USGS
science for a changing world

Water Quality and Trophic Status of Fort Cobb Reservoir, Southwestern Oklahoma, 2006

Chapter 8 of

Assessment of Conservation Practices in the Fort Cobb Reservoir Watershed, Southwestern Oklahoma

Compiled by the U.S. Geological Survey and the Agricultural Research Service

Scientific Investigations Report 2010–5257

U.S. Department of the Interior
U.S. Geological Survey

Water Quality and Trophic Status of Fort Cobb Reservoir, Southwestern Oklahoma, 2006

By James F. Fairchild, Ann L. Allert, and Kathy R. Echols

Chapter 8 of
Assessment of Conservation Practices in the Fort Cobb Reservoir Watershed, Southwestern Oklahoma

Compiled by the U.S. Geological Survey and the Agricultural Research Service

Scientific Investigations Report 2010–5257

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

This and other USGS information products are available at http://store.usgs.gov/
U.S. Geological Survey
Box 25286, Denver Federal Center
Denver, CO 80225

To learn about the USGS and its information products visit http://www.usgs.gov/
1-888-ASK-USGS

Suggested citation:
Fairchild, J.F., Allert, A.L., and Echols, K.R., 2011, Water quality and trophic status of Fort Cobb Reservoir, southwestern Oklahoma, 2006, chap. 8 *of* Becker, C.J., ed., Assessment of conservation practices in the Fort Cobb Reservoir watershed, southwestern Oklahoma: U.S. Geological Survey Scientific Investigations Report 2010–5257, 18 p.

Contents

Figures

Tables

Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
millimeter (mm)	0.03937	inch (in.)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Water Quality and Trophic Status of Fort Cobb Reservoir, Southwestern Oklahoma, 2006

By James F. Fairchild, Ann L. Allert, and Kathy R. Echols

Abstract

Eutrophication of reservoirs frequently occurs because of excessive nutrient inputs caused by anthropogenic activities, including row-crop agriculture. The trophic status of Fort Cobb Reservoir, Oklahoma, was assessed in April, July, and September 2006. The Fort Cobb Reservoir was highly eutrophic, with the greatest concentrations of nutrients and chlorophyll-*a* being measured in the upper reaches of the reservoir. Water quality generally improved toward the dam, but remained eutrophic. Analysis of vertical water-quality profiles indicated that the Fort Cobb Reservoir was well mixed, with little thermal stratification. Comparison of these data to nutrient-loading data indicated that nutrients were primarily delivered during peak storms along with large sediment loads.

Introduction

Fort Cobb Reservoir is a 16.6-square-kilometer reservoir in a 813-square-kilometer watershed in Caddo County, southwestern Oklahoma (fig. 1). The reservoir is managed by the Bureau of Reclamation for drinking water supplies, flood control, recreation, and fish and wildlife habitat (Oklahoma Water Resources Board, 2005). Fort Cobb Reservoir lies in a watershed dominated by sandy loam soils. Land use in the watershed is primarily agricultural with about 88 percent cropland and pasture, 5 percent forest, 5 percent roads, and less than 2 percent water (Starks and others, chapter 5 of this report). Primary row crops grown in the watershed include wheat, peanuts, and cotton. Livestock operations in the watershed are dominated by pasture grazing of cattle and several large confined animal feeding operations used for hog production. Martin (2002) cited U.S. Department of Agriculture statistics which indicated that Caddo County contains about 130,000 head of cattle and 12,000 hogs; however, those counts were county-based statistics that do not necessarily relate directly to numbers of livestock in the Fort Cobb Reservoir watershed.

The Fort Cobb Reservoir has been listed by the State of Oklahoma as being impaired in the 305(b) Report to Congress (Oklahoma Department of Environmental Quality, 2000) because of excessive amounts of nutrients, sedimentation, and pesticides from row crops and livestock production. Nutrients can enter local streams by surface runoff, or can directly percolate into groundwater because of the sandy soil texture. Ultimately, these nutrients are transported to Fort Cobb Reservoir and contribute to water quality and trophic conditions in the reservoir.

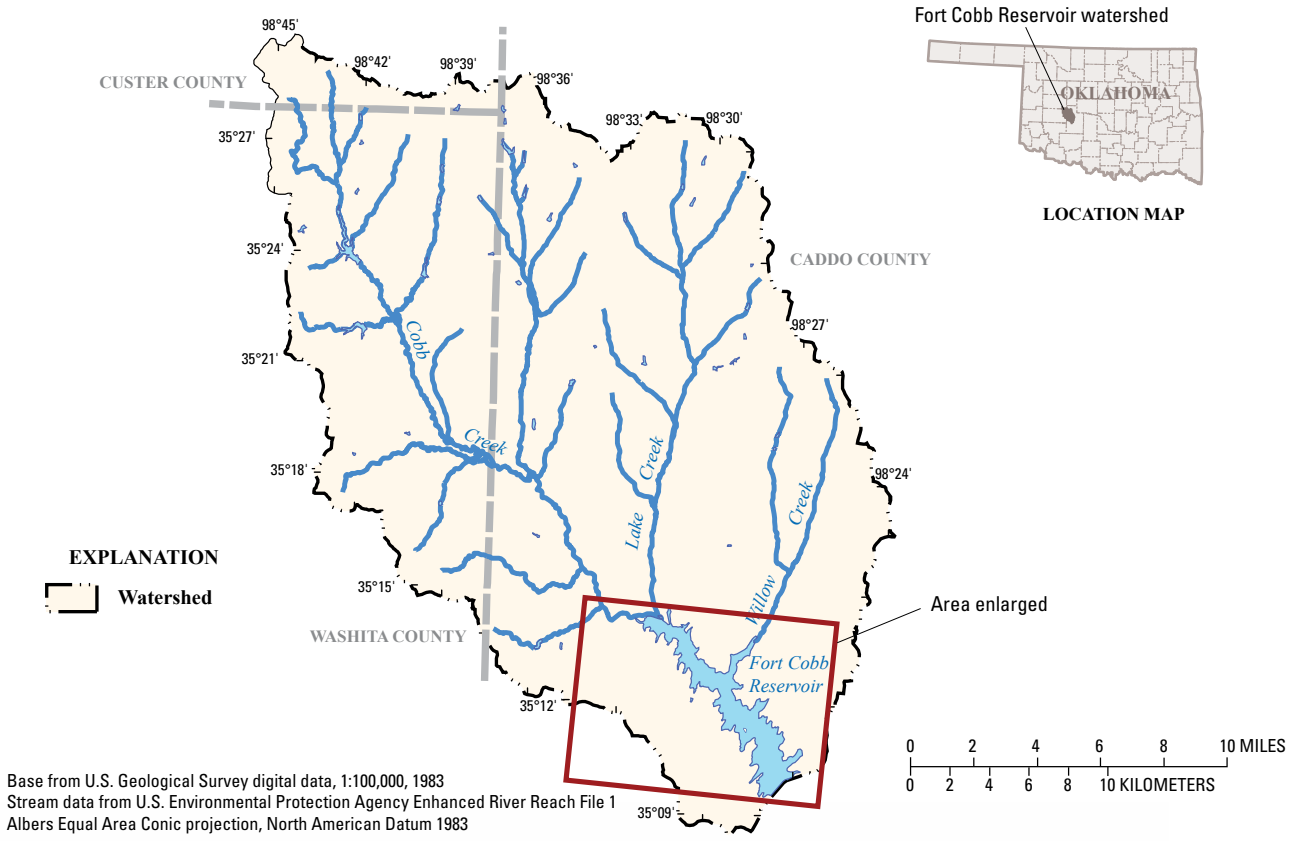
The water-quality assessment of the Fort Cobb Reservoir described in this chapter had three objectives: (1) to determine the trophic status of the Fort Cobb Reservoir, (2) to determine the seasonal and spatial variation of water quality in the Fort Cobb Reservoir, and (3) to integrate these results with separate studies of historical and current land use in relation to nutrient loading of the reservoir. This assessment is a component of a Central Region Integrated Science Project (CRISP) funded by the U.S. Geological Survey (USGS) to promote interdisciplinary science and research opportunity within the USGS and with other cooperating agencies.

Methods and Materials

Water-quality in the Fort Cobb Reservoir was evaluated during 3-day intervals in April, July, and September 2006. Sample sites were selected to evaluate a longitudinal water-quality gradient extending from the upper end of the reservoir to the dam (table 1; fig. 1). Additional measurement sites were selected to evaluate spatial differences in chlorophyll-*a* and phycocyanin concentrations in the reservoir. Data were collected to compare in relation to land-use data, nutrient loading to the reservoir, and comparison to imaging spectroscopy data.

Water-Quality Monitoring and Analysis

The list of water properties and constituents collected at sites randomly distributed in the reservoir and analytical methods are presented in table 2. Spatial and temporal depth profiles of conductivity, pH, temperature, and dissolved oxygen were measured using a Model 556 YSI probe and data logger to determine seasonal stratification patterns (obtained from YSI Instruments, Yellow Springs, Ohio). Transparency of water (Secchi depth) was determined using a 300-millimeter Secchi disk (obtained from Wildlife Supply Co., Buffalo, New York).



