Oklahoma Water Resources Board

Lake Thunderbird Water Quality 2007

for the

Central Oklahoma Master Conservancy District

September 2008

Final Report

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

Executive Summary

2007 marked the wettest year on record for Central Oklahoma. Large rainfall amounts and temperatures lower than in previous years ended drought conditions for Lake Thunderbird. High amounts of precipitation contributed to larger inflows and an annual hydraulic residence time of 0.90 years, significantly lower than in all previous years the lake has been sampled. The onset of water column stratification began in May, with the establishment of an anoxic hypolimnion occurring by the end of this month. After the summer stratification period, mixing of the water column had been completed by mid-October.

Lake Thunderbird continues to be a eutrophic system, demonstrating potential for high levels of algal biomass in 2007. High inflows contributed to significant amounts of nutrients into the lake. 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 forms by algal uptake. Nutrients (nitrogen and phosphorus) were in the range of co-limitation to nitrogen limitation of algal growth. Chlorophyll-*a* concentrations, which are used as an indicator of algal biomass, were similar to those of previous years, while taste and odor complaints to the City of Norman slightly increased. Oxidation-reduction potentials remained low during the summer growing season, providing conditions that allow for the solubilization of metals and sediment-bound phosphorus.

The 2007 monitoring data supports the 303 (d) integrated listing of Lake Thunderbird as impaired due to excessive turbidity and low dissolved oxygen. The Oklahoma Department of Environmental Quality Water Quality Division (ODEQ) currently has Lake Thunderbird prioritized for the completion of a TMDL. 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). The Standards (OAC 785:45-5-10 (7)) require SWS lakes to meet a long-term average concentration water quality standard of 10µg/L chlorophyll-*a* at a depth of 0.5 meters below the surface. This requirement was not met in 2007.

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 by mitigating low dissolved oxygen and decreasing chlorophyll-*a* concentrations 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 and chlorophyll-*a*)
- Extending water quality monitoring to year round in-lake and also into the watershed
- Evaluative processes to include estimating watershed nutrient loads and place in context of in-lake loads using predictive modeling

Table of Contents

List of Figures

List of Tables

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) had provided water quality monitoring and evaluation services to the COMCD since 2000. The objective in 2007 was to continue routine environmental monitoring of Lake Thunderbird for the COMCD.

Lake Thunderbird was listed as Category 5 (303d list) in the State's 2006 Integrated Report as impaired 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). Because of these impairments, Lake Thunderbird will undergo a Total Maximum Daily Load (TMDL) analysis by the Oklahoma Department of Environmental Quality (ODEQ) in 2008-2009. 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 2007, 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 3, respectively. 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 Hydrolab parameters measured include oxidation-reduction potential, dissolved oxygen saturation and concentration, temperature, specific conductance, and pH. In addition, samples were collected for laboratory analysis of alkalinity, chloride, sulfate, total suspended solids, total organic carbon, and phosphorus and nitrogen series. Chlorophyll-*a* and turbidity samples were also collected, along with Secchi disk depth.

Table 1. 2007 water quality sampling dates and parameters measured.

	4/10	4/25	5/10	5/30	6/14	6/25	7/10	7/25	8/9	8/23	9/6	9/20	10/22
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	X
Water Quality	X	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	X
TOC	X	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	X
Nutrients	X	X	X	X	X	X	X	X	X	X	X	X	X

Hydrolab parameters, 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.

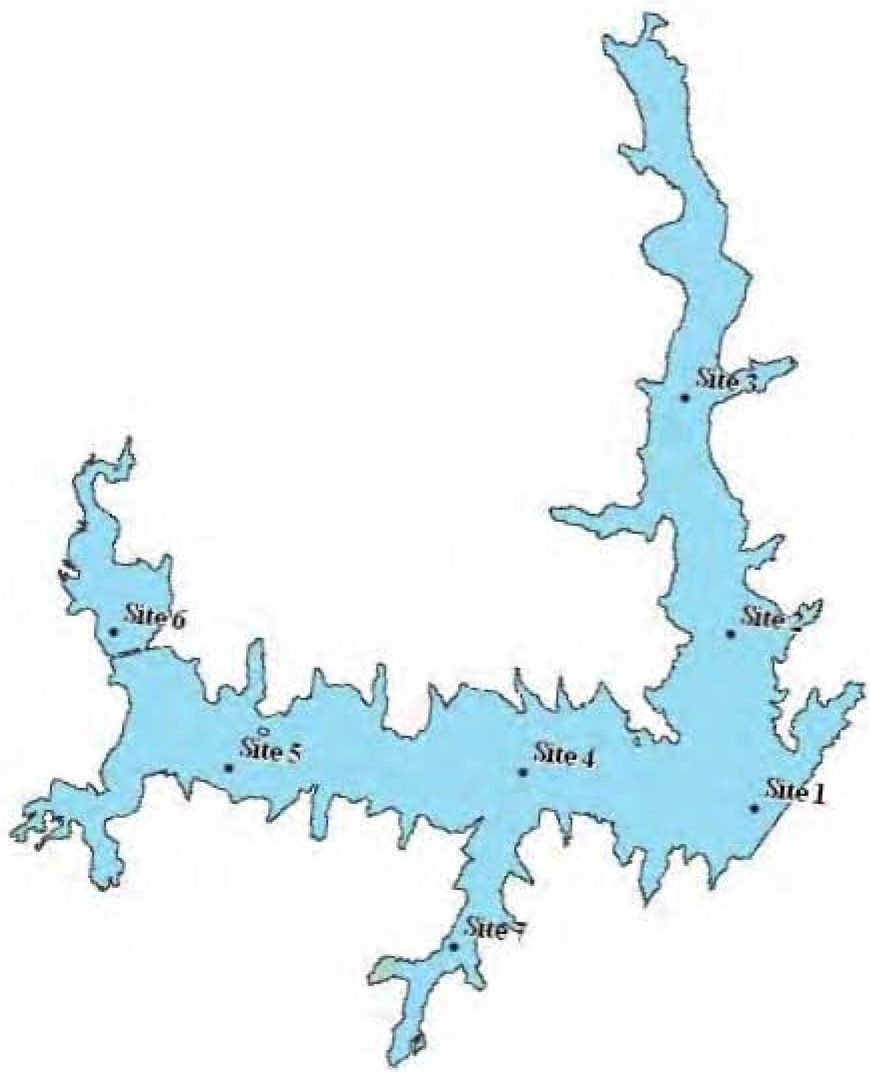

Figure 1. Lake Thunderbird 2007 sampling sites

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 2007. Lake elevations and inflows can vary

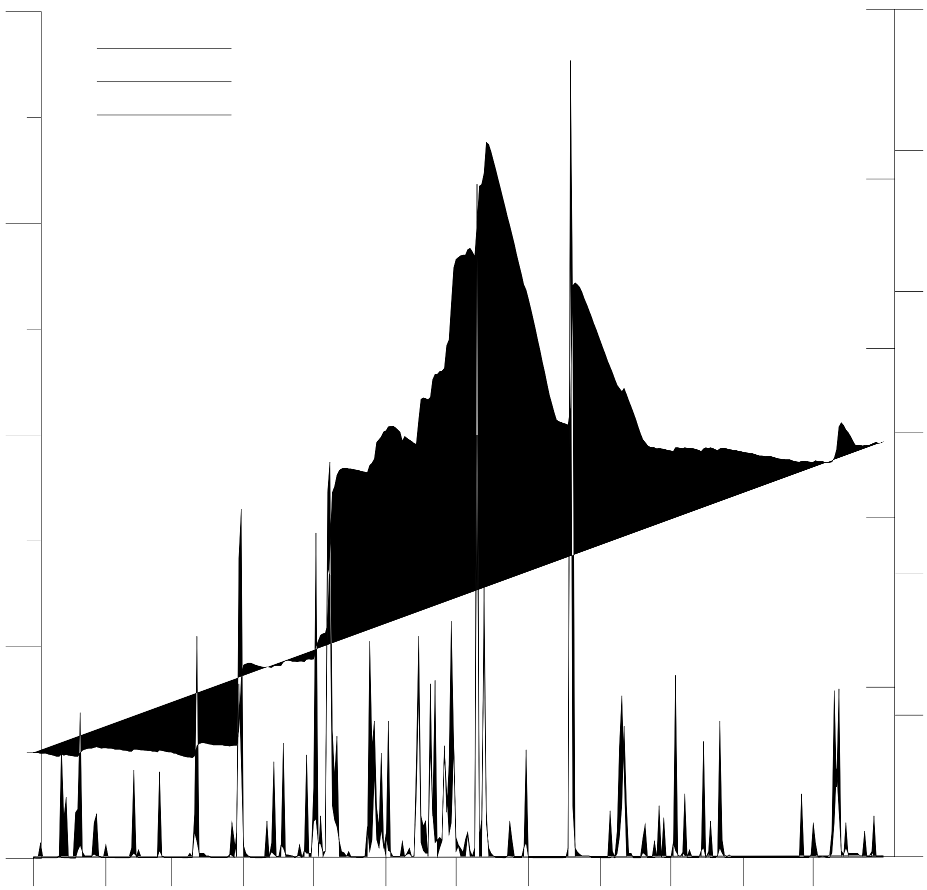

Figure 2. 2007 Inflow, precipitation, and elevation data for Lake Thunderbird, with sample dates indicated.

considerably with rainfall patterns. For example, elevations in 2007 went from approaching the lowest levels on record (around 1030.8 feet) to the second highest elevation on record (1048.23). Calendar year 2007 marked central Oklahoma as the wettest year on record, with an average annual rainfall of 52.3 inches (**Table 2**) (OCS, 2007). All seasons in 2007 experienced above average rainfall amounts with the exception of fall, with only 63% of normal rainfall. In previous years of sampling on Lake Thunderbird, rainfall amounts have been below normal to normal.

Table 2. Rainfall amounts in inches and percent of normal rainfall amounts in Central Oklahoma, and yearly rainfall totals from the Norman mesonet station(OCS 2007a and 2007b).

	2001		2002		2003		2004		2005		2006		2007	
	Total	**%**	**Total**	**%**	**Total**	**%**	**Total**	**%**	**Total**	**%**	**Total**	**%**	**Total**	**%**
Winter	7.57	145	4.65	89	4.00	76	5.07	97	5.48	105	1.30	23	5.83	112
Spring	9.74	79	9.61	78	7.68	62	7.93	61	4.01	32	9.37	79	17.3	144
Summer	5.80	59	10.0	103	10.6	108	14.1	144	15.3	156	6.89	71	23.7	244
Fall	8.28	78	9.36	88	6.41	61	11.7	110	3.69	35	7.23	67	6.56	63
Annual Total	31.4	83	35.1	92	27.1	71	38.4	101	28.5	75	22.0	60	52.3	140
Norman Total	28.7	76	29.4	77	27.5	72	36.0	94	22.7	60	22.4	56	56.1	148

In addition to hydrology, air temperature can also influence lake characteristics such as stratification patterns and primary productivity. 2007 average daily temperature values are illustrated in **Figure 3**. Temperatures were lower than those observed in previous years (OWRB 2008).

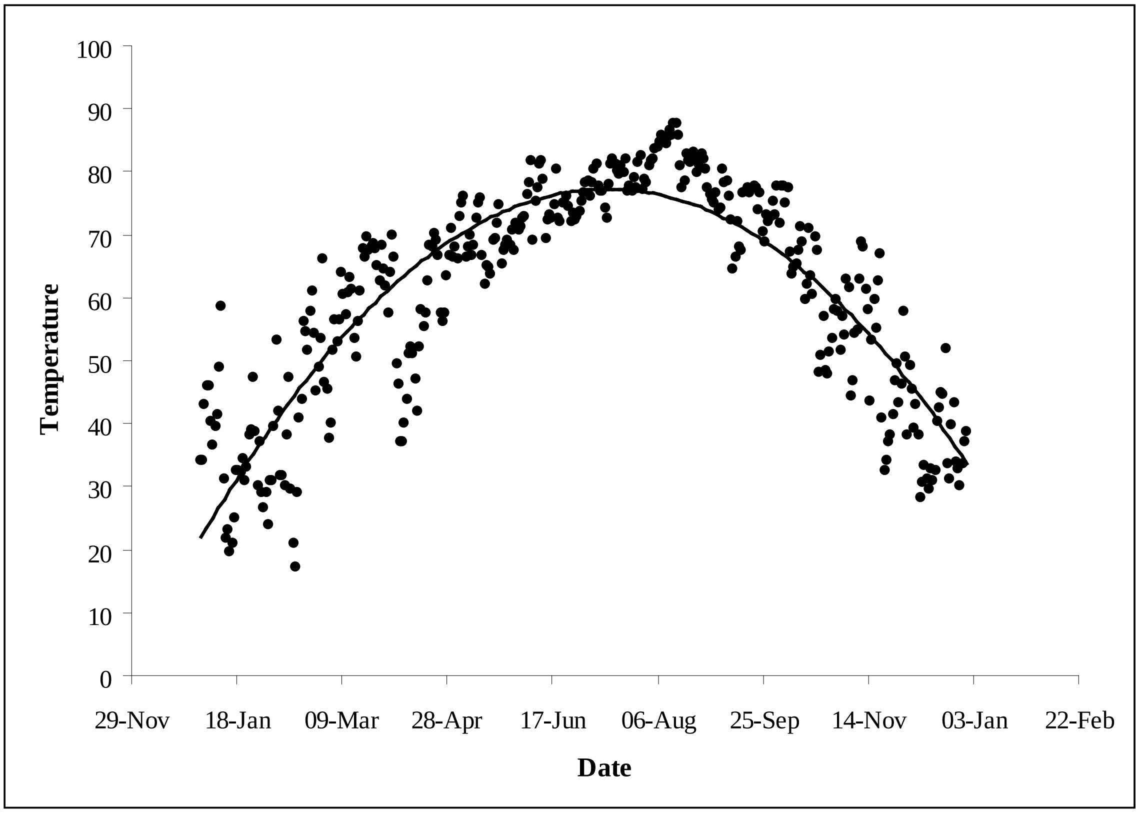

Figure 3. Average 2007 temperature values at the Norman mesonet station.

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 water body such as a lake is given by:

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

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 in equation 2.

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

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. 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.

$Q_E = E_v * A_s$

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

A summary of the water budget calculations on a monthly basis for Lake Thunderbird, using inflows generated by the USACE, is presented in **Table 3**. 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 of **Table 3**. 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.

