Oklahoma Water Resources Board

Lake Thunderbird Water Quality 2004

for the

Central Oklahoma Master Conservancy District

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Final Report

Oklahoma Water Resources Board
3800 N. Classen Boulevard
Oklahoma City, OK 73118

Executive Summary

Lake Thunderbird monitoring data from 2004 showed a eutrophic lake with likely periods of excessive algae growth. Chlorophyll-a, although not directly comparable to previous years' data sets, indicated algae growth similar to that in 2003. Another measure of productivity, duration of anoxia, was consistent with previous years' assessments. Recent 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. Should sufficient data be presented to show the lake is fully supporting its beneficial uses with respect to each parameter the lake can be "de-listed" for the parameters. De-listing removes the state requirement for the completion of a TMDL for that parameter. 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. Data was not conclusive enough to suggest de-listing Lake Thunderbird for either parameter.

It is reasonable to expect Lake Thunderbird to maintain eutrophic (high) summer time algae growth with occasional periods of excessive algae growth without additional management. While algae growth borders on excessive, it is also reasonable to expect spikes in customer complaints in September for the City of Norman. It is likely that strong reducing conditions in the hypolimnion serve to "store" taste and odor causing chemicals throughout the stratification period. It is not until this water is mixed and oxidized (dissolved oxygen in the lake recovers) that complaints fall towards "normal". It is in September when hypolimnetic water mixes to the surface, surface dissolved oxygen sags, and number of complaints increases. Maintaining a more oxidized hypolimnion would allow for taste and odor (T&O) causing chemicals to degrade. An oxidized hypolimnion also has the benefit of reducing the release of nutrients from the lake bottom. It is likely that active intervention, such as the use of a pneumatic device, is needed to provide enough oxidation to flatten out September T&O complaints.

The most direct method to reduce T&O chemicals is for the lake to not produce them in the first place. As the magnitude of nutrient reductions needed to solve the problem may not be feasible, alternative measures should be examined. The following recommendations are steps toward mitigating the T&O problem in Lake Thunderbird.

1. Determine the feasibility of oxygenating the hypolimnion of Lake Thunderbird.
2. Modify nutrient sampling schedule
    a. In-lake for lake nutrient budget
    b. Tributary for external nutrient budget
3. Evaluative processes: include development of lake water and nutrient budget as well as initiate processes to determine watershed nutrient loading

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Introduction

Lake Thunderbird was constructed by the Bureau of Reclamation and began operation in 1966. Designated uses of the dam and the impounded water are flood control, municipal water supply, recreation, and fish and wildlife propagation. As a municipal water supply, Lake Thunderbird furnishes raw water for Del City, Midwest City, and the City of Norman under the authority of the Central Oklahoma Master Conservancy District (COMCD). The Oklahoma Water Resources Board (OWRB) has provided water quality-based environmental services for the COMCD since 2000. The focus of OWRB contractual services to the COMCD has been the management of Lake Thunderbird. In cooperation with the municipalities of Norman, Midwest City, and Del City, the COMCD and OWRB have set a water quality based goal for Lake Thunderbird (chlorophyll-a is to not exceed 20 µg/L), the conservation pool of Lake Thunderbird has been mapped and its capacity determined, the currently installed aeration device has been evaluated and lake management adjusted to enhance water quality, and finally, a comprehensive data set is being compiled to track lake water quality over the long term.

Lake Thunderbird is listed in the state's Integrated Report as a category 5 water (303d listing) having impaired water quality for fish and wildlife propagation due to excess turbidity and low dissolved oxygen. The following are direct links to the ODEQ website for the Integrated Report and 303d list, respectively:
http://www.deq.state.ok.us/WQDnew/305b_303d/2002_integrated_report_final.pdf
http://www.deq.state.ok.us/WQDnew/305b_303d/2002_ir_app_c_category_5.pdf
Because of its impaired status, Lake Thunderbird is slated for Total Maximum Daily Load (TMDL) allocations to be completed by the Oklahoma Department of Environmental Quality Water Quality Division (ODEQ) for the parameters of dissolved oxygen and turbidity. It is likely that had the COMCD not ceased operation of the in-lake aeration device Thunderbird would also be listed as impaired due to excessive nutrients (due to high chlorophyll-a). The Integrated Report lists the source of impairment for Low DO and turbidity as unknown. Historical COMCD water quality data suggests high algae productivity contributes significantly to the low dissolved oxygen problem while the current turbidity issue is relegated to the upper end of the Little River upstream of Alameda Drive. Although listed as impaired for fish and wildlife propagation, Lake Thunderbird State Park continues to be one of the most highly utilized state parks in Oklahoma.

The objective in 2004 was to continue routine environmental monitoring of Lake Thunderbird. Modifications from past years' routine were to decrease sample frequency to monthly, increase data intensity by including nutrient analysis with every sample event and extend the timeline into November to better bracket seasonal effects. Recommendations for 2005 water quality management are presented.

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 while 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 14 to November 30, 2004 on a monthly basis with some biweekly sampling (**Table 1)**. 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 sampled parameters are chlorophyll-a, algae species identification and enumeration, total organic carbon, turbidity, and Secchi disk depth.

Table 1: Sampling dates for specific parameters.

Date	Water Quality	Hydrolab	Chlorophyll-a	Algae	TOC	Turbidity
03/03/04	X*	X*	X*	X*		X*
04/14/04	X	X	X	X		X
04/30/04		X	X	X		X
05/13/04		X	X	X		X
05/27/04		X	X	X		X
06/08/04	X*	X*	X*			X*
06/24/04		X	X	X		X
07/22/04	X	X				X
08/30/04	X			X	X	X
09/16/04	X	X	X		X	X
09/23/04		X				X
10/14/04	X	X			X	X
11/30/04	X**	X**	X	X	X	X

*BUMP data
**No site 1 data collected

Algae and nutrient samples were collected only at sites 1, 2, and 4. Chlorophyll-a, turbidity, and hydrolab data were collected at all sites, with the exception of chlorophyll-a at site 7. Total organic carbon sampling was initiated in August on a monthly sampling schedule at sites 1, 2, 3, 4, and 6. Nutrient and TOC samples were collected at the surface and 0.5 m from the bottom of the water column. Not all data collection events followed contractual obligations. For example, the March sample event was performed through the Beneficial Use Monitoring Program (BUMP) of the OWRB and so did not follow the contracted procedures. In the same manner, algae samples were taken during FY-05 (not requested in the FY-05 contract) but for the OWRB's statewide Harmful Algae Bloom (HAB) project. OWRB staff also performed extra field sample events to ensure proper characterization of stratification. For example the delay in

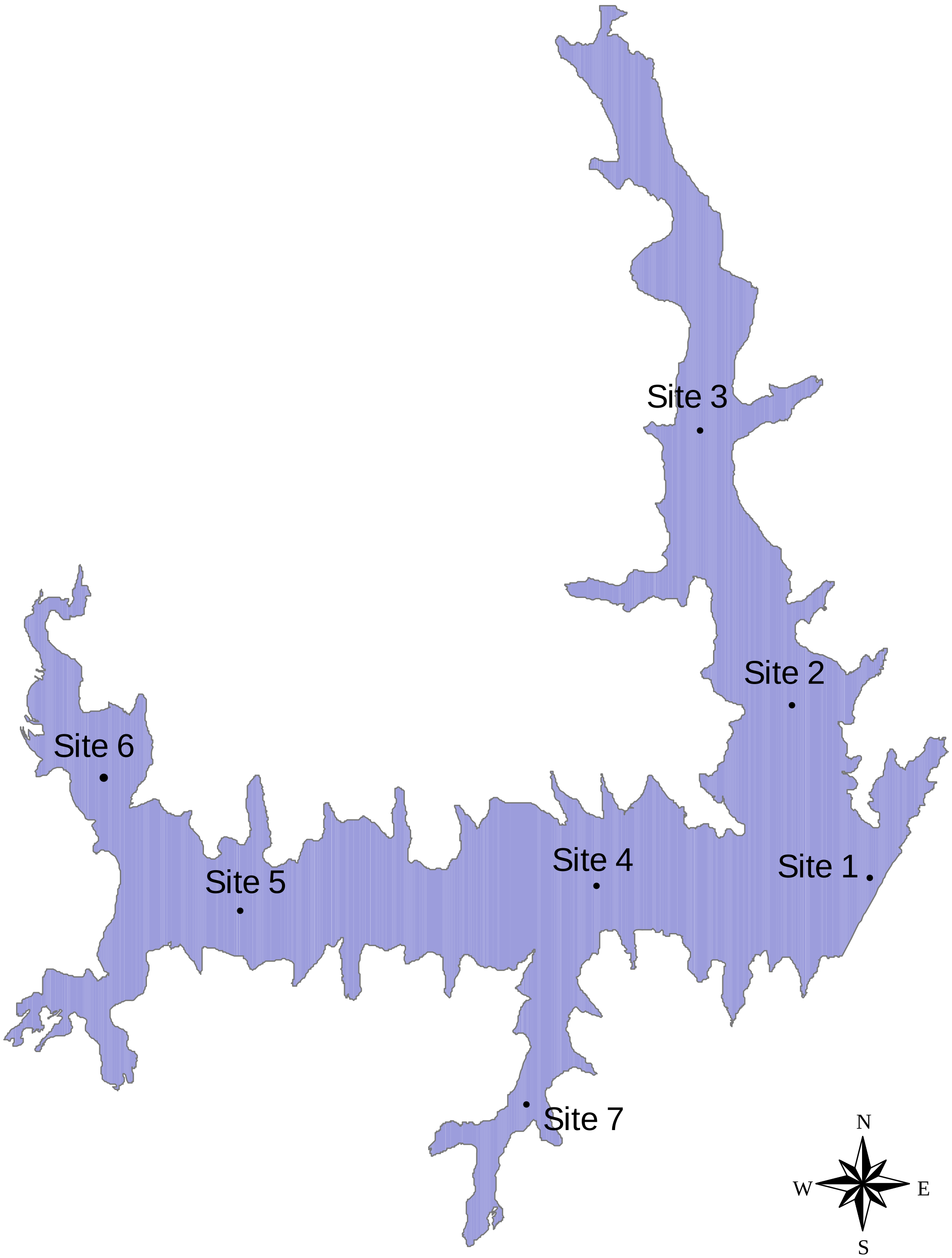

Figure 1: Lake Thunderbird sample sites.

establishing a monitoring contract until August 2004 should have eliminated any sampling from occurring in July. In order to minimize the impact to the data OWRB staff performed a field trip to the lake in July collecting data not requiring laboratory analysis (**Table 1**). Even with these extra non-contractual efforts, data gaps were present during the summer growing season. These gaps made it difficult to provide direct comparisons with previous sampling periods. Due to the data gaps, the diagnostic parameters for this report will be temperature and dissolved oxygen and nitrogen and phosphorus constituents and duration of anoxia in the hypolimnion.

Climate

In interpreting the results of water quality sampling, knowledge of some of a lake's hydrologic characteristics is essential. Lake hydrology, including changes in the lake's elevation and inflow, has a major impact on the chemical and biological processes that occur within the lake. Stormflow events influence nutrient and sediment loading into the lake, resuspension of lake sediments, and stratification patterns. Changes in lake elevation and nutrient loading can also affect the extent of anoxia in the water column and the hypolimnetic oxidation-reduction potential, which in turn affects solubilization of nutrients and metals from the hypolimnetic sediment.

