PHYSICOCHEMICAL LIMNOLOGY OF CADDO LAKE, TEXAS AND LOUISIANA

by

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INTRODUCTION

In recent years there has been an increasing demand for water in the southern United States. This demand has increased as population and industry in the region have grown. The former reliance on groundwater reserves and the depletion of those reserves has caused surface water sources such as lakes and reservoirs to become increasingly important. In fact, the Texas Water Development Board (1968) has predicted that the aquifers that now supply approximately half of the water for East Texas will contribute only a minute fraction of the projected amount of water needed in the region by the year 2020.

In order to maintain high quality surface water it is essential to monitor the physicochemical conditions of streams, lakes, and reservoirs so that point and nonpoint sources of pollution can be identified. Large bodies of water, such as Caddo Lake, are regionally important as sources of domestic and industrial water and also provide valuable recreation areas.

Caddo Lake is one of the largest lakes of natural origin in Texas and Louisiana. Its shallow basin is covered with extensive bald cypress swamps and marshy areas that provide excellent wildlife habitats. Water from

Caddo Lake is used by several cities including Shreveport, Louisiana. Also, the off-shore oil industry of the lake has been an important part of the regional economy.

The objective of this study was to describe the physicochemical limnology of Caddo Lake by measuring some of the important physical and chemical parameters of the water and statistically analyzing the temporal and spatial variations of those parameters. Special consideration was given to the possible effects of the off-shore oil industry on the physicochemical condition of the lake.

LITERATURE REVIEW

Hutchinson (1957) thoroughly described the fundamental physical and chemical concepts of lakes. Frey (1963) characterized the lakes of North America by compiling information from many limnological studies done on lakes throughout the continent.

Many water quality studies have been published on the lakes and reservoirs in the East Texas and western Louisiana region around Caddo Lake. The earliest study was done by Cheatum et al. (1942) on the limnology of Ellis Lake. Rawson and Lansford (1970) investigated the water quality of Sam Rayburn Reservoir as did Adler (1971) and Harry (1974). Pesnell (1971) and Harry (1974) examined the physicochemical limnology of Toledo Bend Reservoir. Harry (1974) and Johnson (1976) did water quality studies on Striker Creek Reservoir. Harry (1974), the Texas Department of Water Resources (1978), and Smith (1979) analyzed the water quality of Murvaul Reservoir. Almquist (1977) studied the physicochemical limnology of Houston County Reservoir. Taylor (1980) examined the physicochemical limnology of Nacogdoches Reservoir. The Texas Water Quality Board (1976) investigated the water quality of Lake O' the Pines.

Dawson (1973) examined the influence of Sam Rayburn Reservoir on the water quality of the Angelina River and Attoyac Bayou. Walker (1973) studied the effects of impoundments on the water quality of the Trinity River. McCullough et al. (1977) and Crouch (1978) examined the water quality of Livingston Reservoir in relation to the eutrophic condition of the reservoir. McCullough et al. (1979) studied the physicochemical limnology of Bayou Pierre and its tributaries. Hughes and Leifeste (1965) surveyed the water quality in the Neches River basin. Reece (1979) examined the physicochemical conditions in six oxbow lakes in the Neches River basin.

Water quality studies have been made on other natural lakes in the lower Mississippi River basin. Moore (1950) examined the limnology of Lake Providence in northwestern Louisiana. Baine and Yonts (1937) and Shore (1952) did chemical studies on Reelfoot Lake, Tennessee. Reed (1981) reported physicochemical data for two oxbow lakes in northwest Louisiana.

Literature concerning freshwater oil pollution is scarce. Wiebe, Burr, and Faubron (1934) were among the first researchers to investigate the problem of oil pollution in freshwater bodies in Texas. The biodegradation of oil in polluted water under aerobic conditions was examined by Ludzack and Kinkead (1956). Ward and Brock (1976a, 1976b) studied the factors that influence the rate of biochemical oxidation of oil in lakes. A large-scale study on the effects and fate of oil in Lake Maracaibo, Venezuela was conducted by the Battelle Memorial Institute, Pacific Northwest Laboratories (1974).