Most notable in 2007 was the large variation in lake capacity. The lake fluctuated from a low of approximately 67,623 acre-feet to a high of approximately 153,327 acre-feet. Just this recharge to Lake Thunderbird, over 85,000 acre-feet, represents the more than cumulative capacity of the conservation pool.

Table 3. Lake Thunderbird water budget calculations

	INPUTS			OUTPUTS				RESULTS		
Month	Inflow	Rainfall	**Total Inputs**	Evaporation	Water Supply	Releases	**Total Outputs**	I-O	ΔV	Error
Jan	2380	1041	3421	593	1329	0	1922	1499	520.23	-979
Feb	1577	388	1965	1151	1181	0	2332	-367	-474.09	-107
Mar	14588	1953	16541	1783	1375	0	3158	13383	8598.26	-4785
Apr	4274	803	5077	2268	1392	0	3660	1417	722.858	-694
May	40294	5425	45719	3283	1485	0	4768	40951	31798.8	-9152
Jun	43736	3844	47580	3873	1469	5756	11098	36482	23718.8	-12763
Jul	34383	3934	38317	5141	1631	35772	42544	-4227	-4424.8	-198
Aug	29534	3976	33510	5477	1795	32210	39482	-5972	-5402.3	570
Sep	11514	1665	13179	11770	1726	21086	34582	-21403	-15795	5608
Oct	3858	1519	5377	3022	1657	0	4679	698	-102.9	-801
Nov	1190	169	1359	1955	1432	0	3387	-2028	-1440.6	587
Dec	10413	1579	11992	1159	1241	4818	7218	4774	2984.15	-1790
Total	197741	26296	224037	41475	17713	99642	158830	65207	40703	-24504

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 0.90 years for 2007 and an annual average hydrologic residence time of 4.72 years since 2001 (including 2007 data). The shorter 2007 residence time reflects the increased inflows due to high rainfall amounts. Had the lake started the year at conservation pool, the residence time would have been even shorter. This is further evidenced when comparing the total inputs (224,037 acre-feet) verses total outputs (158,830 acre-feet) representing an increased annual pool and potential replacement of stored water. Only in February, July, August, September, and November were inputs predicted to be slightly less than outputs (decreasing pool months) (**Figure 4**).

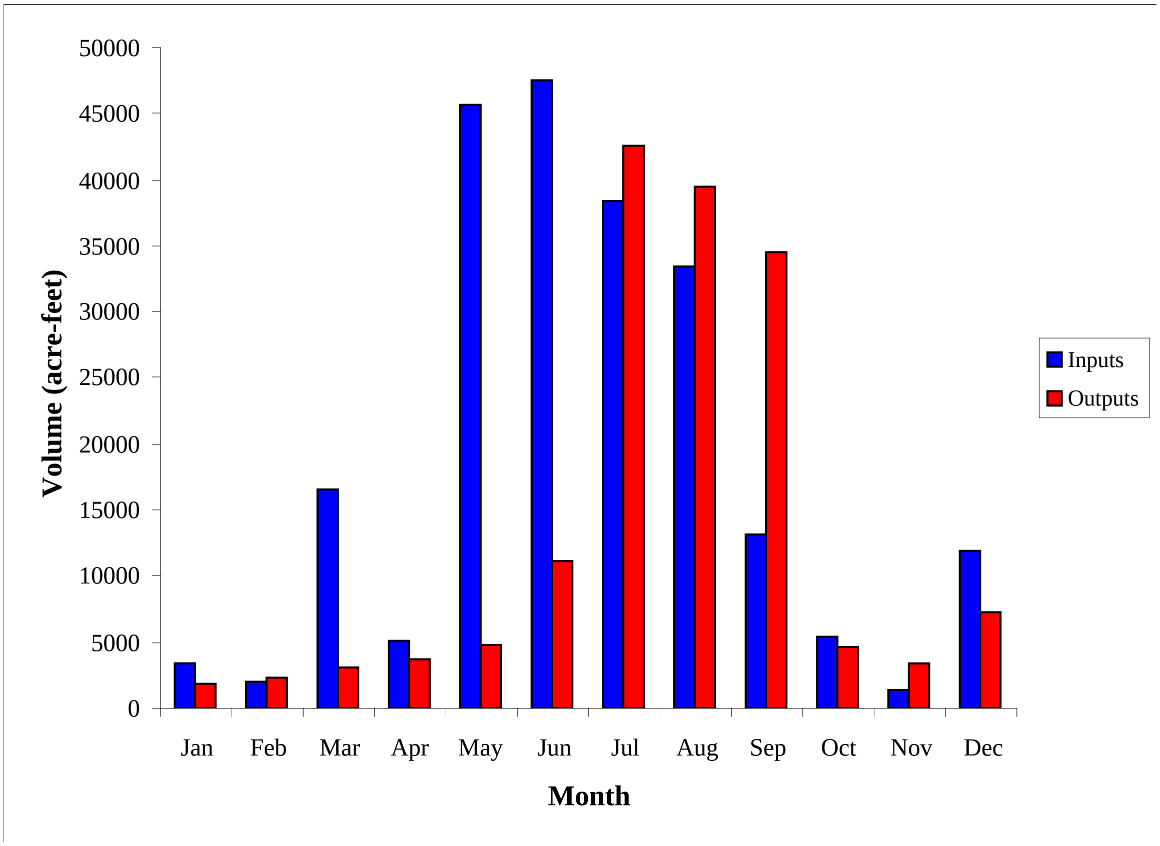

Figure 4. 2007 Lake Thunderbird inflows and outflows by month.

For the period of calendar year 2007, 88% of the inputs into Lake Thunderbird were from inflows, while the majority of outputs were from gated dam releases (**Figure 5**). This differs from previous drought years, where the proportion of inflow comprised less of the total input and evaporation was the source of the majority of outputs (OWRB, 2008).

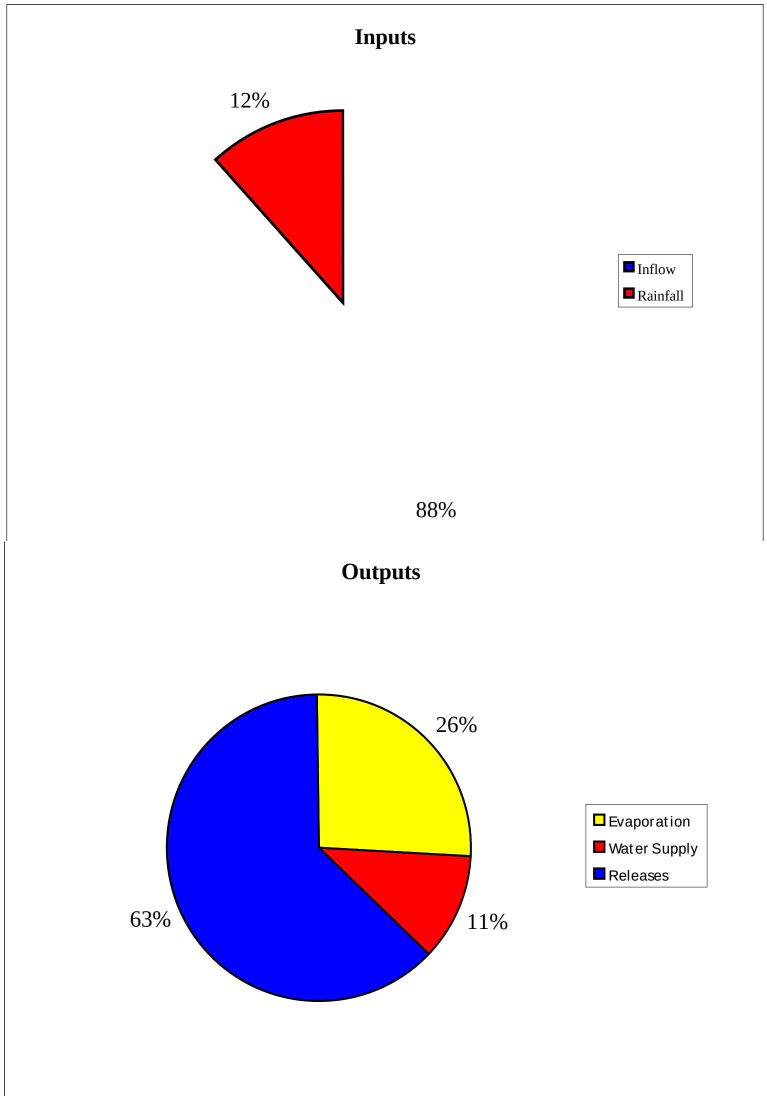

Figure 5. 2007 Lake Thunderbird input and output sources expressed as the percent of totals.

Sources of error

Although robust, the hydrologic budget does contain error. For example, 9 of the 12 months show a negative (underestimate) for the monthly budget with an annual averaged error of –2042 acre-feet per month. Ideally, error would be evenly distributed (as many underestimates as overestimates). Although seemingly significant, the average monthly magnitude of error was 1.9% of the lake’s normal pool capacity. This suggests the error is nominal and heightened by the high flow conditions. This is further demonstrated by the highest month of error, June, being associated with the month of highest lake inputs. Based on the simplifying assumptions made in calculating some of the parameters, the following potential sources of error have been identified.

- Evaporation rates used in the calculation of water losses due to evaporation were calculated rather than measured. Piping of pore water and subsequent evaporation from the exposed lake bottom were not considered in 2007 (potentially yielding a lower than actual evaporation rate)

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

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

- 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 change the calculation of inflows.

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 of water at depth intervals 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 the decomposition processes occurring in the hypolimnion and not recharged.

Figure 6. Temperature and dissolved oxygen vertical profile for Lake Thunderbird at its period of greatest thermal stratification in 2007 (August 9), with labeled regions.

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 can have implications for epilimnetic water quality.

At the beginning of 2007 sampling, conditions were relatively isothermal at site 1, with fairly constant dissolved oxygen (DO) levels throughout the water column (**Figure 7**). By May 10, thermal stratification was developing and DO concentrations were decreasing at a steady rate with depth. Strong stratification had set in by May 30, with an isothermal epilimnetic layer present from the surface to 10 meter depth (**Figure 7**). August 9 was the period of greatest stratification, with a distinct metalimnion between 6 and 8 meters and a completely anoxic hypolimnion. After this date, epilimnetic temperatures began to decline and the depth of the metalimnion began to descend in September. By October 22 the lake had completely mixed and returned to isothermal conditions. Dissolved oxygen depletion in the hypolimnion closely followed the thermal stratification pattern, with surface values in the 6-8 mg/L range. Hypolimnetic anoxia persisted until isothermal conditions returned in October (Figure 8). Evidence of the progression of lake turnover is seen in the marked decrease in DO to below 6 mg/L in the upper water column on September 20. By October 22, DO levels had recovered to almost 7 mg/L.

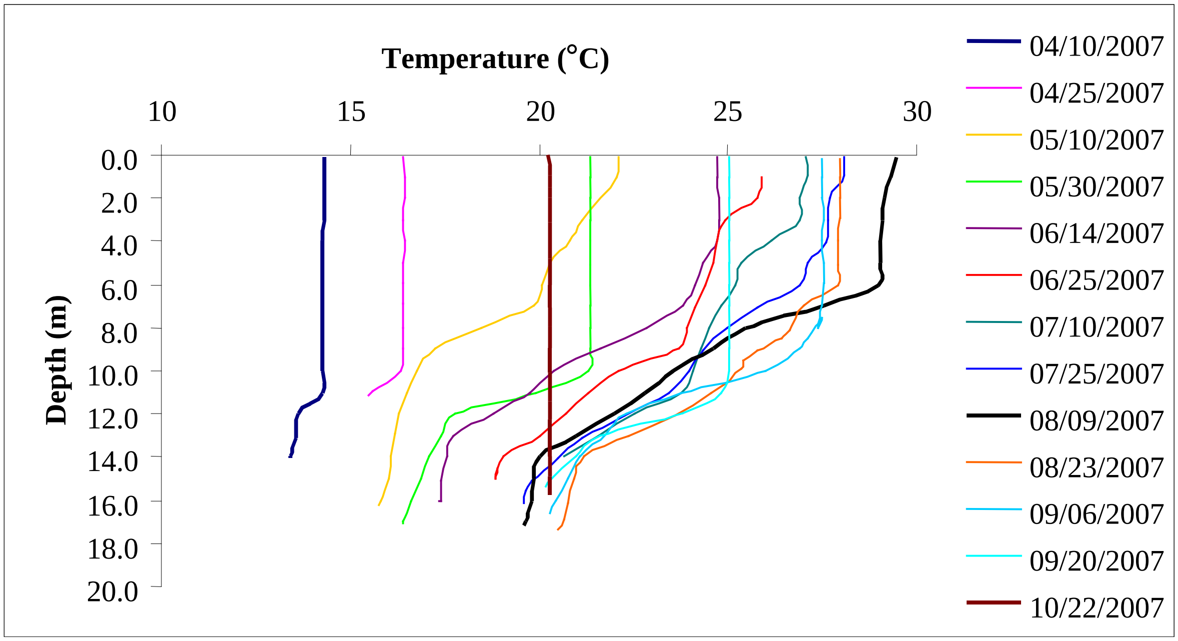

Figure 7. 2007 Lake Thunderbird site 1 depth profiles of temperature at every sampling event.

