Oklahoma Water Resources Board

Lake Thunderbird
Water Quality
2006

for the

Central Oklahoma Master Conservancy District

September 2007

Final Draft Report

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

Executive Summary

2006 marked the first year of a robust nutrient sampling regime. This sample scheme yielded greater detail for key lake water quality parameters and will lay the foundation for future lake management activities. 2006 data from Lake Thunderbird was consistent with a eutrophic system demonstrating potential for high levels of algal biomass. Nutrient data suggest phosphorus and nitrogen were co-limiting nutrients of algal growth in 2006. Chlorophyll-a values, which are used as an indicator of algal concentrations, were slightly higher than in the previous year. 2006 air temperatures at the lake were higher than normal and rainfall amounts were lower than normal, as was the case in the 2005 sampling year. The drought of 2006 contributed to an annual hydraulic residence time of 5.4 years, almost double the annual average from 1995 - 2006. Epilimnetic dissolved nitrogen and phosphorus followed similar trends as in 2005 with a consistent build up of nutrients over the monitoring season. The onset of water column stratification began in May, with the establishment of an anoxic hypolimnion occurring by the 1st of June. After the summer stratification period, mixing of the water column had been completed by the end of September, with a subsequent lake-wide oxygen sag. By the end of October dissolved oxygen had recovered.

Monitoring data was compared to the Oklahoma Water Quality Standards. In 2003, Lake Thunderbird was determined to be impaired for dissolved oxygen and turbidity; in 2004, the lake was impaired for turbidity and not impaired for dissolved oxygen; in 2005, the lake was impaired for both parameters; and in 2006 Lake Thunderbird was impaired for turbidity and dissolved oxygen. The 2006 data supports the 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). 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.

Active lake management is needed for Lake Thunderbird to meet OWQS for turbidity, dissolved oxygen and chlorophyll-a. Lake-wide reduction of algae is needed to meet OWQS by mitigating low dissolved oxygen and decreasing chlorophyll-a. Suspended solids control is needed 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 around in-lake and also into the watershed
- Evaluative processes could include:
  a) Estimate watershed nutrient load and place in context of in-lake load using predictive modeling
  b) Estimate average in-lake phosphorus concentration needed to meet chlorophyll-a criteria

Table of Contents

List of Figures

List of Tables

Introduction

The primary objective in 2006 was to continue routine environmental monitoring and data collection for the on-going nutrient budgeting of Lake Thunderbird, with monitoring frequency remaining bi-weekly. Five vertical interval nutrient profile samples were collected at site one to enhance nutrient budget data. Lake Thunderbird is a Sensitive Water Supply Reservoir, and is thus required to meet a chlorophyll-a standard of 10µg/L to meet Environmental Protection Agency regulations. Recommendations for 2007 water quality management are presented. The 2006 sample season represents the first full summer of Lake Thunderbird nutrient sampling of Lake Thunderbird in well over 20 years.

Water Quality Evaluation

Lake Thunderbird was sampled at the sites indicated in **Figure 1**. Sites 1, 2, and 4 represent the main body of the lake, site 3 represents the Hog Creek arm, sites 5 and 6 represent the Little River arm of the lake and site 7 represents the Clear Creek arm. Water quality sampling occurred from April 13, 2006 to October 31, 2006 on a biweekly basis, with one winter sample collected on February 28, 2006. Water quality parameters include nitrogen and phosphorus series, total suspended solids, alkalinity, and chloride. Hydrolab parameters include oxidation-reduction potential, dissolved oxygen, temperature, specific conductance, and pH. The other sampling parameters are chlorophyll-a, total organic carbon, turbidity, and Secchi disk depth.

Nutrient and TOC surface samples were collected at sites 1, 2, and 4 while surface chlorophyll-a, turbidity, and hydrolab data were collected at all sites (**Table 1**). Additional nutrient samples were collected at 4 meters from the surface, 8 meters, 12 meters, and the deepest sample taken at 0.5 meters from the bottom (usually 15 meters) to chemically characterize vertical gradients within Lake Thunderbird. Hourly data records from the National Weather Service and the Corps of Engineers for Lake Thunderbird were examined to develop a climatic and hydrologic view of the lake.

Table 1: Sampling Dates for Specific Parameters

Date	2/28	4/13	4/20	5/2	5/18	6/1	6/15	6/29	7/13	7/26	8/10	8/24	9/14	9/27	10/10	10/31
Nutrients	x		x	x	x	x	x	x	x	x	x	x	x	x	Site 1	x
Hydrolab	Sites 1,2,4		x	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	x	x	
TOC	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x
Tubidity	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Secchi	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

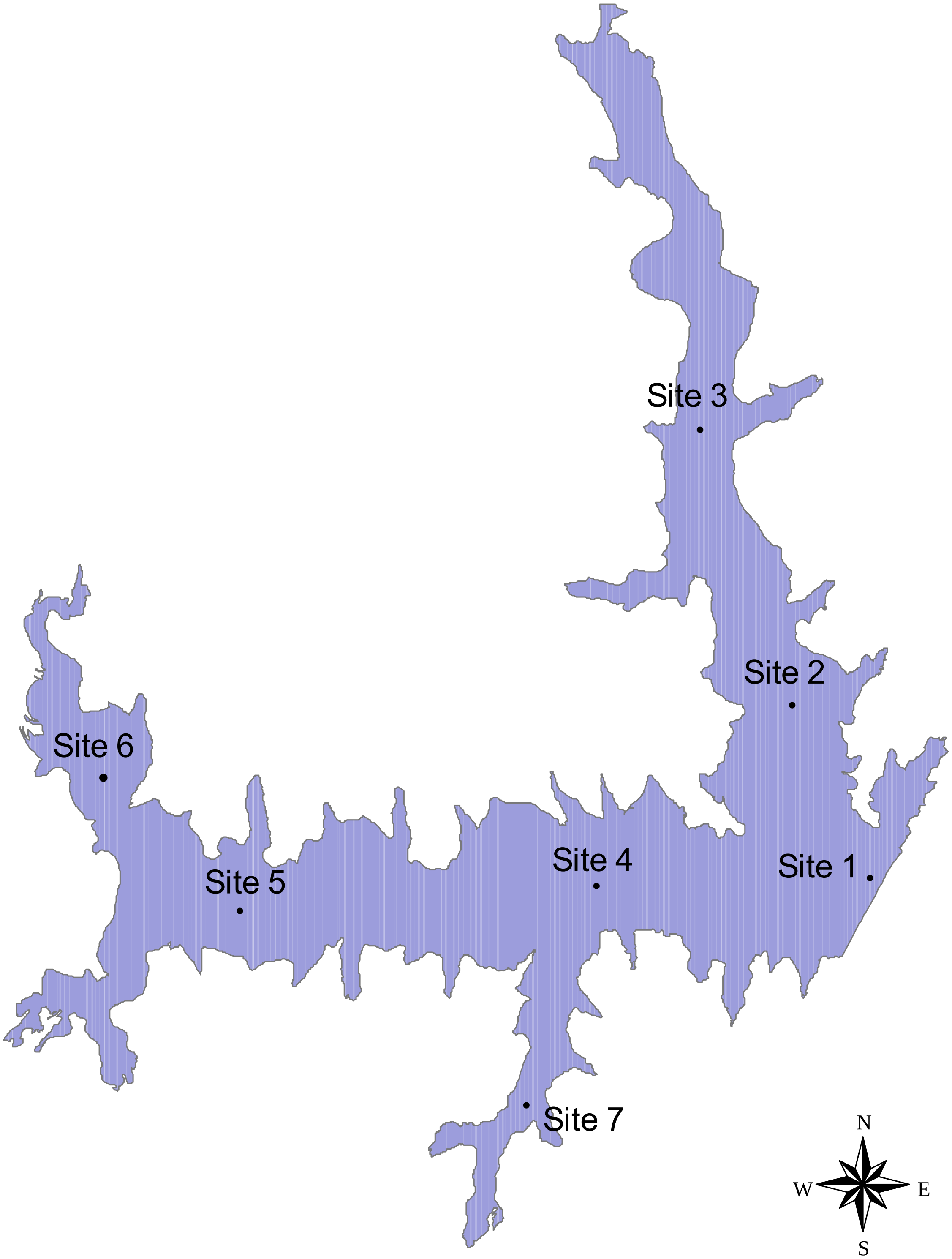


Figure 1: Lake Thunderbird Sample Sites

Climate

2006 was a year of dropping pool elevation marked by lower than normal rainfall and runoff into Lake Thunderbird (**Figure 2**). Only one rainfall event resulted in an inflow rate greater than 1000 cfs. The severe winter drought (23% of normal rainfall) followed by lower than normal rainfall in each subsequent season deepened the drought experienced in 2005 (**Table 2**). With the dryer season also came warmer than normal temperatures when compared to the previous monitoring seasons (**Figure 3**). For each year, a third order polynomial trend line was also plotted. Air temperature data show slightly higher temperatures through July and August than in all other years. Fall temperatures show a steeper decrease than in previous years, and closely follow the trends of 2001 and 2003. Climatic temperatures would predict higher than normal algae growth due to increased water temperatures in the spring through late September.