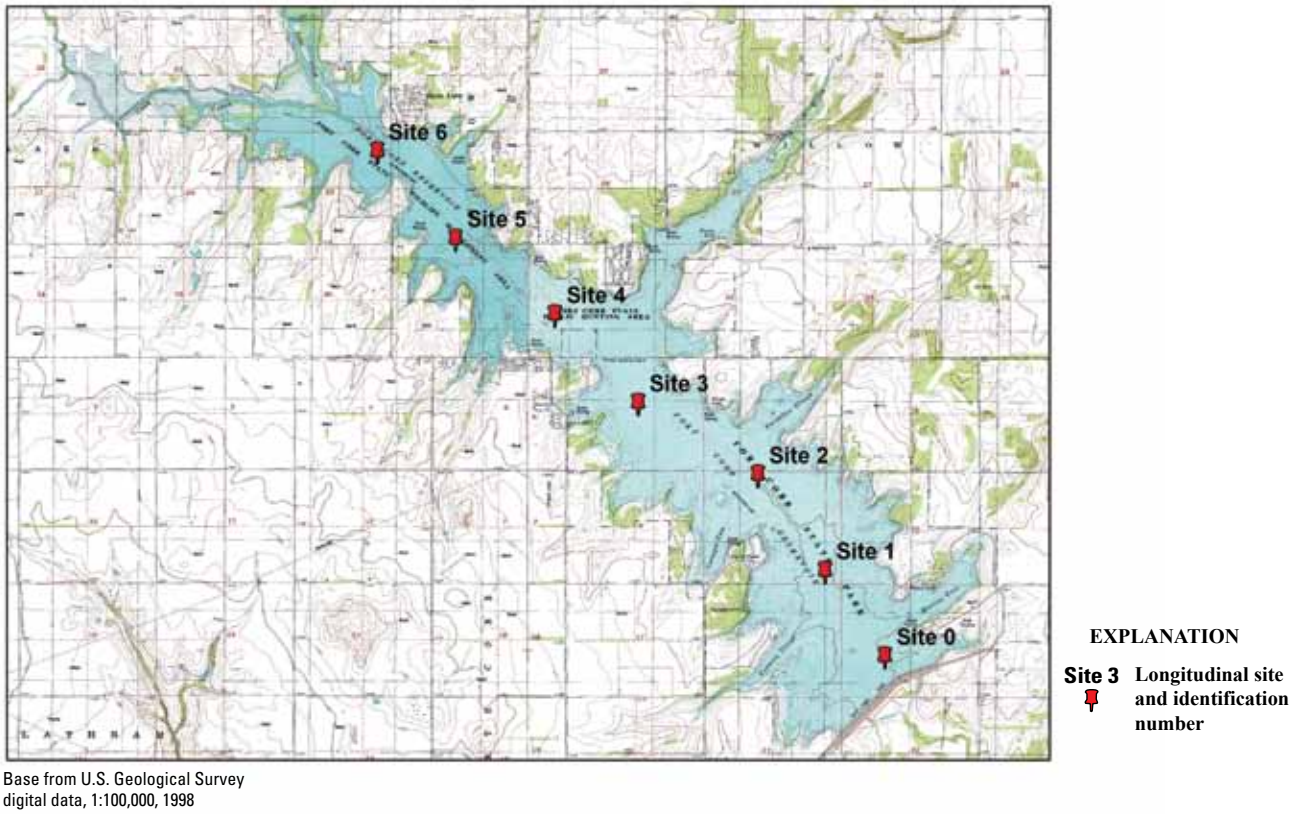


Figure 1. Location of the study area in the Fort Cobb Reservoir watershed and longitudinal sampling sites, southwestern Oklahoma.

Table 1. Longitudinal sampling sites used during the Fort Cobb Reservoir study, 2006.

[m, meters; GPS, Global Positioning System; mi, mile; NW, northwest; °, degrees; ', minutes]

Site	Location/ comments	Depth (m)	North GPS	West GPS
0	0 mi NW from dam	12	35° 9.905'	98° 27.054'
1	1 mi NW from dam	12	35° 10.606'	98° 27.734'
2	2 mi NW from dam	10	35° 11.342'	98° 28.251'
3	3 mi NW from dam	8	35° 11.893'	98° 29.171'
4	4 mi NW from dam	5	35° 12.573'	98° 29.808'
5	5 mi NW from dam	3	35° 13.155’	98° 30.571'
6	6 mi NW from dam	1	35° 13.824'	98° 31.176'

Table 2. List of water properties and constituents sampled and analytical methods used for the Fort Cobb Reservoir study, 2006.

[ELISA, Enzyme-Linked Immunosorbent Assay]

Matrix	Water properties and constituents sampled	Analytical method
Water	Particulate organic carbon	Oxidation/coulometric
Water	Total nitrogen/ phosphorus	Colorimetric (Persulfate digestion)
Water	Turbidity	YSI Probe
Water	pH	YSI Probe
Water	Alkalinity	Titrimetric
Water	Hardness	Titrimetric
Water	Conductivity	YSI Probe
Water	Dissolved oxygen	YSI Probe
Water	Temperature	YSI Probe
Water	Secchi depth	300-millimeter secchi disk
Phytoplankton	Biomass (*in vitro* chlorophyll-*a*)	Turner Model AU-10
Phytoplankton	Biomass (*in vivo* chlorophyll-*a*)	Turner Aquafluor
Phytoplankton	Biomass (*in vivo* phycocyanin)	Turner Aquafluor
Phytoplankton	Microcystin	ELISA
Location	Global Positioning System	Garmin mapper

Surface-water samples were collected by using a 4-meter (m) long depth-integrating hose sampler and were analyzed for total nitrogen, total phosphorous, particulate organic carbon, algal biomass, and microcystin. Water samples were filtered on Gelman Type A/E glass fiber filters and stored at -20 degrees Celsius until analysis at the USGS Columbia Environmental Research Center (CERC), Columbia, Missouri. Samples to be analyzed for total nitrogen and total phosphorus concentrations were digested by using the persulfate methods described in Standard Method 4500-P (Eaton and others, 2005) followed by measurement using colorimetry (total nitrogen, sodium salicyilate/nitro-prusside method; total phosphorus, ascorbic acid method) with a Technicon AAII Autoanalyzer (obtained from Technicon Industrial Systems, Tarrytown, New York). Particulate organic carbon was measured by using a Coulometrics Model 5020 Carbon Analyzer (obtained from UIC, Inc., Joliet, Illinois). Algal biomass was estimated by using *in vivo* and *in vitro* measurement of concentrations of chlorophyll-*a* (a primary pigment in green algae) and *in vivo* measurement of phycocyanin (a primary pigment in cyanobacteria, that is, blue-green algae). Spatial measurements of *in vivo* chlorophyll-*a* and phycocyanin concentrations were made by using the hand-held fluorometer at 30 locations in the reservoir on each sampling date during April, July, and September, 2006 for comparison to the standardized longitudinal gradients (sites 0-6) to evaluate potential influences of highly used recreation areas and specific tributaries on the standing crop of phytoplankton. *In vivo* chlorophyll-*a* and *in vivo* phycocyanin concentrations were analyzed by using a Turner Aquafluor handheld meter (obtained from Turner Designs, Inc., Sunnyvale, California). The *in vitro* chlorophyll-*a* concentration was determined after extraction in 90 percent buffered acetone by using a Turner Model AU-10 Fluorometer (obtained from Turner Designs, Inc., Sunnyvale, California) according to Standard Method 10200 H (Eaton and others, 2005).

The plankton community of eutrophic reservoirs is frequently dominated by cyanobacteria. Cyanobacteria are considered to be a threat to water quality for several reasons including taste, odor, and the production of chemical substances such as microcystin that can be toxic to mammals and birds (National Institute of Environmental Health Sciences, 2010). Samples analyzed for microcystin were subsequently thawed, resuspended, and extracted in 50 milliliters (mL) in CERC well water by using a series of three freeze-thaw cycles. Subsequently, samples were refiltered by using a glass fiber filter and measured for total microcystin by using an Enzyme-Linked Immunosorbent Assay (ELISA, Lequin, 2005). Microcystins were quantified by using a standard curve ranging from 0 to 5 micrograms per liter (µg/L) microcystin. Procedural and matrix blanks were processed with each batch of samples. Method detection limits were determined to be 0.1 µg/L microcystin.

Trophic Classification

Carlson (1977) proposed a series of Trophic State Indices (TSIs) for lakes and reservoirs based on chlorophyll-*a*, Secchi depth, and total phosphorus. The equations for calculating these indices are as follows:

TSI(SD) = 60 - 14.41 ln(SD)

TSI(CHL) = 9.81 ln(CHL) + 30.6

TSI(TP) = 14.42 ln(TP) + 4.15,

where

TSI = Trophic State Index,

SD = Secchi depth reading, in meters,

CHL = Chlorophyll, in micrograms per liter,

TP = Total phosphorus, in micrograms per liter, and

1n = natural logarithm.

The ranges of trophic states, from oligotrophic to hypereutrophic, are listed in table 3. The State of Oklahoma relies primarily on chlorophyll-*a* readings to evaluate reservoir trophic status because of concerns about the influence of suspended sediments that can bias Secchi readings downward (from mineral turbidity) and bias total phosphorus upward (from phosphorus adsorbed to sediments) (Oklahoma Department of Environmental Quality, 2000). The ranges of chlorophyll-based trophic states and narrative water-quality descriptions are listed in table 4.

Statistical Analysis of Data

Water-quality and related data were analyzed by using the Statistical Analysis System (SAS, Statistical Analysis System Institute, 1990). Data were tested for normality of distribution by using Proc Univariate (Shapiro Wilk's Statistic). Data were normally distributed; therefore, statistical analyses

Table 3. Trophic State Index (TSI) thresholds from Carlson (1977).[1]

[m, meter; µg/L, microgram per liter]

Constituent	Oligotrophic	Mesotrophic	Eutrophic	Hypereutrophic
TSI	30	40	50–60	70
Secchi depth (m)	8	4	2–1	0.5
Chlorophyll-*a* (µg/L)	0.95	1.6	7–20	55
Total phosphorus (µg/L)	0	12	24–40	90

[1] Note: Classifications are for relative comparison only and must be adjusted for site-specific conditions as described by Carlson (1997). For further information refer to Web page at http://dipin.kent.edu/tsi.htm.

Table 4. Classification of trophic status used in Oklahoma based on the chlorophyll index component of Carlson's Trophic State Index (TSI) from Carlson (1977).[1]

[Chl, chlorophyll; <, less than; >, greater than]

Chlorophyll TSI (range)	Trophic state	Narrative reservoir conditions
< 40	Oligotrophic	Reservoir typified by low nutrients, low productivity, high clarity, and good water quality.
41 to 50	Mesotrophic	Reservoir with increased levels of nutrients and productivity.
51 to 60	Eutrophic	Reservoir with elevated nutrients, sedimentation, productivity, and decreased clarity.
> 60	Hypereutrophic	Reservoir with very high levels of nutrients, productivity, and decreased clarity. Nuisance algae, low dissolved oxygen, and fish kills likely or common leading to loss of recreational use.

