2008	10		<10.0	<10.0	<10.0	<10.0	<0.10	<0.05	<0.05		<0.10	<0.005	<0.005	<0.50	
07/09/2008	10		<10.0	<10.0	<10.0	<10.0	<0.10	<0.05	<0.05		<0.10	<0.005	<0.005	<0.50	
07/21/2008	10		<10.0	<10.0	<10.0	<10.0	<0.10	<0.05	<0.05		<0.10	<0.005	<0.005	<0.50	
08/04/2008	10		<10.0	<10.0	<10.0	<10.0	<0.10	<0.05	<0.05		<0.10	<0.005	<0.005	<0.50	
08/18/2008	10		<10.0	<10.0	<10.0	<10.0	<0.10	<0.05	<0.05		<0.10	<0.005	<0.005	<0.50	
09/02/2008	10		<10.0	<10.0	<10.0	<10.0	<0.10	<0.05	<0.05		<0.10	<0.005	<0.005	<0.50	
09/22/2008	10		<10.0	<10.0	<10.0	<10.0	<0.10	<0.05	<0.05		<0.10	<0.005	<0.005	<0.50	
10/16/2008	10			<10.0			<0.10			<0.05	<0.10	<0.005	<0.005	<0.50	<0.50
12/08/2008	10			<10.0			<0.10			<0.05	<0.10	<0.005	<0.005	<0.50	

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

Date	Chlorophyll-a			Paired	
	site 1 a	Site 1 b	Site 9	avg	SD
4/22/08	5.11	4.44	4.09	*4.55*	*0.52*
5/12/08	5.73	*	5.74	*5.74*	*0.01*
5/21/08	11.1	20.1	15.8	*15.67*	*4.50*
6/4/08	14.9	19.7	10.4	*15.00*	*4.65*
6/18/08	16.2	13.3	10.1	*13.20*	*3.05*
7/9/08	21.9	28.9	25.6	*25.47*	*3.50*
7/21/08	20.2	33.5	31	*28.23*	*7.07*
8/4/08	30.7	30.5	31.8	*31.00*	*0.70*
8/18/08	6.76	40.8	39.1	28.89	19.18
9/2/08	52.3	50.4	47.8	*50.17*	*2.26*
9/22/08	34.9	35.6	45.2	*38.57*	*5.76*
10/16/08	19.8	20.7	20.6	*20.37*	*0.49*
12/08/08	6.63	*	5.58	*6.11*	*0.74*
				avg SD	**4.03**
				min	0.01
				max	19.18

Date	Pheophytin-a			Paired	
	Site 1 a	Site 1 b	Site 9	avg	SD
4/22/08	0.16	1.78	0.62	0.85	0.83
5/12/08	1.38	*	2.23	1.81	0.60
5/21/08	20.8	4.28	3.85	9.64	9.66
6/4/08	9.22	4.98	13	9.07	4.01
6/18/08	0.14	4.41	1.91	2.15	2.15
7/9/08	1.45	3.62	7.96	4.34	3.31
7/21/08	24.3	4.39	4.06	10.92	11.59
8/4/08	0.58	0.83	0.43	0.61	0.20
8/18/08	50.7	<0.1	<0.1	16.93	29.24
9/2/08	1.44	2.09	2.05	1.86	0.36
9/22/08	6.36	5.11	6.97	6.15	0.95
10/16/08	3.18	2.92	2.99	3.03	0.13
12/08/08	0.785	*	1.32	1.05	0.38
				avg SD	**4.88**
				min	0.13
				max	29.24

Laboratory Results of Duplicate Samples for COMCD Lake Thunderbird Water Quality Sampling April 22, 2008 – December 8, 2008