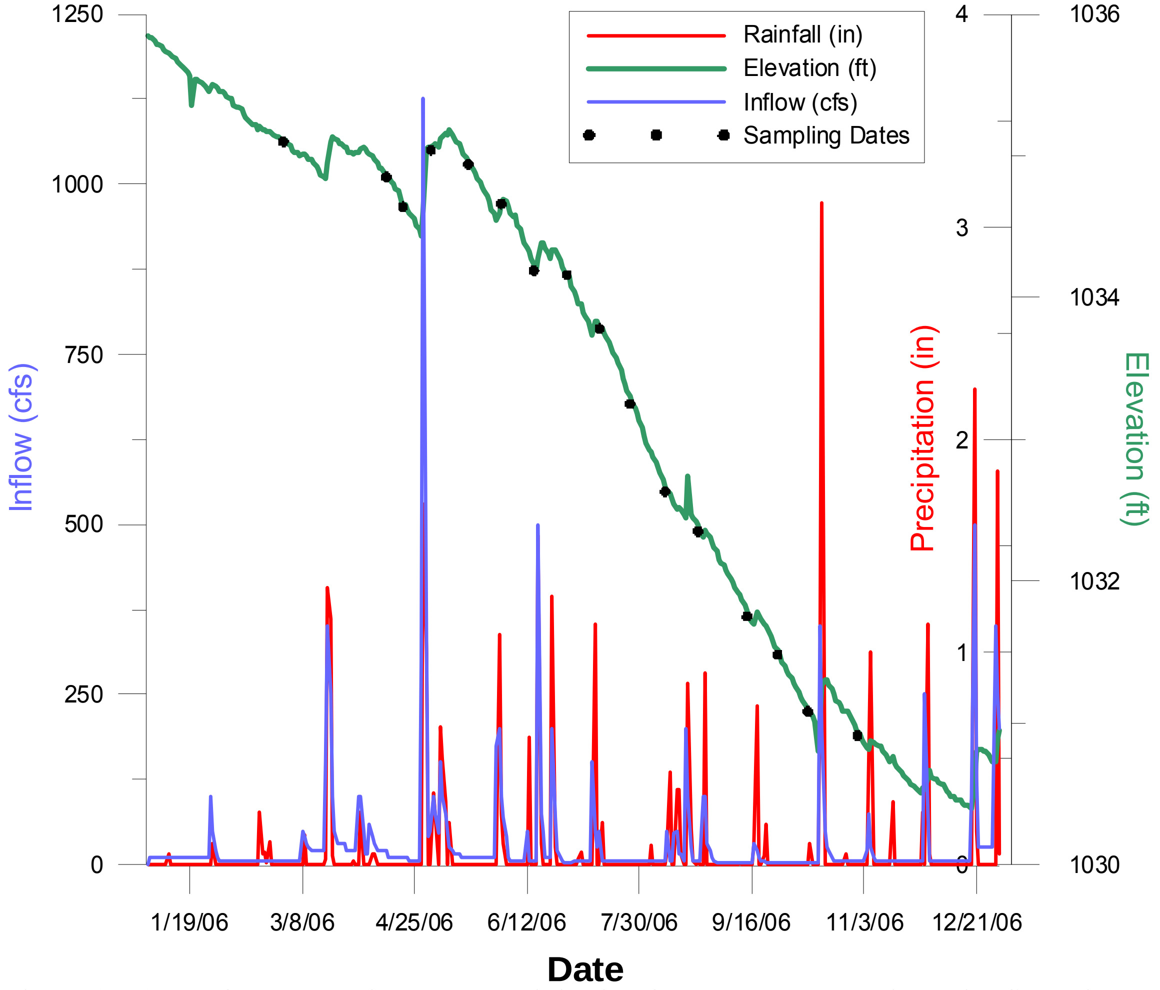


Figure 2: 2006 Inflow, Elevation, and Precipitation for Lake Thunderbird, with Sampling Dates

Table 2: Rainfall Normals and Extremes for Central Oklahoma (OCS, 2006a)

	2001		2002		2003		2004		2005		2006	
	Total	%	Total	%	Total	%	Total	%	Total	%	Total	%
Winter	7.57	145%	4.65	89%	4	76%	5.07	97%	5.48	105%	1.30	**23%**
Spring	9.74	79%	9.61	78%	7.68	62%	7.93	64%	4.01	**32%**	9.37	79%
Summer	5.8	59%	10.03	103%	10.55	108%	14.08	144%	15.27	156%	6.89	71%
Fall	8.28	78%	9.36	88%	6.41	61%	11.67	110%	3.69*	**35%***	7.23	67%
Annual Total	31.37	83%	35.1	92%	27.11	71%	38.43	101%	28.45	75%	22.02	60%
Norman Total	28.73	76%	29.4	77%	27.51	72%	35.95	94%	22.71	60%	22.38	56%

* approximation

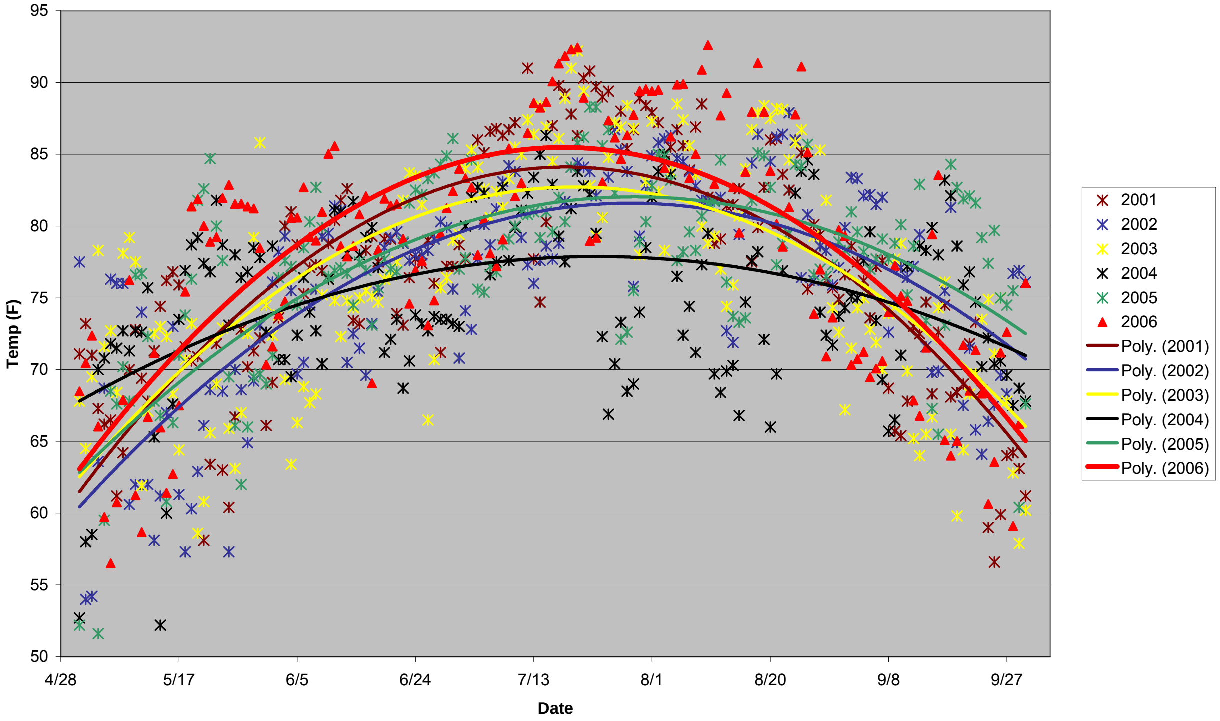


Figure 3: Air Temperature (F) Reported at Norman Mesonet Station (OCS, 2006b)

Hydraulic 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 (directly on the lake surface)

Precipitation was estimated from the direct rainfall measurements/data provided by the 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.

Evaporation

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 annual 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 Releases

Water released from Lake Thunderbird includes gated dam releases and water supply releases. Both are reported by the USACE.

Change in Lake Volume

Change in volume or storage was recorded by the USACE at the end of every day. The lake volumes corresponding to the stages were computed and the difference between them is the change in volume for that month. The volumes 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 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 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	875	58	933	1,963	1,405	-	3,368	-2435	-2200	235
Feb	278	180	458	1,346	1,129	-	2,475	-2017	-1925	92
Mar	2,817	1,029	3,846	2,432	1,309	-	3,741	106	-330	-436
Apr	4,711	1,182	5,893	3,587	1,534	-	5,121	772	165	-607
May	2,579	1,248	3,827	3,801	1,645	-	5,446	-1619	-2047	-428
Jun	2,567	1,406	3,973	4,174	1,856	-	6,030	-2057	-2930	-873
Jul	809	493	1,302	4,680	2,128	-	6,808	-5506	-5103	403
Aug	1,686	1,087	2,773	4,135	2,154	-	6,289	-3515	-3758	-243
Sep	313	348	661	2,862	1,825	-	4,687	-4026	-3793	233
Oct	1,492	1,252	2,744	2,065	1,744	-	3,809	-1065	-2004	-939
Nov	1,140	947	2,087	1,168	1,389	-	2,557	-470	-1167	-697
Dec	3,550	1,353	4,903	891	1,330	-	2,221	2682	1436	-1246
Total	22,817	10,583	33,400	33,104	19,448	-	52,552	-19152	-23656	-4504

Once a hydraulic budget has been constructed, retention times can be estimated. The hydraulic detention 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 an average hydraulic residence time of 2.17 years, averaged over the 11-year record of lake levels, and 5.44 years for 2006. The longer 2006 residence time reflects the severity of drought in 2006. This is further evidenced when comparing the total inputs (33,400 acre-feet) verses total outputs (52,552 acre-feet) representing a dropping annual pool. Finally only in March, April and December were inputs predicted to be greater than outputs (gaining pool months) (**Figure 4**).

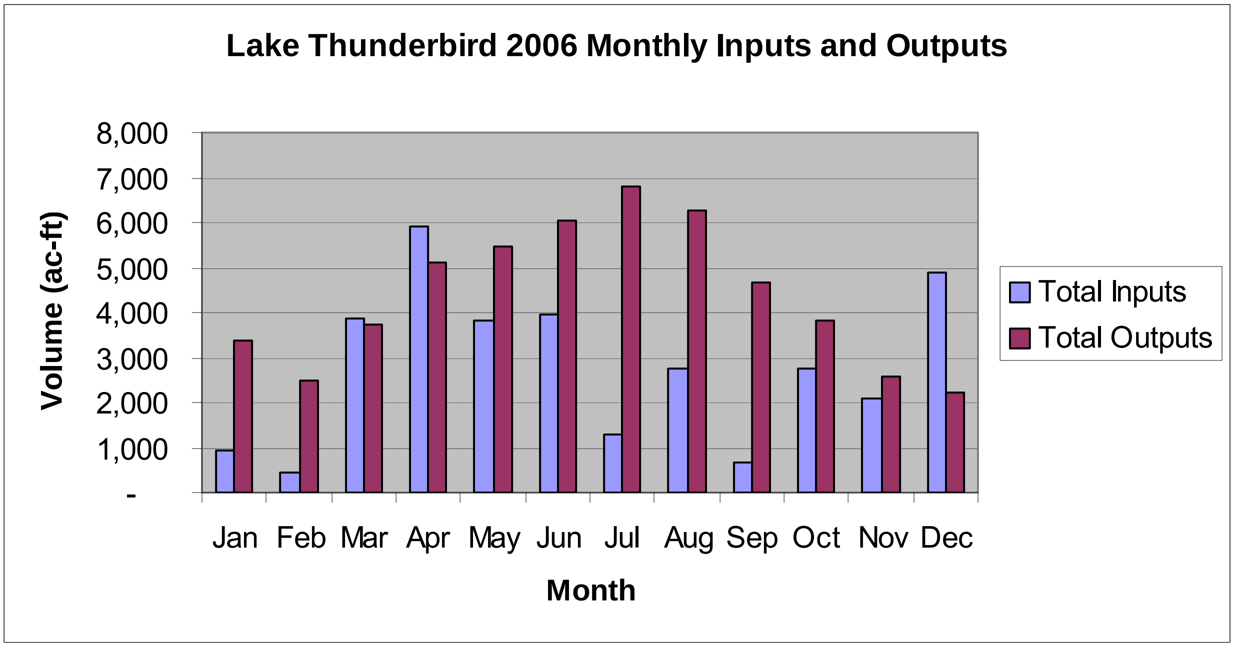


Figure 4: Monthly inflows compared with outflows for Lake Thunderbird, 2006.

During this last drought year, 77% of the input to Lake Thunderbird was from inflow while evaporation accounted for 59% of the water lost from the lake with only 11% of the total spilled below the dam (**Figure 5**). During non-drought years a larger portion of input would be expected from runoff with a greater proportion amount of loss from spillage.