Several physicochemical studies have been made on Caddo Lake. However, in these studies only a limited number of parameters and too few locations were sampled to properly characterize a lake as large as Caddo Lake. Some of the earliest studies that included Caddo Lake were conducted by Fuss (1959) and Geagan and Allen (1961). Fish surveys conducted on Caddo Lake by Gray (1955) and Dorchester (1963) included some water quality data. Since 1960 the U.S. Geological Survey (1975, 1982) has monitored the water quality of Caddo Lake, its tributaries, and other lakes in the region. The Water and Sewerage Department of the City of Shreveport, Louisiana (1982) has been monitoring the water quality of Caddo Lake, Cross Lake, and their tributaries since 1956. Duncan (1964) compiled water quality records for Louisiana, including Caddo Lake, from 1959 to 1963. The water quality of the Cypress Bayou basin was surveyed by Leifest (1968). Shampine (1971) investigated the limnology of the lake as part of a survey of Louisiana lakes and reservoirs.

The U.S. Environmental Protection Agency (1977) thoroughly examined the water quality of Caddo Lake and many other lakes and reservoirs in Texas, Louisiana, and

Arkansas as part of the National Eutrophication Survey. The Texas Water Quality Board (1977) also did a comprehensive study on the water quality of Caddo Lake.

DESCRIPTION OF THE STUDY AREA

Caddo Lake is located in Caddo Parish, Louisiana and Harrison County and Marion County, Texas. The lake is about 30 km northeast of Marshall, Texas and 30 km northwest of Shreveport, Louisiana. Caddo Lake is in the Cypress Bayou drainage basin that covers 7101 km^2 (U.S. Environmental Protection Agency, 1977) of which 6835 km^2 is in Texas (Texas Water Quality Board, 1977). The drainage basin is mostly forested, but has some pasture and recreational land-use (Texas Water Quality Board, 1977). The major tributary of Caddo Lake is Cypress Bayou. Much of the water in Cypress Bayou flows from Lake O' the Pines 33 km west of Caddo Lake. James Bayou, Kitchen's Creek, Harrison Bayou, Watson Bayou, Tiger Branch, and several other smaller streams also drain into the lake.

Caddo Lake is one of the oldest lakes in Texas and Louisiana, probably dating back several hundred years. Caddo Lake was once part of a large chain of lateral lakes in the lower Red River basin. The lakes in this chain were formed by obstructive logjams and sediments impounding the waters of the tributaries of the Red River (Frey, 1963). This series of logjams became known as the "Great Raft" and extended 250 km from Arkansas to

Alexandria, Louisiana. Indian legends concerning Caddo Lake suggest that the lake was formed during the New Madrid earthquake of 1811 and 1812, but according to Walker (1983), this is doubtful.

The logjam impounding Caddo Lake was removed in 1873 and the lake slowly drained to a size smaller than the present lake (Walker 1983). In 1914 Caddo Dam was constructed by the United States government to bring the pool elevation to the present level of 51.36 m above mean sea level. In 1971 the existing earthfill dam was constructed by the U.S. Army Corps of Engineers to replace the older dam. The dam is owned by the Board of Commissioners, Caddo Levee District (Texas Water Development Board, 1974).

The surface area of Caddo Lake is 132.09 km^2 (32,639 acres) with a mean depth of 1.8 m, and a volume of only 231.896×10^6 m^3 (U.S. Environmental Protection Agency, 1977). The mean hydraulic retention time of Caddo Lake was calculated by the U.S. Environmental Protection Agency (1977) to be 42 days. The actual retention is probably longer because the study was conducted during a year of abnormally high precipitation. The mean annual precipitation in the watershed is 113.7 cm (U.S. Environmental Protection Agency, 1977).