[1] Information from Oklahoma Department of Environmental Quality (2000).

were conducted on untransformed data. Data were analyzed by using a two-way analysis of variance (ANOVA) for main effects (location and date) and interactions (Snedecor and Cochran, 1967). Treatment locations were subsetted as uplake (sites 5 and 6, near tributary inflows), midlake (sites 3 and 4), and downlake near the dam (sites 0, 1, and 2) (table 1). Associations among variables were examined by using Pearson-Product Moment correlations (r). Highly correlated data-group pairs had r values greater than 0.50, moderately correlated data-group pairs had r values between 0.50 and 0.33, and poorly correlated data-group pairs had r values less than 0.33. Significance levels were designated by p-values less than or equal to 0.05.

Water Quality and Trophic Status of Fort Cobb Reservoir

Temporal and Spatial Assessment of the Water Quality of Fort Cobb Reservoir

Algal Biomass

In vitro (solvent extracted) chlorophyll-*a* is the primary variable used to estimate algal biomass in reservoirs. Concentrations of chlorophyll-*a* ranged from 20 to 65 µg/L during the study, which are typical of hypereutrophic states (fig. 2). Chlorophyll-*a* concentrations varied with time much more than the TSI-Chl parameter that is log-transformed. Chlorophyll-*a* concentration averaged 36 µg/L across all sites and dates, with the greatest chlorophyll-*a* concentrations being measured in water samples collected in September (table 5, fig. 2). Date and location were significant main effects (table 6); no statistical interaction was observed. *In vivo* (unextracted) chlorophyll-*a* concentration was measured as a rapid assessment tool for spatial and temporal mapping of chlorophyll-*a* in the field. These data are reported as relative fluorescence units (RFU) and are not equivalent to chlorophyll-*a* concentrations because of particulate scatter/absorption; however, *in vivo* chlorophyll-*a* concentration was highly correlated with *in vitro* measures (r = 0.515, p = 0.017) and was used for the September flyover comparisons of remote sensing data (in chapter 6 of this report). *In vivo* chlorophyll-*a* concentration averaged about 4.32 RFU during the study, with greatest concentrations being observed in September (similar to the *in vitro* concentrations). Date and location were significant main effects for *in vitro* chlorophyll-*a* and date was a significant main effect for *in vivo* chlorophyll-*a*; however, the date*location interaction was not significant for either of those variables (table 6).

Fort Cobb Reservoir is dominated by blue-green algae (Fairchild and others, 2004). Therefore, *in vivo* phycocyanin concentrations, similar to the *in vivo* chlorophyll-*a* concentrations, were measured as an assessment tool for mapping algal abundance in the field (Wetzel, 1983). *In vivo* phycocyanin concentrations also are reported as relative fluorescence units (RFU) similar to *in vivo* chlorophyll-*a*. The mean *in vivo* phycocyanin concentration was 19.34 RFU and, similar to the chlorophyll-*a* measurements, the mean *in vivo* phycocyanin concentration was greatest in September (29.92 RFU) (table 5) contemporaneous with the greatest imaging spectroscopy study described in chapter 6 of this report. Date and location were significant main effects controlling *in vivo* phycocyanin concentrations; there were no significant date*location correlations (table 6).

The mean particulate organic carbon concentration was 3.59 mg/L for all sampling sites and dates. Location had a significant effect on particulate organic carbon, with the highest concentrations being measured in water samples collected in the shallow, upper reaches of the reservoir (fig. 3). Date had no relation to particulate organic carbon concentration (table 6). Furthermore, particulate organic carbon concentrations were not significantly correlated with *in vitro* chlorophyll-*a* concentrations, because the primary sources of particulate organic carbon in the reservoir probably are living and dead algae, bacteria, and zooplankton. However, particulate organic carbon concentration was significantly correlated with total concentrations of phosphorus (r = 0.494, p = 0.023) and nitrogen (r = 0.627, p = 0.002) (table 7) in water samples collected from this reservoir.

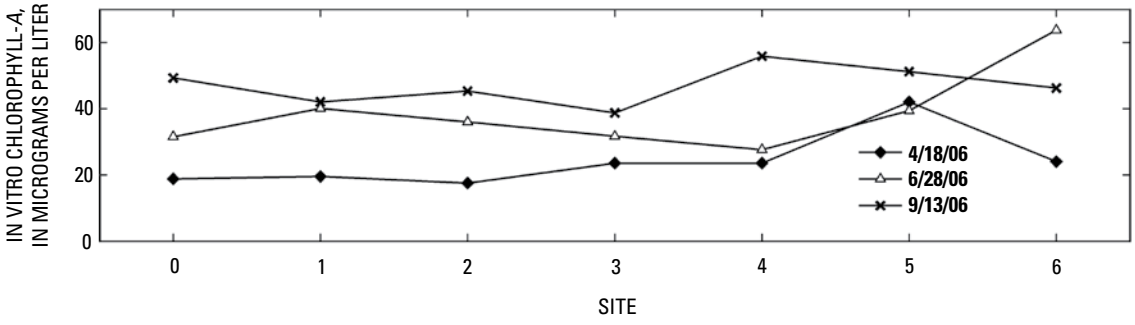


Figure 2. Longitudinal graph of chlorophyll-*a* concentration by date and site in the Fort Cobb Reservoir, southwestern Oklahoma, 2006.

Table 5. Sampling dates and mean limnological constituent values and concentrations measured in the Fort Cobb Reservoir by month (n=7 sites) and combined total (n=21 sites) in 2006.[1]

[TSI, Trophic State Index; Chl, chlorophyll; TP, total phosphorus; µg/L, microgram per liter; RFU, relative fluorescence unit; mg/L, milligram per liter; NTU, nephelometric turbidity unit; m, meter; µmhos, micromhos]

Constituent	Apr. 18	June 28	Sept. 13	Total
TSI-Chl	61 (3)[1]	66 (3)	68 (1)	65 (9)
TSI-TP	66 (8)	78 (4)	77 (2)	74 (8)
TSI-Sechhi	60 (10)	67 (8)	67 (8)	65 (9)
In vitro chlorophyll-*a* (µg/L)	24 (8)	38 (12)	47 (6)	36 (13)
In vivo chlorophyll-*a* (RFU)	3.50 (2.63)	3.66 (0.90)	5.82 (1.21)	4.32 4 (1.99)
In vivo phycocyanin (RFU)	8.05 (6.34)	20.06 (7.50)	29.92 (6.92)	19.34 (11.28)
Particulate organic carbon (mg/L)	3.81 (1.68)	3.48 (0.78)	3.46 (1.55)	3.59 (1.33)
Microcystin (µg/L)	0.01 (0.00)	0.22 (0.17)	0.03 (0.04)	0.08 (0.14)
Turbidity (NTUs)	12.3 (11.5)	12.5 (12.8)	13.8 (18.4)	12.9 (13.8)
Secchi depth (m)	1.14 (0.51)	0.67 (0.24)	0.66 (0.28)	0.82 (0.41)
Total nitrogen (mg/L)	0.99 (0.32)	1.18 (0.32)	1.29 (0.18)	1.15 (0.30)
Total phosphorus (mg/L)	0.08 (0.06)	0. 18 (0.07)	0.15 (0.02)	0.14 (0.06)
Total nitrogen: Total phosphorus ratio	13.9 (4.3)	6.7 (0.3)	8.5 (0.8)	9.7 (4.0)
Conductivity (µmhos)	511 (72)	517 (15)	477 (6)	502 (44)
pH	8.5 (0.1)	8.8 (0.1)	8.6 (0.1)	8.6 (0.2)
Dissolved oxygen (mg/L)	8.90 (2.18)	14.40 (2.85)	9.83 (2.33)	11.0 (3.4)

[1] Numbers (in parentheses) represent 1 standard deviation.

Table 6. Probability values (*p*-values) derived from two-way analysis of variance (ANOVA) of water-quality data collected from the Fort Cobb Reservoir, 2006 (all surface-integrated combined, n=21).

[TSI, Trophic State Index; Chl, chlorophyll; TP, total phosphorus, significance tested at *p*-value less than or equal to 0.05 level]

Variable	Model (*p*)	Date (*p*)	Location (*p*)	Date location interaction (*p*)
TSI-Chl	**0.0005**	**0.0001**	**0.0158**	0.1982
TSI-TP	**0.0005**	**0.0002**	**0.0035**	0.1568
TSI-Sechhi	**0.0021**	**0.0452**	**0.0001**	0.9119
In vitro chlorophyll-*a*	**0.0037**	**0.0006**	**0.0341**	0.3878
In vivo chlorophyll-*a*	**0.0246**	**0.0324**	0.0898	0.0923
In vivo phycocyanin	**0.0005**	**0.0001**	**0.0067**	0.8977
Microcystin	0.0508	**0.0088**	0.6760	0.4322
Particulate organic carbon	0.1173	0.7324	**0.0078**	0.8177
Turbidity	0.1082	0.9158	**0.0006**	0.9206
Secchi depth	**0.0001**	**0.0002**	**0.0001**	0.0840
Total nitrogen	**0.0324**	0.0720	**0.0046**	0.7929
Total phosphorus	**0.0071**	**0.0036**	**0.0065**	0.5775
Total nitrogen: Total phosphorus ratio	**0.0001**	**0.0001**	**0.0072**	**0.0015**
Conductivity	0.6561	0.3108	0.5446	0.7929
pH	**0.0397**	**0.0119**	**0.0343**	0.7404
Dissolved oxygen	**0.0013**	**0.0005**	**0.0289**	0.0654

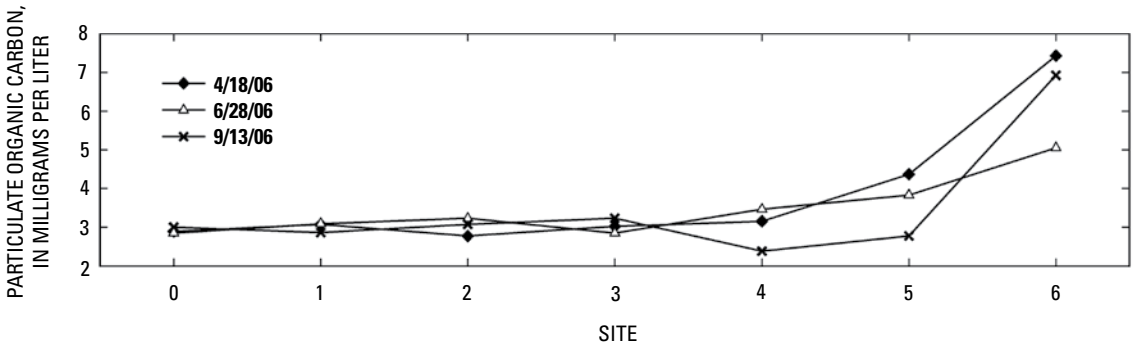


Figure 3. Longitudinal graph of particulate organic carbon concentrations by date and site in the Fort Cobb Reservoir, southwestern Oklahoma, 2006.