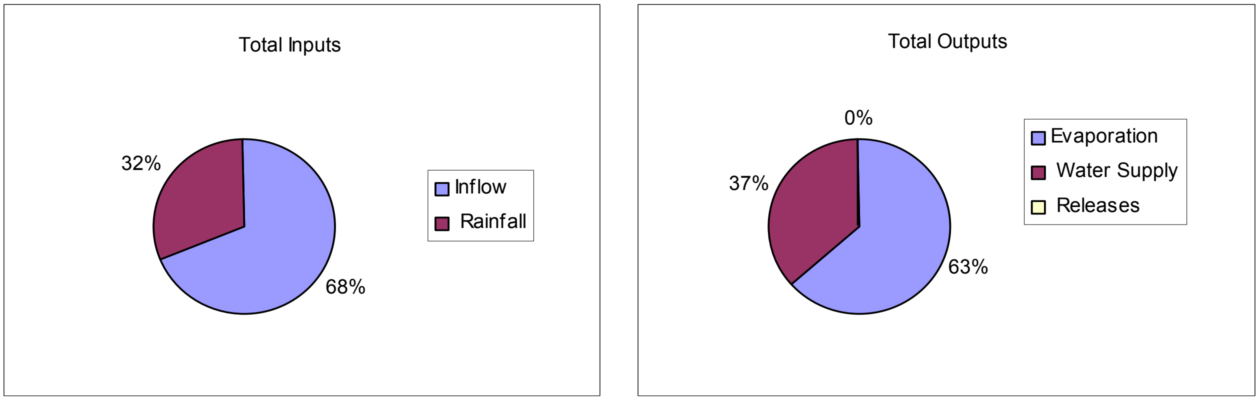


Figure 5: Summary of inflow and outflow sources as percent of the total for Lake Thunderbird in 2006

Sources of Error

Although robust, the hydraulic budget does contain error. For example, 8 of the 12 months show a negative (underestimate) for the monthly budget with an annual averaged error of –373 acre-feet per month. Ideally, error would be evenly distributed (as many underestimates as overestimates). Although seemingly significant, the monthly magnitude of error was never greater than less than 1.2% of the lake capacity. This suggests the error is nominal and heightened by drought conditions. 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 2006(potentially yielding a lower than actual evaporation rate)

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

- Transpiration through plants and seepage through the dam were assumed to be negligible. The low lake levels and subsequent recession of vascular aquatic plants supported this assumption in 2006.

- 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 hydraulic budget is robust enough to support lake nutrient budget development.

Temperature and Dissolved Oxygen

In late spring and during summer when temperatures rise, lakes generally stratify thermally with a warmer, lighter layer of water (epilimnion) overlying a colder, deeper, and denser layer of water (hypolimnion). There is usually a transition layer between the epilimnion and the hypolimnion called the metalimnion or thermocline. The thermocline isolates the hypolimnion from the epilimnion and the atmosphere (**Figure 6**). **Figure 6** demonstrates the depletion of dissolved oxygen in the lower layer of the lake due to stratification and decaying organic matter in the hypolimnion, which consumes oxygen, while the metalimnetic barrier minimizes oxygen recharge from the epilimnion.

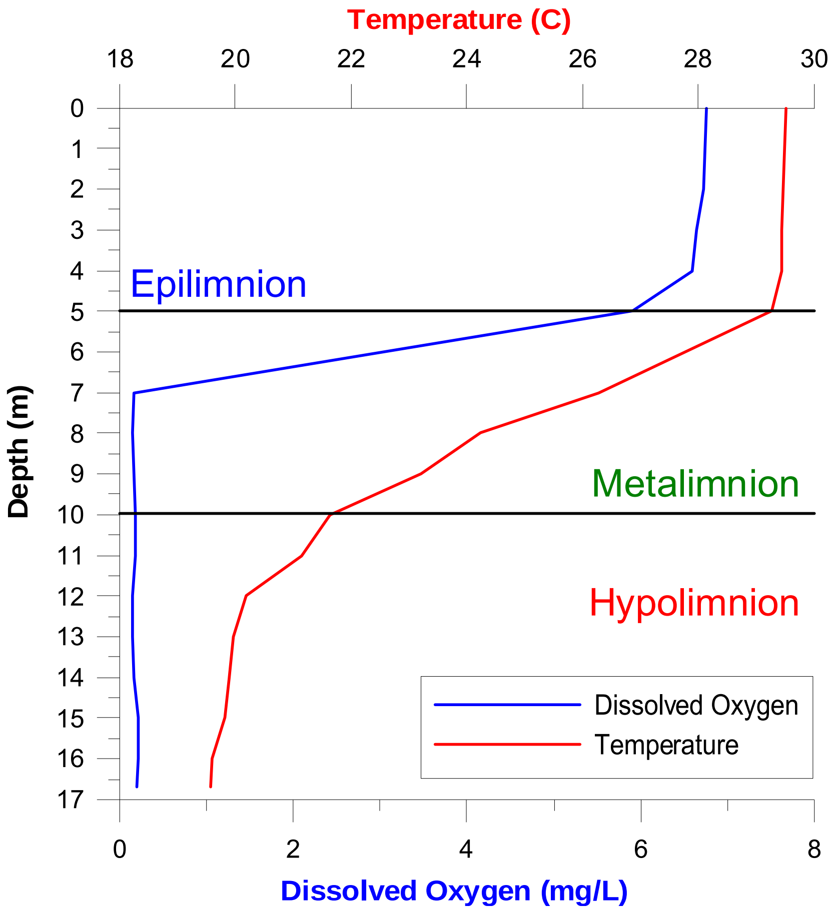


Figure 6: Temperature and Dissolved Oxygen Profile for Lake Thunderbird Showing Three Distinct Layers (epilimnion, metalimnion and hypolimnion)

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 and epilimnetic temperatures match the top of the metalimnion. As cooling continues the thermocline disappears and fall mixing or “turnover” occurs. 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.

In 2006 increasing epilimnetic temperature serves to strengthen thermal stratification (**Figures 7 and 8**). Also notable is the rapid depletion of oxygen in the hypolimnion from May through June of 2006 (**Figure 7**). Oxygen consumption started at the sediment and worked upward through the hypolimnion. Epilimnetic temperatures peaked in mid-August, with depth varying from 7 to 10 meters in the summer while a portion of the metalimnion was depleted of oxygen. Cooling of the epilimnion, combined with warmer than usual hypolimnetic temperatures, mixed much of Lake Thunderbird by the beginning of September, with complete mixing of the lake occurring by the end of September through October (**Figure 9**). By late October dissolved oxygen had recovered to near 100% saturation.

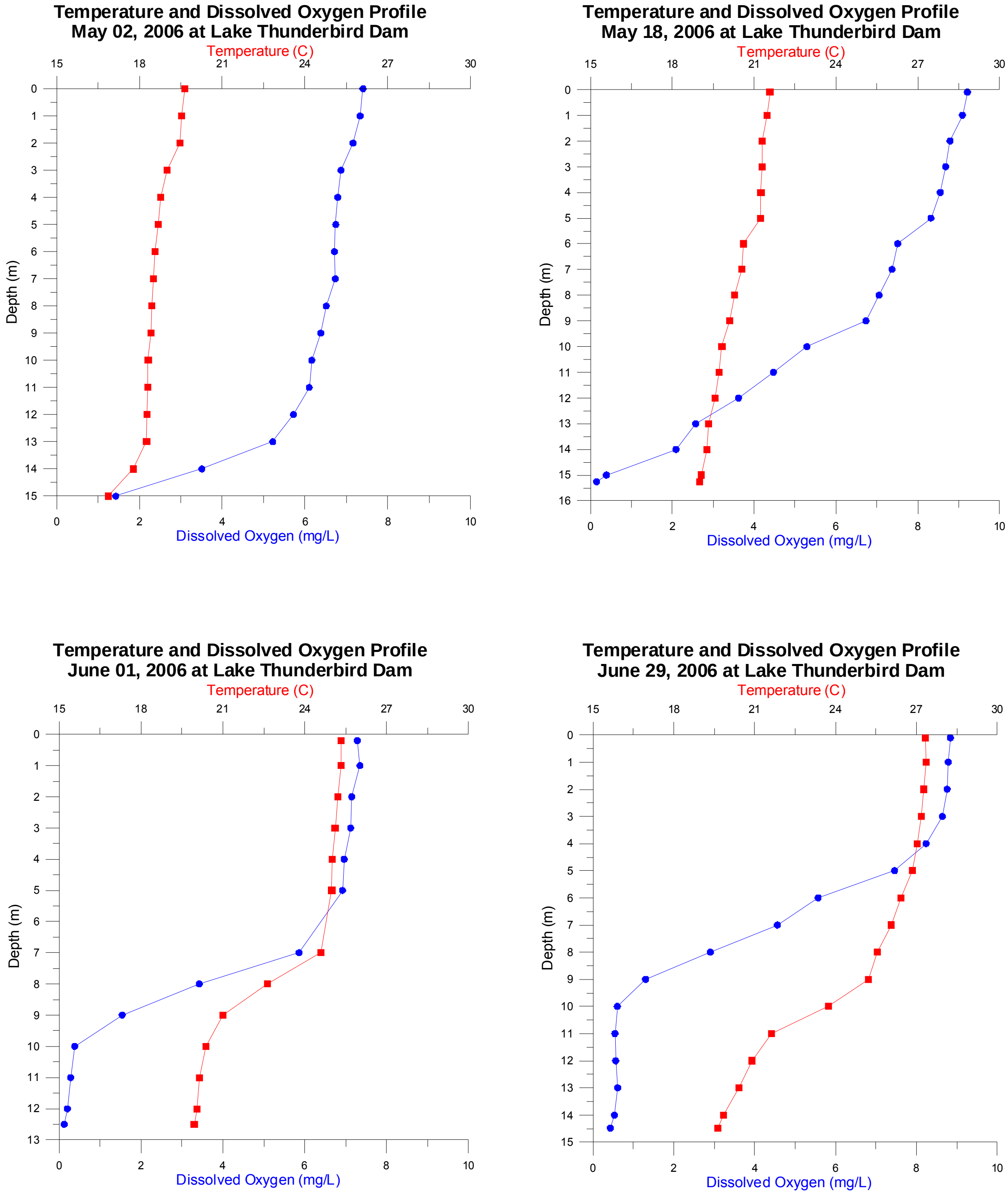


Figure 7: Temperature and Dissolved Oxygen Profiles for Site 1: May 2, 2006 – June 29, 2006. Showing the strengthening of thermal stratification and onset of hypolimnetic anoxia.