Aquatic macrophytes grow prolifically in the shallow waters of Caddo Lake. The western arm of the lake formed by Cypress Bayou is a bald cypress (Taxodium distichum) swamp. Bald cypress also grows along the shores and in scattered groves throughout the lake. Many other aquatic macrophytes, such as American lotus (Nelumbo lutea) and Duckweed (Lemna sp.) are found near the shores and in the bald cypress swamp region.

The lake directly overlies two major geologic formations. Recent alluvium and the Wilcox Group which was deposited in the Eocene. The Wilcox is a silty and sandy clay formation with beds of clay, lignite, silt, and quartz sand. Ironstone deposits are also common in the formation. The highly productive Caddo-Pine Island oil and gas field is located in James Bayou and the eastern area of Caddo Lake. Oil is pumped from a wide range of Cretaceous formations varying from 274 m to 2540 m below the surface (Shreveport Geological Society, 1953). Intense oil production began in this field during the 1920's, and some of the first off-shore platform oil wells ever constructed were on Caddo Lake. Over 100 producing off-shore oil wells could be seen from the sampling stations used in this study, and the total number on the lake was probably much greater.

Much of the soil adjacent to the lake belongs to the Forbing-Grove-Wrightsville association. This association is characterized by nearly level to moderately sloping and moderately to poorly drained soils that have loamy surface layers and clayey subsoils. Many of the other soil associations in the Caddo Lake drainage basin are similar (Edwards et al., 1980).

Caddo Lake is a source of water for the surrounding region. Water from Caddo Lake flows down Twelvemile Bayou where it is used as a domestic water source by the City of Shreveport, Louisiana. Another important user of the lake water is a Southwest Electric Power Company generating plant. The generating plant has a once-through type cooling system, and the hot water discharge is near the dam. Caddo Lake receives wastewater from the Longhorn Ordinance Plant at Karnack, Texas, and also receives municipal wastewater from Jefferson, Texas by way of Cypress Bayou.

Nine sampling stations were chosen to characterize the physicochemical limnology of Caddo Lake (Figure 1). Stations 1, 2, and 3 were located in the bald cypress swamp region. Stations 4, 5, 6, and 7 were located in the relatively unsheltered, open water region of the lake, while Stations 8 and 9 were located in the oil-producing region of the lake. The locations of the sampling stations were as follows:

Station 1 was located at Devil's Elbow in the channel of Cypress Bayou approximately 1.6 km north of Uncertain, Texas. The water depth at this station was about 6 m.