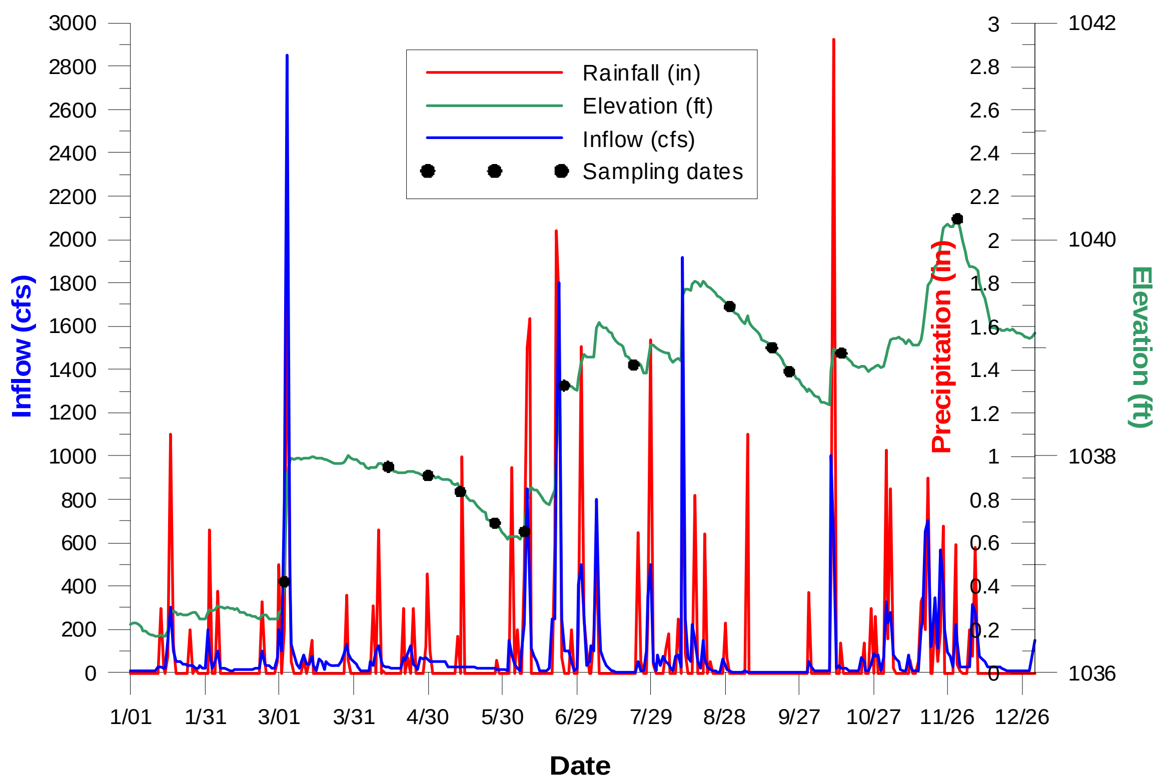

Figure 2: 2004 Inflow, Elevation, and Precipitation for Lake Thunderbird, with sampling dates

Figure 2 shows Lake Thunderbird's inflow, elevation, rainfall, and sampling dates for the 2004 reporting period (OCS, 2005a). Lake levels can vary considerably with area rainfall patterns. Consulting Oklahoma Climatological Survey data showed that 2004 was a normal rainfall year for central Oklahoma when considered on an annual basis, with 101% of the normal amount of precipitation. Rainfall by season was less typical (**Table 2**), with 97% of the normal rainfall for the winter, 64% in the spring, 144% in the summer, and 110% in the fall (OCS, 2005b).

Table 2: Rainfall Normals and Extremes for Central Oklahoma (OCS, 2005b).

	2001		2002		2003		2004	
	Total	%	Total	%	Total	%	Total	%
Winter	7.57	145%	4.65	89%	4.0	76%	5.07	97%
Spring	9.74	79%	9.61	78%	7.68	62%	7.93	64%
Summer	5.8	59%	10.03	103%	10.55	108%	14.08	144%
Fall	8.28	78%	9.36	88%	6.41	61%	11.67	110%
Annual Total	31.37	83%	35.1	92%	27.11	71%	38.43	101%

Rainfall patterns have varied in the past few years, with annual rainfall totals from 71% to 101% of normal levels. 2004 has been the most normal of the sampled years.

Air temperature will also impact lake dynamics by influencing stratification patterns and lake productivity rates. Temperature also impacts algal community structure; different types of algae have different optimal temperature ranges for maximum growth. Average daily temperature data for the growing seasons of 2001 through 2004 are shown in **Figure 3**.

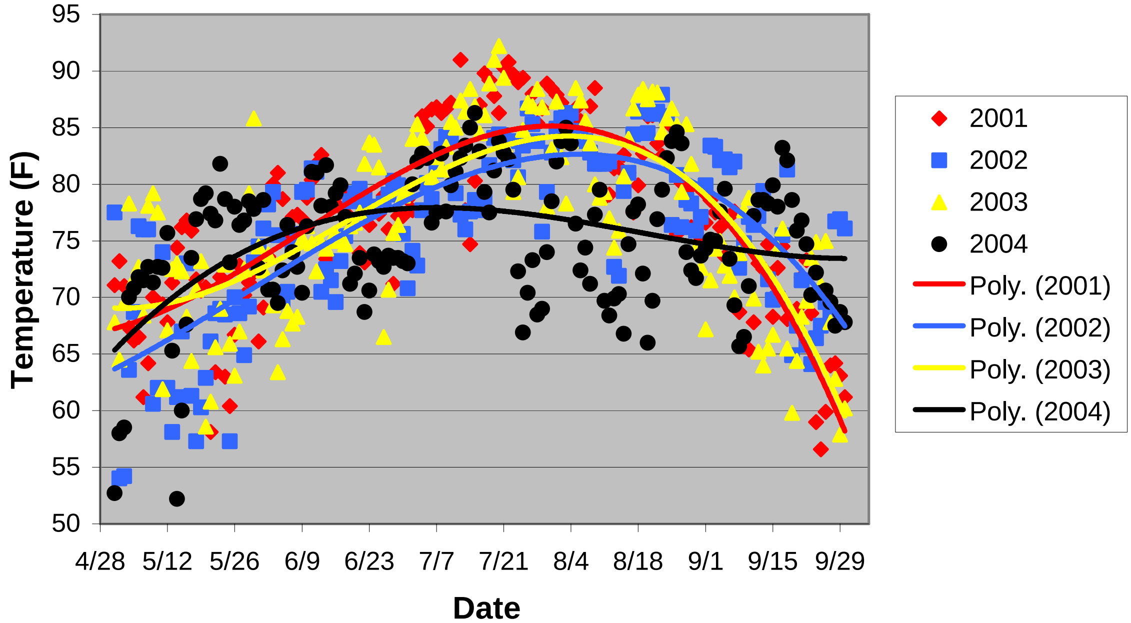

Figure 3: Air Temperature (F) reported at Norman Mesonet station (OCS, 2005a).

For each year, a third order polynomial trend line was also plotted. Compared to the normal temperature pattern, 2004 had warmer spring temperatures and lower summer temperatures. It is reasonable to assume that the epilimnion of Lake Thunderbird would not have gotten as warm as previous years.

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 4**). The figure also shows the depletion of dissolved oxygen in the lower layer of the lake due to stratification and decaying organic matter in the hypolimnion. Decaying matter consume oxygen while oxygen recharge from the epilimnion is minimized by the metalimnetic barrier.

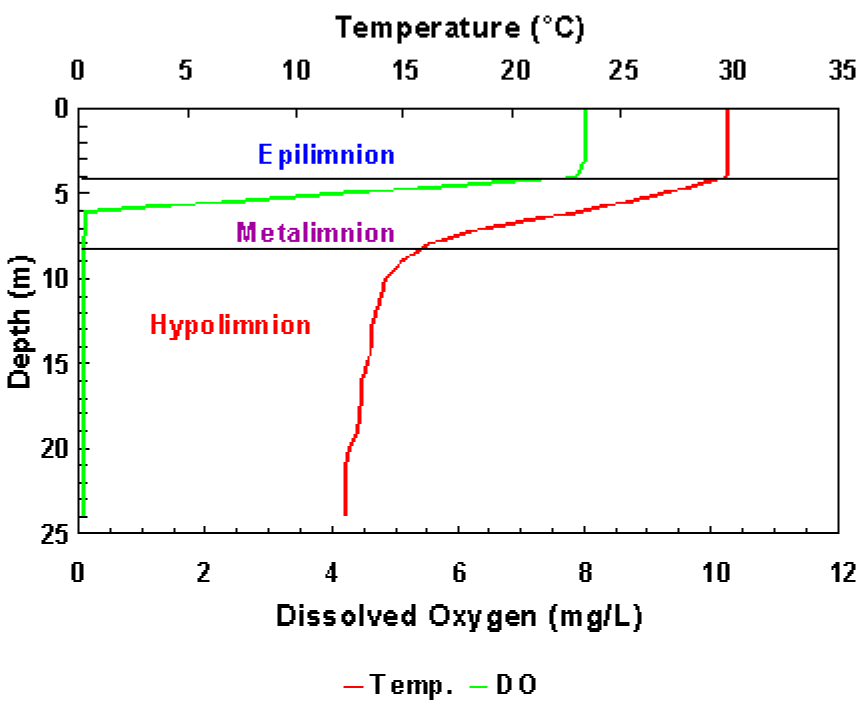

Figure 4: Temperature and dissolved oxygen profile for a typical eutrophic lake showing three distinct layers (epilimnion, metalimnion and hypolimnion).

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.

On April 14, 2004, conditions were relatively isothermal at site 1, with constant dissolved oxygen (DO) levels throughout the water column (**Figure 5**). By April 30, weak stratification was beginning to develop below 7.0 m, paired with decreasing DO concentrations with depth. On this date, the temperature differential was less than 2 degrees, which would cause a partitioning of water layers, but it would take very little wind/wave energy to disrupt this weak stratification. Strong stratification had set in by May 13, with an epilimnetic layer present from the surface to 8.0 m depth (**Figure 6**), constantly until July. Destratification was documented in September, with a deepening of the mixed (epilimnetic) layer to 13 or 14 m, and lake turnover was complete by October 14 (**Figure 7**). DO depletion in the lower (hypolimnetic) layer closely followed the lake stratification pattern, with surface values in the 6-8 mg/L range. Hypolimnetic anoxia persisted until lake destratification was complete in October, and evidence of the progression of lake turnover is seen in the marked decrease in DO to below 4 mg/L in the upper water column on September 23. By October 14, DO levels had recovered to around 6 mg/L.