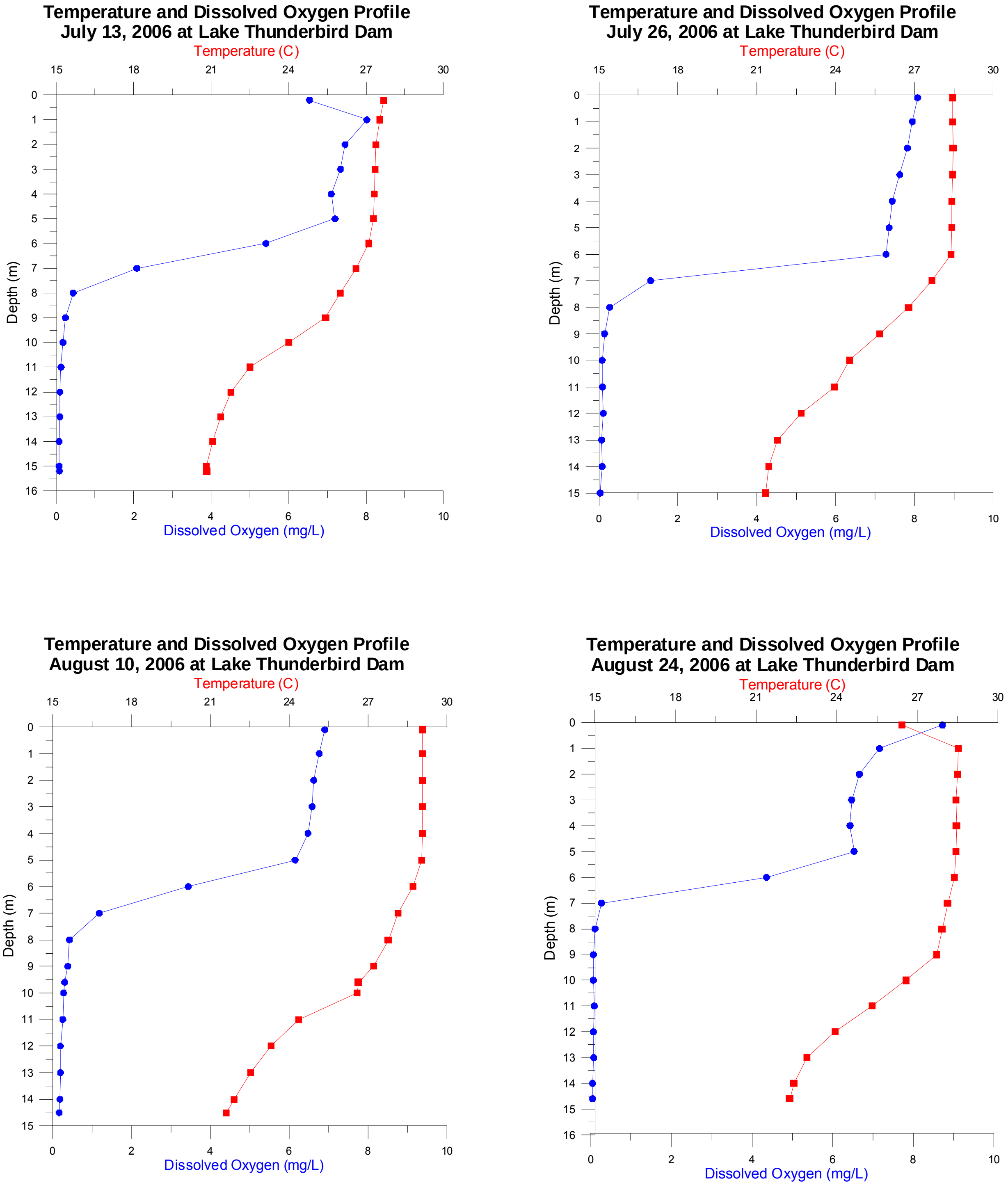
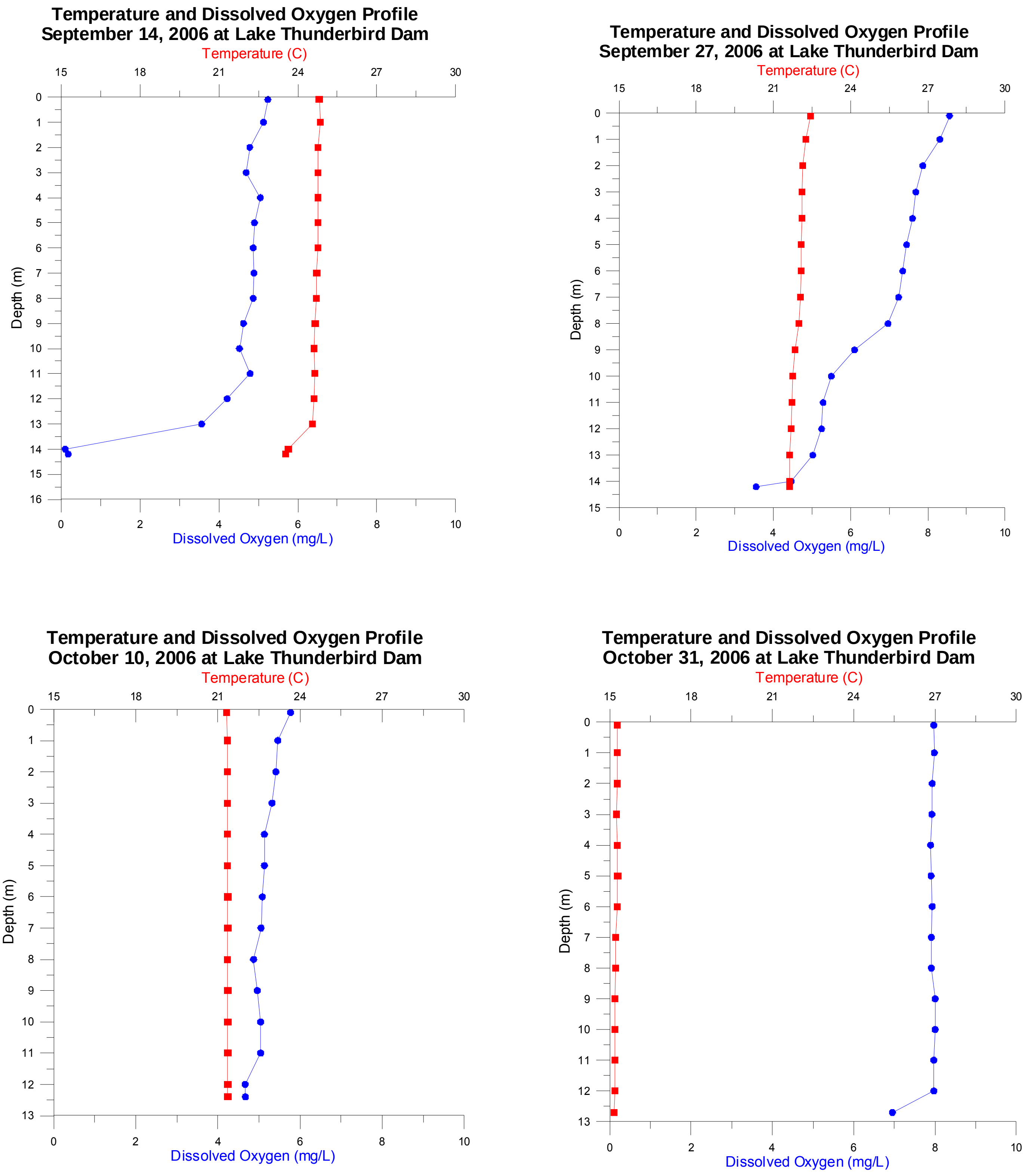


Figure 8: Temperature and Dissolved Oxygen Profiles for Site 1: July 13, 2006 – August 24, 2006. Showing the deepening of the epilimnion. The mixing of hypolimnetic waters into the epilimnion explains the relatively low dissolved oxygen record in August.


Temperature and Dissolved Oxygen Profile September 14, 2006 at Lake Thunderbird Dam

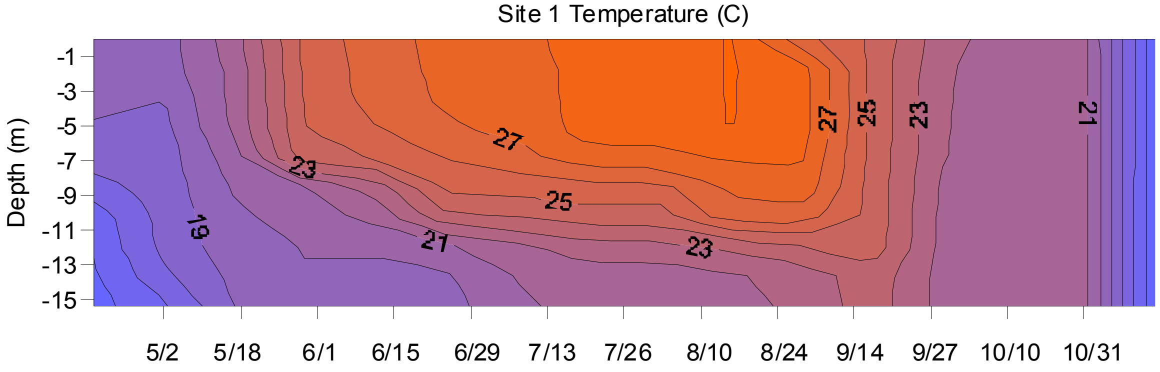
Temperature and Dissolved Oxygen Profile September 27, 2006 at Lake Thunderbird Dam

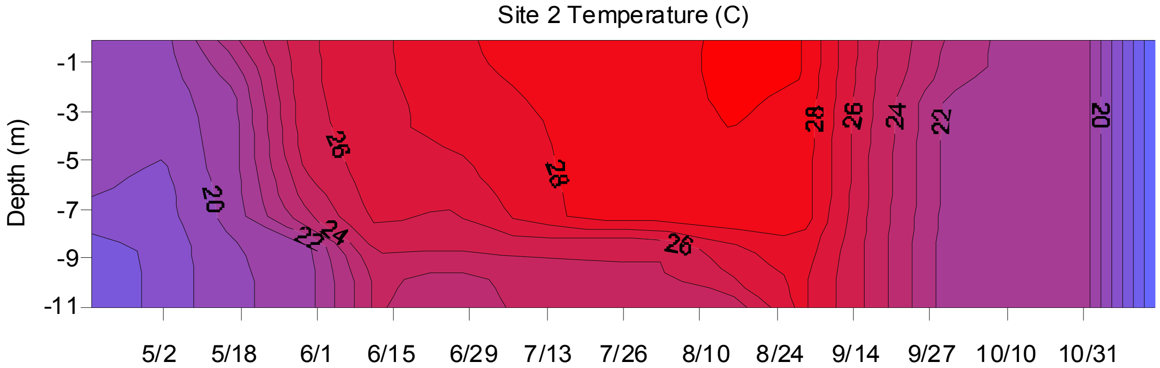
Temperature and Dissolved Oxygen Profile October 10, 2006 at Lake Thunderbird Dam

Temperature and Dissolved Oxygen Profile October 31, 2006 at Lake Thunderbird Dam

Figure 9: Temperature and Dissolved Oxygen Profiles for Site 1: September 14,2006 – October 31, 2006. Showing complete turnover and recovery of dissolved oxygen (Oxidation of reduced hypolimnetic components).

An alternate method for showing lake data is by using 3-dimensional plots termed isopleths, which display parameter variations in depth over time. The following isopleths show the same temperature (**Figure 10**) and dissolved oxygen (**Figure 11**) data, in a summarized form, for sites 1, 2, and 4. Each line on the isopleths represents a specific temperature or dissolved oxygen (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. Again, thermal stratification seems to have initiated by late-April with epilimnetic heating to a maximum by mid-August. Cooling though the late summer and early fall resulting in mixing of the metalimnion and hypolimnion until isothermal conditions are reached. Complete lake mixing appears to be earlier than normal partially due to the warmer than normal hypolimnion.