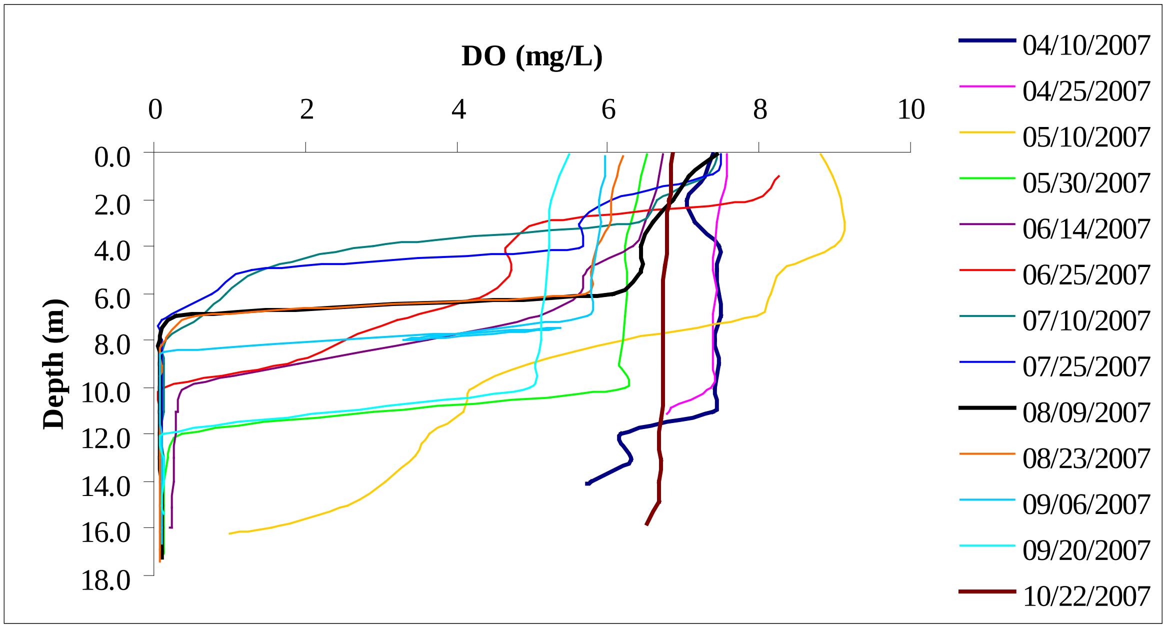

Figure 8. 2007 Lake Thunderbird site 1 depth profiles of dissolved oxygen at every sampling event.

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, in a summarized form, for sites 1 (**Figure 9**), 2 (**Figure 10**), and 4 (**Figure 11**). These sites represent the lacustrine zone of Lake Thunderbird, the deepest part of the lake. 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.

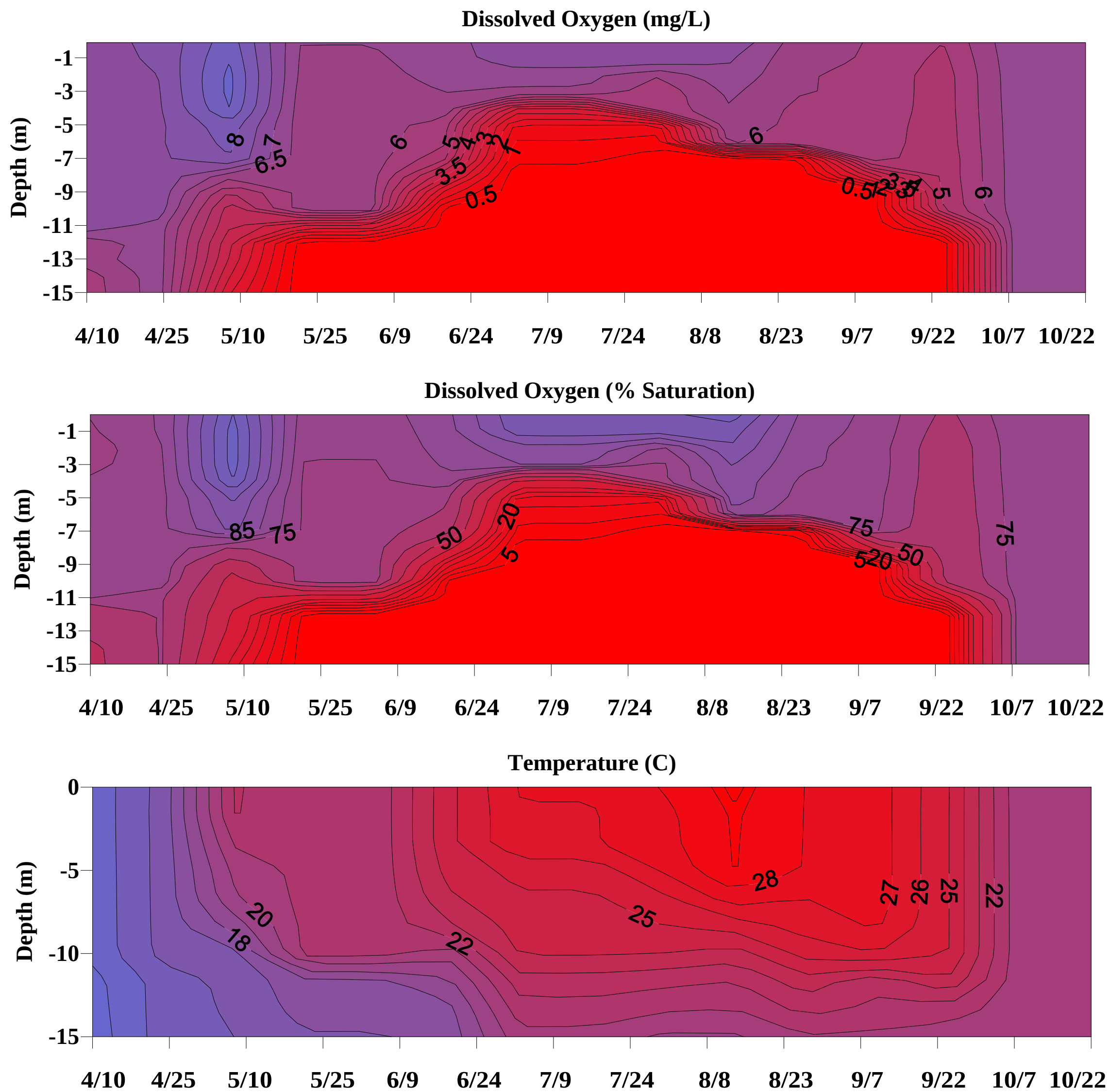

Figure 9. 2007 Lake Thunderbird dissolved oxygen concentration (mg/L), dissolved oxygen percent saturation (%DO), and temperature (°C) with depth at site 1, by date.

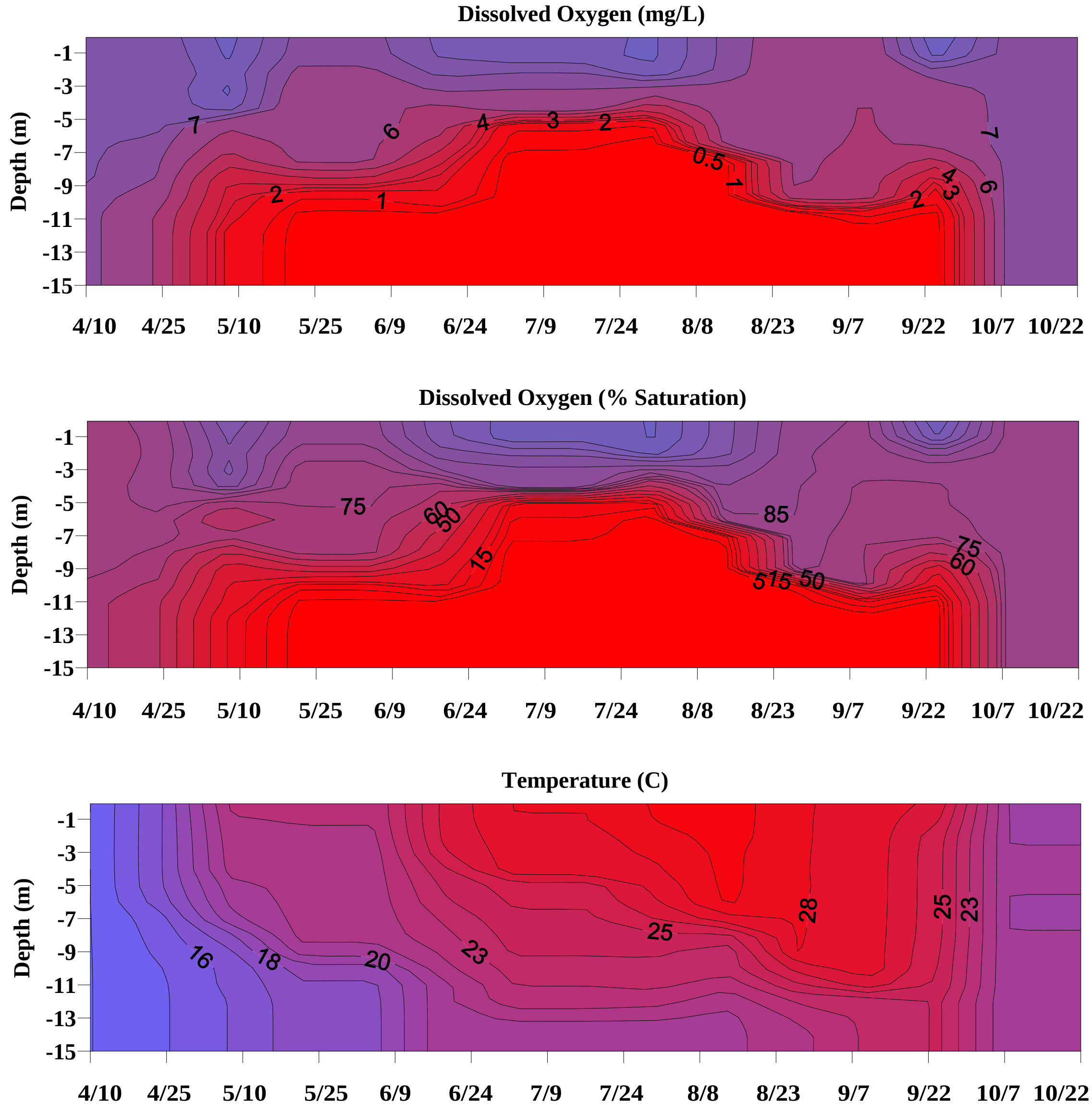

Figure 10. 2007 Lake Thunderbird dissolved oxygen concentration (mg/L), dissolved oxygen percent saturation (%DO), and temperature (°C) with depth at site 2, by date.

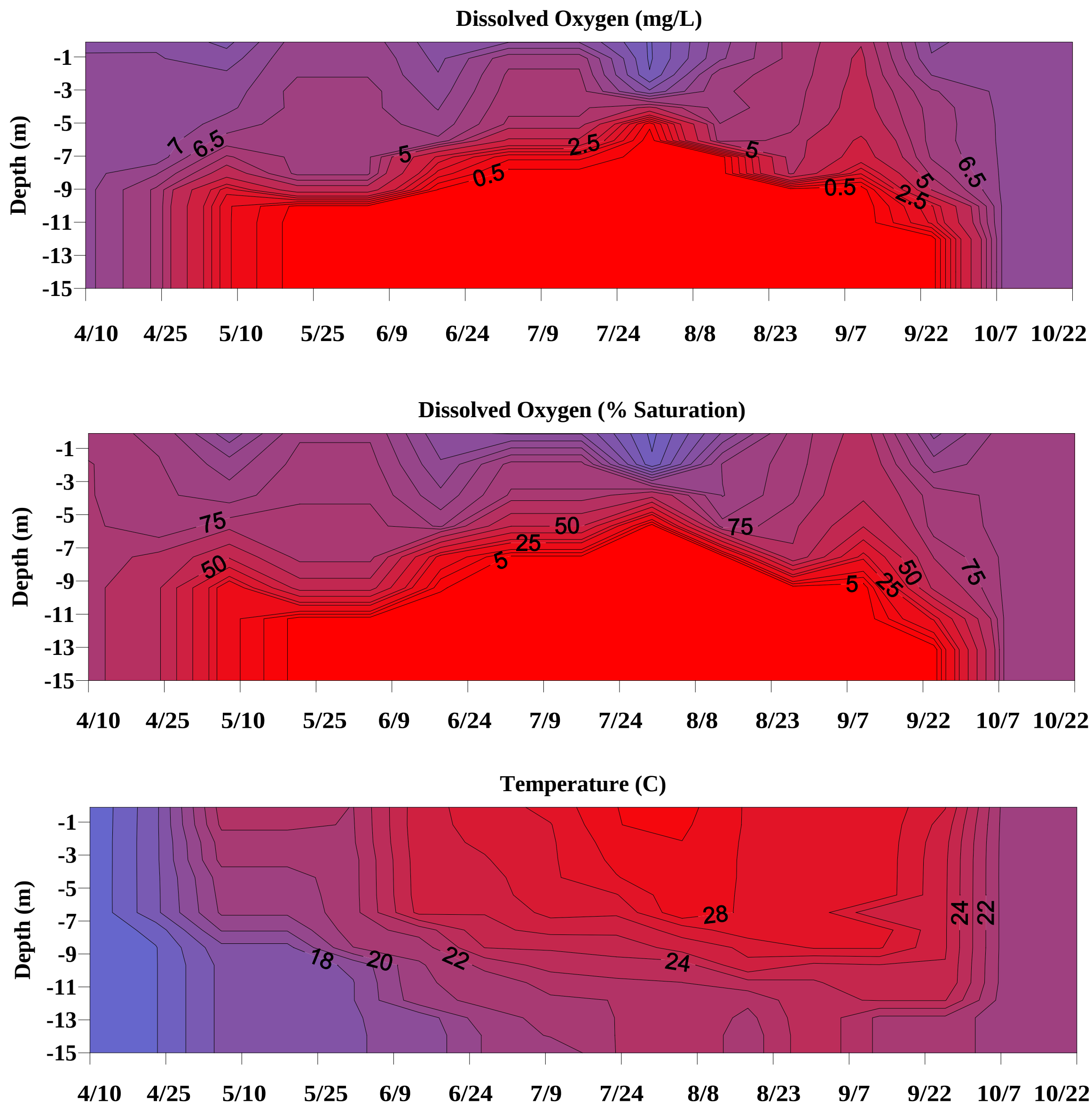

Figure 11. 2007 Lake Thunderbird dissolved oxygen concentration (mg/L), dissolved oxygen percent saturation (%DO), and temperature (°C) with depth at site 4, by date.

2007 stratification began to develop at the beginning of May, with strong stratification patterns observed by the end of May. Stratification peaked in mid-August, with mixing events occurring until complete lake turnover by late October. 2007 appears to have been a typical year with respect to stratification patterns. Anoxia in the hypolimnion, defined as less than 2 mg/L of dissolved oxygen, followed the thermal stratification pattern. 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. 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. 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.

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.

At site 1, anoxic (less than 2 mg/L of dissolved oxygen) conditions began at 5 meters below the water's surface and persisted to decrease with depth throughout the hypolimnion on the July 10 sample date. Although anoxia began developing in May, July 10 was the first date this site did not meet the water column beneficial use requirement of no more than 50% anoxic. This persisted for the following three sample dates of July 25, August 9, and August 23, until anoxia receded past 8.5 meters depth on September 6 and the lake was again meeting the dissolved oxygen criteria. Sites 2 and 4 experienced anoxia in greater than 50% of the water column on the July 10 and July 25 sample dates.