Table 7. Regression coefficients and probability values for limnological parameters measured in the Fort Cobb Reservoir, 2006.

[Bold values indicate significant correlation: Chl, chlorophyll-*a*; TSI, trophic state index; POC, particulate organic carbon; Micro, microcystin; TP, total phosphorus; TN, total nitrogen; Secchi, Secchi depth; Temp, temperature; DO, dissolved oxygen; Turb, turbidity; Cond, conductivity]

		Pearson correlation coefficient, r																
		Chl (TSI)	**TP (TSI)**	**Secchi (TSI)**	***In vitro* Chl**	**POC**	**Micro**	**TP**	**TN**	**TN:TP ratio**	**Secchi**	***In vivo* Chl**	***In vivo* phyco-cyanin**	**Temp**	**DO**	**pH**	**Turb**	**Cond**
Probability, p	Chl (TSI)	1.000	**0.666**	**0.579**	**0.984**	0.095	-0.362	**0.532**	**0.468**	**-0.680**	**-0.717**	**0.523**	**0.831**	**0.569**	0.207	0.269	0.365	**-0.576**
	TP (TSI)	**0.001**	1.000	**0.732**	**0.587**	0.429	-0.112	**0.952**	**0.819**	**-0.932**	**0.852**	**0.606**	**0.733**	**0.707**	0.312	0.004	0.273	-0.038
	Secchi (TSI)	**0.006**	**0.001**	1.000	**0.588**	**0.782**	-0.392	**0.723**	**0.768**	**-0.591**	**-0.945**	**0.624**	**0.758**	0.264	-0.061	-0.312	**0.568**	-0.072
	In vitro Chl	**0.001**	**0.005**	**0.005**	1.000	0.092	-0.378	**0.467**	**0.434**	**-0.583**	**-0.686**	**0.515**	**0.836**	**0.498**	0.129	0.247	**0.445**	**-0.568**
	POC	0.683	0.525	**0.001**	0.675	1.000	-0.107	**0.494**	**0.627**	-0.250	**-0.620**	**0.546**	0.389	-0.182	-0.254	**-0.677**	0.431	0.090
	Micro	0.338	0.774	0.297	0.316	0.784	1.000	-0.158	-0.341	0.008	0.478	-0.306	-0.457	0.452	0.082	0.362	-0.148	0.477
	TP	**0.013**	**0.001**	**0.001**	**0.033**	**0.023**	0.684	1.000	**0.900**	**-0.801**	**-0.794**	**0.545**	**0.671**	**0.604**	0.176	-0.106	0.258	0.070
	TN	**0.032**	**0.001**	**0.001**	**0.049**	**0.002**	0.370	**0.001**	1.000	**-0.570**	**-0.760**	**0.632**	**0.710**	0.262	-0.199	-0.383	0.262	-0.001
	TN:TP ratio	**0.001**	**0.001**	**0.005**	**0.006**	0.275	0.784	**0.001**	**0.007**	1.000	**0.778**	**-0.493**	**-0.612**	**-0.810**	**-0.563**	-0.184	-0.219	0.089
	Secchi	**0.001**	**0.001**	**0.001**	**0.001**	**0.003**	0.193	**0.001**	**0.001**	**0.001**	1.000	**-0.622**	**-0.785**	**-0.472**	-0.157	0.128	**-0.465**	0.193
	In vivo Chl	**0.015**	**0.004**	**0.003**	**0.017**	**0.011**	0.428	**0.011**	**0.002**	**0.023**	**0.003**	1.000	**0.719**	0.177	-0.133	-0.331	0.376	-0.117
	In vivo phyco-cyanin	**0.001**	**0.001**	**0.001**	**0.001**	0.081	0.217	**0.001**	**0.001**	**0.003**	**0.001**	**0.001**	1.000	**0.467**	0.026	0.029	0.352	0.232
	Temp	**0.007**	**0.001**	0.247	**0.022**	0.430	0.222	**0.004**	0.250	**0.001**	**0.001**	0.442	**0.033**	1.000	**0.716**	**0.625**	0.100	0.041
	DO	0.369	0.169	0.793	0.578	0.266	0.834	0.446	0.388	**0.008**	0.496	0.565	0.912	**0.001**	1.000	**0.587**	-0.022	0.047
	pH	0.238	0.986	0.168	0.281	**0.001**	0.338	0.646	0.087	0.425	0.580	0.143	0.902	**0.002**	**0.005**	1.000	-0.263	0.742
	Turb	0.104	0.231	**0.007**	**0.043**	0.051	0.705	0.260	0.251	0.341	**0.034**	0.093	0.117	0.667	0.924	0.249	1.000	-0.104
	Cond	**0.006**	0.869	0.757	**0.007**	0.698	0.195	0.765	0.997	0.700	0.403	0.613	0.312	0.861	0.839	0.742	0.652	1.000

Algal Toxins

Total microcystin concentrations in water averaged 0.08 µg/L during the study and ranged from nondetectable (April) to peak values in June (0.55 µg/L) (fig. 4, table 5); this peak value corresponds to about one-half of the maximum limit for drinking water of 1 µg/L (World Health Organization, 1996; Chorus and Bartram, 1999). However, microcystin concentrations varied widely on a spatial and temporal basis and were not well correlated with any other measured limnological parameter (table 7). The general lack of relation of microcystin concentrations with other variables commonly has been observed in other studies; lack of predictability of factors associated with algal blooms is known to vary by species, strain, and other unknown factors (Graham and others, 2006). Determination of phytoplankton community composition was beyond the scope of this study. However, Fairchild and others (2004) identified 76 phytoplankton taxa in a 2-year study of the Fort Cobb Reservoir conducted from 2000 to 2002. The phytoplankton community was dominated by the cyanobacteria (Phylum Cyanophycota) at all reservoir sites. The rest of the community was dominated by Bacillariophyta, Chlorophycota, Chrysophyta, Cryptophycophyta, Euglenophyta, and the Pyrrophycophyta; however, these phyla were of low proportion compared to the cyanobacteria. Primary cyanobacterial genera in order of occurrence were *Microsystis*, *Wollea*, *Anabaena*, *Oscilliatoria*, *Merismopedia*, *Anabaenopsis*, and *Aphanizomenon* spp. The species composition observed was consistent with that of hypereutrophic reservoirs (Wetzel, 1983). Therefore, the dominance of cyanobacteria in the phytoplankton community is a major concern for water quality in Fort Cobb Reservoir. Cyanobacteria blooms are frequently associated with taste-and-odor problems in reservoirs. In addition, many species of cyanobacteria, including *Microcystis* sp., can produce hepatotoxins and neurotoxins that are harmful to mammals (Carmichael, 1992, 1997; Kotak and others, 1993, 1995). *Microcystis aeruginosa* was the most commonly observed species of cyanobacteria in Fort Cobb Reservoir by Fairchild and others (2004).

Turbidity and Secchi Depth

Mean turbidity of all water samples was 12.9 nephelometric turbidity units (NTUs) (table 5), and was significantly affected by location but not by date (table 6). Secchi depth, which is a measure of visual water clarity, ranged from 0.1 to 1.6 m during the study (fig. 5). The highest water clarity was observed at the dam (site 0) in April 2006. Secchi depth decreased uplake to site 6, where water clarity was highly reduced regardless of date. Secchi depth averaged 0.82 m during the study and averaged 1.14, 0.67, and 0.66 m for the April, June, and September sampling dates, respectively (table 5). Two-way ANOVA indicated that date and location were significant factors related to depth; location was a slightly larger factor than date primarily because of the influence of site 6 on the dataset (table 6). Secchi depth was significantly negatively correlated with turbidity ($r = 0.465$, $p = 0.034$) (table 7).

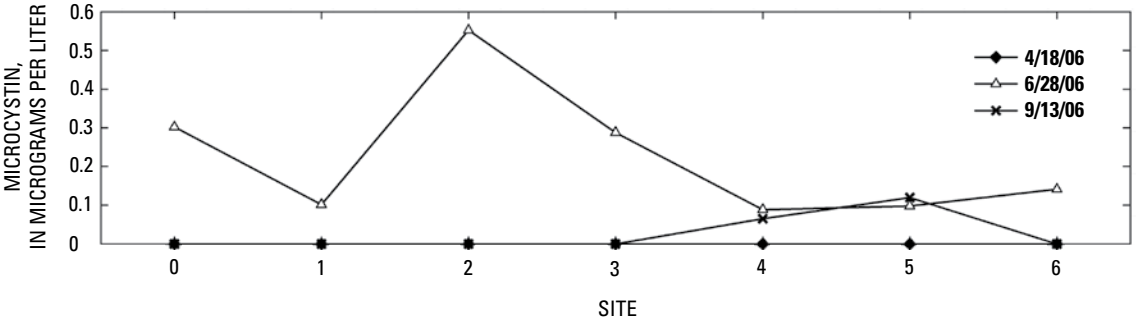


Figure 4. Longitudinal graph of microcystin concentrations by date and site in the Fort Cobb Reservoir, southwestern Oklahoma, 2006.

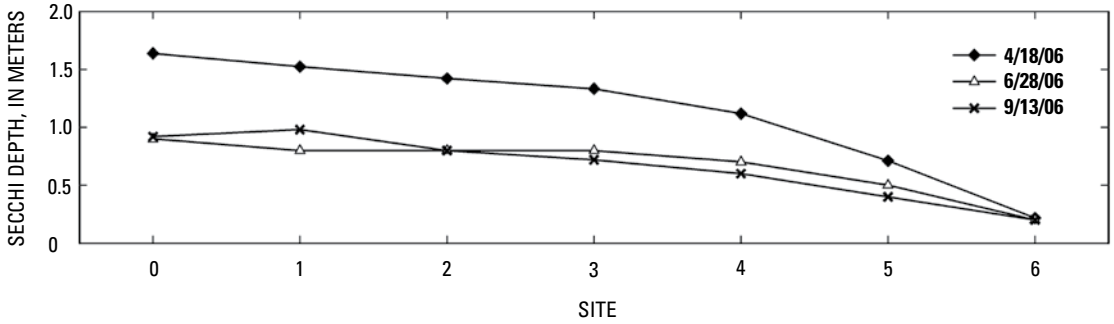


Figure 5. Longitudinal graph of Secchi depth by date and site in the Fort Cobb Reservoir, southwestern Oklahoma, 2006.