Site 1 Temperature (C)


Site 2 Temperature (C)

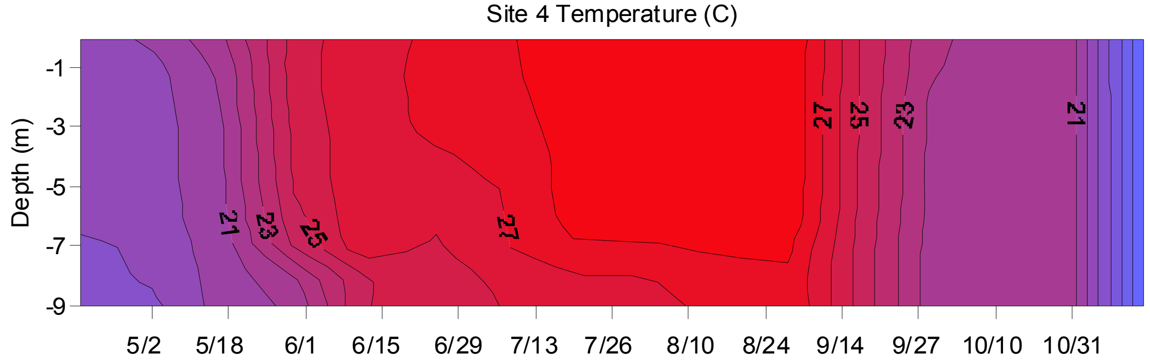
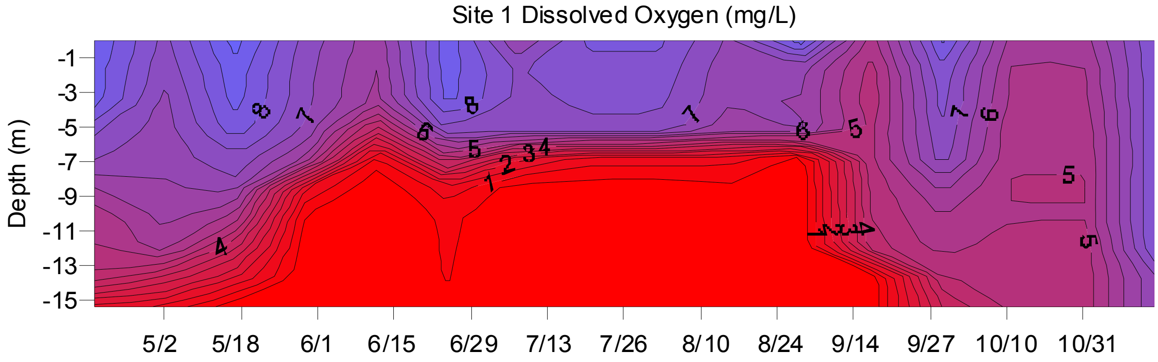
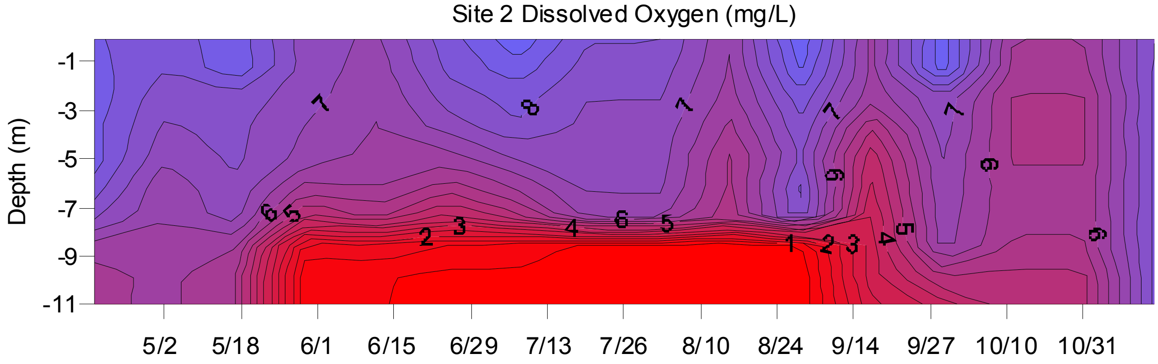

Site 4 Temperature (C)

Figure 10: 2006 Temperature Isopleths for Sites 1, 2, and 4





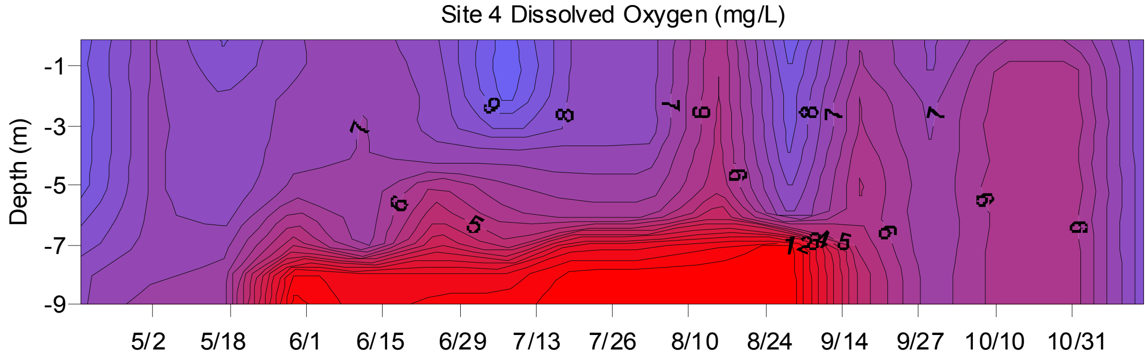


Figure 11: 2006 Dissolved Oxygen Isopleths for Sites 1, 2, and 4

Anoxia (or anaerobic conditions) in the lower (hypolimnetic) layer of the lake, 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 are reached at the lake bottom, nutrients and other constituents are solubulized from the sediment into the water. When mixing events occur, the 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.

Stratification began to develop by the first May sampling event, but the lake was not strongly stratified until May 18, 2006. On May 18, the hypolimnion was fully depleted of oxygen, with values under 2 mg/L from a depth of 9m to the lake bottom. After that date, the anoxia rose to depths that could be considered metalimnetic. Through June, July, and into the beginning of August, dissolved oxygen below 2 mg/L was observed from 7m to the lake bottom. On September 14 the depth of the hypolimnion began to drop, along with the anoxic area. Between September 14 and October 10, complete mixing of the water column occurred, and by October 31, the bottom of the water column was no longer anoxic. Because anoxia persisted after thermal stratification was disrupted, lake turnover likely occurred closer to October 10 than to the previous sample date.

Nutrients

Nutrient samples were collected fourteen times during the 2006 sampling season. Samples taken in April and May represent spring conditions; 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, and dissolved nutrients and total nutrients were compared. Dissolved nutrient concentrations include nutrients that are available for algal growth. High values in the epilimnion generally indicate that nutrients are immediately available for algal growth while high values in the hypolimnion indicate nutrients available for future algal growth. Higher dissolved nitrogen values in bottom samples show hypolimnetic accumulation of ammonia, which is expected when the hypolimnion is anaerobic.

Dissolved nutrients (nitrogen and phosphorus) in the epilimnion can also indicate what may be limiting algal growth. Generally, when both nitrogen and phosphorus are readily available, nutrients are not limiting to algal growth, and excessive chlorophyll-a values are expected. When dissolved phosphorus is readily available but very low to no dissolved nitrogen, algal growth may be limited by nitrogen. High to excessive levels of algal growth 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 using specialized cells called heterocysts. Blue-green algae are the only type of algae that produce heterocysts and are major producers of harmful toxins and chemicals that can cause taste and odor problems.

Phosphorus limitation is the desirable state 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. For general use, nutrient limitation is often described by the ratio of total nitrogen to total phosphorus concentrations (TN:TP). A recent study by Dzialowski (2005) has broken the ratio into three ranges instead of two. TN:TP ratio of less than or equal to 7:1 is defined as nitrogen-limited, a ratio of 8-18:1 is considered a co-limitation of both nitrogen and phosphorus and greater than 26:1 is defined as phosphorus-limited.

Thunderbird had TN:TP ratios in the 20's to 30's over the years indicating the lake was phosphorus-limited, but with more detailed ratios for the 2006 data the lake falls within a co-limitation of nitrogen and phosphorus (**Figure 12**). It is notable that no ratio in 2006 was above 26:1, which in all other years showed clear phosphorus limitation of algal growth.

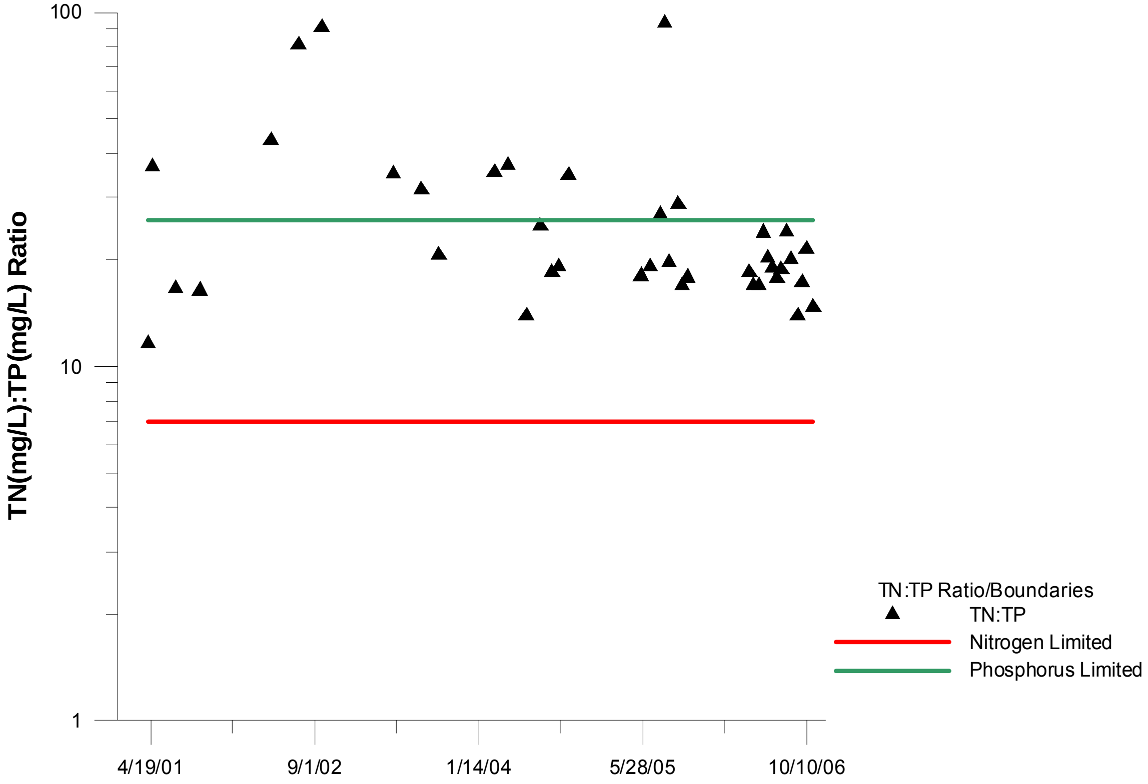


Figure 12: Surface Comparison of Total Nitrogen and Total Phosphorus Ratio at Site 1: 2001-2006

A comparison of nutrient concentrations across the five sampled years shows the common trend for Lake Thunderbird. Maximum concentrations are measured in the hypolimnion while the lake is stratified, and increased utilization of dissolved nitrogen occurs in the summer.