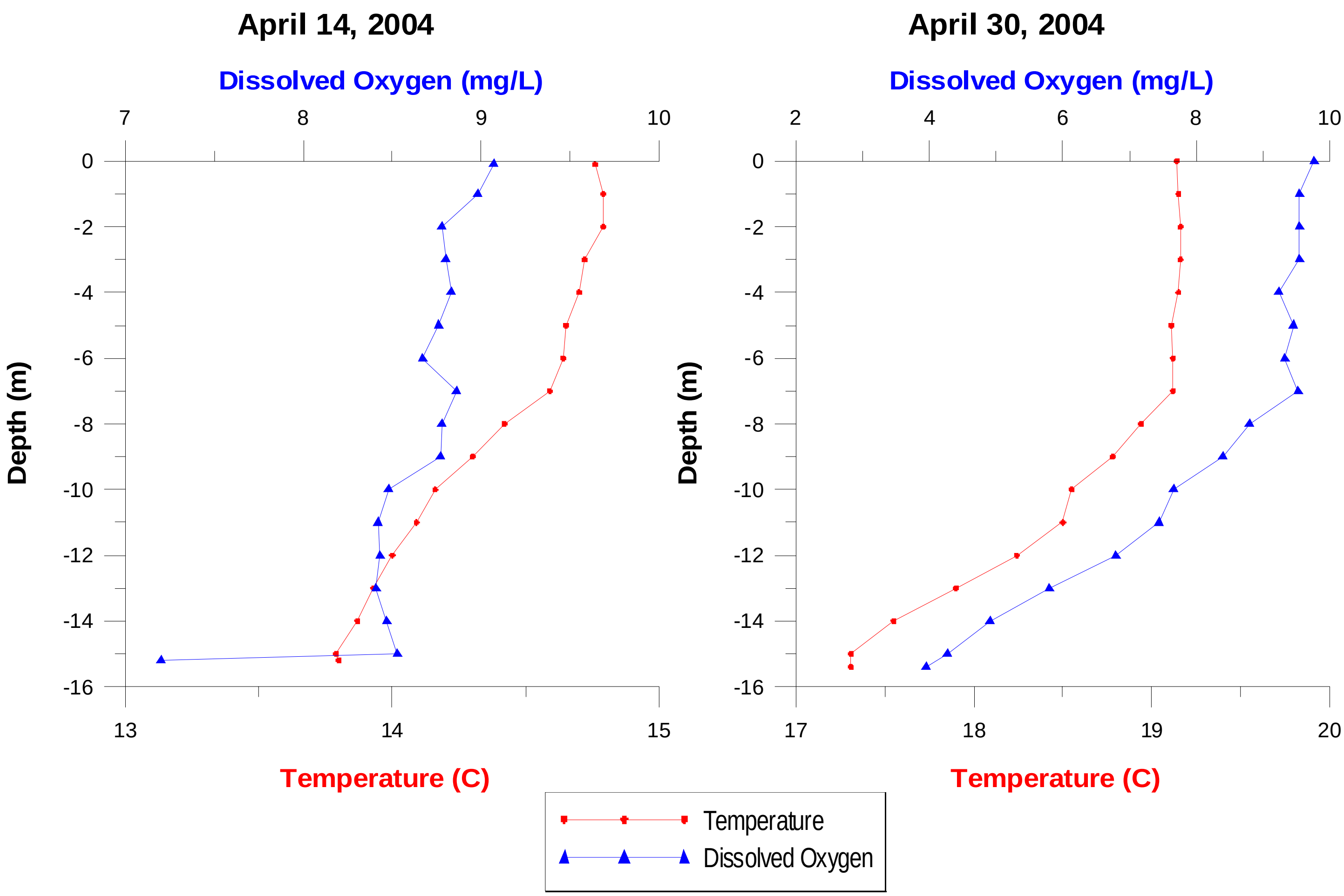

Figure 5: Temperature and dissolved oxygen profiles for site 1: April 14 and 30, 2004.

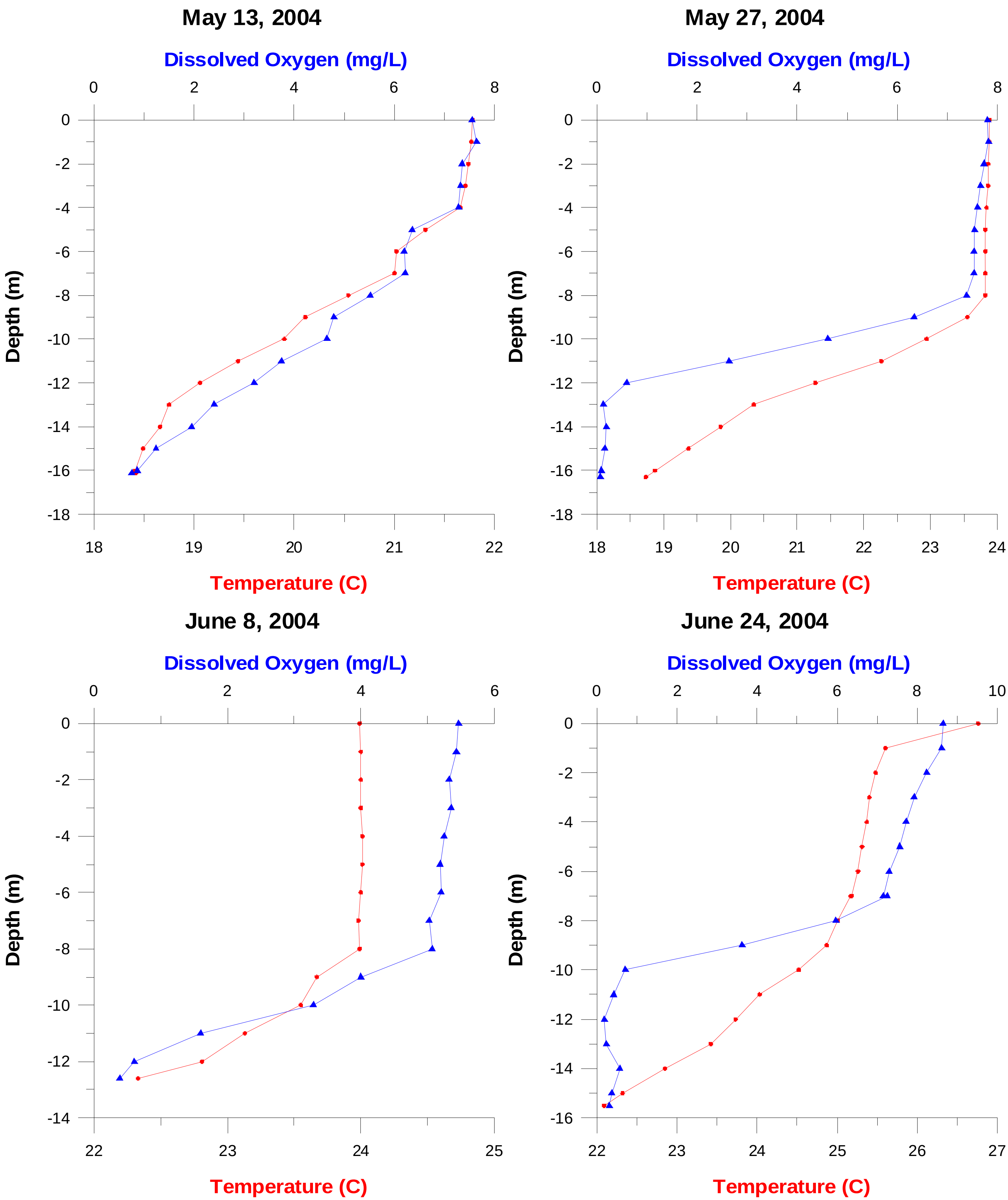

Figure 6: Temperature and dissolved oxygen profiles for site 1: May 13 - June 24, 2004.

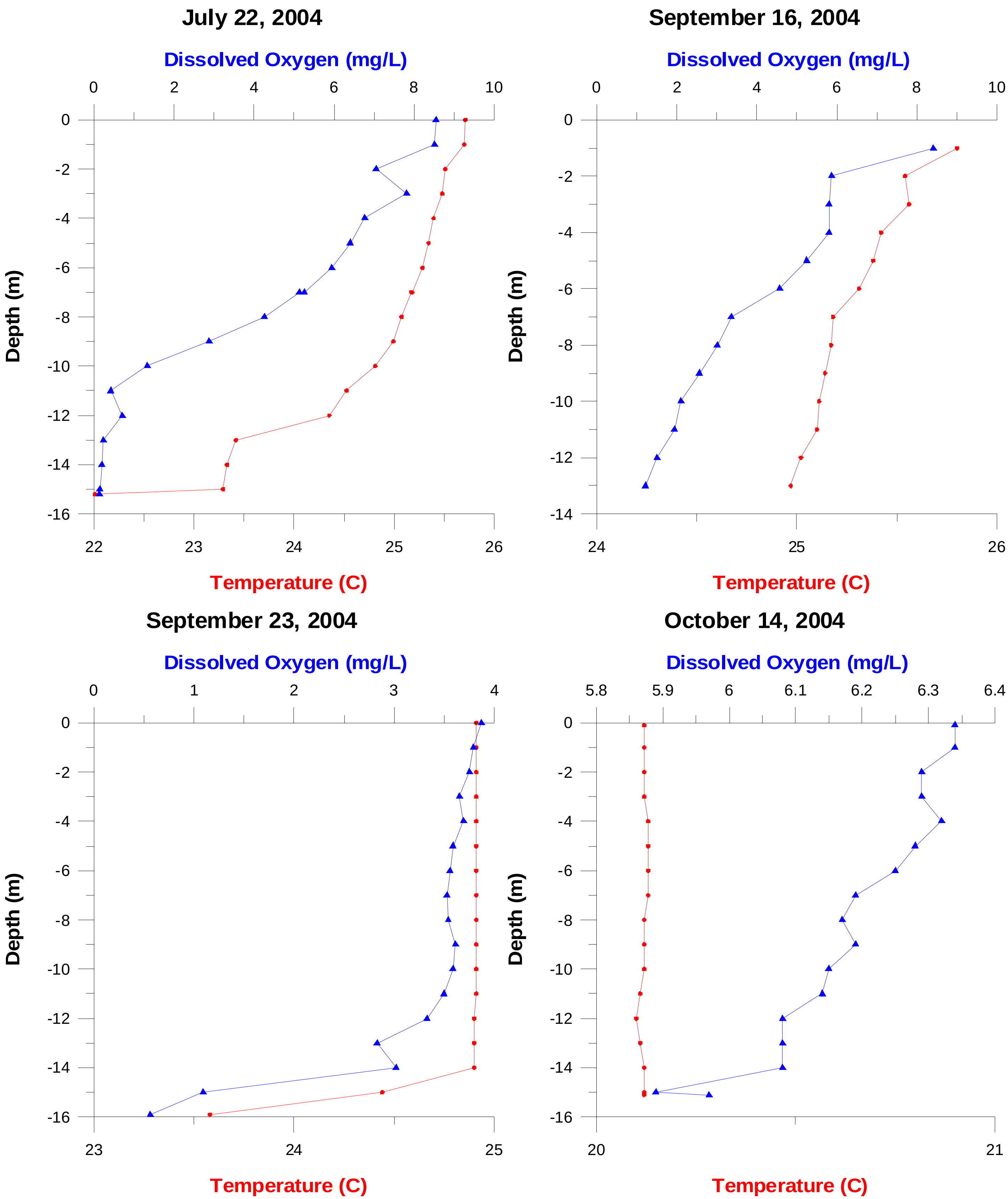

Figure 7: Temperature and dissolved oxygen profiles for site 1: July 22 – October 14, 2004.

An alternate method for showing 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 (**Figure 8**) and dissolved oxygen (**Figure 9**) data, in a summarized form, for sites 1, 2, and 4. 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.