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 2007 average of 30 centimeters at site 6 to 76 centimeters at site 2. The lacustrine sites (1, 2, and 4) had the greatest Secchi depths, while the riverine or transition zone sites had the least clear water. As depicted in **Figure 12**, site 6 is the only site significantly different from sites 1, 2, and 4 in respect to Secchi depth transparency (ANOVA: $F=4.256$, $p<0.001$; site 6, Tukey HSD, sites 1, 2, and 4 $p<0.03$). 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.

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 2007, 29% of Lake Thunderbird samples exceeded the

25 NTU criteria. While all sites had at least one sample greater than 25 NTU, sites 5, 6, and 7 had the highest turbidity values (**Figure 13**). Site 6 was significantly different from all other sites with the exception of site 5, in regards to turbidity (ANOVA: F=5.045, $p<.001$). This data indicates that the Little River arm of Lake Thunderbird is more turbid than either Hog Creek or Clear Creek arms and is driving the turbidity impairment.

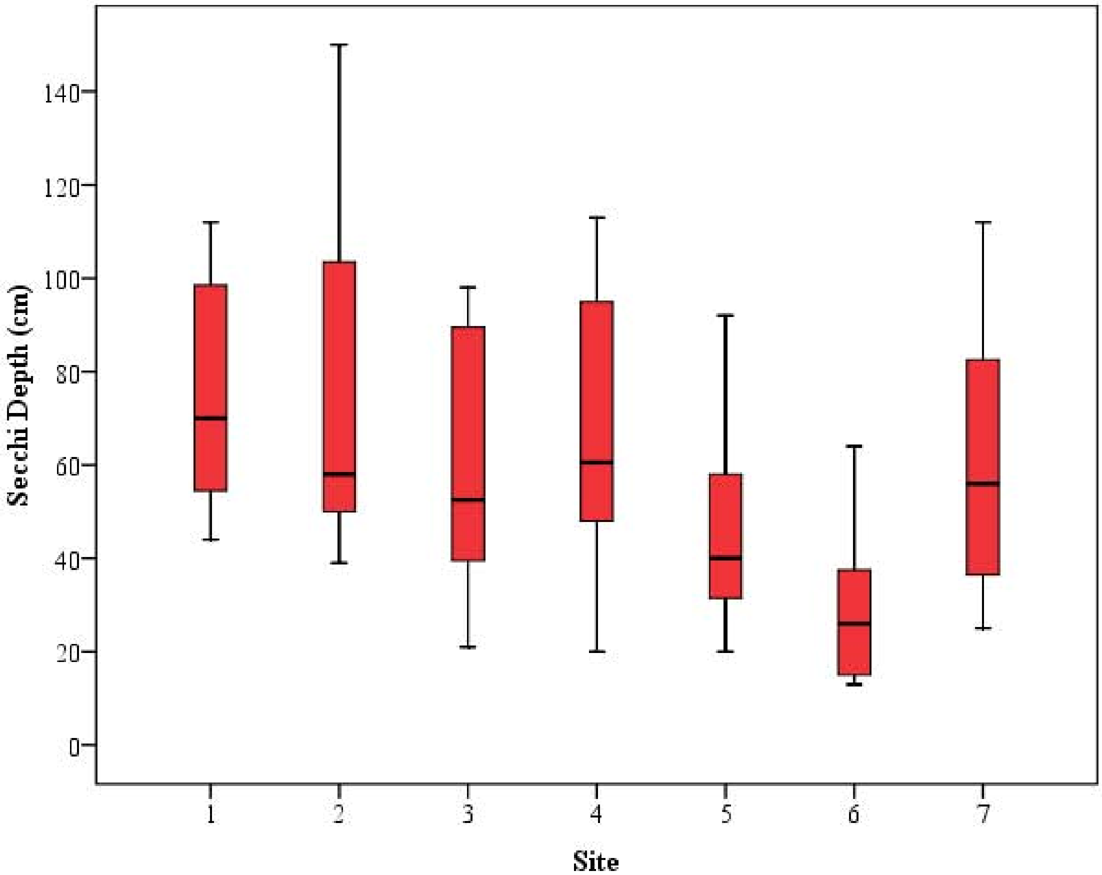

Figure 12. 2007 Lake Thunderbird Secchi disk depth, in centimeters, by site, where boxes represent 25% of the data distribution above and below the median (horizontal black line), and lines (or whiskers) represent the other 50% of the data distribution.

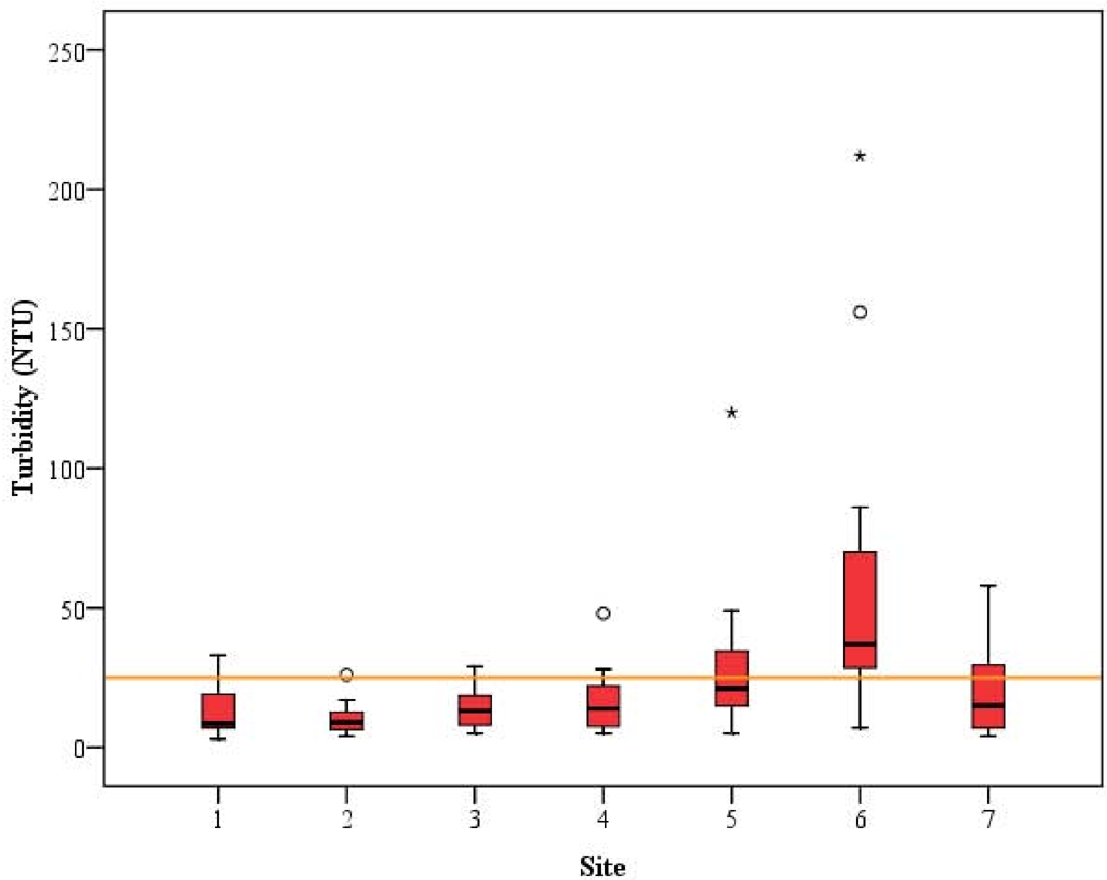

Figure 13. 2007 Lake Thunderbird turbidity, in NTU's, by site. The orange line along the x-axis represents the 25 NTU turbidity criteria. Symbols (* and o) represent outliers in the dataset.

Nutrients

Nutrient samples were collected thirteen times during the 2007 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* 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 blue-green algae (cyanobacteria). In the absence of adequate dissolved nitrogen, 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 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 blue-green algae. A recent study by Dzialowski *et al.* (2005) has broken the molecular ratio 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. In 2006 the lake fell within a co-limitation range of nitrogen and phosphorus. An average TN:TP concentration ratio of 24 at the surface of sites 1, 2, and 4 was observed in 2007 (**Figure 14**). Co-limitation of nutrients most likely occurred throughout the year, although nitrogen limitation is approached. High inflows and shorter residence times could be a reason for the lack of a common trend in nutrient ratios for the year.

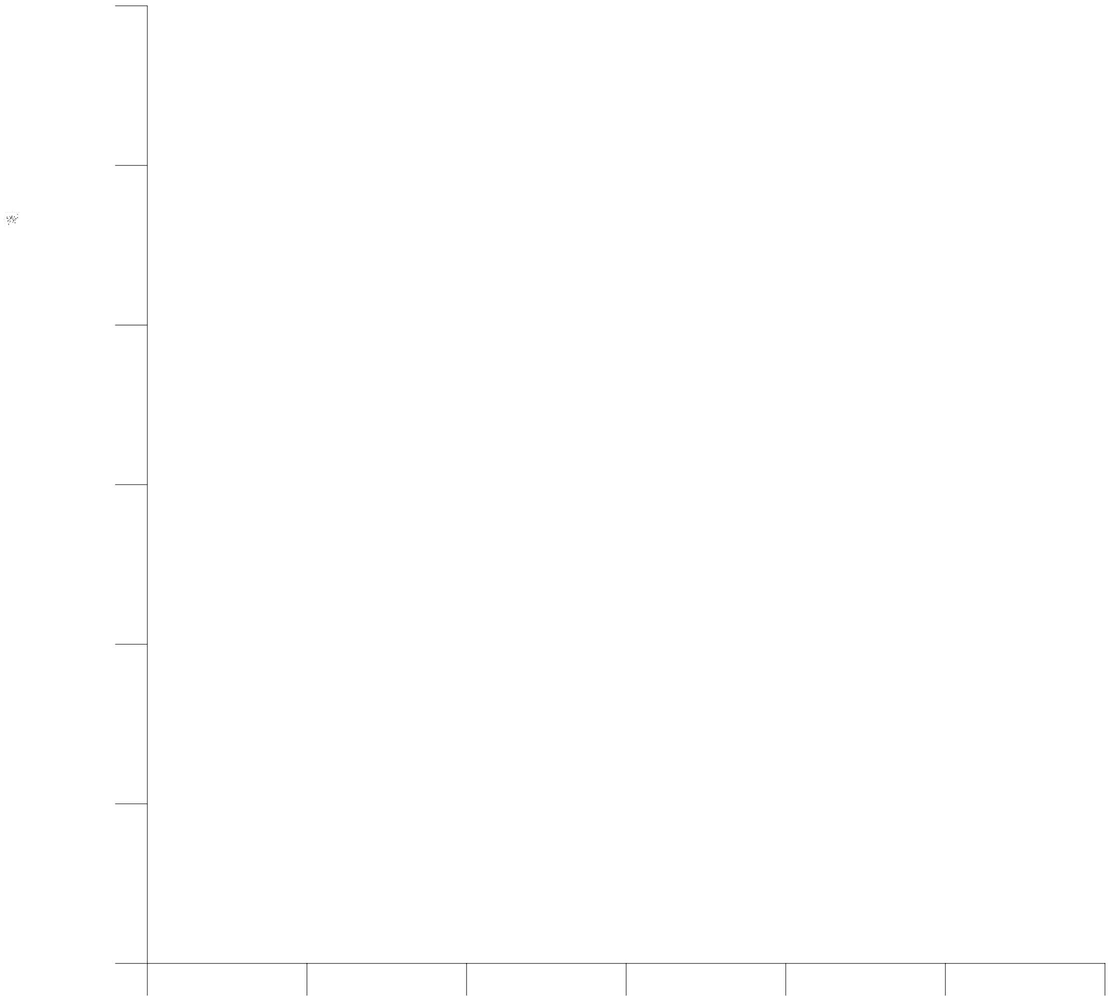

Figure 14. Total nitrogen to total phosphorus ratios at the surface of Lake Thunderbird during 2007.

Phosphorus

Total and ortho-phosphorus concentrations produced patterns typical of seasonal ecological cycles in lakes (**Figure 15**). While ortho-phosphorus comprised the majority of total phosphorus values in early spring 2007, these values sharply dropped at the surface of sites 1, 2, and 4 after the end of May (**Figure 16**). Ortho-phosphorus values fell below detection limits at the end of June and throughout July, indicating depletion by algal uptake. These dates also coincide with high Secchi disk depths, which could be a result of algal populations being depleted after a period of high growth, as their consumers increase in abundance, or from a period of significantly high inflow events.