In 2006, surface dissolved nitrogen concentrations were similar to 2005 and relatively lower than in previous years (**Figure 13**). Surface total and dissolved nitrogen was consistently measured at or below the detection level of 0.05 mg/L for all sampled dates. These low surface dissolved nitrogen concentrations support a conclusion of nitrogen limitation for algae. Dissolved nitrogen was noted near the lake bottom and largely in the form of ammonia, associated with the anaerobic hypolimnion (**Figure 14**).

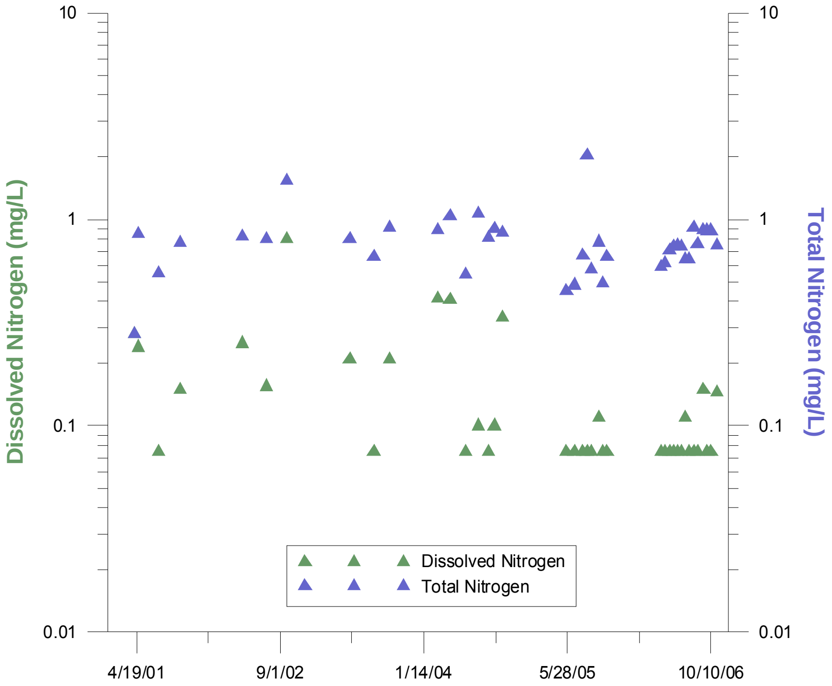


Figure 13: Surface Comparison of Total Nitrogen and Dissolved Nitrogen Species Concentrations at Site 1: 2001-2006

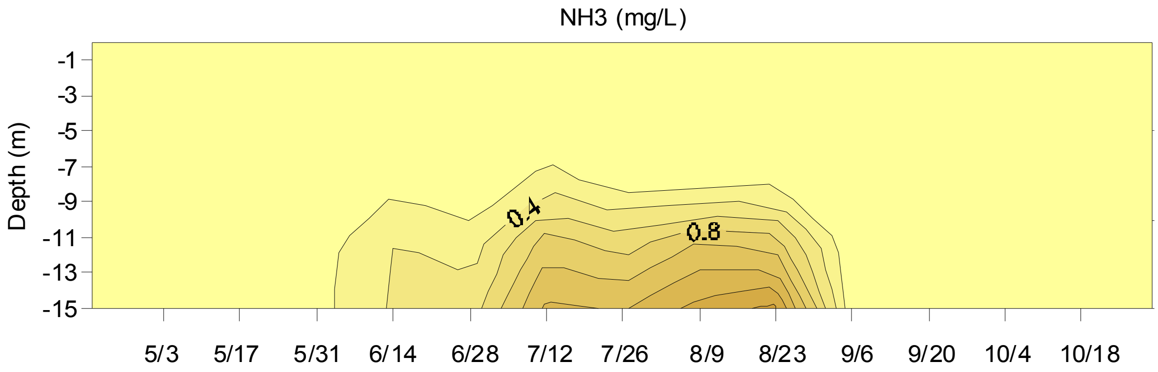


Figure 14: Plot of ammonia versus depth over time Site 1 April 2006 - October 2006

A seasonal pattern for ortho-phosphorus seems to be emerging from the increased monitoring (**Figure 15**). In both 2006 and 2005 surface ortho-phosphorus initially decreases then recovers by the end of the sample season. This shows the utilization of easily available phosphorus early summer and the regeneration of ortho-phosphorus 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.

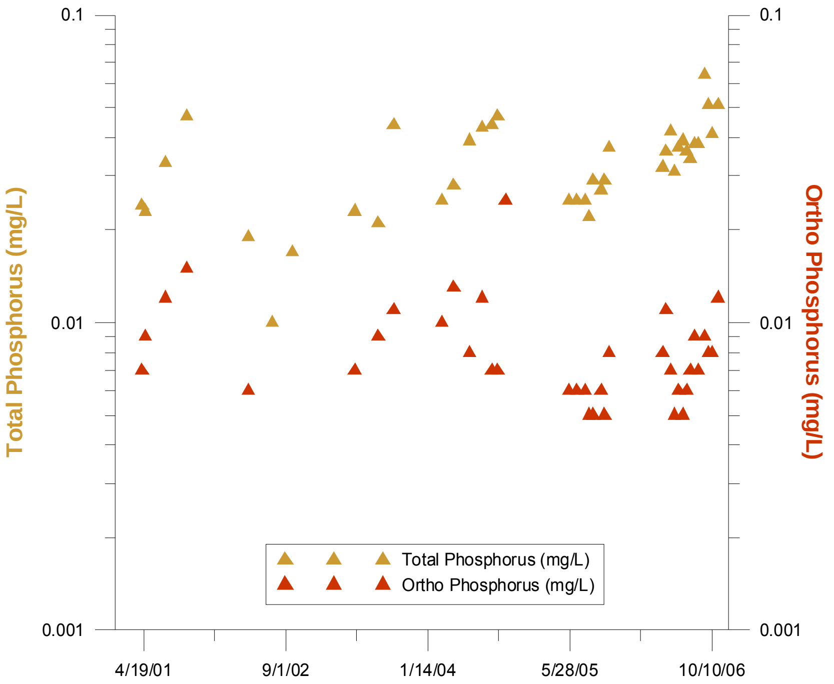


Figure 15: Surface Comparison of Total Phosphorus and Ortho (dissolved) Phosphorus Concentrations at Site 1: 2001-2006

Total phosphorus values in 2005 and 2006 show a seasonal increase representing an accumulation of epilimnetic phosphorus. The most likely source for epilimnetic accumulation of phosphorus is from the hypolimnion (**Figure 16**). 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 incorporation of the hypolimnion.

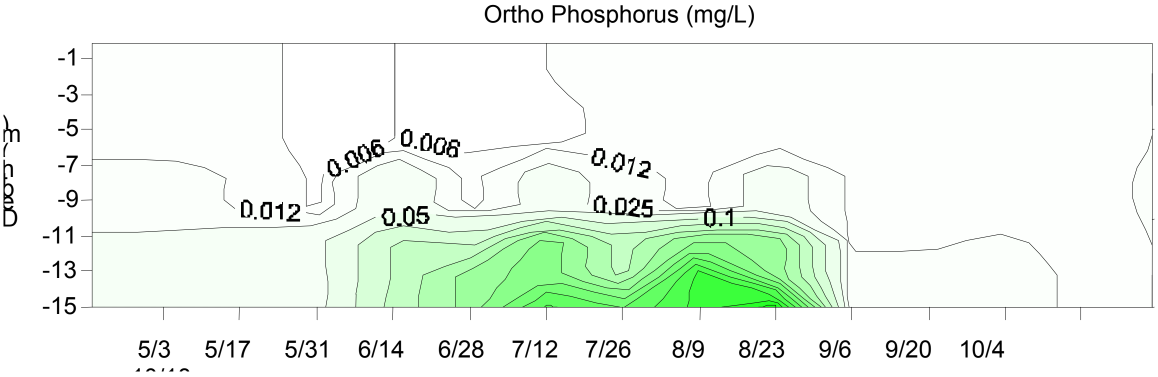


Figure 16: Plot of ortho-phosphorus versus depth over time Site 1 April 2006 - October 2006.

Nutrient Budget

A phosphorus budget for Lake Thunderbird was prepared integrating the estimated outflows from the water budget with the lake water quality data. The constructed budget shows pre-stratification lake phosphorus mass near 3,600 kg (**Table**). The lowest (3,510 kg) and highest (6,804 kg) amounts of lake total phosphorus were April 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 2006.

Month	Lake	Runoff	Sediment	Rainfall	Releases	Water Supply
January	NA	NA	NA	1	0	61
February	3583	NA	NA	2	0	49
March	NA	NA	NA	13	0	57
April	3510	NA	NA	15	0	63
May	4396	NA	NA	15	0	71
June	4771	NA	NA	17	0	86
July	5763	NA	NA	6	0	96
August	5450	NA	NA	13	0	114
September	4603	NA	NA	4	0	128
October	4241	NA	NA	15	0	105
November	NA	NA	NA	12	0	76
December	NA	NA	NA	17	0	65

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 2006. 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. 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 inflow, dry deposition and sediment flux. To complete the massing of Lake Thunderbird phosphorus, sample dates were averaged to yield monthly amounts. Monthly phosphorus mass plotted for 2005 and 2006 show a similar pattern of baseline levels in February, steady increase to a mid-summer peak (coinciding with stratification peak) followed by a decline as stratification breaks up (**Figure 17**). 2006 monitoring data was more consistent resulting in a smoother plot than 2005. Both years show the phosphorus mass in October (following break up of stratification and oxidation of hypolimnetic waters) to be significantly higher than at the onset of stratification.

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. Partitioning between these three sources require more accurate estimates of inflow load. It is important to note that the month of July recorded the lowest monthly water recharge and the highest phosphorus lake mass. This underscores the influence of sediment nutrient release on the lake nutrient status. Until water quality data is available for the tributaries to the lake, sediment influence can be put in context of the phosphorus mass from runoff and total phosphorus inputs.

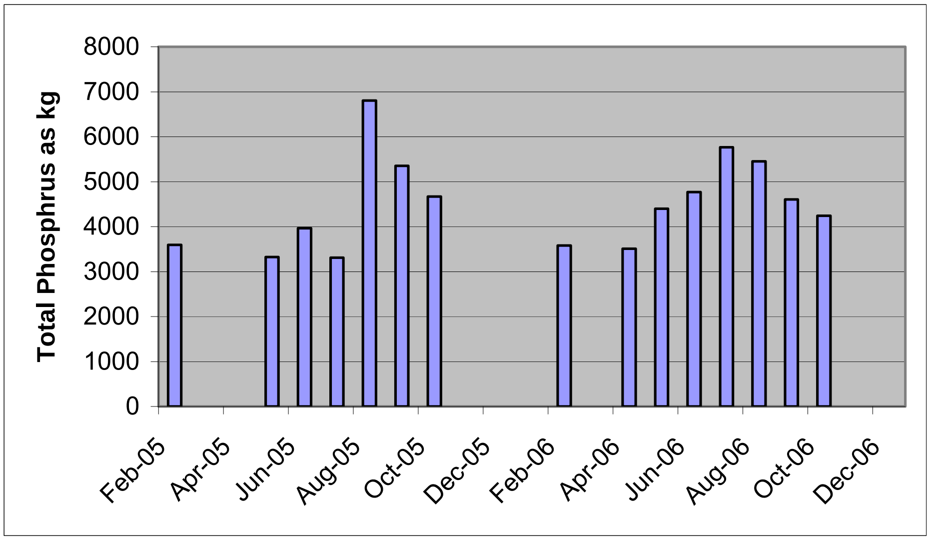


Figure 17: Monthly Phosphorus Mass (as kg P) of Lake Thunderbird 2005 - 2006

Chlorophyll-a

Chlorophyll-a, the molecule or pigment common to all algae, is a commonly accepted proxy of algal biomass. Goal setting in 2000 by the COMCD, the three municipalities, and OWRB resulted in an upper limit of 20 µg/L of chlorophyll-a for open water sites during the growing season. This upper limit represents a commonly accepted boundary between high (eutrophic) and excessive (hypereutrophic) algae growth. The boundary between eutrophic and lower (mesotrophic) algae growth is 7.2 µg/L.