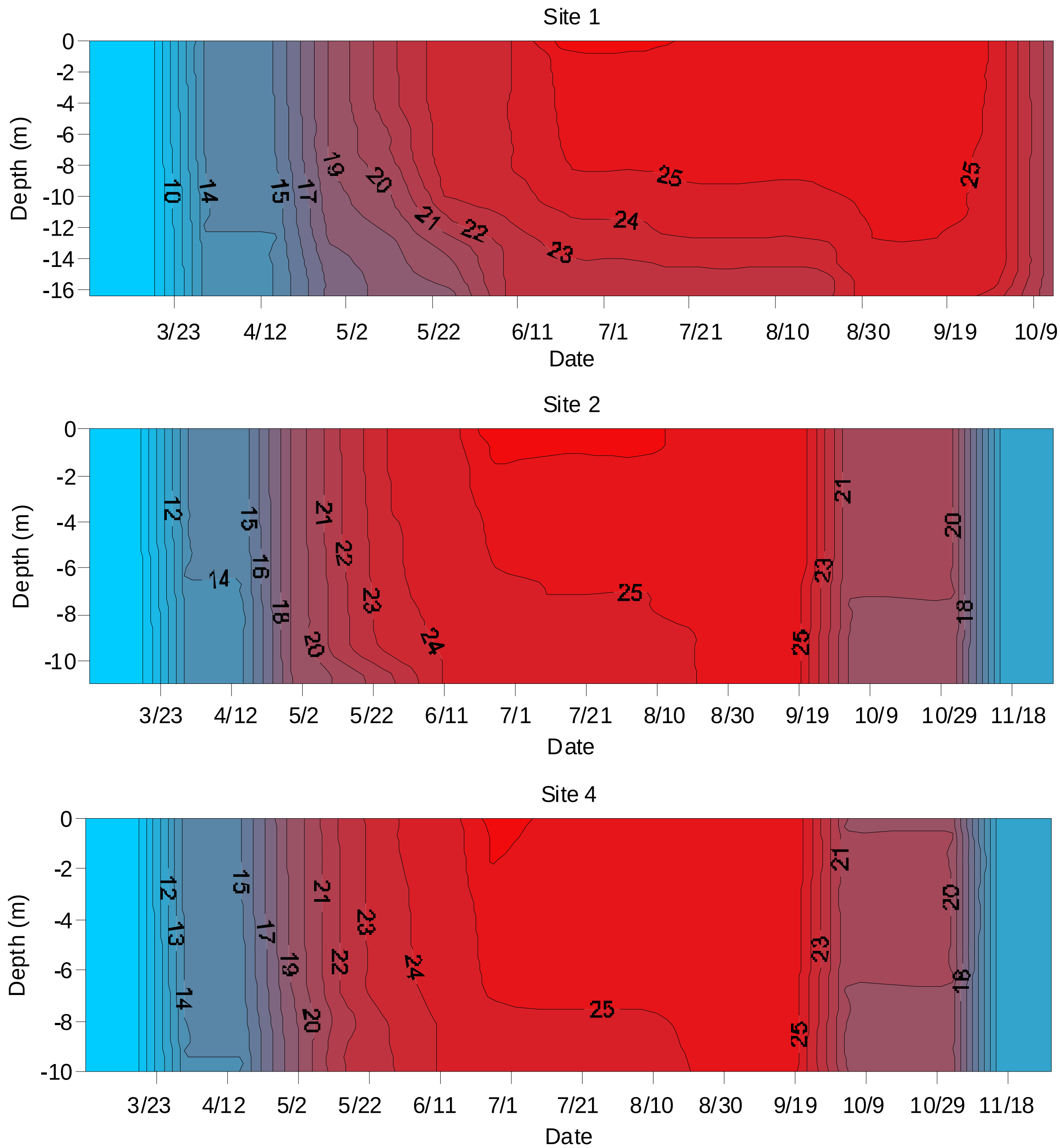

Figure 8: 2004 Temperature isopleths for sites 1, 2, and 4.

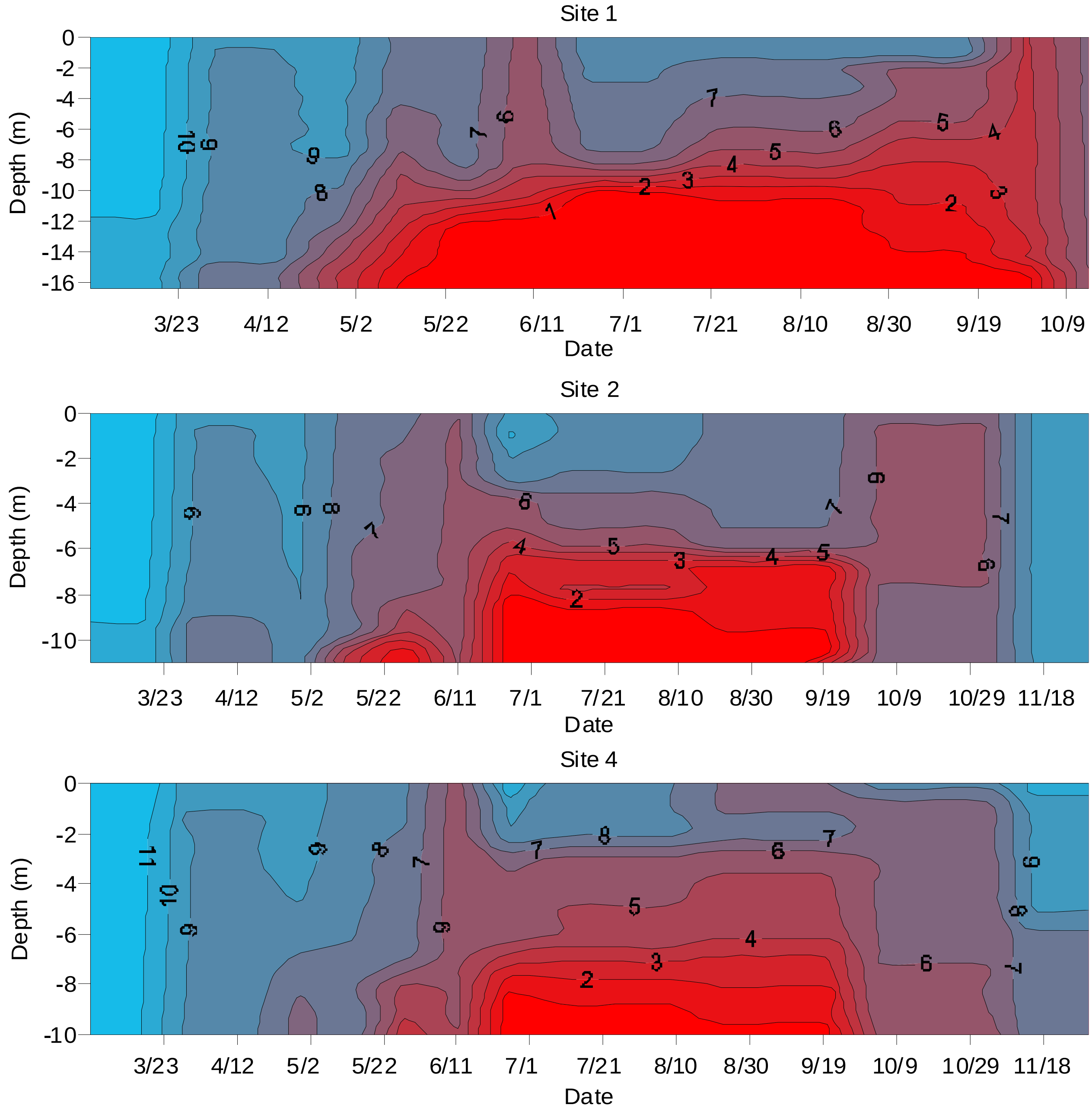

Figure 9: 2004 Dissolved oxygen isopleths for sites 1, 2, and 4.

2004 stratification began to develop at the end of April, with strong stratification observed by mid-May. Destratification began to be evident in September and was completed by mid-October. 2004 appears to have been a typical year with respect to stratification patterns. Stratification in 2004 was similar to that seen in 2001 and 2003, though not 2002 due to the late spring destratification event observed that year.

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.

Dissolved oxygen at the main lake sites showed similar plots for 2001 through 2004, as compared to the stratification pattern. 2004 dissolved oxygen levels also showed the progression of anaerobic conditions from deeper to shallower sites seen in 2001 and 2001. This pattern of dissolved oxygen depletion does not follow the generalized pattern expected for reservoirs. According to Thornton (1990), anaerobic conditions normally occur first in the shallow transition zone and progress to the deeper sites. The pattern of dissolved oxygen depletion progressing from shallow to deeper sites was observed in 2002, which was most likely due to 2002’s unusual climatic conditions which caused a break in stratification in late May and shortened anaerobic conditions.

For all three years and at all sites, anaerobic conditions were observed in the hypolimnion. A comparison of days stratified versus days when an anaerobic hypolimnion was observed is a useful indicator of primary productivity or algae growth. When the number of days match for stratified and anaerobic conditions it can be concluded that high to excessive algae growth occurred. When the lake is stratified but the hypolimnion is not anaerobic, lower productivity levels can be assumed. A comparison of stratification versus the presence of anaerobic conditions (**Table 3**) suggests relative productivity levels for the 2001 to 2004 sampling seasons.

Table 3: Comparison of stratified versus anaerobic hypolimnion as number of days for Lake Thunderbird site 1, 2001-2004.

Days	2001	2002	2003	2004
Stratified	139	126	138	134
Anaerobic	139	103	125	134
Difference	0	23	13	0
%Time Anaerobic	100%	82%	91%	100%

This data suggests algae growth was highest in 2001 and 2004, and algae growth in 2003 was somewhere between those high years and 2002. The duration of stratification was also consistent for 2001, 2003, and 2004, the three years with relatively normal weather patterns. The presence of anaerobic conditions also predicts the release of nutrients from the sediment. These nutrients in turn will stimulate algae growth upon reaching the epilimnion. Higher algae growth then further increases the extent of anaerobic conditions.

Nutrients

Nutrient samples were collected six times during the 2004 sampling season. In addition, two routine BUMP nutrient samples collected by the OWRB were used to augment the data set. Samples taken in April and May represent spring conditions; samples from June, July, and August represent summer conditions; and samples from September, October, and November represent fall conditions.

While several measures of nitrogen and phosphorus were made, only dissolved nutrient totals are presented. Dissolved nutrient totals represent the nutrients available for algal growth. High values in the epilimnion generally indicate nutrients immediately available for algal growth while high values in the hypolimnion indicate nutrients available for future algae growth. The 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 algae growth. Generally when they are both available, nutrients are not limiting algae growth and excessive chlorophyll-a values are expected. When dissolved phosphorus is readily available but very low dissolved nitrogen, algae growth may be limited by nitrogen. High to excessive levels of algae growth can be expected under nitrogen-limited conditions. Nitrogen-limited conditions 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 the major producers of toxins and chemicals that cause taste and odor problems.

Phosphorus limitation is the normal and much more desirable state for most freshwater systems. Under phosphorus limiting conditions, typically more desirable green algae will be present replacing 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 TN:TP ratio of less than 7:1 is defines as nitrogen-limited, and greater than 7:1 is defined as phosphorus-limited. Thunderbird consistently has TN:TP ratios in the 20’s to 30’s, indicating the lake is phosphorus-limited.

A comparison of nutrient concentrations across all four sampled years shows the common trend for Lake Thunderbird. Maximum concentrations are measured in the hypolimnion while the lake is stratified, and surface nitrogen concentrations decrease in the summer as the growing season progresses. In 2004, there were two notable differences. Surface dissolved nitrogen concentrations were much higher in the spring, with concentrations of around 0.4 mg/L in April and May of 2004, as opposed to the normal concentrations of less than 0.25 mg/L in previous years (**Figure 10**). The other difference is that the hypolimnetic peak in nutrient concentrations was not evident until August (**Figure 11**). Generally, July sampling captures the nutrient release. In 2004, only better nutrient sample coverage allowed the delayed peak in hypolimnetic nutrients to be observed.