Total Nitrogen, Total Phosphorus, and Nitrogen/Phosphorus Ratio

The mean total nitrogen concentration of all of the water samples was 1.15 mg/L (fig. 6 and table 5) and was significantly related to location but not date (table 6). The mean total phosphorus concentration, frequently used as a trophic indicator, of all of the samples was 0.14 mg/L (fig. 7 and table 5); date and location were significant effects on total phosphorus concentration (table 6).

Limnologists frequently use the ratio of total nitrogen to total phosphorus to evaluate nutrient limitation. Most freshwater aquatic systems are phosphorus-limited, whereas marine systems commonly are nitrogen-limited (Wetzel, 1983; Rabalais and others, 2001). Nitrogen/phosphorus ratios (N/P ratios) of about 16 (range from 10 to 20) are considered optimum for phytoplankton production; numbers exceeding 20 are usually considered to be phosphorus-limited, whereas ratios less than 10 are considered to be nitrogen-limited (Wetzel, 1983; Geider and LaRoche, 2002). However, regional departures from these ratios can occur, such as when light is limiting because of turbidity or other factors. The mean N/P ratio in all of the water samples was 9.7; the highest mean N/P ratio was measured in April 2006 (N/P ratio = 13.9 prior to the algal bloom and decreased thereafter to 6.7 and 8.5 in June and September, respectively) (fig. 8 and table 5). Date ($p=0.0001$, location ($p = 0.0072$), and the date*location interaction (0.0015) were all significant effects related to N/P ratio (table 6). The significant date*location interaction indicates that processes that drive nutrient availability and phytoplankton response vary in time and space. During the mid-summer to late summer, however, the data clearly indicate that nitrogen limitation is occurring (for example, N:P ratio less than 10); it has been hypothesized that nitrogen limitation favors the growth of cyanobacteria that can "fix" atmospheric nitrogen in cells and thus out-compete other phytoplankton species for available phosphorus (Wetzel, 1983).

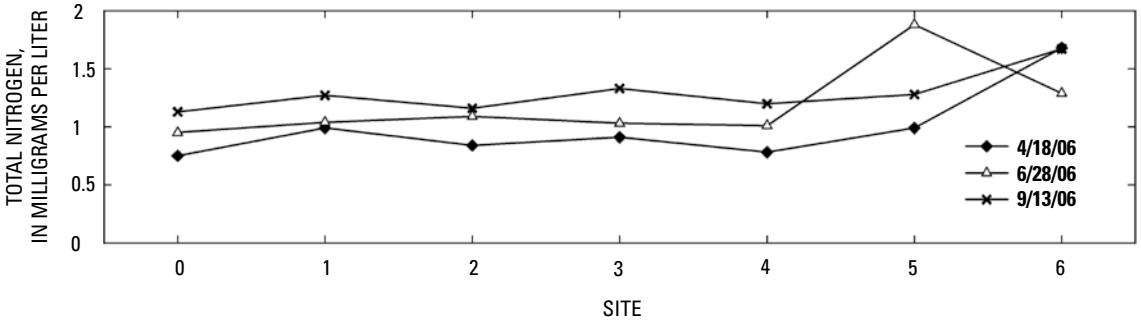


Figure 6. Longitudinal graph of total nitrogen concentration by date and site in the Fort Cobb Reservoir, southwestern Oklahoma, 2006.

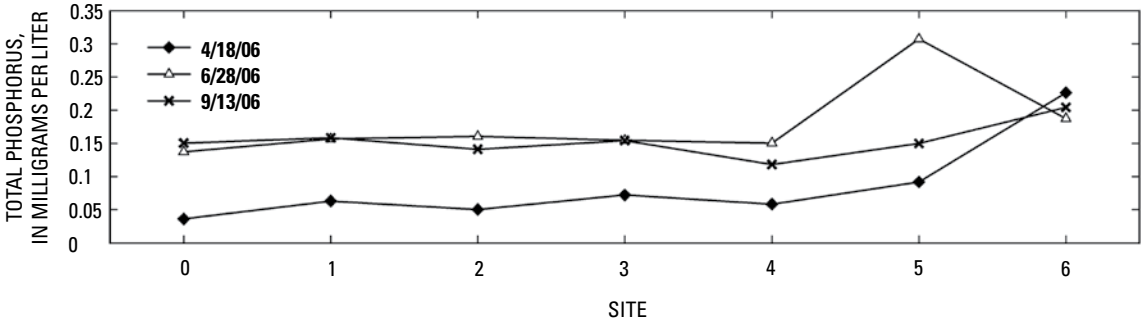


Figure 7. Longitudinal graph of total phosphorus concentration by date and site in the Fort Cobb Reservoir, southwestern Oklahoma, 2006.

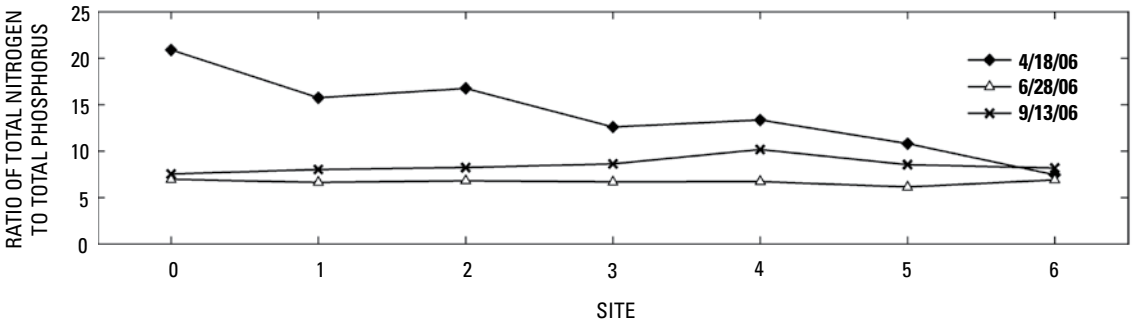


Figure 8. Longitudinal graph of total nitrogen to total phosphorus ratio by date and site in the Fort Cobb Reservoir, southwestern Oklahoma, 2006.

Conductivity, pH, and Dissolved Oxygen

Conductivity, a measure of ionic strength of surface waters, averaged 502 micromhos (µmhos) across all sites and dates (table 5). However, no significant effects of date or location on conductivity were indicated (table 6). However, conductivity was significantly negatively correlated to *in vitro* chlorophyll concentration ($r = -0.568$, $p = 0.007$) and TSI-Chl ($r = -0.576$, $p = 0.006$) possibly because of precipitation of ions during periods of high algal biomass and productivity (table 7) (Wetzel, 1983).

The mean pH of all of the water samples was 8.6 (table 5). Date ($p = 0.0119$) and location ($p = 0.0343$) were significant effects (table 6) on pH. The highest mean pH (8.8) was in June during the peak in algal blooms, probably because of photosynthetic uptake of carbon dioxide. However, the general pH range was narrow, in part because of the high buffering capacity of the reservoir and the fact that in situ pH usually was measured in early morning. pH is known to vary diurnally in aquatic systems because of carbon metabolism (Wetzel, 1983). However, diurnal variations in pH were not evaluated for this report.

Seasonal and spatial analysis of dissolved oxygen concentrations indicated that date ($p = 0.0005$) had a stronger effect than spatial location ($p = 0.0289$) (table 6). The mean dissolved oxygen concentration in all of the water samples was 11.0 mg/L (table 5). The highest concentrations of dissolved oxygen were measured in June during the peak of primary productivity (mean = 14.4 mg/L), which is above saturation. However, average concentrations remained greater than 8.0 mg/L in water samples collected from the reservoir surface. Thus, in spite of the hypereutrophic conditions, dissolved oxygen concentrations usually remained well above levels of concern for fish (that is, 5 mg/L; Francis-Floyd, 2009), even during morning hours when lowest dissolved oxygen concentrations are expected. High dissolved oxygen probably is maintained because of a combination of wind mixing of the reservoir and overnight release of dissolved oxygen from super-saturated algal cells.

Reservoir Water Quality: Vertical Trends and Assessment of Stratification

Reservoirs frequently have vertical stratification of temperature and dissolved oxygen. Vertical stratification of these properties can profoundly influence reservoir dynamics because of changes in dissolved oxygen availability and subsequent nutrient exchange/dynamics with sediments (Wetzel, 1983). Therefore, vertical stratification of temperature and dissolved oxygen concentration was monitored in the reservoir at regular intervals.

A marked thermocline was never observed during any of the monthly samplings (fig. 9), which is similar to the results of a 2-year study of this reservoir by Fairchild and others (2004). Differences in temperatures across months reflected annual air temperatures and remained well below levels of concern for fish: 20 degrees Celsius for indigenous warm water fish (State of Washington Department of Ecology, 2010).

In contrast, strong vertical differences in dissolved oxygen were observed across dates and sites (fig. 10). In particular, data from the June sampling revealed dissolved oxygen depletion with increasing depth at sites 0, 1, 2, 3, and 4; depletion was not as severe at site 5 because of wind mixing and shallower depth. Similar dissolved oxygen depletions were observed by Fairchild and others (2004) in 2000–2002 though not as severe as in the sampling conducted for this report. The primary factor associated with dissolved oxygen depletion is light limitation, when high concentrations of algal biomass decrease the depth of the photic zone, thereby diminishing oxygen replenishment by primary producers at greater depths. Concomitant with decreased primary productivity is the continued respiratory demand that further depletes dissolved oxygen. Low dissolved oxygen is further exacerbated during cloudy weather with low wind mixing (Francis-Floyd, 2009).

Vertical profiles of pH also reflected strong seasonal and spatial trends (fig. 11). The highest values of pH generally occurred in June and September during the highest periods of primary production. During photosynthesis, dissolved carbon dioxide is assimilated into carbohydrate by algae; this change in bicarbonate concentrations shifts pH upward (Livingtone, 1963, p. G9). The greatest vertical trends in pH occurred in June during high periods of primary productivity, in which pH decreased with depth linearly from the surface to the bottom. This decrease probably is related to reduced primary productivity at increasing depth because of light limitation.