Typically, the chlorophyll-a peak in Lake Thunderbird's open water sites occurs from the beginning of August to mid-September as stratification peaks. High chlorophyll-a values were noted late into 2006 sample season (**Figure 18**). Overall, 2006 concentrations were slightly higher than 2005. In a fashion similar to nitrogen and phosphorus, surface chlorophyll-a gradually increases over the sample season. Over all, 86% of the main body site samples were eutrophic in 2006 while six of forty-two (14%) samples exceeded the COMCD goal (20 µg/L).

The State of Oklahoma has set a 10 µg/L chlorophyll-a standard (using a rolling 2 yr. average) for Sensitive Water Supply (SWS) lakes**.** Examination of **Figure 19** shows the fluctuation of chlorophyll-a values over the past seven years by plotting a rolling 2-year average. Although only 29% of 2006 chlorophyll-a samples were at or less than 10 µg/L, achieving the Standard is an obtainable goal in the near future. This is highlighted by noting that the low chlorophyll-a in 2002 resulted in a rolling average just above the 10µg/L standard. Active management will be needed to reach this standard.

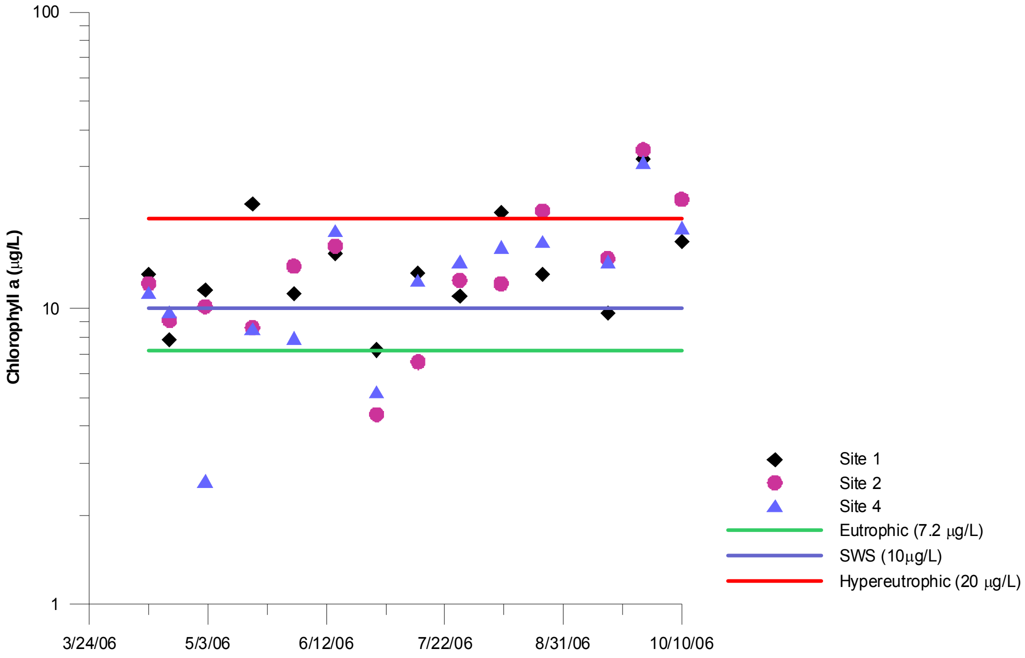


Figure 18: 2006 Chlorophyll-a of Lacustrine Sites

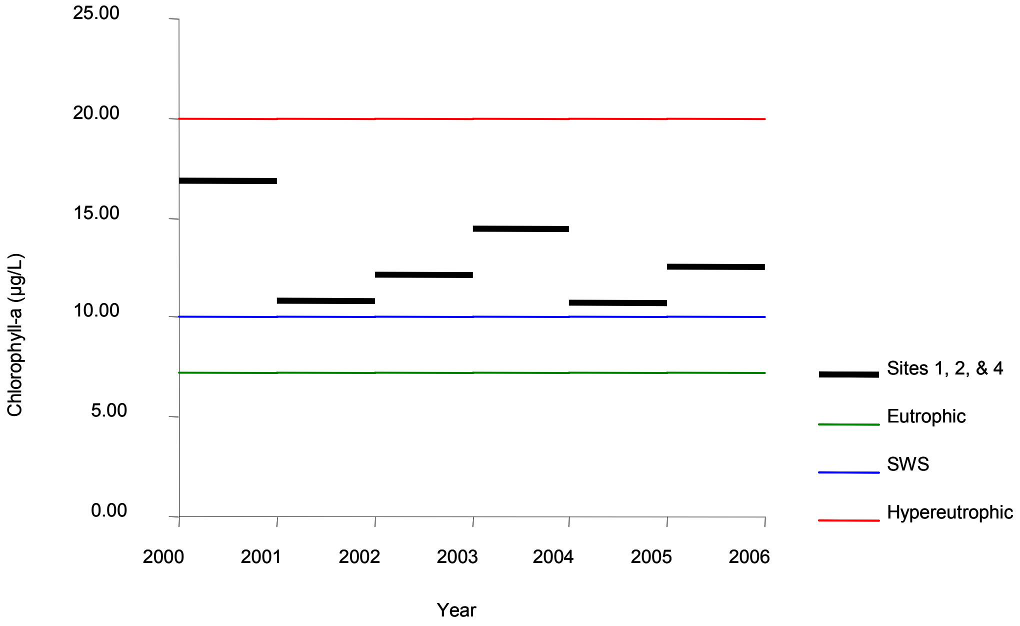


Figure 19: 2000- 2006 Chlorophyll-a for Main Body Sites (Rolling 2 yr. Average)

Taste and Odor Complaints

Taste and odor complaints can act as another indicator of lake productivity and are tracked by the City of Norman (**Figure 20**). Chemicals that have objectionable taste and/or odors in water are generally byproducts of algal productivity, and mostly attributable to species of blue-green algae (Cyanophyta). Typically, taste and odor events occur when significant hypolimnetic erosion occurs. Comparing the relative number of taste and odor complaints for each September gives an idea of the relative amount of organic material and nutrients released from the hypolimnion. In 2006, the total number of complaints (seven) approximated those in 2005 (eight). 2005 and 2006 peak complaint months fall short of the massive complaints received in 2003 and 2004.

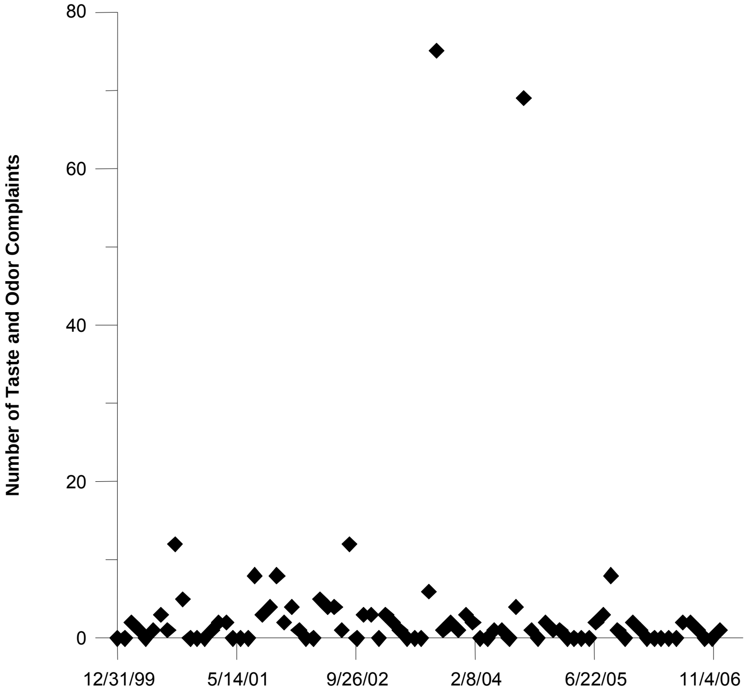


Figure 20: 2000 - 2006 Taste and Odor Complaints, City of Norman

Total Organic Carbon

Another measure of organic content is total organic carbon (TOC). The main body of the lake is represented with surface samples from sites 1, 2, and 4. Total organic carbon concentrations generally showed an increase over the sampling season (**Figure 21**). Following lake destratification, TOC increased to slightly higher levels than seen in the spring. TOC showed some variation by site, with lower concentrations recorded at site 1, at the dam and the highest at site 2, on the Hog Creek arm.

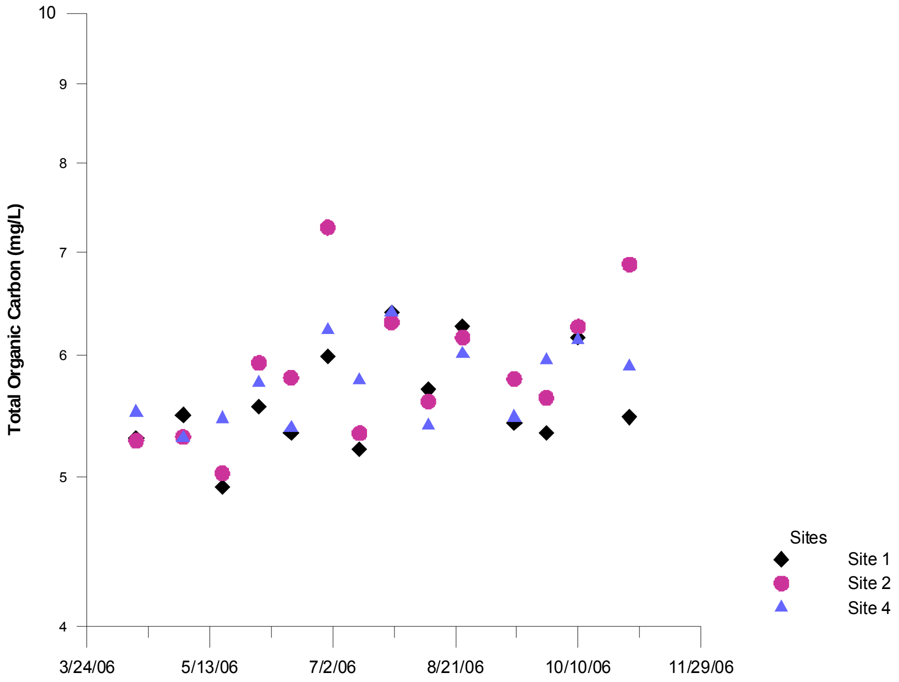


Figure 21: Surface Total Organic Carbon for Sites 1, 2, and 4 at Lake Thunderbird, 2006

Oklahoma Water Quality Standards

Lake Thunderbird was listed on the 2002 303(d) list as impaired due to low dissolved oxygen and turbidity, both as the cause unknown. 2006 data were compared against the Oklahoma Water Quality Standards (OWQS) to check these and the new chlorophyll-a standard.