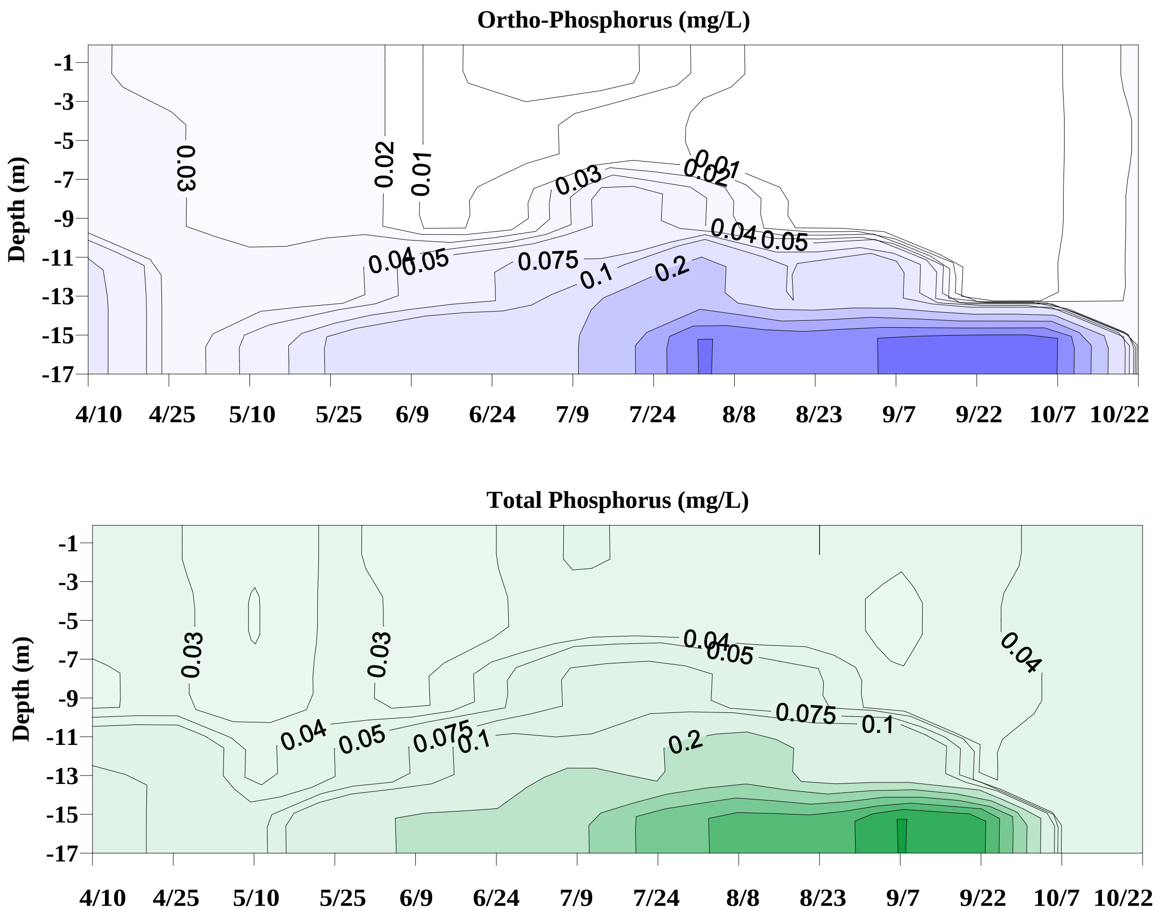

Figure 15. 2007 Lake Thunderbird ortho-phosphorus and total phosphorus contours with depth, by date, at site 1.

Site 1 at 4 meters below the water's surface generally follows the same epilimnetic pattern as at the surface (**Figure 16**). Site 1 at 8 meters below the surface is in the general region of the metalimnion. Beginning around the end of June, large spikes of total and ortho-phosphorus at this depth indicate a large influx. Possible causes are the collection of sinking detritus at the thermal gradient, interfow of stormwater and diffusion of nutrients from the lake sediment due to progression of anoxia (**Figure 17**).

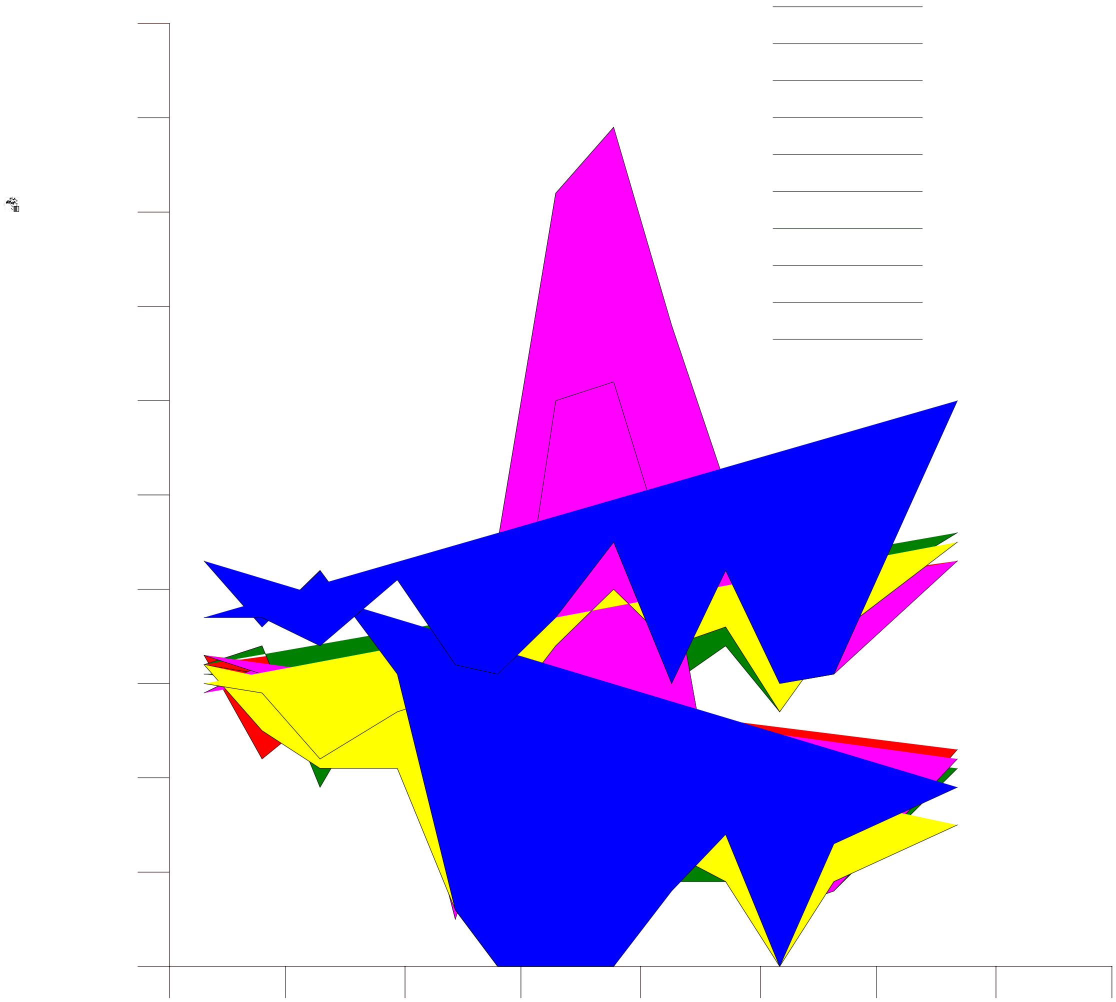

Figure 16. 2007 Lake Thunderbird total and otho-phosphorus (P) at the surface of sites 1 (1S), 2, and 4 and at 4 and 8 meters below the surface of site 1 (1-4m and 1-8m).

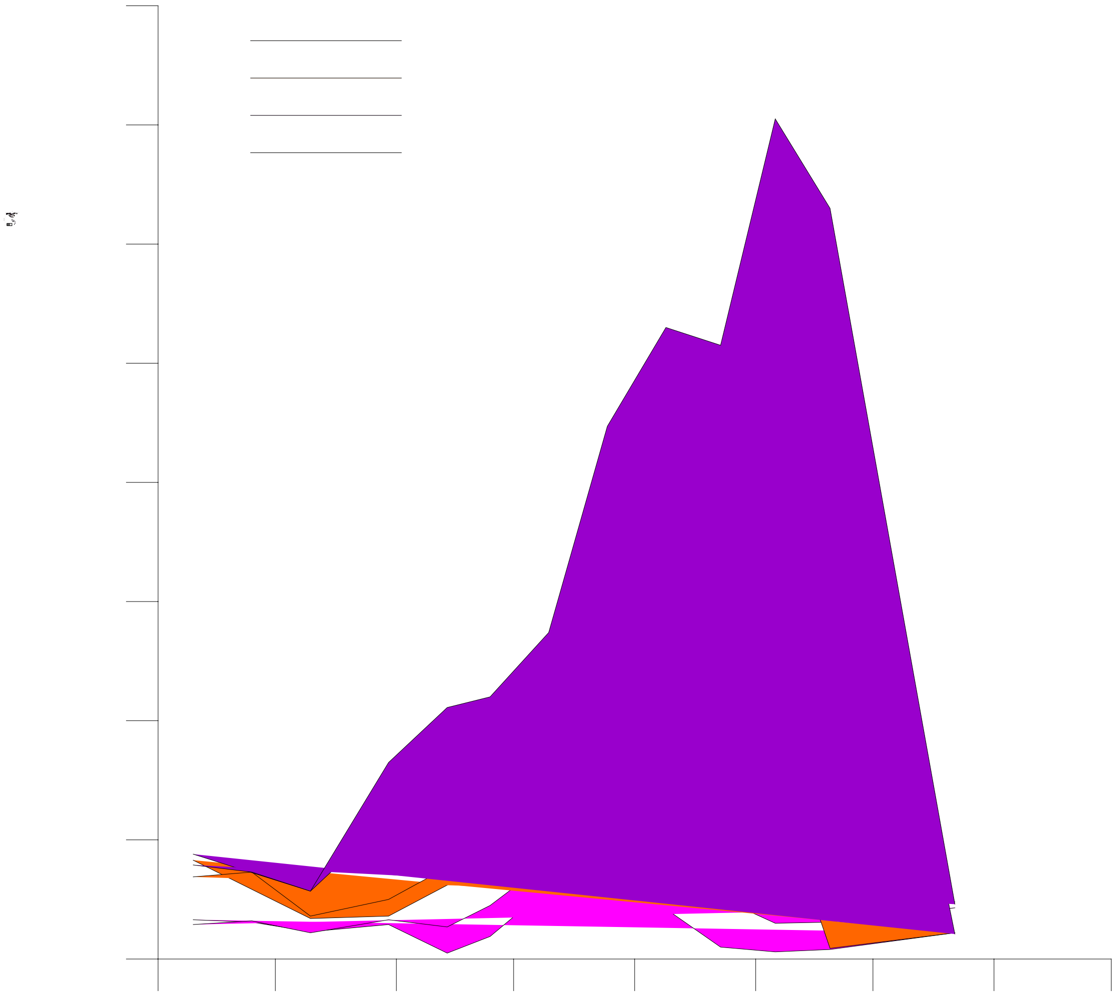

Figure 17. 2007 Lake Thunderbird total and otho-phosphorus (P) at the bottom (1B), 12 meters and 8 meters below the surface of site 1 (1-12m and 1-8m).

Nitrogen

Total and dissolved nitrogen concentrations also produced patterns typical of seasonal ecological cycles in lakes (**Figure 18**). Organic forms of nitrogen accounted for the majority of total nitrogen in 2007 (**Figure 19**). Dissolved nitrogen decreased to below detection limits in the epilimnion after the end of May, while total nitrogen concentrations increased (**Figure 19**). Epilimnetic dissolved forms of nitrogen fell below detection limits for most of the summer growing season, indicating depletion by algal uptake and nitrogen-limiting conditions. Large concentrations of hypolimnetic nitrogen from July until fall turnover suggest release and accumulation across the sediment due to the progression of anoxia, and accumulation of settling particulate organic matter (**Figure 20**, **Figure 21**). This conclusion is further supported by the presence of ammonia as the main constituent in bottom samples (**Figure 21**, **Figure 22**).

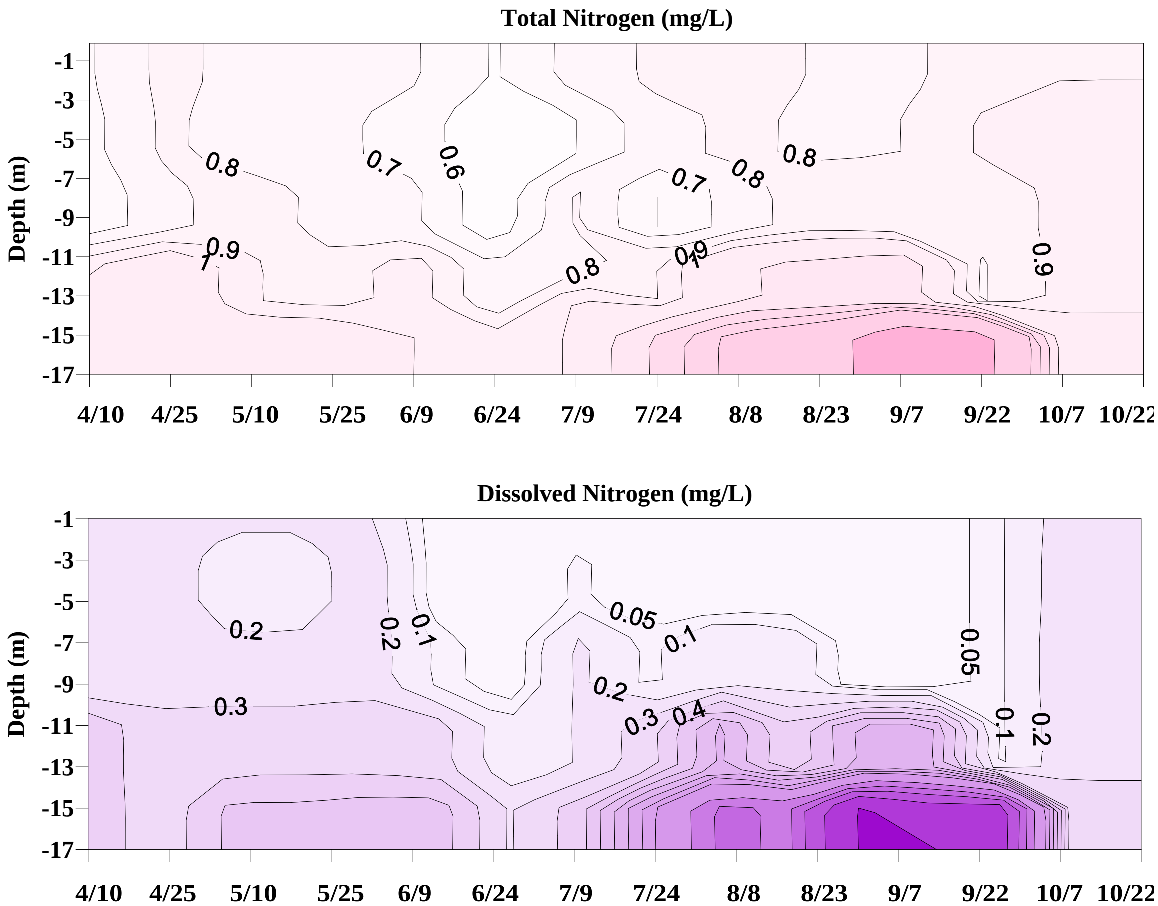

Figure 18. 2007 Lake Thunderbird total nitrogen and dissolved nitrogen contours with depth, by date, at site 1.