Station 2 was located in the downstream portion of

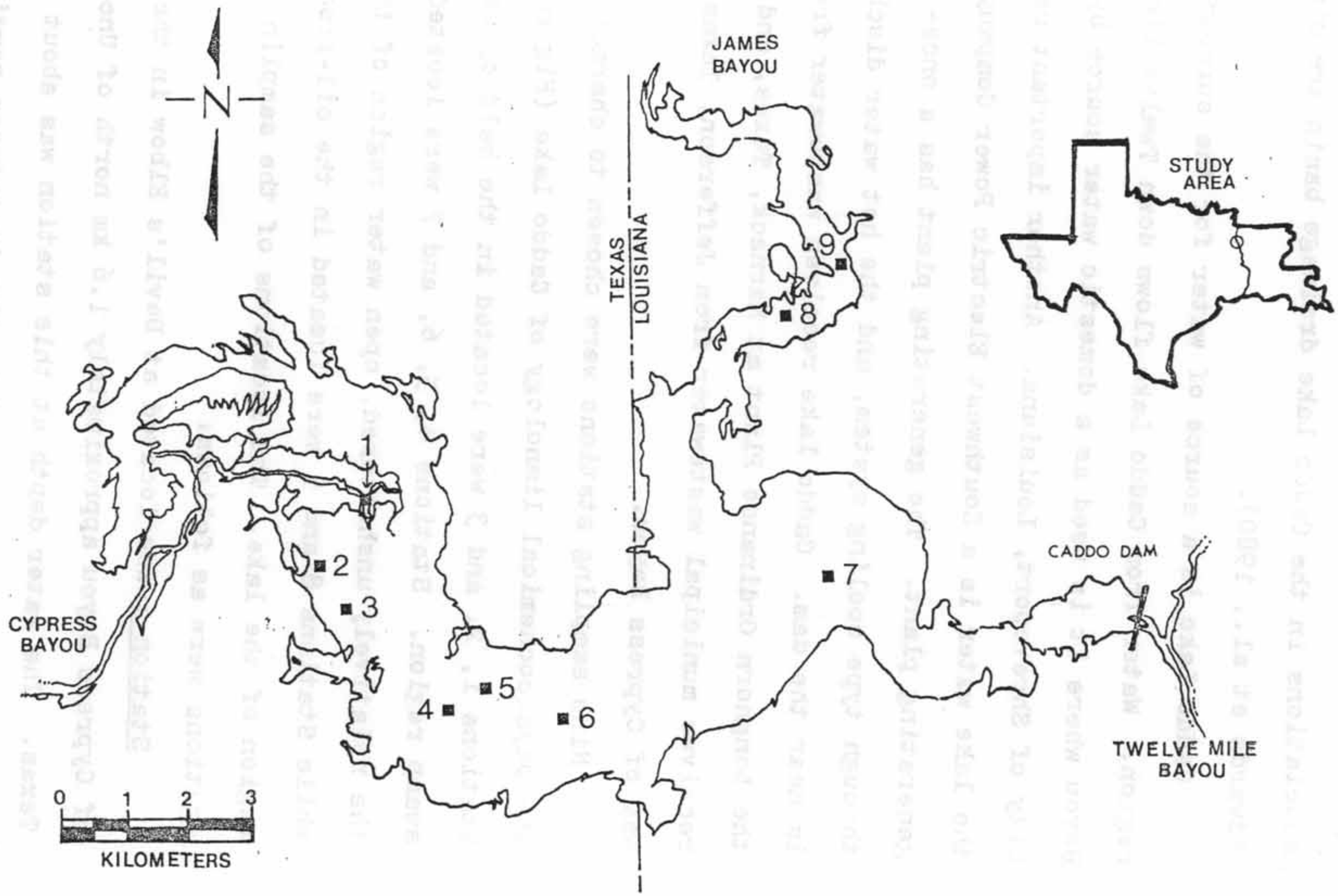


Figure 1. Map of Caddo Lake showing the locations of the sampling stations.

the Government Ditch about 500 m north of Uncertain, Texas. The depth was approximately 2 m at this station.

Station 3 was located approximately 200 m east of Uncertain, Texas in a back-water area known as Turtle Shell Lake. The water depth at this station was about 1 m.

Station 4 was located near Twin Island on Boat Lane 1-P approximately 800 m north of Long Point. The site of this station was about 50 m east of the furthest growth of the lily pads (*Nelumbo lutea*) extending out from the bald cypress groves around Twin Island. The depth was about 1 m at this station.

Station 5 was located approximately 1 km northwest of Long Point in a small grove of bald cypress near the intersection of Boat Lanes 5 and 1-D. Water depth was about 1 m at this station.

Station 6 was located approximately 1 km south of Miller's Point near the crossing of Boat Lanes 5 and 1-N near the Texas-Louisiana state line. Water depth at this station was about 2 m.

Station 7 was approximately 1.1 km south of Oil City, Louisiana in the open water area known as Big Lake. It was located near EMCO oil well number 289. Water depth was about 2 m at this station.

Station 8 was located approximately 2 km northwest of Oil City, Louisiana in the oil-producing portion of James Bayou near Boat Lane Marker E-68. The station was located close to Allen Brothers oil well number 23. The depth at this station was about 2 m.