NOTE: less than symbol represents below detection limit report

Date	Site	Secchi	Turbidity	True Color	Alkalinity	Susp. Solids	Chloride	Sulfate	Ammonia as N	Nitrite as N	Nitrate as N	Nitrite-Nitrate as N	Kjeldahl Nitrogen as N	Ortho-P as P	Total P as P	Total Organic Carbon	Dissolved Organic Carbon	Chlorophyll-a	Pheophytin-a
04/22/2008	9	68	16		163	<10.0	18.2	18.4	<.10	<.05	0.22		0.57	0.022	0.032	5.41		4.09	0.62
05/12/2008	9	62	8	34	163	<10.0	18.1	13.5	<0.10	<0.05	0.24		0.56	0.011	0.029	5.22		5.74	2.23
05/21/2008	9	75	11	25	174	<10.0	18.3	14.9	<0.10	<0.05	0.12		0.56	0.006	0.029	5.23	4.93	15.8	3.85
06/04/2008	9	90	9	16	175	<10.0	18.4	12.8	<0.10	<0.05	<0.05		0.54	<0.005	0.026	5.34		10.4	13
06/18/2008	9	74	10		171	<10.0	17.6	14.8	<0.10	<0.05	<0.05		0.53	0.006	0.031	5.53		10.1	1.91
07/09/2008	9	84	6		165	<10.0	18.1	14	<0.10	<0.05	<0.05		0.71	0.008	0.033	5.74	5.58	25.6	7.96
07/21/2008	9	75	7		158	12	18.5	13.3	<0.10	<0.05	<0.05		0.75	0.01	0.028	6.15		31	4.06
08/04/2008	9	58	6		151	<10.0	19	13.5	<0.10	<0.05	<0.05		0.8	0.009	0.026	6.73		31.8	0.43
08/18/2008	9		6		159	<10.0	17.4	11	<0.10	<0.05	<0.05		0.72	0.009	0.03	5.86	5.23	39.1	<0.10
09/02/2008	9	51	6		151	<10.0	17.4	11.8	<0.10	<0.05	<0.05		0.87	0.012	0.041	5.92		47.8	2.05
09/22/2008	9	70	5		150	<10.0	18	11	<0.10	<0.05	0.09		0.75	0.008	0.035	5.87		45.2	6.97
10/16/2008	9	61	14			13			<0.10			0.27	0.65	0.022	0.04	5.34	5.1	20.6	2.99
12/08/2008	9	73	15			13			<0.10			0.35	0.53	0.028	0.02	5.31		5.58	1.32
04/22/2008	1	68	16	56	162	<10.0	18.4	18.3	<.10	<.05	0.23		0.56	0.021	0.029	5.35		5.11	0.16
05/12/2008	1	62	11	31	164	<10.0	18.1	13.8	<0.10	<0.05	0.25		0.5	0.01	0.028	5.09		5.73	1.38
05/21/2008	1	75	9	23	170	<10	18.6	15	<0.10	<0.05	0.12		0.63	0.006	0.031	5.13	4.98	11.1	20.8
06/04/2008	1	90	11	18	170	<10	18.4	12.9	<0.1	<0.05	<0.05		0.56	<0.005	0.025	5.47		14.9	9.22
06/18/2008	1	74	10	27	171	<10	17.7	13.8	<0.1	<0.05	<0.05		0.54	0.005	0.03	5.47		16.2	0.14
07/09/2008	1	84	9	12	166	<10	17.4	14.8	<0.1	<0.05	<0.05		0.73	0.007	0.032	5.9	5.52	21.9	1.45
07/21/2008	1	75	7	12	157	13	18	13.7	<0.1	<0.05	<0.05		0.79	0.01	0.03	6.69		20.2	24.3
08/04/2008	1	58	6	9	151	<10	19.3	12.7	<0.1	<0.05	<0.05		0.82	0.008	0.025	6.69		30.7	0.58
08/18/2008	1	74	6	11	157	<10	17.7	11.2	<0.1	<0.05	<0.05		0.79	0.01	0.025	5.72	5.29	6.76	50.7
09/02/2008	1	51	6	23	152	<10	17.2	11.6	<0.1	<0.05	<0.05		0.89	0.013	0.041	5.89		52.3	1.44
09/22/2008	1	70	6	7	152	<10.0	17.8	10.5	<0.10	<0.05	0.08		0.74	0.008	0.036	5.93		34.9	6.36
10/16/2008	1	61	17	20	153	15	17.7	12.0	<0.10			0.28	0.67	0.023	0.041	5.35	5.09	19.8	3.18
12/08/2008	1	73	15	31	160	<10	18.3	13.8	<0.10			0.36	0.55	0.027	0.023	5.61		6.63	0.79