Reservoir Water Quality: Intensive Seasonal Mapping of Algal Biomass

Spatial maps of *in vivo* concentrations of chlorophyll (primarily green algae) (fig. 12) and phycocyanin (primarily cyanobacteria, commonly referred to as blue-green algae) (fig. 13) constructed from measurements made throughout the reservoir during seasonal water-quality samplings done on April 19, June 19, and September 14, 2006 indicated extreme seasonal and spatial differences in the reservoir that were not revealed by the longitudinal mapping at the basic seven reservoir sites. The upper, shallow end of the reservoir contained high concentrations of green algae and cyanobacteria regardless of date. These high concentrations occur largely because of the shallow nature of the upper end of the reservoir where light penetration and nutrient concentrations remain high. In contrast, during warmer months higher levels of productivity were observed throughout the reservoir. This high productivity may reflect increased nutrient input from point sources during the recreational season. These data also reflect the value of using *in vivo* mapping techniques to gain greater resolution of water quality in the reservoir compared to conventional *in vitro* sampling, which requires increased time and effort.

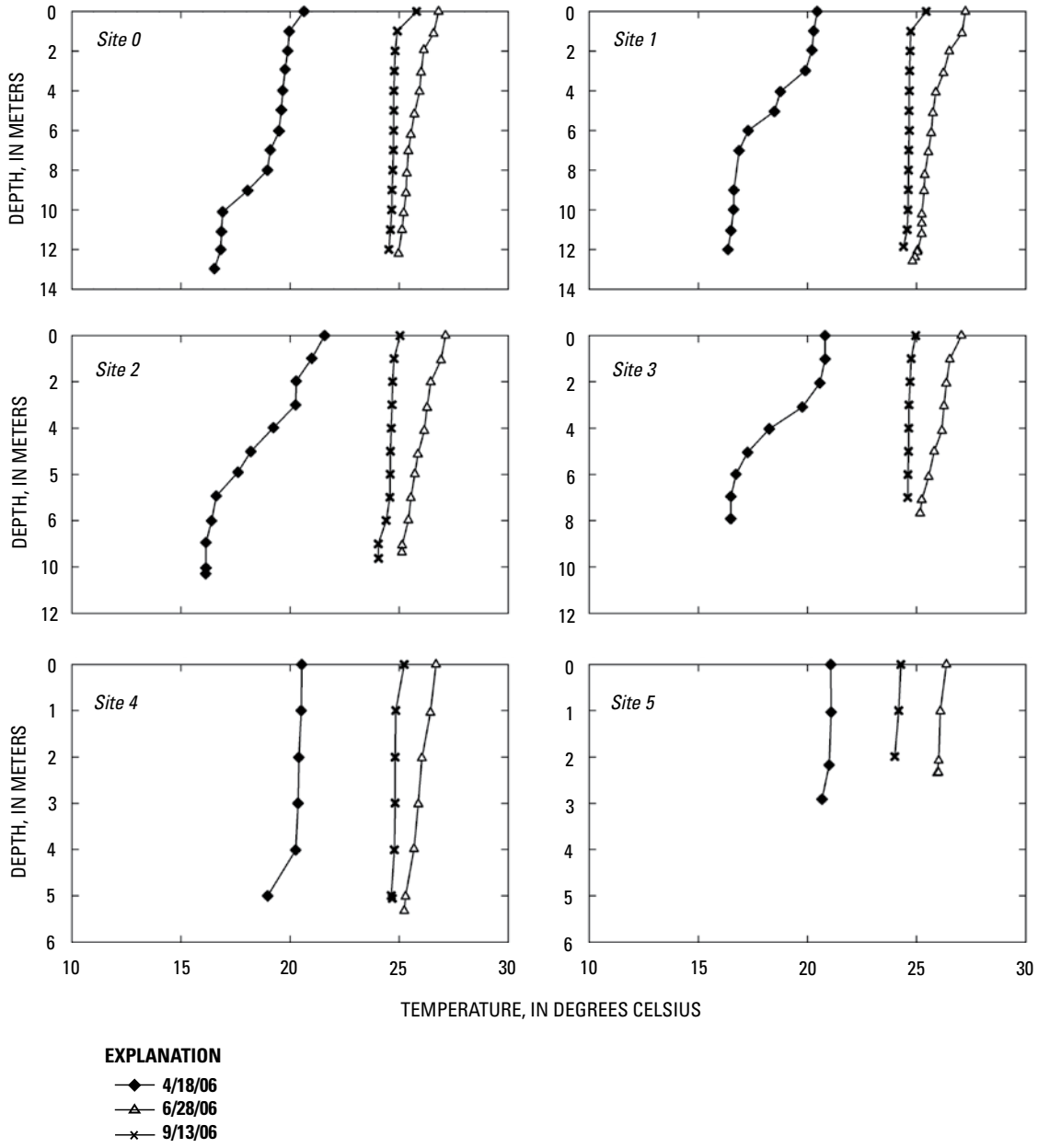


Figure 9. Depth profiles of water temperature by site in the Fort Cobb Reservoir, southwestern Oklahoma, 2006.

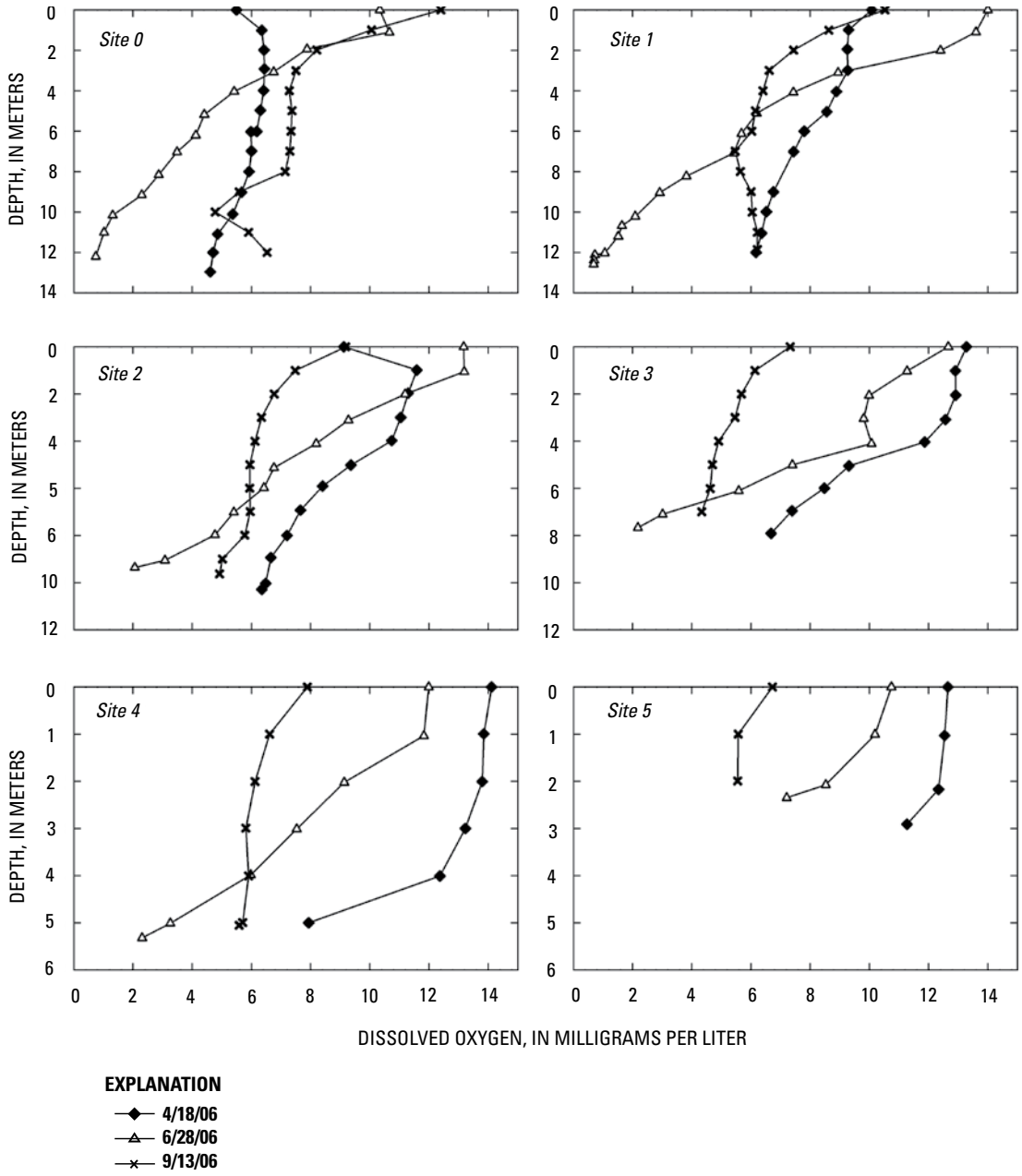


Figure 10. Depth profiles of dissolved oxygen concentration by site in the Fort Cobb Reservoir, southwestern Oklahoma, 2006.