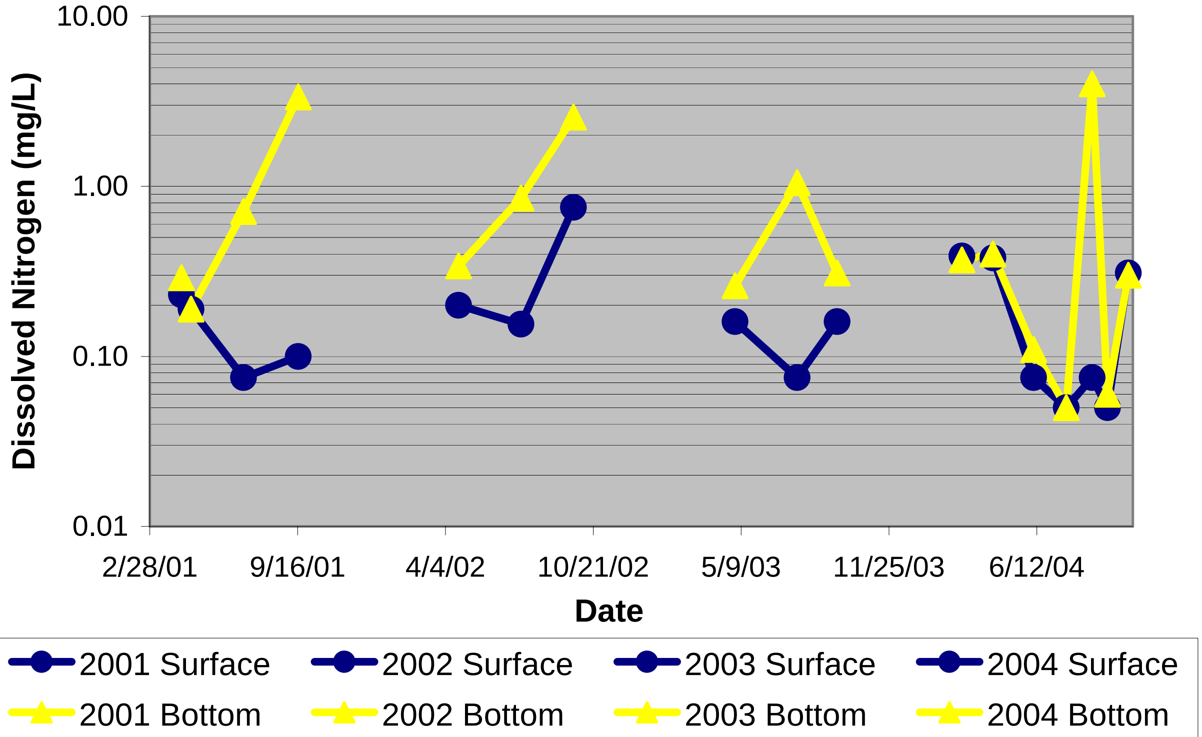

Figure 10: Total dissolved nitrogen species concentrations at site 1: 2001-2004.

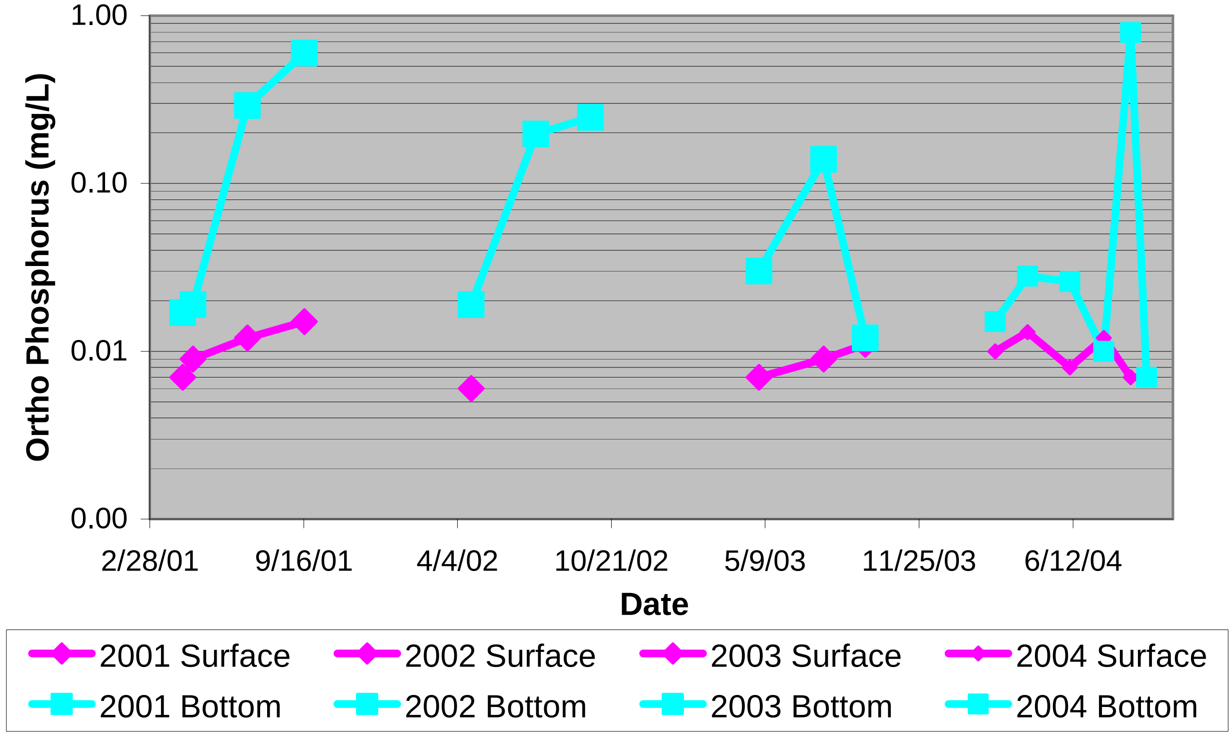

Figure 11: Dissolved ortho phosphorus concentrations at site 1: 2001-2004.

While the peak in hypolimnetic nutrient concentrations was delayed until August in 2004, the magnitude of the peaks was considerably higher than in previous years. In 2004, the peak nitrogen concentration was 4.0 mg/L, compared to the previous maximum of 3.35 mg/L in 2001, and the peak 2004 ortho phosphorus concentration was 0.794 mg/L, compared to the previous maximum of 0.599 mg/L in 2001. Otherwise, nutrient concentrations in 2004 were consistent with previous years' sampling.

Chlorophyll-a

Chlorophyll-a, the molecule or pigment common to all algae for growth, is a commonly accepted measure of algae content. 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.

Due to the decreased frequency of summer sampling in 2004, this year's chlorophyll-a data cannot be directly compared to that of previous years. When sampling regimes do not match, especially for parameters so greatly affected by seasonality, direct comparison should not be made. Therefore, an assessment of the eutrophy goal based on chlorophyll-a alone was not performed.

Typically, the chlorophyll-a peak in Lake Thunderbird's open water sites occurs from the beginning of August to mid-September when stratification peaks, such as seen in 2003 (**Figure 12**).

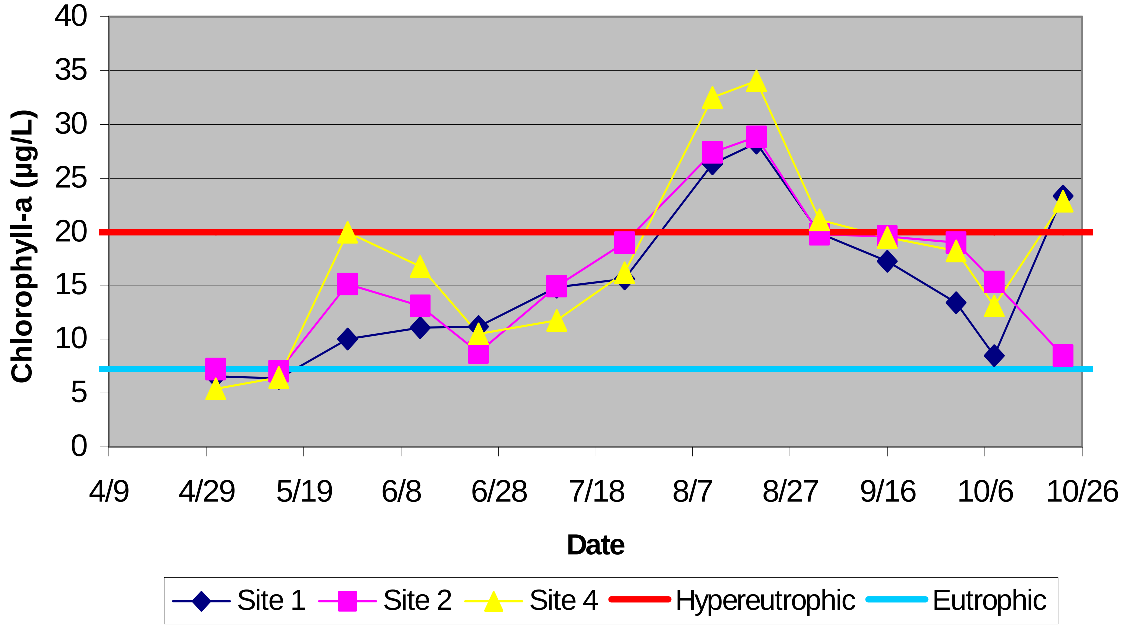

Figure 12: 2003 chlorophyll-a concentrations for main body sites.

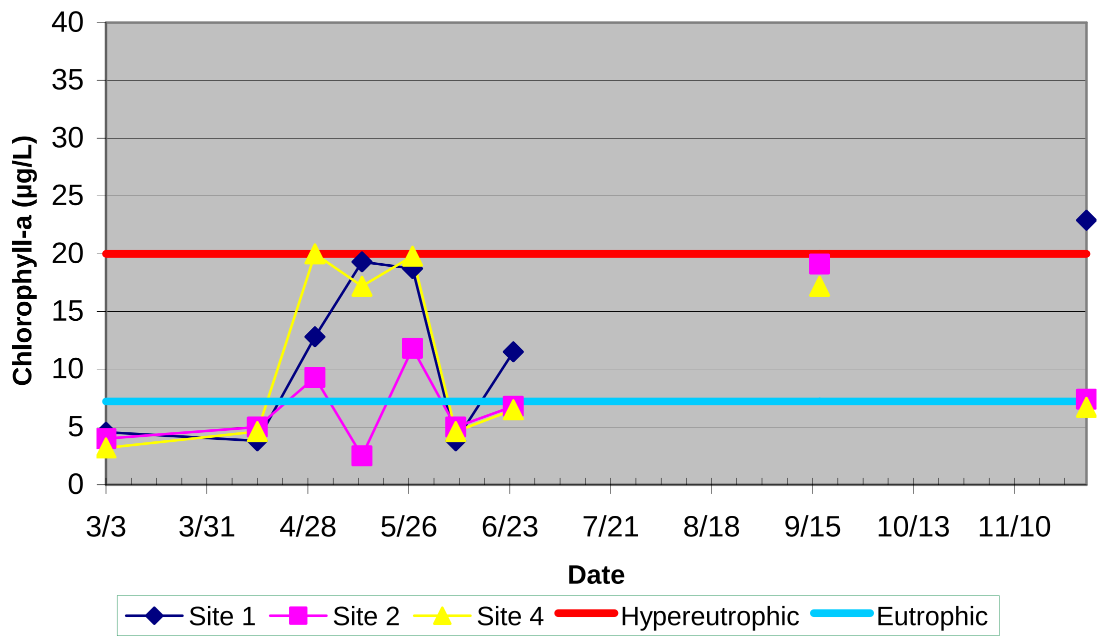

Figure 13: 2004 Chlorophyll-a concentrations for main body sites.

2004 sampling missed the majority of the growing season. Based on what data is available, the 2004 sampling season appears to follow the chlorophyll-a values collected from 2003 closely. Spring samples were sometimes below the eutrophic boundary, but typically between eutrophic and hypereutrophic, and the late summer sample and post-turnover sample were both near the hypereutrophic boundary (**Figure 13**).