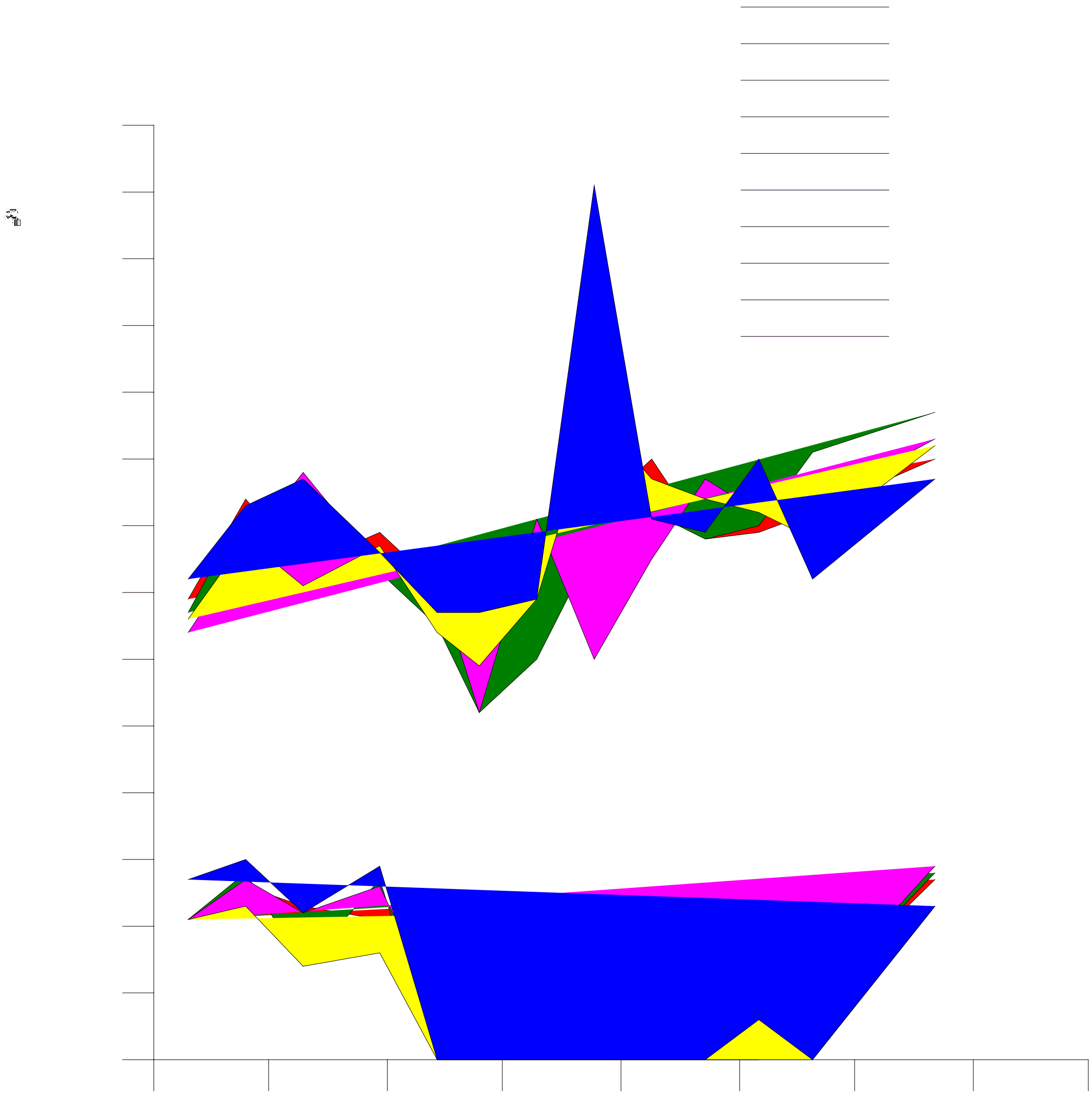

Figure 19. 2007 Lake Thunderbird total and dissolved nitrogen (N) at the surface of sites 1 (1S), 2, and 4 and at 4 and 8 meters below the surface of site 1 (1-4m and 1-8m).

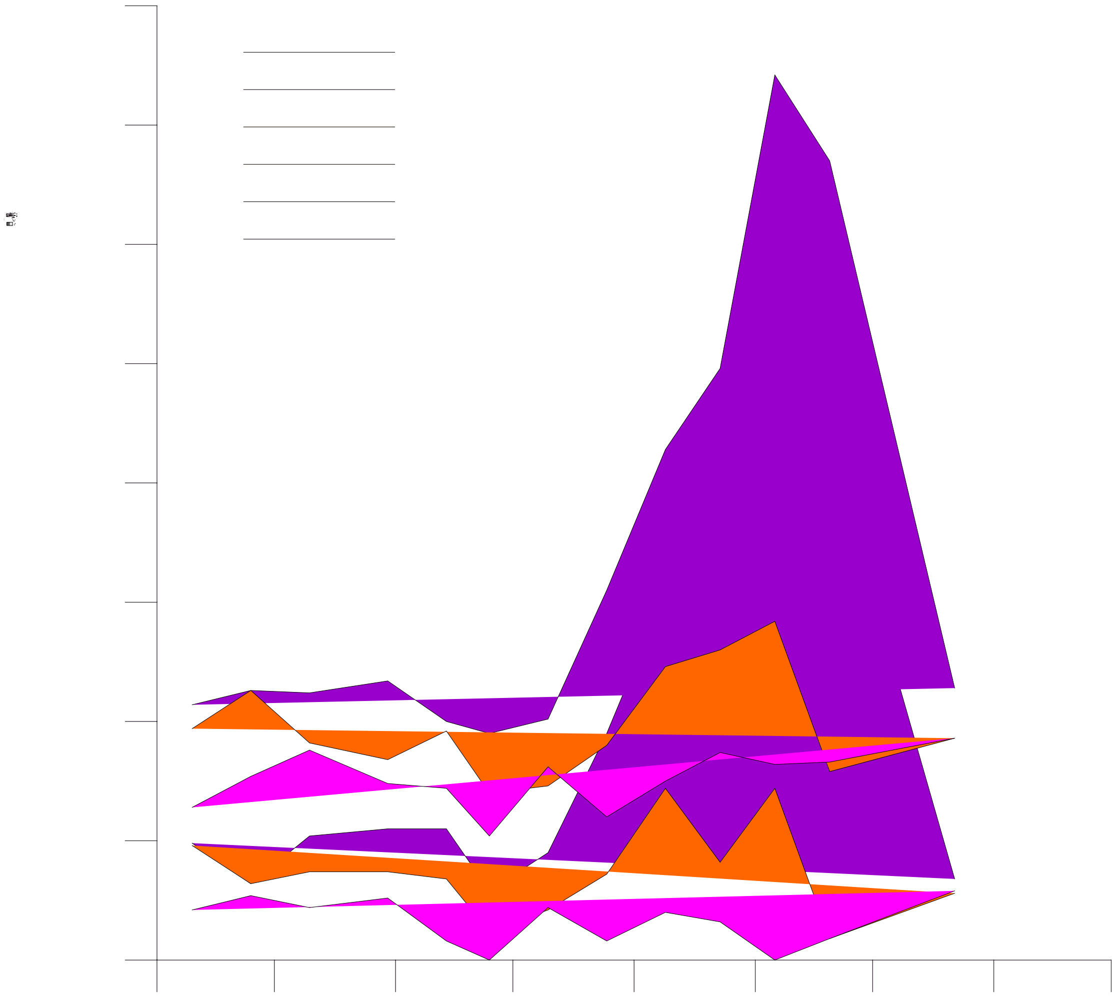

Figure 20. 2007 Lake Thunderbird total and dissolved nitrogen (N) at the bottom (1B) and 8 and 12 meters below the surface of site 1 (1-8m and 1-12m).

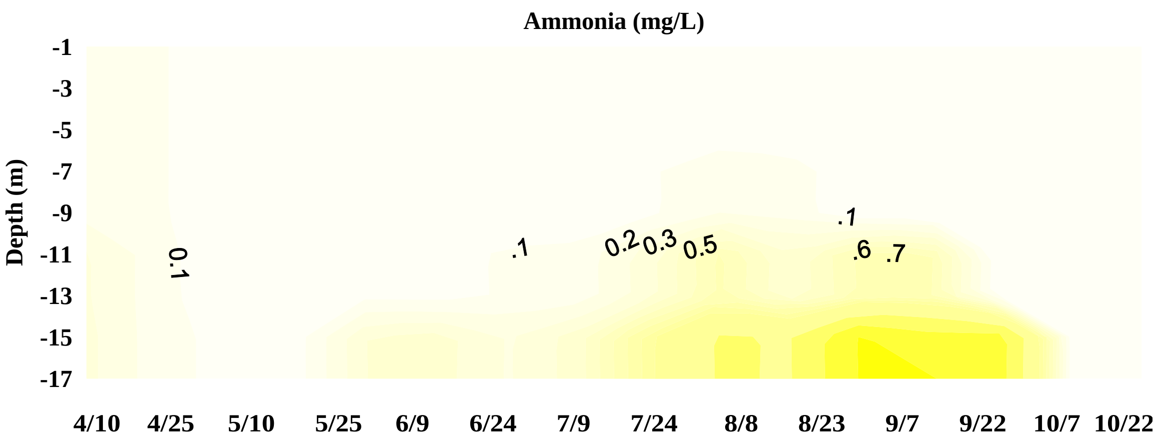

Figure 21. 2007 Lake Thunderbird ammonia contours with depth, by date, at site 1.

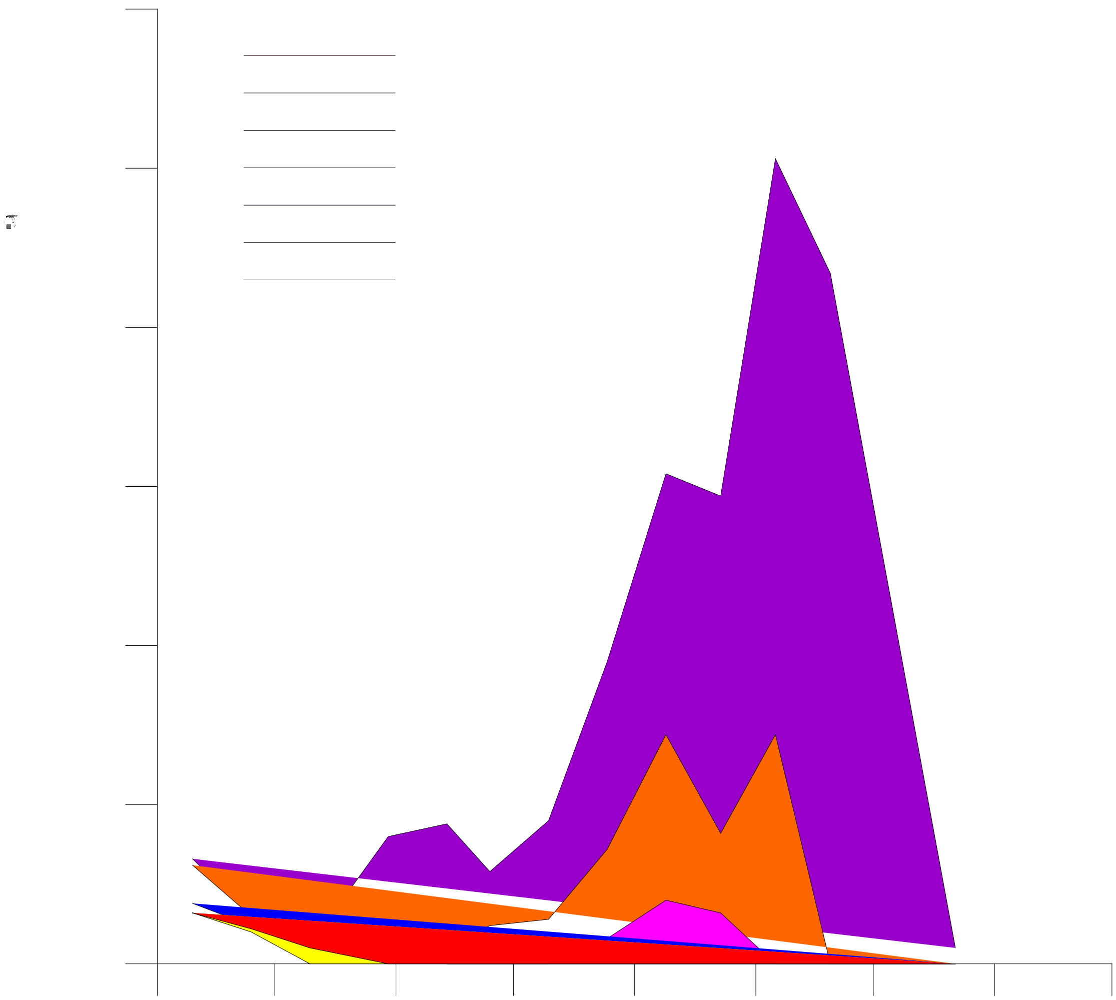

Figure 22. 2007 Lake Thunderbird ammonia concentrations at the surface of sites 1 (1-S), 2, and 4, and at the bottom (1B), 4 (1-4m), 8 (1-8m) and 12 (1-12m) meters below the surface of site 1.

Nutrient Budget

A phosphorus budget for Lake Thunderbird was prepared integrating the estimated outflows from the water budget with lake water quality data. The constructed budget demonstrates pre-stratification lake phosphorus mass for 2007 in the range of approximately 1,900-3,200 kg (**Table 4**). The lowest (1,920 kg) and highest (10,845kg) amounts of lake total phosphorus occurred in January and July, respectively. Enhancements to increase the accuracy of the nutrient budget include assessing dry deposition and estimates of inflow load. This preliminary budget has set the foundation for understanding lake nutrient dynamics and placing external (runoff) and internal (sediment mediated release) in context of water quality based goals.

Table 4. Partitioning of Lake Thunderbird phosphorus mass for nutrient budget as kilograms of total phosphorus in the lake (runoff, sediment release and direct rainfall) and out of the lake due to gated releases and water supply withdraw during 2007.