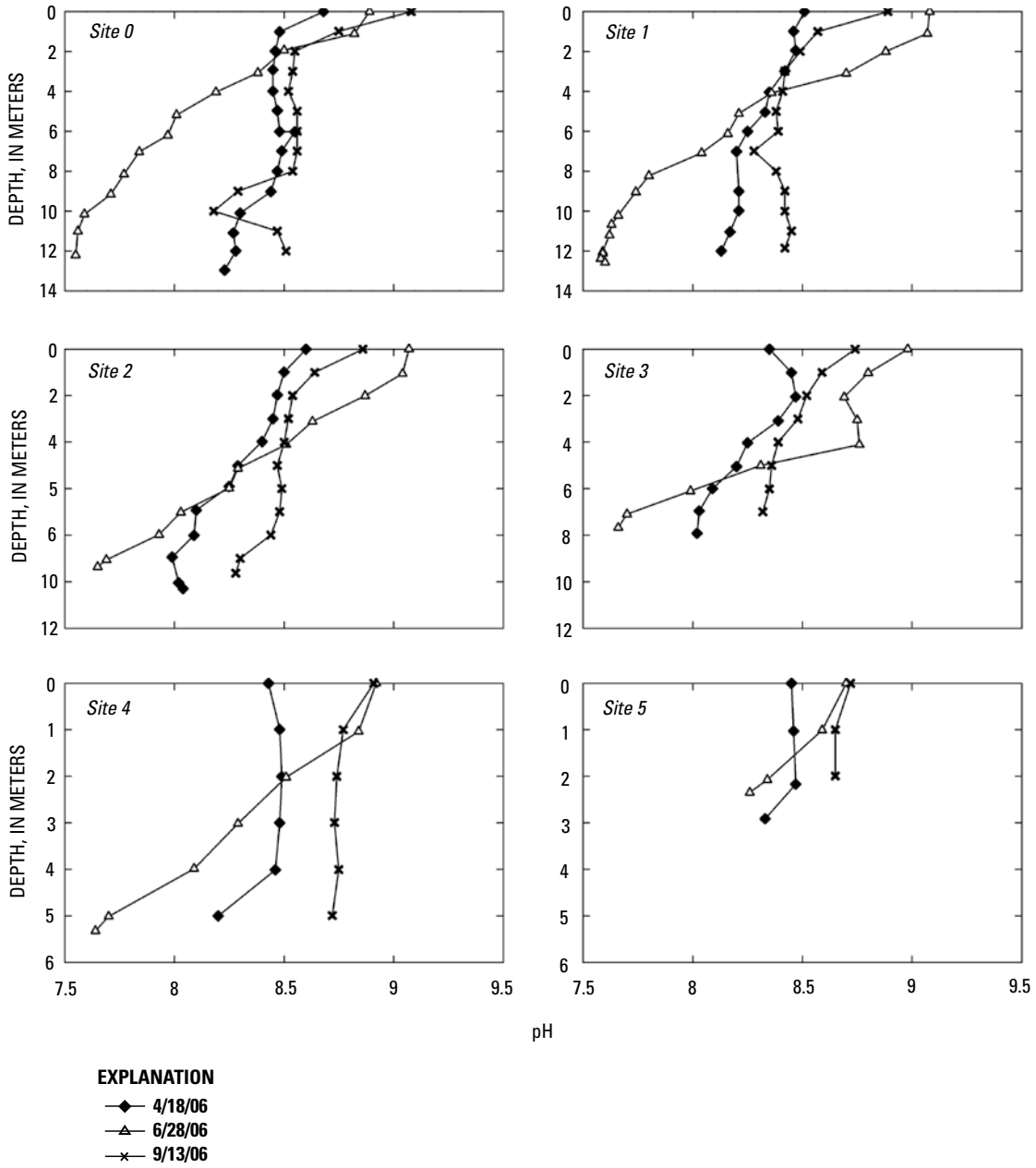


Figure 11. Depth profiles of pH by site in the Fort Cobb Reservoir, southwestern Oklahoma, 2006.

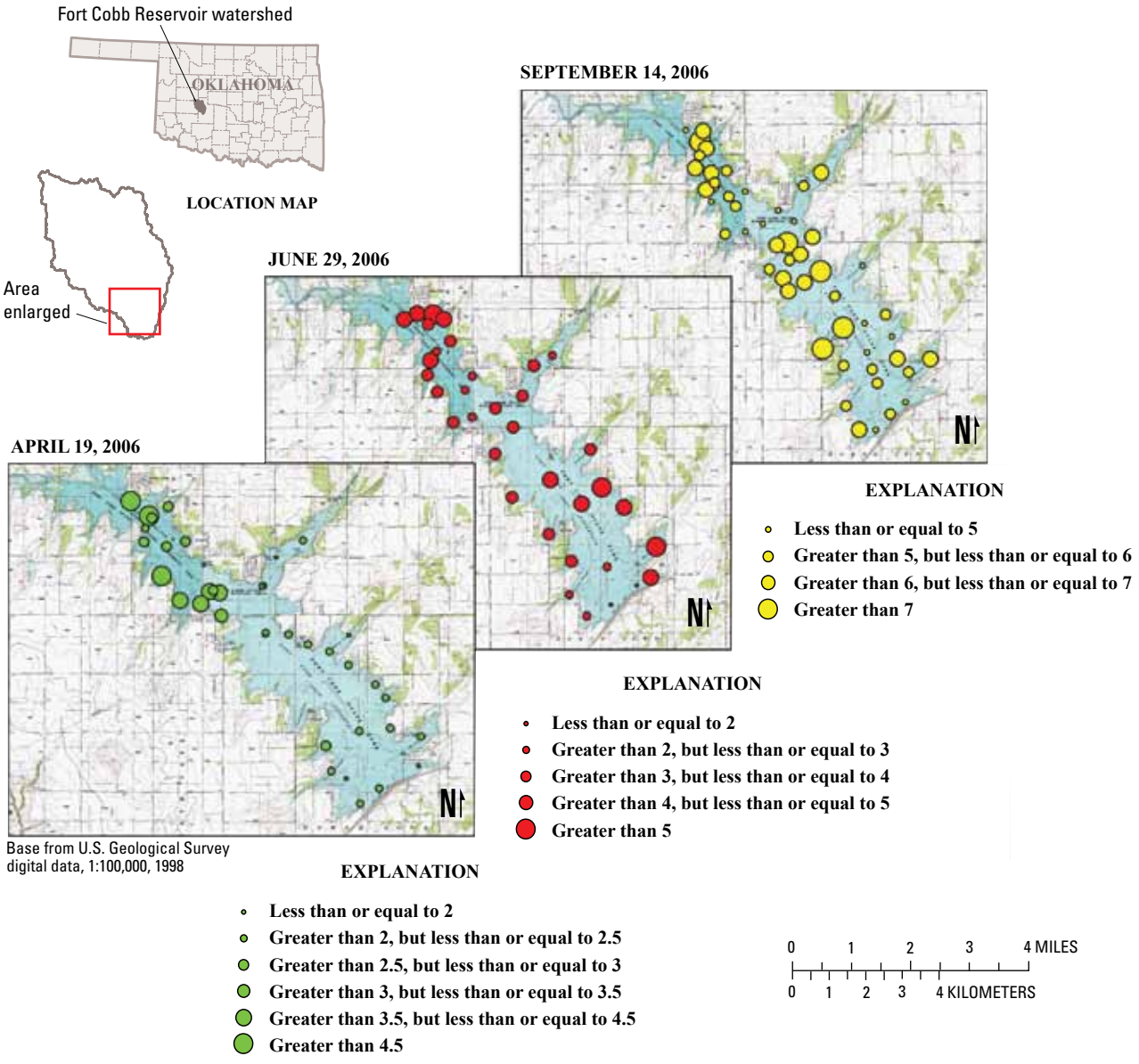


Figure 12. Spatial distribution of *in vivo* chlorophyll-*a* algae by month in the Fort Cobb Reservoir, southwestern Oklahoma, 2006.

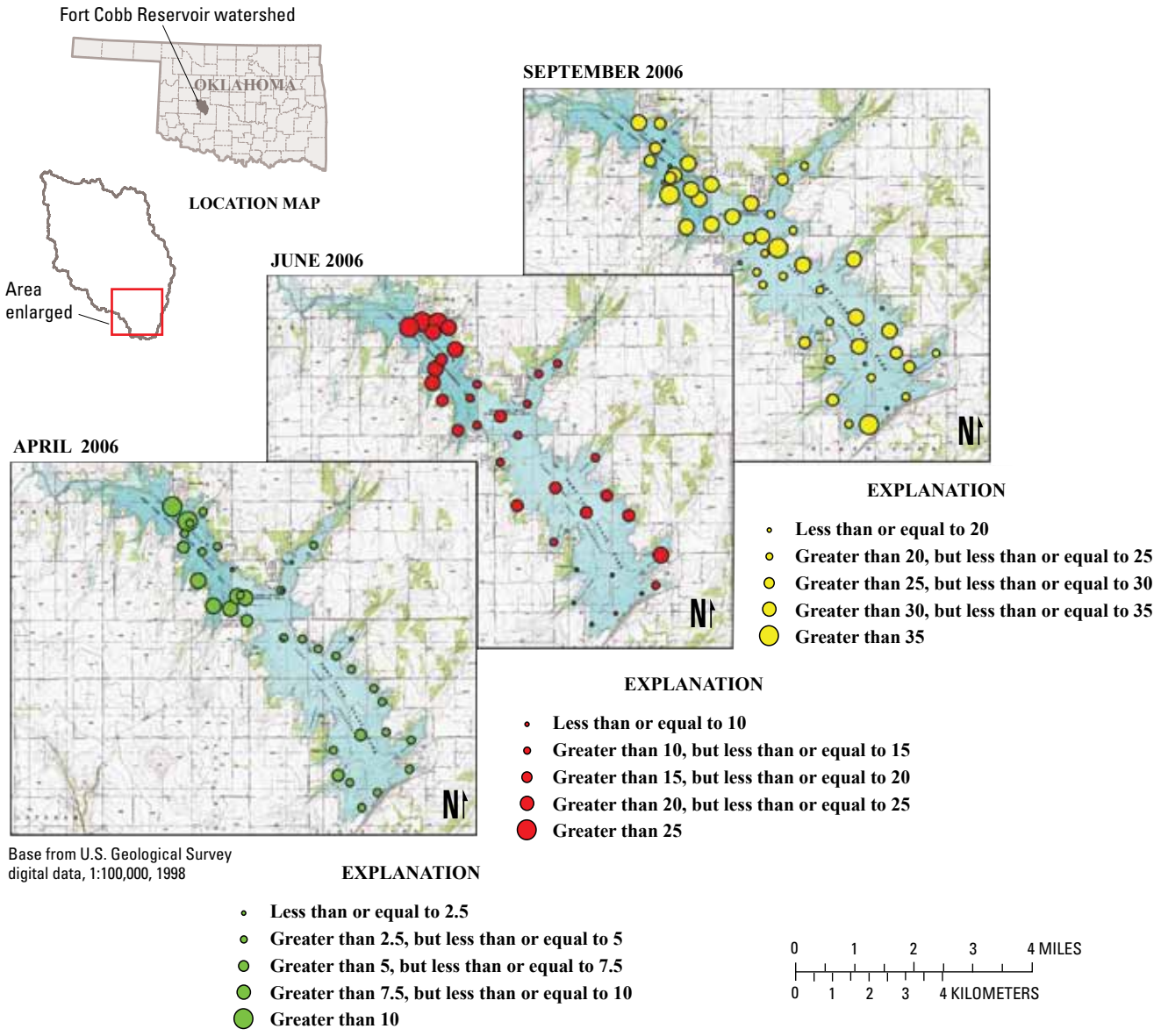


Figure 13. Spatial distribution of *in vivo* phycocyanin algae by month in the Fort Cobb Reservoir, southwestern Oklahoma, 2006.