Algae

Algae data can be interpreted based on cell density and by cell biovolume. Cell density is a measure of the total number of cells per volume of water. **Figure 14** shows the algae cell density values measured for Lake Thunderbird in 2004. According to this data, the largest number of algal cells were present in the lake in mid-spring, with a peak on May 13, 2004. Hutchinson (1967) uses a threshold of 15,000 cells per mL as an indicator of eutrophic or nutrient rich systems. Throughout the late spring and summer, Lake Thunderbird had cell density values over the eutrophic threshold.

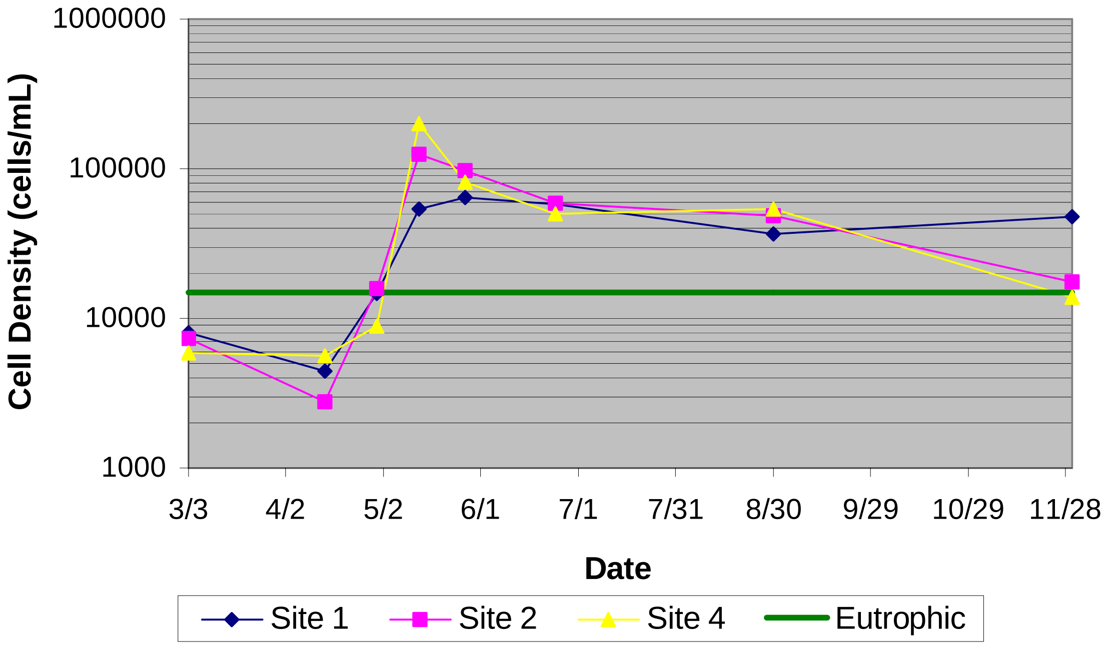

Figure 14: 2004 algae cell density for Lake Thunderbird main body sites.

In the first spring event of 2004, total cell density at all three main body sites was dominated by members of the Bacillariophycaceae (diatom) family, mainly of genus *Cyclotella*, with 83% of the total cell density from this family. For the rest of sampled dates, the majority of the total cell density was dominated by members of the Cyanophyta (blue-green) family, with 71-83% of total cell density from this family. Early in the spring, the dominant blue-greens were members of genera *Synechococcus* and *Synechocystis*. Starting in May, the dominant blue-greens switched to several species of *Aphanocapsus* and *Merismopedia tenuissima*. Towards the summer, *Cylindrospermopsis raciborskii* also gained dominance (**Figure 15**). Cell density numbers show the main dominant blue-green species were of genus *Aphanocapsus*, which grow in microscopic colonies in primarily mesotrophic lakes (Wehr, 2003).

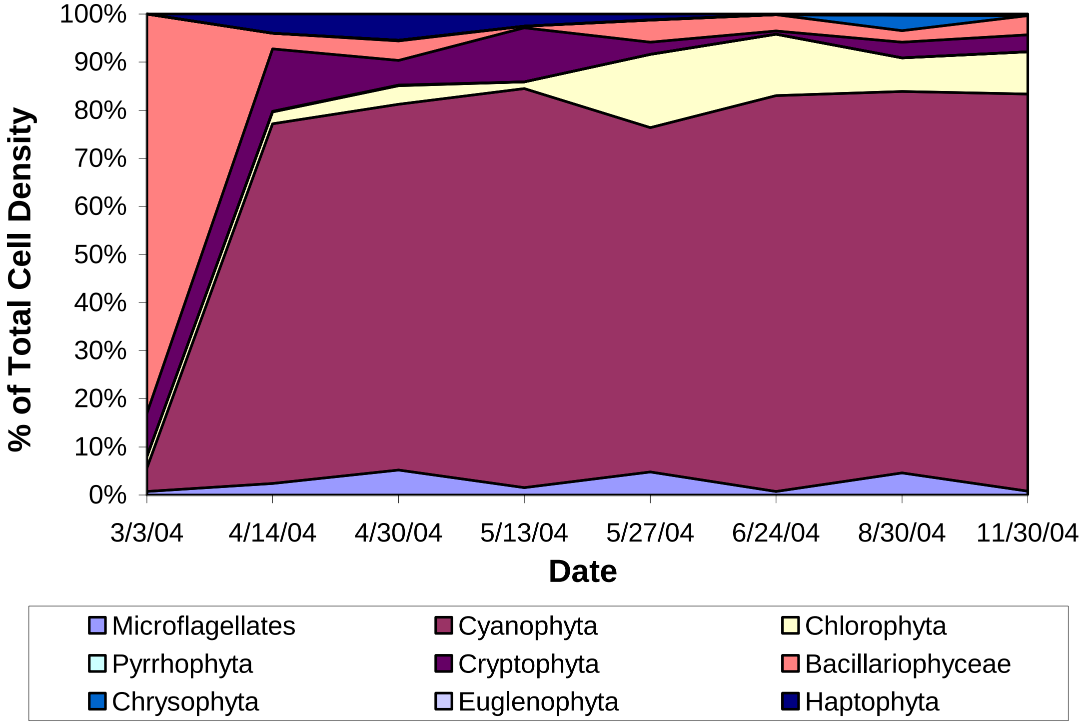

Figure 15: 2004 Overall % Algal cell density for main body sites, segregated by taxa.

While cell density is a useful measure of algal productivity because an accepted criterion of eutrophy is available, cell biovolume is often a more accurate measure of productivity. In cases where algal cells of particular taxa are extremely small, cell density can bias interpretation towards the smaller-celled taxa. Cell biovolume is the most accurate way to compare different types of algae when cell sizes vary. The plot of biovolume shows a sharp contrast to that seen with cell density. The May 13 peak observed using cell density is also seen on a cell biovolume plot (**Figure 16**), but cell biovolume continued increasing, with an August 30, 2004 peak. The increase in cell biovolume but not cell density after May 13 indicates a shift in the algal community from small-celled to larger-celled algae.

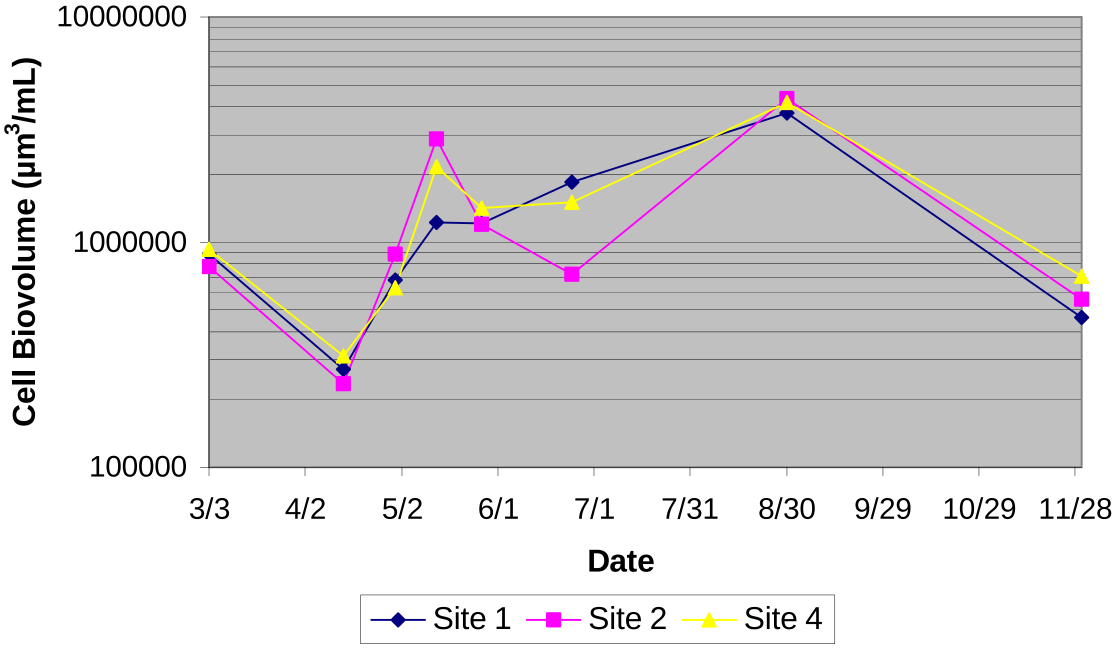

Figure 16: 2004 algae cell biovolume for main body sites.

When relative algal abundance is compared by cell biovolume rather than cell density, taxa dominance is much less pronounced (**Figure 17**). On the initial March 3 sample date, diatoms (Bacillariophycaceae) are still dominant, with 94% of the total cell biovolume, but the dominant species are from two genera: *Cyclotella* and *Cyclostephanos*, both present in roughly equal volumes. After March 3, members of the Bacillariophycaceae family made up around 30-40% of the total cell biovolume on most sampled dates, but with decreased amounts measured on May 13 and August 30. The major genera involved were *Cyclotella* and *Aulacoseira*. Two other families of algae represented most of the rest of the total cell biovolume: Cryptophyta and Cyanophyta (blue-greens). In the Cryptophyta family, Cryptomonas sp. and Rhodomonas minuta showed some dominance in the early spring. On April 14, 45% of the total biovolume and on May 13, 51% of the total biovolume was represented by cryptophytes. Members of the blue-green (Cyanophyta) family made up roughly 30-40% of the total cell biovolume during most of the growing season, excluding the March 3 samples, when diatoms were dominant. When cryptophytes were dominant, the relative percent of cyanophytes decreased to 20% of the total. Typically, many different species of blue-green algae were present in every sample and several species were present in large volumes. *Anabaena flos-aquae* was the dominant cyanophyte in the spring months. *Oscillatoria agardhii* was co-dominant at site 2 on April 30, but was not found in any other sample on any date. In the June and August samples the species found in large numbers were *Aphanizomenon issatschenkoi, Pseudanabaena limnetica, Pseudanabaena galeata*, and *Cylindrospermopsis raciborskii*. *Cylindrospermopsis raciborskii* made up 50% of the total biovolume sampled on August 30.