Month	Lake	Runoff	Sediment	Rainfall	Releases	Water Supply
January	1920	NA	NA	1.3	0	38
February	NA	NA	NA	0.5	0	NA
March	NA	NA	NA	2.4	0	NA
April	3195	NA	NA	1.0	0	55
May	3682	NA	NA	6.7	0	49
June	4912	NA	NA	4.7	201	51
July	10845	NA	NA	4.9	1699	74
August	8539	NA	NA	4.9	1381	77
September	5769	NA	NA	2.1	837	68
October	6059	NA	NA	1.9	0	92
November	NA	NA	NA	0.2	0	NA
December	NA	NA	NA	1.9	NA	NA

Lake monitored data was used for internal inputs and outputs of phosphorus. Lake water quality data was collected by the OWRB for the purpose of nutrient budgeting in calendar year 2007. Vertical profiles of physical parameters were used to establish internal reservoir dynamics. Partitioning between epilimnetic, metalimnetic and hypolimnetic layers allowed the massing of phosphorus for each sample date (**Table 5**). 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. Monthly phosphorus masses demonstrate a 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 significantly higher (about double) than at the onset of stratification.

Table 5. 2007 Lake Thunderbird site 1 phosphorus mass at depth intervals by sample date. Red cells represent hypolimnetic accumulation of phosphorus.

Depth (m)	9-Jan	10-Apr	25-Apr	10-May	30-May	14-Jun	25-Jun	10-Jul	25-Jul	9-Aug	23-Aug	6-Sep	20-Sep	22-Oct
0 - 1	244	534	575	438	682	564	429	800	726	662	770	600	738	849
1 - 2	224	471	448	369	623	524	612	949	818	658	768	592	697	960
2 - 3	206	402	434	335	545	432	518	874	845	576	677	518	565	808
3 - 4	206	457	462	289	481	394	471	684	695	525	700	454	516	511
4 - 5	166	301	304	257	473	367	406	568	591	426	618	402	441	517
5 - 6	216	230	238	223	405	335	408	727	538	402	435	323	478	697
6 - 7	67	184	195	192	307	254	448	698	702	460	492	336	332	425
7 - 8	125	194	162	162	240	199	317	847	711	500	708	265	260	333
8 - 9	116	108	146	134	197	163	346	771	860	510	375	231	213	326
9 - 10	83	94	143	125	213	176	418	642	929	752	236	435	230	241
10 - 11	32	70	85	99	143	163	431	667	879	837	705	534	132	205
11 - 12	235	41	81	72	107	145	369	521	947	748	690	502	88	84
12 - 13		21		44	72	111	281	384	682	585	411	382	55	53
13 - 14		6		28	51	77	204	454	603	382	455	410	163	31
14 - 15		3		12	29	43	107	699	445	221	329	237	129	13
15 - 16				5	10	16	92		250	105	255	136	77	3
16+				1	5	7			188	44	60	68		2
Total	**1920**	**3116**	**3275**	**2783**	**4582**	**3968**	**5857**	**10283**	**11408**	**8393**	**8685**	**6426**	**5113**	**6059**

It is important to note that during mixed or oxidized lake conditions, ortho-phosphorus represents approximately one-quarter the total phosphorus in the lake while this proportion doubles from August through October. This proportional increase corresponds to an accumulation of phosphorus in the hypolimnion. Three possibilities exist for the hypolimnetic accumulation of ortho-phosphorus: accumulation of dying algae (settling) from the epilimnion, release from the sediment, and plunging runoff from the watershed. For example, the large portion of total phosphorus noted in the 8-12 meter segment of Lake Thunderbird on July 10 and 25 is a reflection of the July peak seen at 8 meters, and is most likely due to a plunging inflow (**Figure 16**). Partitioning between these three sources require more accurate 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.

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 seven sites at each sampling event during 2007. In terms of mean chlorophyll-*a* concentrations, no sites were significantly different from one another (ANOVA: $F=1.265$, $p=0.28$) (**Figure 23**). Chlorophyll concentrations reached their peak in late July and August, following the clear water phase and depletion of dissolved nutrients in the epilimnion (**Figure 24**). In 2007, 80% of samples were considered eutrophic based on a 7.2 μg/L division between mesotrophy (Wetzel 2001). This is slightly lower than the 86% of eutrophic samples in 2006.

Goal setting by the COMCD in previous years yielded a maximum chlorophyll-*a* limit of 20 μg/L. During the 2007 sampling season, 38% of chlorophyll-*a* samples exceeded this upper limit. This number is higher than the 14% of samples over the goal in 2006, and could be due to excessive nutrient inputs from run-off events in this extremely wet year.

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)). Only 31% of 2007 samples were below this concentration, which is similar to the 29% of 2006 samples at or below 10 μg/L. 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 in 2009 that should address specific recommendations in regards to thwarting nutrient pollution.

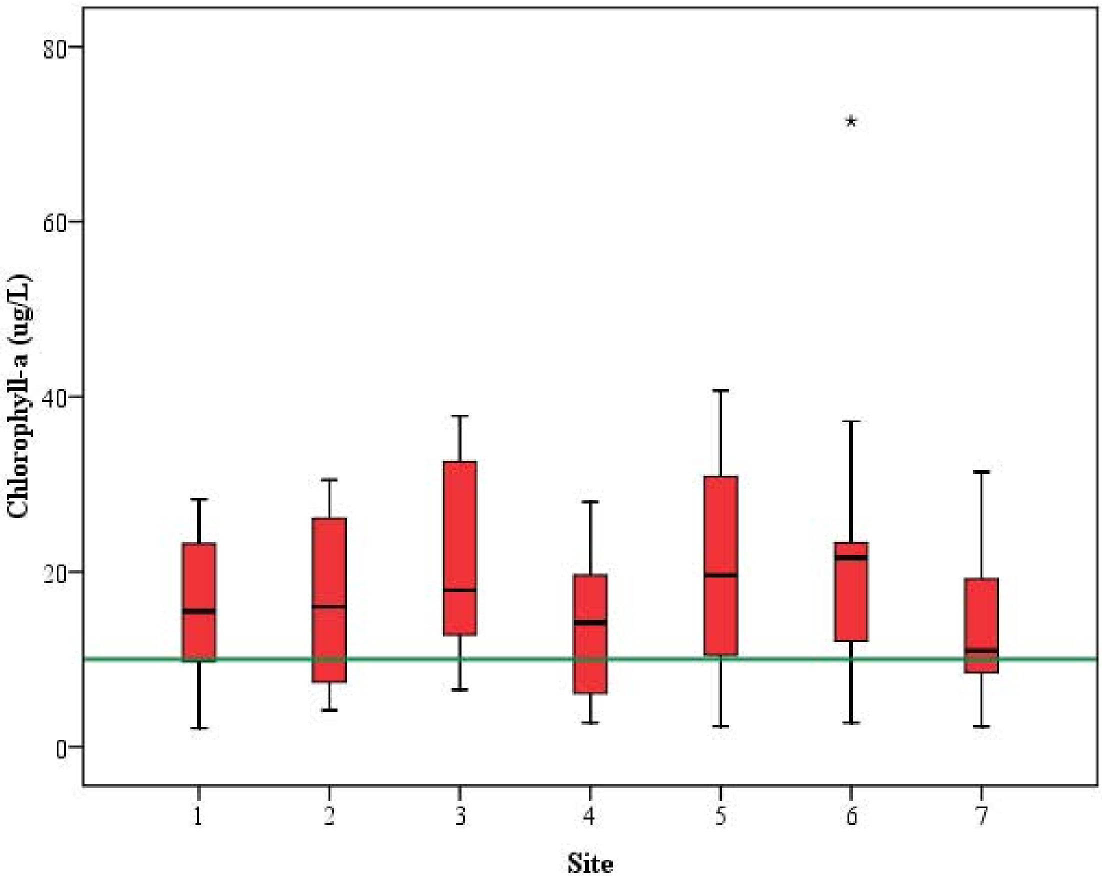

Figure 23. 2007 Lake Thunderbird chlorophyll-*a* (μg/L) averages by site number, where 10 μg/L indicates the water quality standard for sensitive water supplies (SWS).

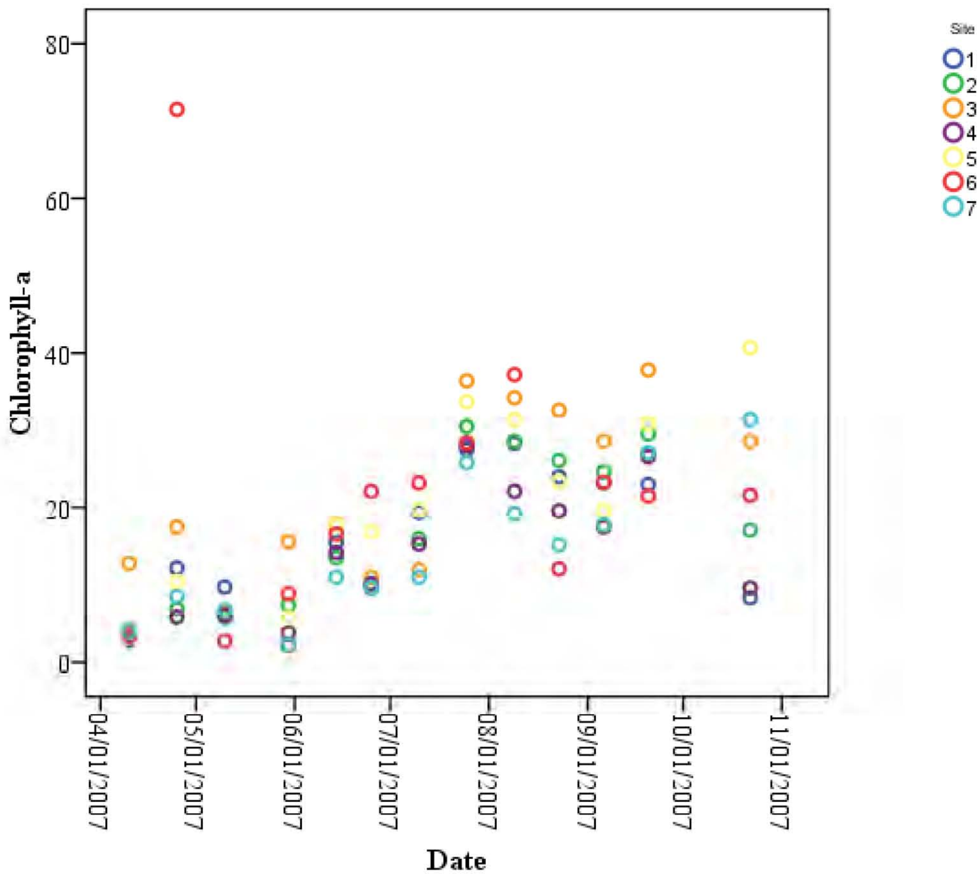

Figure 24. 2007 Lake Thunderbird surface chlorophyll-*a* (μg/L) values by site at each sample event.

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 February (14) and August (16) (**Figure 25**). 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 26)**. Although the number of complaints in February surpasses numbers during previous years, winter complaints are often associated with cyanobacterial dominance of the algal community. Similar increases in winter taste and odor problems can be expected with further progression of eutrophication.

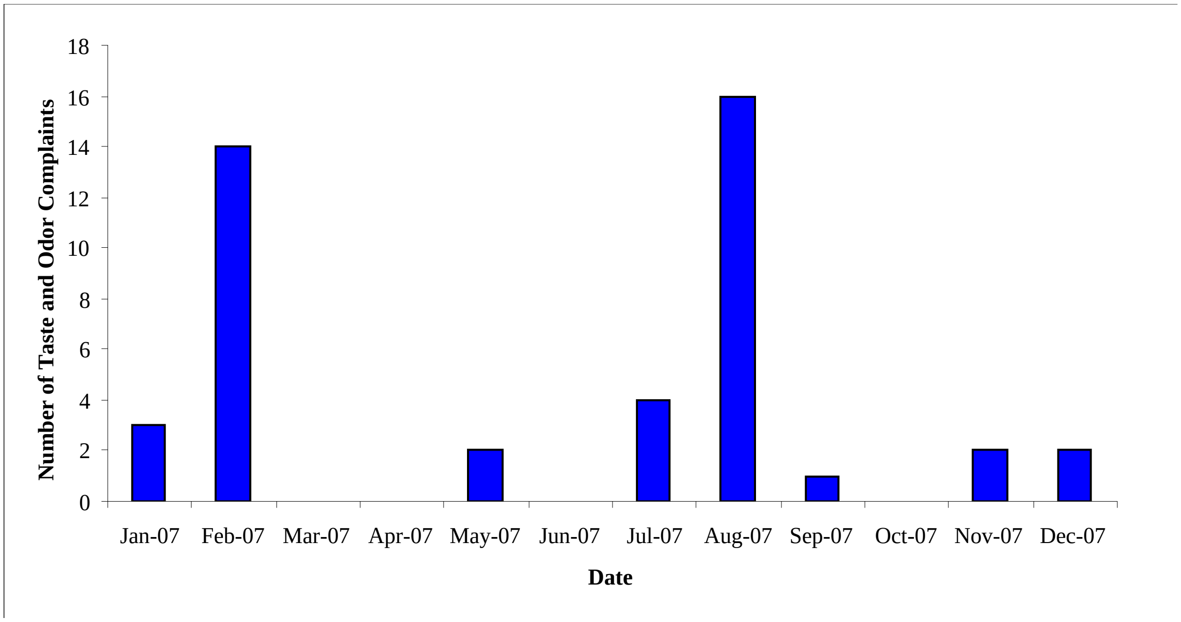

Figure 25. Taste and odor complaints to the City of Norman during 2007.