Data Requirements

The Use Support Assessment Protocols (USAP) of the OWQS has temporal and spatial requirements for data used to determine beneficial use attainment. Sampling sites should be spaced to give a representative view of the lake. The data should not have seasonal bias, and should not be older than five years old. There is a minimum requirement of 20 samples on a lake of this size, and the samples should be collected using standard methods. The current sample design satisfies these requirements although sampling is biased toward the growing season and against the winter season.

Water Quality Criteria

For dissolved oxygen and turbidity, the beneficial use with applicable criteria is the fish and wildlife propagation use. There are two criteria for DO in lakes, using percent water column anoxia and surface DO levels. If greater than 70% of the water column has DO concentrations of less than 2 mg/L, the fish and wildlife propagation beneficial use is not considered to be supported. If between 50% and 70% of the water column has DO less than 2 mg/L, the beneficial use will is considered partially supported. Whether a water body is partially or not supporting its beneficial use, either of these assessments yields an impaired listing. A single event with inadequate DO through the water column will yield a non-support assessment.

The screening level for surface DO is 4 mg/L from June 16 to October 15, and 5 mg/L for the rest of the year. The fish and wildlife propagation beneficial use will not be supported if greater than 25% of samples are below the screening level, partially supported if the number of samples below the screening level is between 10% and 25%, and fully supporting if less than 10% of the samples fall below the screening level. Use assessments other than fully supported (partially or not supporting) presumes the beneficial use to be impaired or not attained. To be fully supporting for dissolved oxygen, both water column and surface screening must yield fully supporting for an overall assessment of fully supporting.

For turbidity, the screening level for lakes is 25 NTUs. If greater than 25% of samples are above the screening level, the lake is not supporting the fish and wildlife propagation beneficial use due to turbidity. A partially supporting assessment is made if between 10% and 25% of samples are above the screening level, and the use is fully supported if less than 10% of samples are above the screening level. Use assessments other than fully supported (partially or not supporting) presumes the beneficial use to be impaired or not attained.

Beneficial Use

In 2006, 24% of turbidity samples were above the screening level of 25 NTUs, which means that Lake Thunderbird is partially supporting the fish and wildlife propagation beneficial use with respect to turbidity (**Figure 22**). A review of 2005 data show 13% and 2004 data show 19% of the turbidity samples exceeded the 25 NTU criteria. 2006 data supports the impaired listing of fish and wildlife propagation in Lake Thunderbird due to turbidity. Turbidity appears to have increased from the previous years.

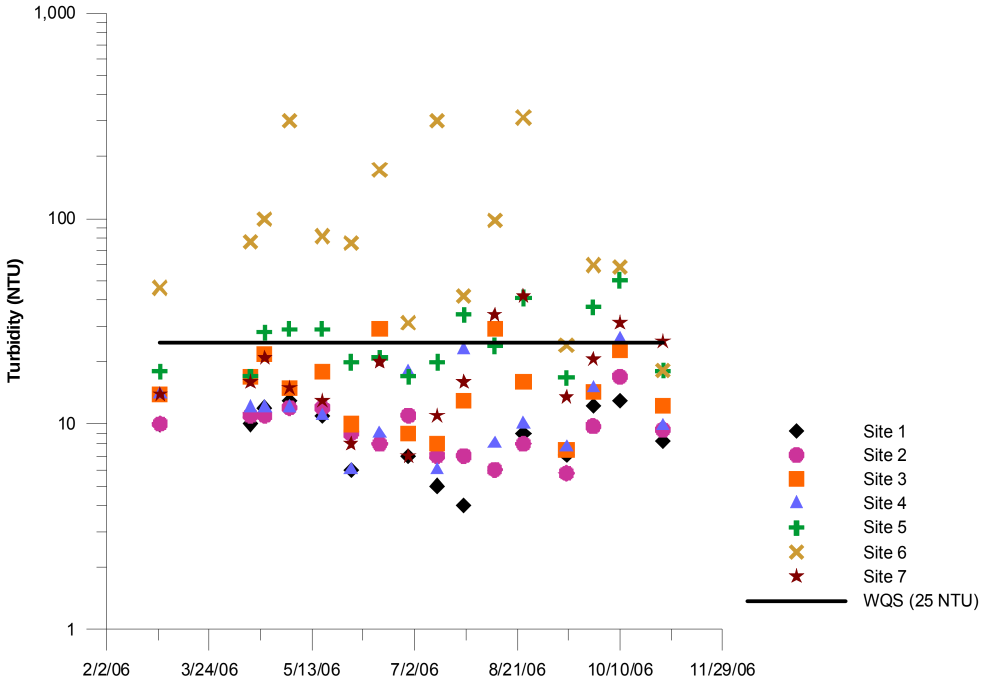


Figure 22: 2006 Turbidity Values for All Sampled Sites

When surface screening levels are used to assess dissolved oxygen in 2006, the beneficial use was fully supported. Measurements showed 98% (2 of 96) of the surface dissolved oxygen concentration above the screening level. Both samples were on the same day August 10, 2006 and were at site 5 and site 7. Although surface valued passed screening, the water column values support an impaired listing for Lake Thunderbird fish and wildlife propagation due to low dissolved oxygen.

With respect to dissolved oxygen, Lake Thunderbird was partially supporting the fish and wildlife propagation beneficial use in 2006. When considered using percent water column anoxia, anoxic conditions were first seen at 7 m, which yields approximately 53% of the water column anoxic at site 1. There were five specific events where anoxia was reached in approximately 50% of the water column. June 15th was the first event and the water column fluctuated just below 50% until July 26th. Anoxia was consistently greater than 50% of the water column from July 26th until the September mixing occurred.

Summary & Discussion

Climatic Effects

As in the previous several years, Lake Thunderbird did not receive normal inflow, with 2006 annual rainfall total around 56-60% of the normal 38 inches. The spring and summer seasons had between 71-79% of normal rainfall. The lowest rainfall occurred in the winter season, with 23% of normal rainfall. According to the Oklahoma Climatological Survey, the winter of 2006 was the 1st driest in a record of 85 years. The lowest annual rainfall total for central Oklahoma was 22.02 inches, compared to the 22.36 inches recorded at Norman for 2006. Air temperatures in 2006 showed elevated spring and summer temperatures and lower fall temperatures.

Lake levels did not recharge during the 2005-2006 winter season and continued to drop from the lowest level in 2005 of approximately 1,036 feet. A large inflow event in April produced a slight increase of elevation but throughout spring, summer, and fall there was continued decrease. By the end of the year, the lake was at an elevation of 1030 ft, which is 9 ft below the conservation pool elevation.

Taste & Odor Complaints, Algae and DO

The tendency towards high to excessive algae growth is the likely driving force behind the spike in taste and odor complaints experienced by the City of Norman. Monitoring data from the past six years show a consistent drop in surface dissolved oxygen (DO) for the entire monitored area each September. This drop or sag in surface dissolved oxygen is the result of hypolimnetic waters mixing with the surface. As the reduced chemicals from the hypolimnetic water are oxidized, surface DO falls. The intensity of reducing conditions and amount of mixing that occurs determines the intensity and volume of the DO sag in September. The mixing of reduced hypolimnetic waters and spike in taste and odor complaints in September are likely directly linked.

For the most part, the accumulation of dead and dying algae cells in the hypolimnion drive the oxidation-reduction potential of the hypolimnion lower and lower throughout the summer. Low, reducing conditions tend to store taste and odor chemicals released by algae cells much better than in an aerobic environment. In September, significant cooling of the surface water occurs and portions or all of the hypolimnion mixes with the surface lake layer. Oxidation of these released hypolimnetic waters usually brackets taste and odor complaints to September. Dissolved nutrients released from the lake bottom are also brought to the surface to stimulate fall and early winter algae growth.

In 2006, taste and odor complaints were the lowest in seven years. That surface dissolved oxygen did not have the surface water sag typical of other years indicates anoxia was not as severe as other years. For example there were only two surface samples of DO that were below the screening level of 4mg/L while other years have shown lower DO over a greater number of sites. The low DO samples both occurred on August 10th. OWRB did not assess for changes in

City of Norman treatment methods (for instance increased PAC use) as a potential contributor to lowered T&O complaints in 2006.

Oxidizing the Hypolimnion

Maintaining an oxidized hypolimnion will allow for the oxidation of 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 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 another 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 1980's proved too energy intensive to be implanted. It is likely that some active intervention, such as nutrient inactivation or pneumatic oxidation, as opposed to whole-lake mixing, will be needed to provide a hypolimnion oxidized enough to flatten the annual spike in taste and odor complaints.

State Water Quality Standards

Water quality monitoring data was examined to check Oklahoma's Integrated Report listing of Lake Thunderbird as fish and wildlife impaired due to high turbidity and low dissolved oxygen. Lake Thunderbird did not meet its beneficial use for dissolved oxygen, therefore supporting its 303d listing for that parameter. It should be noted, Lake Thunderbird is in queue by the Oklahoma Department of Environmental Quality for a TMDL.

A review of 2006 and 2005 data show Lake Thunderbird to be "partially supported" for turbidity. According to Oklahoma Water Quality Standards "partially supported" yields an "impaired" conclusion and supports the integrated report listing for turbidity. Although there were high turbidity events in August and October of 2006, it was the consistently high turbidity at Site 6 that ensured an impaired conclusion for Lake Thunderbird. However, all available data from representative lake sites must be used in the assessment and Lake Thunderbird will likely remain listed for this parameter.

2006 marked the adoption of a 10 μg/L standard of chlorophyll-a for sensitive water supply (SWS) reservoirs. Lake Thunderbird is currently a SWS reservoir, with mean chlorophyll-a concentrations from the past two years exceeding 15 μg/L. Lake Thunderbird is therefore not meeting the requirements of the new chlorophyll-a standard.

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 also reduce the possibility of September taste and odor problems.

Continued nutrient sampling. Current sample scheme allows effective accounting of phosphorus in Lake Thunderbird.

Extend 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 water quality data is the first step toward a detailed lake nutrient budget (allowing for sediment and tributary sources). Efforts to include year-round monitoring and storm flow events linked to a watershed water quality model are a logical next step.

Additional evaluations. Data sufficient to predict a phosphorus level equivalent to 10 μg/L of chlorophyll-a has been collected. An accounting of suspended solids and nutrient sources from the watershed and internal lake process should be placed in context of a water quality response model. This accounting provides a solid platform towards developing most feasible first steps toward Lake Thunderbird meeting state water quality standards and enhancing raw water quality for COMCD customers.

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