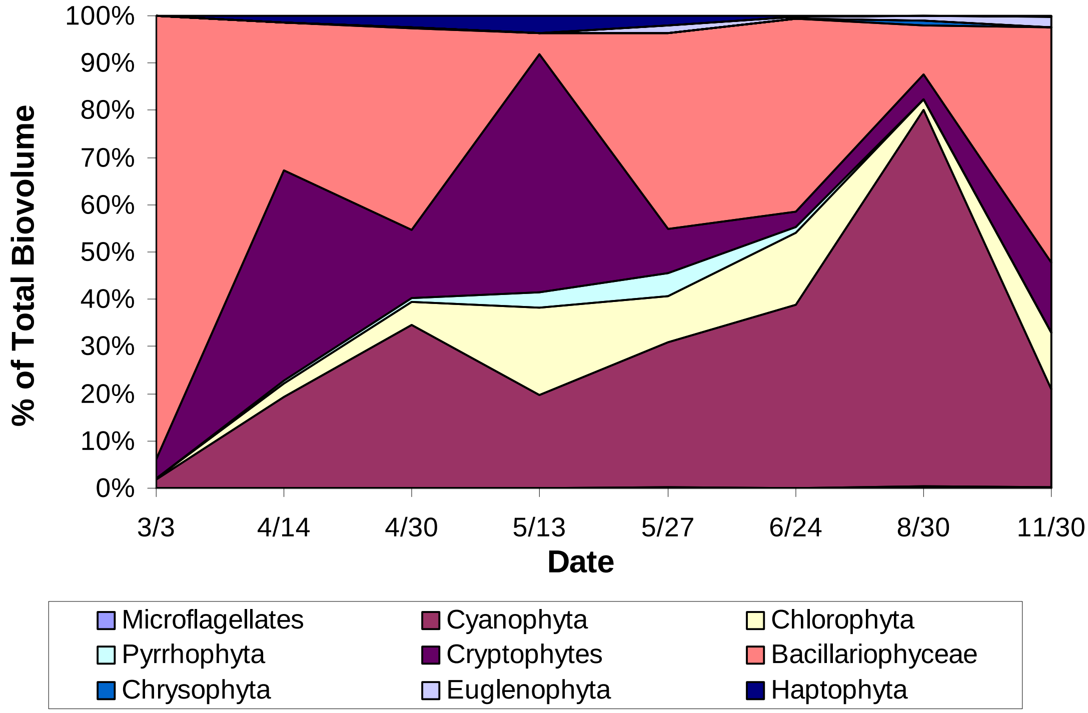

Figure 17: 2004 Overall % Algal biovolume for main body sites, segregated by taxa.

Hutchinson (1967) also describes "eutrophic associations" by the appearance of the following three species: *Aphanizomenon, Anabaena,* and *Oscillatoria*. All three of these genera occurred in Lake Thunderbird. Also, members of the genera *Aphanizomenon, Anabaena, Oscillatoria, Pseudanabaena*, and *Cylindrospermopsis*, in addition to some other genera found in smaller numbers in Lake Thunderbird, are known producers of compounds that cause taste and odor problems. Some of those genera can also produce toxins.

The algal community structure in 2004 was quite different from that seen in 2003. In 2003, cyanophytes showed strong dominance, with around 90% of the total cell biovolume and cell density represented by members of this family. The lower dominance in 2004 could be due to the lower temperature in 2004. Some blue-green algae, particularly *Cylindrospermopsis*, show maximum growth at higher temperatures.

Taste and Odor Complaints

Taste and odor complaints can act as another indicator of lake productivity. Chemicals that have objectionable taste and/or odors in water are byproducts of algal productivity, which are mainly produced by members of the blue-green family (Cyanophyta). Typically, taste and odor events occur in the heat of summer when blue-greens dominate the algal assemblage, and when lake turnover occurs in the fall, and nutrients and organic material form the hypolimnion circulate through the water column.

Comparing the relative number of taste and odor complaints for each September, while the fall turnover is occurring, might give an idea of the relative amount of organic material and nutrients released from the hypolimnion. Although the amount of blue-green algae production in each year could be just as important as the total production for prompting customer complaints. Of the three municipalities that use Thunderbird's water, Norman has kept continuous records of customer complaints for the last few years. Those results are shown in

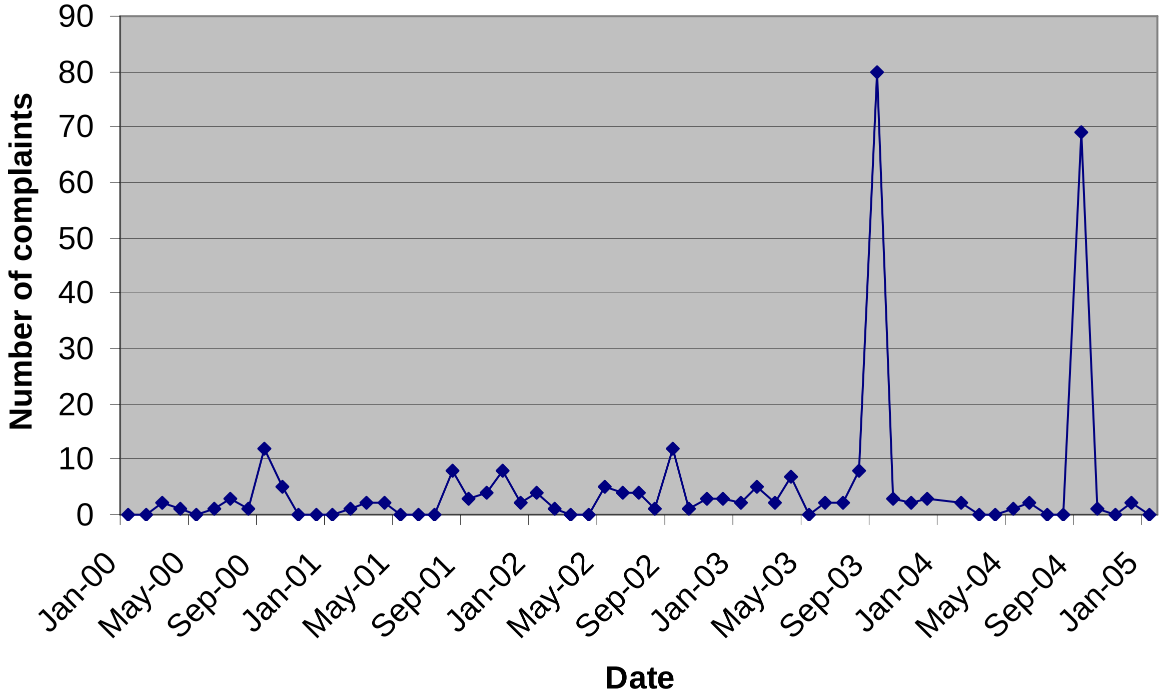

Figure 18.

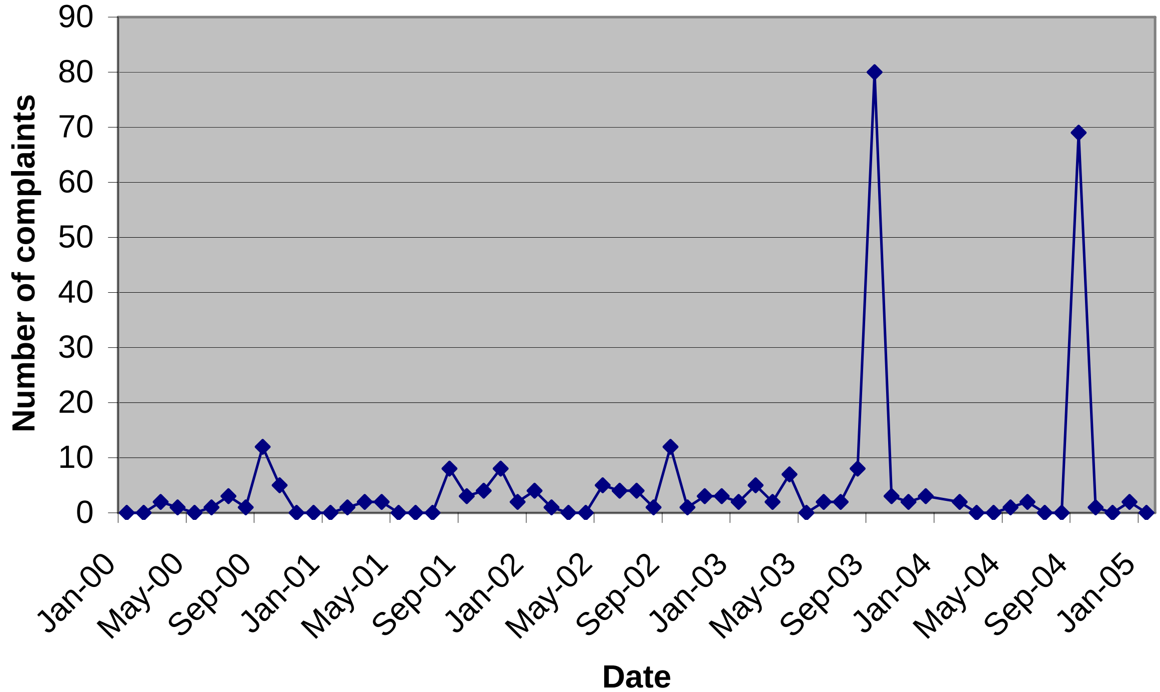

Figure 18: 2000 - 2004 Taste and odor complaints, City of Norman.

In 2004, the number of September complaints was very close to the number in 2003. It is important to note that the September 2004 number was also lower than the actual number of complaints due to incomplete record-keeping. Complaints have peaked every September, but the number of recorded complaints has increased drastically in the last two years. Beginning in 2003, the amount of water withdrawn from Lake Thunderbird for water supply use has also approximately doubled.

Total Organic Carbon

Another measure of organic content undertaken in 2004, at the request of the COMCD, was total organic carbon (TOC). Results for this parameter are presented in **Table 4**.

Table 4: Total organic carbon (mg/L) results. "S" denotes a surface sample while "B" denotes a bottom sample.

Site	8/30/04	9/16/04	10/14/04	11/30/04
1S	5.63			5.21
1B	7.52	5.8	5.82	*
2S		5.62	5.29	5.25
2B	6.43	5.77	5.29	5.88

3S	7.8	6.72	5.59	5.34
4S	5.61	5.66	5.44	5.28
4B	5.24	5.61	5.35	5.19
6S	5.46	5.77	5.36	5.3

*On 11/30/04, TOC could not be collected at 1B due to high wind

TOC results were fairly homogenous at all sites and with depth on all four sampled dates, regardless of whether the lake was stratified or mixed. Some statistical differences were noted using a non-parametric comparison of central tendency with a 10% error rate. For the most part, four of the 28 total sample reports drove the statistical significance. These samples were well above 6 mg/L with three of these reports on 8/30/04 and the fourth from site 3S on 9/16/04. Test results indicating statistical significance are given as dotplots. Here each dot represents a TOC sample while the line represents the average value. These plots allow the reader to see each data point and how the data contribute to the overall statistical conclusion.

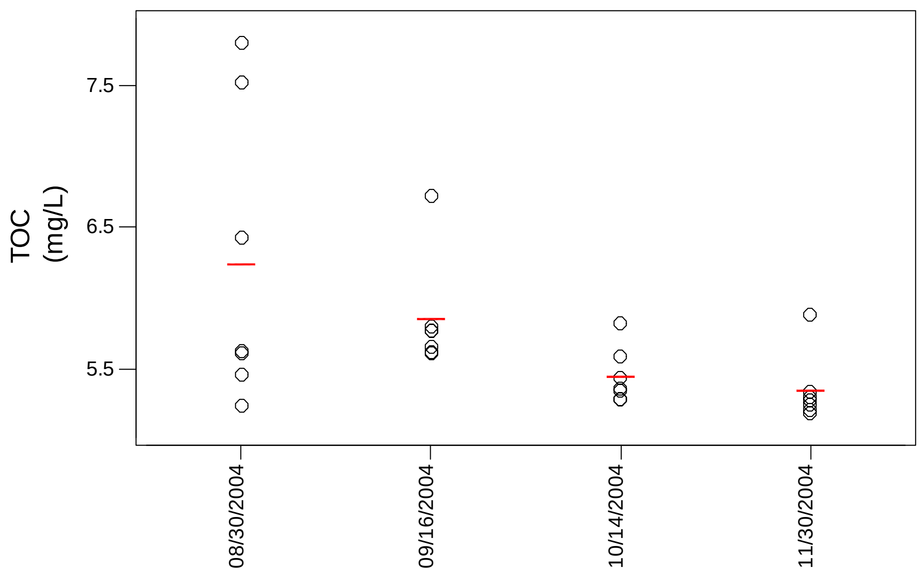

Figure 19: Dotplot of TOC by date for Lake Thunderbird.