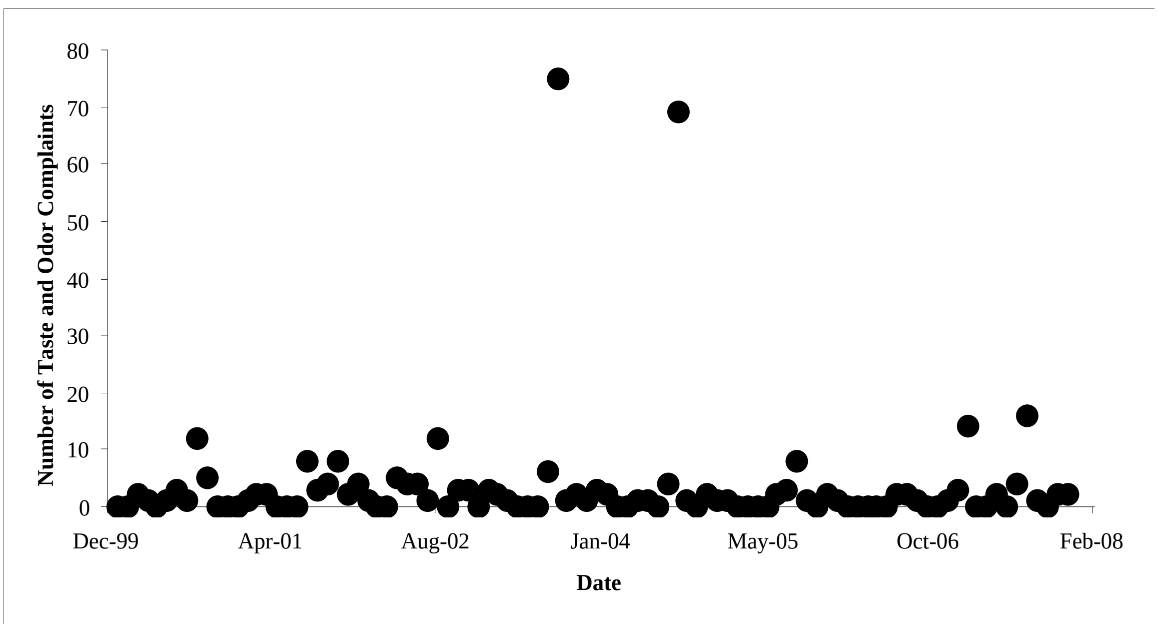

Figure 26. Taste and odor complaints to the City of Norman from 2000 through 2007.

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 during 2007. In general, TOC concentrations increased during spring and early summer, with peak concentrations occurring in late July (**Figure 27**). Concentrations consistently declined after this peak date. This trend is consistent with other proxies of primary production, such as chlorophyll-*a* and pH. Increases in surface pH during the summer months indicate high rates of photosynthesis (**Figure 28**).

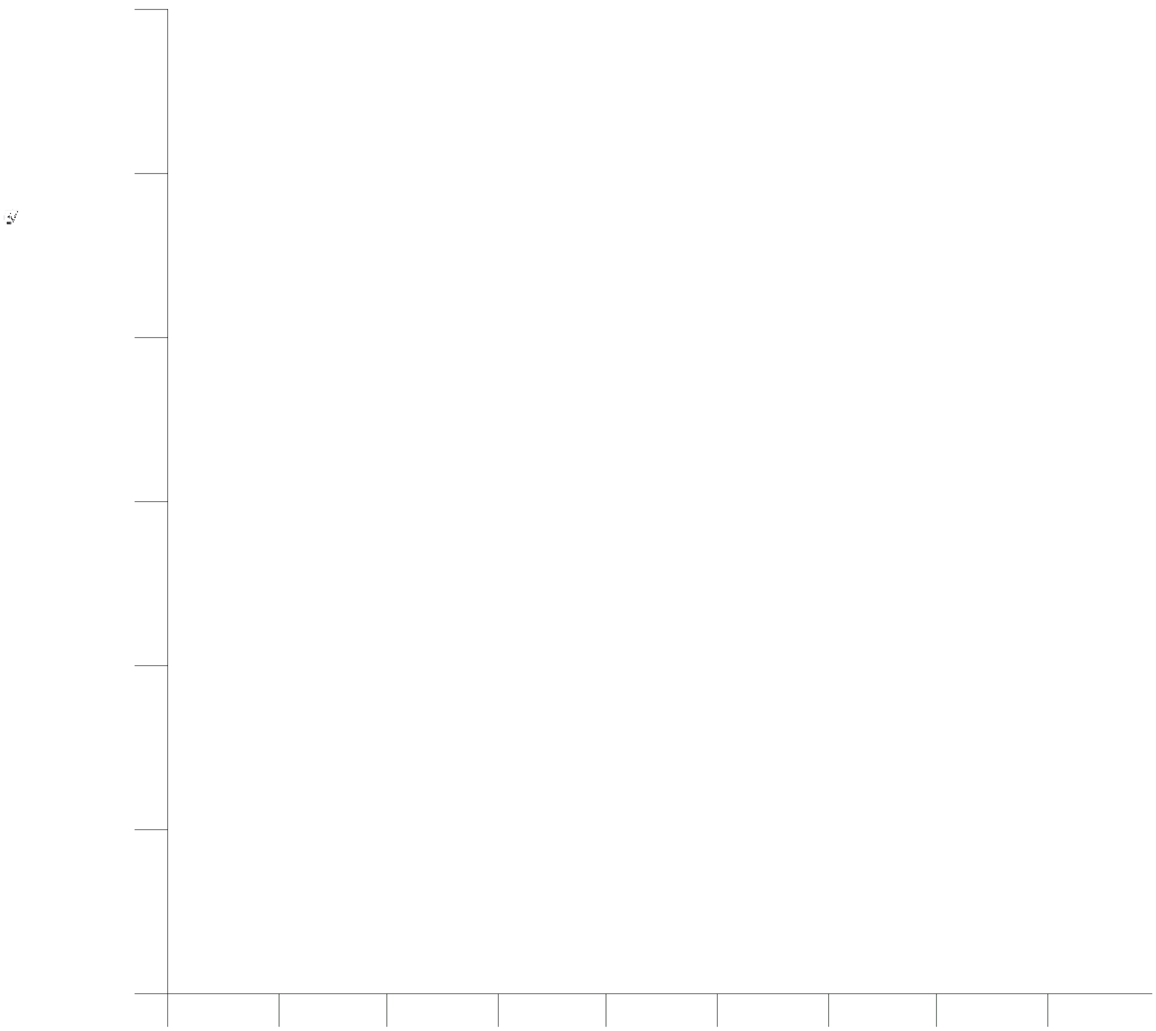

Figure 27. Total organic carbon concentrations at the surface of the three lacustrine sites on Lake Thunderbird during the 2007 sampling season.

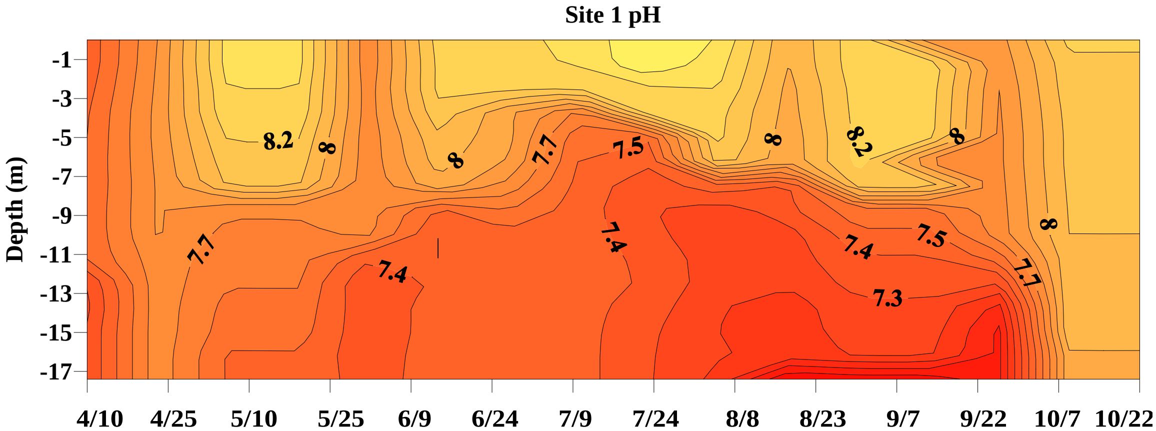

Figure 28. 2007 Lake Thunderbird pH contours at the dam site.

Sinking organic matter in the summer months (due to high algal production) stimulates decomposition processes in the hypolimnion. Initially, oxygen is used as a terminal electron acceptor. As oxygen is depleted, other compounds are reduced by these processes, which is reflected by decreasing hypolimnetic oxidation-reduction (redox) potentials. Ferric iron is reduced to ferrous iron when the redox potential (Eh) approaches 100mV, which can result in the release of ortho-phosphorus that was chemically bound to ferric iron from the sediment. When this phosphorus reaches the epilimnion it can be contribute to additional algae production. Other metals are reduced to soluble forms below this redox potential and into negative values. Among these are manganese, copper, lead, zinc, and aluminum. The byproducts of decomposition processes can also depress pH when sufficient material for decomposition are available (**Figure 28**).

Hypolimnetic redox potentials in Lake Thunderbird approached 100 mV beginning in June 2007 (**Figure 29**). Negative redox values occurred from this time throughout the growing season, until fall turnover when hypolimnetic waters were mixed. Sediment bound phosphorus and common metals such iron will desorbed as redox falls below 100 mV. Low redox potenial associated with anaerobic conditions are also associated with the production of sulfide and methane.

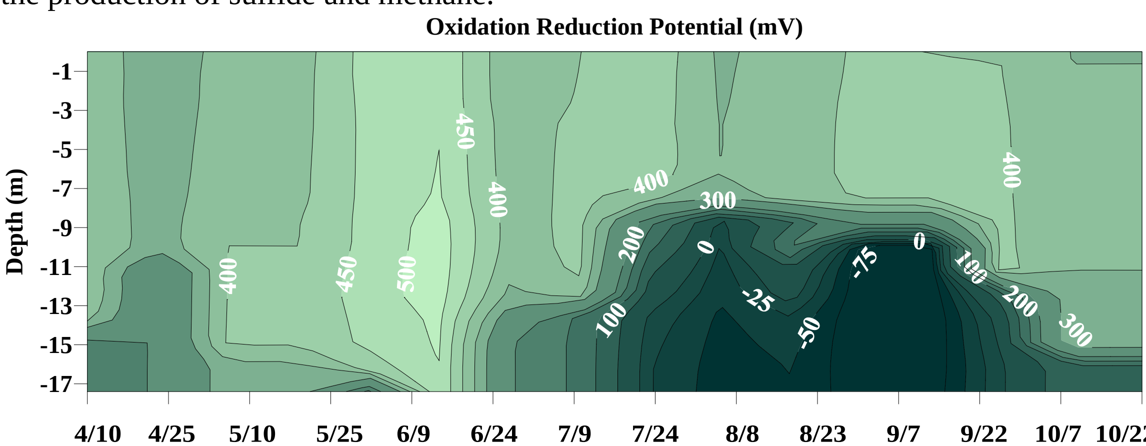

Figure 29. 2007 Lake Thunderbird oxidation-reduction potential contours at the dam site.

Summary and Discussion

Climatic effects

2007 marked the wettest year on record for central Oklahoma. Large rainfall amounts (**Table 2**) lead to above average inflows into Lake Thunderbird, resulting in higher lake elevations and volumes, and increased discharges (**Table 3**). Extreme low elevations at the beginning of the year (~ 1,030.8 ft) increased with rainfall events and peaked at the second highest elevation on record of 1,048.23 ft on July 14. Elevations decreased after this date and stabilized to averages around conservation pool by the end of the year (**Figure 2**). The 2007 climatic events ended a period of drought conditions for Lake Thunderbird. These conditions of significant inflow and retention of nutrients from the watershed predict higher than normal turbidity and enhanced cultural eutrophication. Lower than average temperatures may have slowed algal growth rates in 2007.

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, as predicted by climatic events, were observed in Lake Thunderbird in 2007. These included 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 during the summer growing season. Anoxia occurred during the summer months as well, coinciding with low to negative oxidation-reduction potentials. Most likely, phosphorus and metals were released back into the water column during this time and were re-suspended 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 received taste and odor complaints in 2007 that were most likely related 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.

Oxidizing the hypolimnion

Maintaining an oxidized hypolimnion will allow for the oxidation of nutrients, metals and taste and odor-causing compounds prior to mixing and increase 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* concentrations.

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 2007 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. 2007 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. Data collected in 2008 will further aid in the assessment of these three parameters.

Recommendations

Determine the feasibility of oxygenating the hypolimnion of Lake Thunderbird

Maintaining an oxidized hypolimnion reduces the movement of nutrients from the lake bottom into the epilimnion, where nutrients are used for algae growth. It is possible that this action could eliminate the gradual increase of surface nutrients and consequently excessive algal growth. This action would aid in achieving the 10 μg/L chlorophyll-*a* standard and reduce the possibility of September taste and odor problems.

Continued nutrient sampling

The current sample scheme allows effective accounting of phosphorus in Lake Thunderbird. More intensive data collected at additional sites in 2008 will further support lake analyses.

Extend and improve water quality monitoring

The ability to have a more comprehensive view of Lake Thunderbird would be helpful in understanding seasonal trends and pinpointing problematic areas of inflow. Accumulating tributary inflow water quality data and increasing measured parameters will result in a more accurate and predictive lake nutrient budget. Efforts to include year-round monitoring and increased sample sites and parameters linked to a watershed water quality model are a logical next step. Some of these efforts will be achieved in 2008 sampling.

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

References

Dzialowski, A.R., S.-H. Wang, N.-C. Lim, W. W. Spotts, and D.G. Huggins. 2005. Nutrient limitation of phytoplankton growth in central plains reservoirs, USA. *Journal of Plankton Research* 27(6): 587-595.

Graham, J.L., K.A. Loftin, A.C. Ziegler, and M.T. Meyer. 2008. Guidelines for design and sampling for cyanobacterial toxin and taste-and-odor studies in lakes and reservoirs: U.S. Geological Survey Scientific Investigations Report 2008-5038. Reston, Virginia.

OAC, Oklahoma Administrative Code. 2008. Title 785, Oklahoma Water Resources Board: Chapter 45, Oklahoma's Water Quality Standards, and Chapter 46, Implementation of Oklahoma's Water Quality Standards. http://www.oar.state.ok.us/oar/codedoc02.nsf/frmMain?OpenFrameSet&Frame=Main&Src=_75tnm2shfcdnm8pb4dthj0chedppmcbq8dtmmak31ctijujrgcln50ob7ckj42tbkdt374obdcli00_

OCS, Oklahoma Climatological Survey. 2007. Rainfall Summary Statistics, 2007. http://climate.mesonet.org/rainfall_update.html

Oklahoma Department of Environmental Quality. 2006. The State of Oklahoma 2006 Water Quality Assessment Integrated Report. http://www.deq.state.ok.us/wqdnew/305b_303d/2006_integrated_report_appendix_c_303d_list.pdf

OWRB, Oklahoma Water Resources Board. 2008. Technical Reports. http://www.owrb.ok.gov/studies/reports/reports.php

Wetzel, R.G. 2001. *Limnology: Lake and River Ecosystems*. San Diego, Elsevier Academic Press.