Temporal and Spatial Assessment of the Trophic Status of the Fort Cobb Reservoir

The grand means of TSI during the study were 65 (TSI-Chl), 74 (TSI-TP), and 65 (TSI-Secchi) (table 5); therefore, Fort Cobb Reservoir is considered hypereutrophic on the basis of all three endpoints proposed by Carlson (1977) (table 3). The State of Oklahoma relies primarily on the chlorophyll-based Trophic State Index and narratives provided in table 4 that further indicate that water quality is degraded to levels of both biological and aesthetic concern. Date and location were significant main effects regarding all three indices of trophic status; however, no significant date*location interactions were indicated (table 6).

The chlorophyll-based TSI ranged from 60 to 72 among sites during the study (fig. 14). Average TSI-Secchi values were nearly identical to TSI-Chl values on all dates; however, average TSI-TP values were about 10 percent higher than

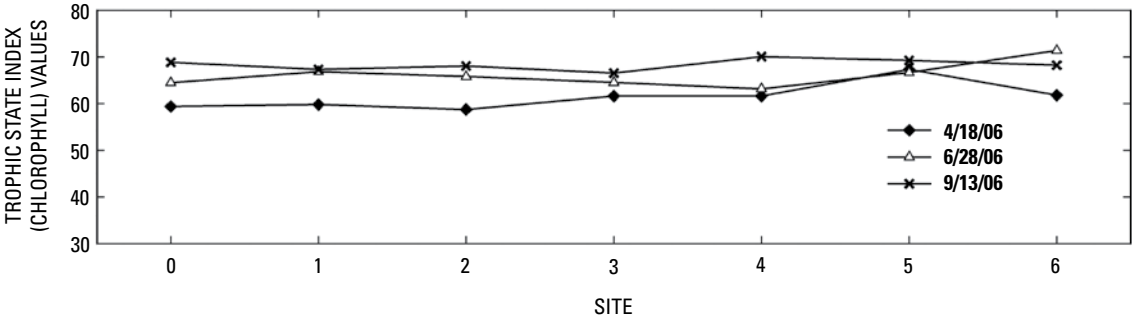


Figure 14. Longitudinal graph of Trophic State Index-chlorophyll measurements by date and site in the Fort Cobb Reservoir, southwestern Oklahoma, 2006.

TSI-Chl or TSI Secchi values (table 5). TSI-Chl was highly correlated with both TSI-TP ($r = 0.666$, $p = 0.001$) and TSI-Secchi ($r = 0.579$, $p = 0.006$) (table 7). Results indicated that the highest TSIs were during the month of September (fig. 14) and that the uplake sites (5 and 6) had consistently higher TSI values compared to the other sites because of two factors: (1) the uplake sites were shallow (less than 3 m depth) and subject to wind-mixing and bioturbation by fish, and (2) the uplake sites are near the point of entry of the two major tributaries (Cobb Creek and Lake Creek) to the reservoir. Similar observations were made by Martin (2002) and Fairchild and others (2004).

Summary and Conclusions

Investigation of the trophic status of Fort Cobb Reservoir, Oklahoma, indicated that the reservoir is hypereutrophic. Maximum concentrations of the algal toxin microcystin occurred during June and approached 50 percent of the concentration of concern to human health (1 µg/L) as established by the World Health Organization. Nutrient concentrations, turbidity, and algal biomass were highest in the upper end of the reservoir (site 6), near the major tributaries. The upper end of the reservoir is shallow (1 m or less), which exacerbates the effects of wind-mixing, and bioturbation in resuspension processes. Water quality improves downlake in a longitudinal trend toward the dam.

Currently (2010), there is a U.S. Environmental Protection Agency-sponsored 319 Non-Point Pollution Prevention Project ongoing in the Lake Creek watershed. This project is providing cost-share incentives and education to landowners in order to reduce nutrient loading to Fort Cobb Reservoir. Results indicate that nutrient reduction is needed if water quality of the reservoir is to be maintained or improved. Erosion reduction, improved nutrient management plans, and fencing of livestock are potential management strategies that may improve water quality. Construction of a physical barrier, such as a rock rip-rap weir in the upper end of the reservoir near Site 6 might aid in sediment retention. Establishment of emergent aquatic plant communities prior to entry into the reservoir may reduce concentrations of nutrients in the lake that contribute to eutrophication. Continued monitoring of water quality in the reservoir and watershed are needed to measure the success of nutrient-reduction programs.

Acknowledgments

This project was funded by the U.S. Geological Survey as a Central Region Integrated Science Project. We thank Lynne Johnson, Steve Olson, and Lyn Osborn of the USGS for their technical assistance.

References Cited

Carlson, R.E., 1977, A trophic state index for lakes: Limnology and Oceanography, v. 22, no. 2, p. 361-369.

Carmichael, W.W., 1992, A status report on planktonic cyanobacteria (blue-green algae) and their toxins: Washington, D.C., U.S. Environmental Protection Agency, EPA/600/R-92/079, 141 p.

Carmichael, W.W., 1997, The cyanotoxins, *in* Callows, J.A., ed., Advances in botanical research, v. 27: London, Academic Press Ltd., p. 211-256.

Chorus, I., and Bartram, J., 1999, eds., Toxic cyanobacteria in water—A guide to their public health consequences, monitoring, and management: London, E & FN Spon, 416 p.

Eaton, A.D., Clesceri, L.S., Rice, E.W., Greenberg, A.E., and Franson, M.H., 2005, eds., Standard methods for the examination of water and wastewater: Washington, D.C., American Public Health Association, 1,368 p.

Fairchild, J.F., Lakish, B., Echols, K., Chapman, D., Johnson, B.T., and Jones, S.B., 2004, An integrated assessment of the trophic status of Fort Cobb Reservoir, Oklahoma—Final report to the Bureau of Reclamation, available online at http://www.cerc.usgs.gov/pubs/center/pdfDocs/Fort_Cobb.pdf (accessed January 2008).

Francis-Floyd, R., 2009, Dissolved oxygen for fish production: University of Florida IFAS Extension, Publication no. FA27, available online at http://edis.ifas.ufl.edu/fa002 (accessed December 10, 2010).

Geider, R.J., and LaRoche, J., 2002, Redfield revisited—Variability of C:N:P in marine microalgae and its biochemical basis: European Journal of Phycology, v. 37, p. 1-17.

Graham, J.L., Jones, J.R., and Jones, S.B., 2006, Microcystin in Midwestern lakes: Lakeline, Summer 2006, p. 32-35, available online at http://ks.water.usgs.gov/studies/qw/cyanobacteria/GrahamJonesJones-LakeLine2006.pdf (accessed December 10, 2010).

Kotak, B.G., Kenefick, S.L., Fritz, D.L., Rousseaux, C.G., Prepas, E.E., and Hrudey, S.E., 1993, Occurrence and toxicological evaluation of cyanobacterial toxins in Alberta lakes and farm dugouts: Water Research, v. 27, no. 3, p. 495-506.

Kotak, B.G., Lam, A.K.-Y., Prepas, E.E., Kenefick, S.L., and Hrudey, S.E., 1995, Variability of the hepatotoxin microcystinLR in hypereutrophic drinking water lakes: Journal of Phycology, v. 31, p. 248-263.

Lequin, R., 2005, Enzyme immunoassay (EIA)/enzyme-linked immunosorbent assay (ELISA): Clinical Chemistry, v. 51, no. 12, p. 2415-2418.

Livingtone, D.A., 1963, Chemical composition of rivers and lakes, data of geochemistry (6th ed.): U.S. Geological Survey Professional Paper 440-G, p. G9.

Martin, D.B., 2002, Fort Cobb Reservoir water quality investigations: Tulsa, Okla., U.S. Fish and Wildlife Service, Report to the Bureau of Reclamation and Fort Cobb Reservoir Master Conservancy District, 84 p., available on line at http://pubs.usgs.gov/ds/270/data/DVD-1/REPORTS/USFWS.Martin.pdf

National Institute of Environmental Health Sciences, 2010, Mycocystin toxicity: National Institute of Environmental Health Sciences, available only online at http://ntp.niehs.nih.gov/ntp/htdocs/Chem_Background/ExSumPdf/Microcystin.pdf (accessed December 10, 2010).

Oklahoma Department of Environmental Quality, 2000, The State of Oklahoma water quality assessment report to Congress, Section 305(b) report: Oklahoma Department of Environmental Quality, 122 p.

Oklahoma Water Resources Board, 2005, Fort Cobb Reservoir in Beneficial Use Monitoring Program—Lake sampling, 2003-2004 draft final report, p. 213: Oklahoma Water Resources Board, available online at http://www.owrb.ok.gov/studies/reports/bump/2004/bump_pdf/lakes/fort_cobb.pdf (accessed December 10, 2010).

Rabalais, N.N., Turner, R.E., and Wiseman, W.J., Jr., 2001, Hypoxia in the Gulf of Mexico: Journal of Environmental Quality, v. 30, p. 320-329.

Snedecor, G.W., and Cochran, W.G., 1967, Statistical methods (6th ed.): Ames, Iowa, Iowa State University Press, 593 p.

State of Washington Department of Ecology, 2010, Part II—Designated uses and criteria, temperature: State of Washington Department of Ecology, available online at http://www.ecy.wa.gov/biblio/wac173201a.html (accessed December 10, 2010).

Statistical Analysis System Institute, 1990, SAS/STAT guide for personal computers, version 6, v. 1 and 2 (4th ed.): Cary, N.C., SAS Institute Inc., 1,685 p.

Wetzel, R.G., 1983, Limnology (2nd ed.): Philadelphia, Pa., Saunders College Publishing, 767 p.

World Health Organization, 1996, Guidelines for drinking-water quality volume 2—Health criteria and other supporting information (2nd ed.): Geneva, World Health Organization, p. 940-949.