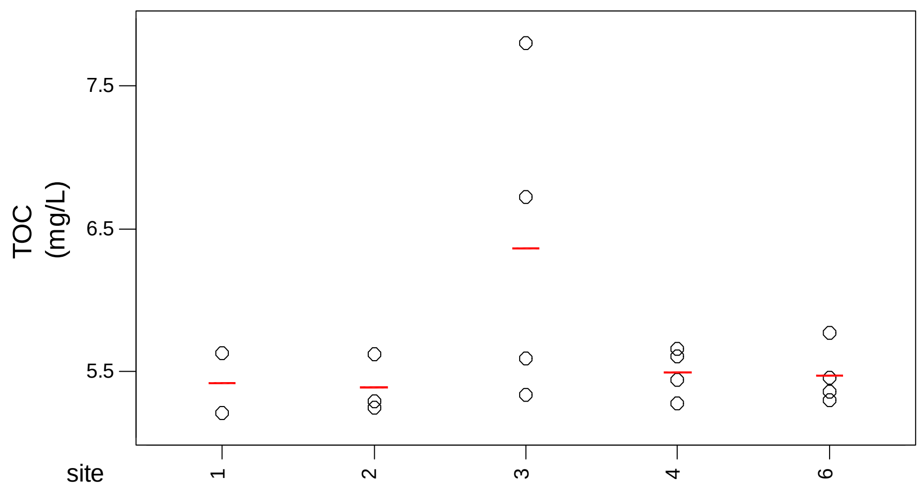

Figure 20: Dotplot of surface TOC by site for Lake Thunderbird 8/30/04 - 11/30/04.

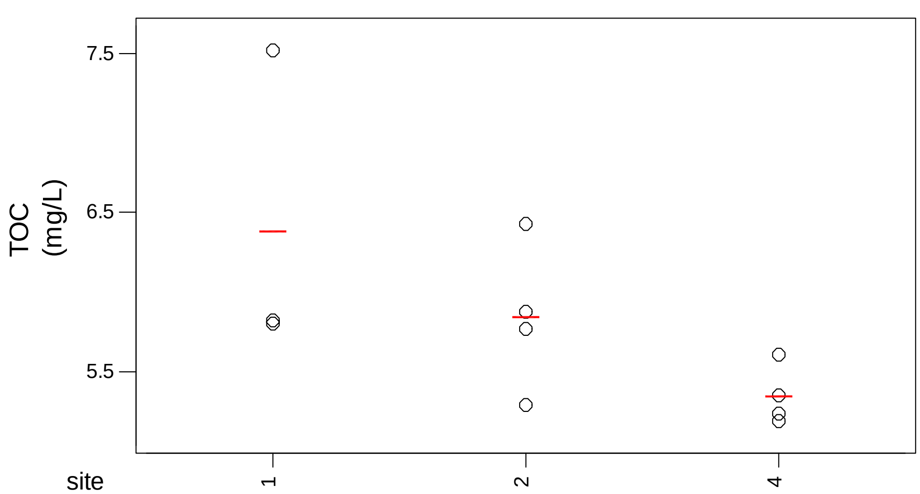

Figure 21: Dotplot of bottom samples by site for Lake Tunderbird 8/30/04 - 11/30/04.

Values for the first sample date, August 30 2004 were significantly higher than those in October and November (**Figure 19**). Of the surface values, site 3 showed values statistically higher than all other sites (**Figure 20**). Of the bottom samples sites 1 and 4 were noted to be statistically different (**Figure 21**).

Oklahoma Water Quality Standards

Lake Thunderbird was listed on the 2002 303(d) list as impaired due to low dissolved oxygen and turbidity, both with unknown causes. To check that listing, those two parameters are presented here using an assessment by the Oklahoma Water Quality Standards (OWQS) of the 2004 data.

Data Requirements

The Use Support Assessment Protocols (USAP) of the OWQS have 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. A minimum of 20 samples is also required on a lake of this size, and the samples should be collected using standard methods.

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 will not be supported. If between 50% and 70% of the water column has DO less than 2 mg/L, the beneficial use will be partially supported. Less than 50% of the water column must have DO values under 2 mg/L to be fully supporting this beneficial use. 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 the impaired or not attained.

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 Assessment

In 2004, 19% 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 2003 data shows 17% of the turbidity samples exceeded the 25 NTU criteria. Both years' data indicates a partially supported system.

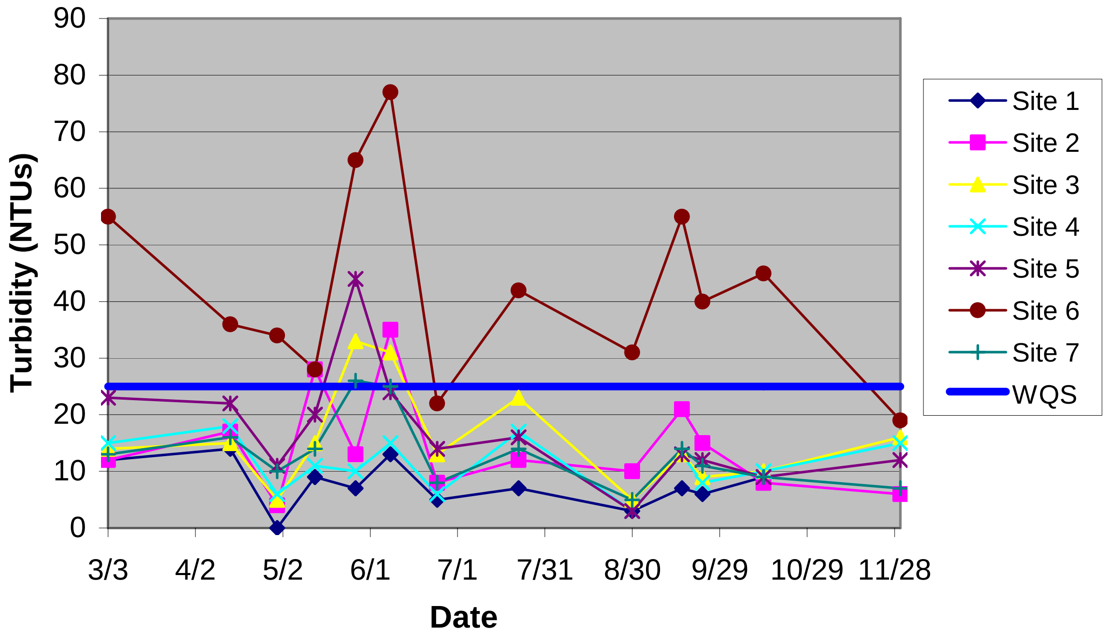

Figure 22: 2004 Turbidity values for all sampled sites.

With respect to dissolved oxygen, Lake Thunderbird was fully supporting the fish and wildlife propagation beneficial use in 2004. When considered using percent water column anoxia, anoxic conditions were first seen at 10 m, which yields 44% of the water column anoxic at site 1. This assessment is most likely due to the reduced summer sampling. In previous years, summer anoxia is generally seen at shallower depths, so that usually the summer events show around 60% of the water column as anoxic. For example, three sample events—June 20, July 10th, and July 24th in 2003—showed DO low enough to conclude partial-support assessment.

When surface screening levels are used to assess dissolved oxygen in 2004, the beneficial use is also fully supported. Only one measurement showed a surface dissolved oxygen concentration below the screening level, which was less than 2% of all measurements.

Summary & Discussion

Climatic Effects

2004 turned out be a fairly normal year in regards to rainfall but abnormal in regards to temperature. Breaking out rainfall by season showed a relatively dry spring balanced by a relatively wet summer. This seasonal pattern started the lake pool elevation some 2.5' below conservation pool (1039') early in the year and ending the year slightly above elevation 1039. The wet weather inflows coincided with three of the nutrient sampling events. A larger data set, distributed evenly between seasons will be needed before assessing the relative influence of inflow events on lake nutrient status. Lower maximum lake temperature, along with slower growth rates, may have lessened the impact of higher spring nutrient levels. Although algae growth may have not have been as high as previous years (due to thermal differences) the duration of anoxic hypolimnion indicates algae growth was comparable to previous years. This data supports previous years' characterization of Lake Thunderbird's trophic status as on the borderline between eutrophic and hypereutrophic.   Algae data were also congruent with a eutrophic system.

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 last five 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 results of hypolimnetic waters mixing with the surface. As the reduced chemical species from the hypolimnetic water are oxidized, surface DO falls. The intensity of reducing conditions and amount of mixing that occurs determines the intensity of the DO sag in September. For instance, DO sagged in 2002 but never below 5 mg/L O_2; all the other monitored years saw a DO sag with surface DO below 4 mg/L O_2. 2002 was the year with the shortest duration of anoxia in the hypolimnion and also when all chlorophyll-a samples were within the goal of <20 µg/L.

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 will tend to store the 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 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.

Oxidizing the Hypolimnion

Increasing the oxidation-reduction potential of the hypolimnion will minimize storage of taste and odor-causing compounds and storage of sediment-mediated release of 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, would 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 algae growth are another avenue. To date no projections are available of what algae (or chlorophyll-a) levels are needed to maintain some semblance of oxidation in the hypolimnion. It is likely that some active intervention, such as nutrient inactivation of pneumatic oxidation, will be needed to provide a hypolimnion oxidized enough to flatten the spike in taste and odor complaints.

State Water Quality Standards

Recent 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. Should sufficient data be presented to show the lake is fully supporting for a given parameter the Lake will be "de-listed" for the parameters. De-listing removes the state requirement for the completion of a TMDL for that parameter.

A review of 2004 and 2003 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 May and early June of 2004, 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.

Application of 2004 dissolved oxygen data yielded a "fully supported" assessment while 2003 data yielded a "partially supported" assessment. The impairment conclusions from the two years yield opposite results. This potential conflict should be tempered by two facts: reduced field sampling performed in July and August of 2004 and the eutrophic to hypereutrophic status of Lake Thunderbird. These suggest the "fully supporting" assessment of 2004 would not be sufficient to de-list Lake Thunderbird for dissolved oxygen.

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 can be used for algae growth. It is possible that this action could eliminate hypereutrophic (excessive) algae growth during the summer period and eliminate the September spike in taste and odor complaints.

Increase nutrient sampling. Routine nutrient data segregated by depth would allow for development of a lake nutrient budget independent of external (tributary) loads.

Extend water quality monitoring to tributary water quality data collection. Accumulating tributary water quality data is the first step toward a detailed lake nutrient budget (allowing for sediment and tributary sources). Efforts to include storm flow events should be a priority.

Evaluative processes. The OWRB recommends that increased monitoring of the lake and tributary are placed in the context of nutrient sources. Additional work will be needed to develop estimates of nutrient sources, loads, and a predictive model. The predictive model can be used to estimate the impact of various management options. The University of Oklahoma, City of Norman, and the Bureau of Reclamation are potential partners to lend technical and fiscal support.

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