Station 9 was located about 200 m west of the mouth of Tiger Branch in the northern part of the oil-producing region of James Bayou near Boat Lane Marker E-76. The station was located between Allen Brothers oil wells number 17 and 29. Water was about 2 m deep at this station.

METHODS

Caddo Lake was sampled monthly at nine stations (Figure 1) from October 1981 to September 1982. Water samples were collected from mid-depth at every station except Station 1. At Station 1 one sample was collected one meter below the surface (1A) and another sample was collected one meter above the bottom (1B).

Physicochemical Methods

Physicochemical analyses that were conducted in the field at each station were depth, water temperature, dissolved oxygen, carbon dioxide, bicarbonate alkalinity, conductivity, and Secchi disc transparency. Weather conditions and other relevant information were recorded as field notes. Water samples were taken in the field with a two-liter Kemmerer bottle and stored on ice in plastic half-gallon bottles until they reached the laboratory.

The laboratory analyses that were made on each sample included five-day biochemical oxygen demand, chemical oxygen demand, calcium, sodium, chloride, pH, phytoplankton chlorophyll a, nitrate-nitrogen, nitrite-nitrogen, ammonium-nitrogen, orthophosphate, total iron, sulfate, total phosphorus, total Kjeldahl nitrogen, total residue, total volatile residue, turbidity, true color, and apparent color. In addition, the water was analyzed for zinc at all stations in October 1981, oils at Station 8 (collected at the air-water interface) in February 1982, and total organic carbon at all stations in September 1982.

Depth was determined using a graduated sounding line. Dissolved oxygen and water temperature were determined at the surface and at one meter depth intervals using a Yellow Springs Model 54 Oxygen Meter equipped with a probe. Conductivity was measured in the same manner using a Yellow Springs Model 33 Conductivity Meter with probe. Secchi disc transparency was measured as described by Lind (1979).

Carbon dioxide and bicarbonate alkalinity were analyzed titrimetrically using La Motte field kits by methods described in <u>Standard Methods</u> (APHA, 1981).

A five-day biochemical oxygen demand (BOD_5) was determined as described in <u>Standard Methods</u> (APHA, 1981) using a Labline Model 844 Incubator and a Yellow Springs Model 54 Oxygen Meter with a Model 5420A BOD Probe. The Permanganate Oxidation Method outlined by the Joint ABCM-SAC Committee (1957) was used to determine the chemical oxygen demand (COD). Total organic carbon (TOC) was analyzed with infrared spectroscopy using an O.I. Corporation Model 524C Carbon Analyzer. The carbon dioxide was first purged from each sample with an O.I.

Corporation Model 524PS Purging and Sealing Unit. All the organic carbon was then oxidized with potassium persulfate to carbon dioxide which was measured on the analyzer. The procedure was described in the operating manual provided with the instrument (O.I. Corporation, 1981).

Calcium and sodium concentrations were measured with a Beckman Flame Spectrophotometer Model B. However, in August 1982 the method used to measure calcium was changed to a calcium hardness titration method (APHA, 1981). Chloride concentration was determined using the Mercuric Nitrate Method described in Standard Methods (APHA, 1981). A Corning Model 12 Research pH Meter was used to determine pH. Phytoplankton chlorophyll a concentrations were measured with a Turner Model 110 Fluorometer using the *in vivo* Method (Lorenzen, 1966).

Colorimetric procedures (APHA, 1981) were used to measure several chemical constituents of the water. These included the Cadmium Reduction Method for nitrate-nitrogen, the Diazotization Method for nitrite-nitrogen, the Nesslerization Method for ammonium-nitrogen, the Ascorbic Acid Method for orthophosphate, the 1,10 Phenanthroline Method for total iron, the Turbidimetric Method for sulfate, and Zincon Method for Zinc. The colorimetric analyses were conducted using a Bausch and Lomb Spectronic 70 Spectrophotometer. Total phosphorus was determined colorimetrically after using the Persulfate Oxidation Method as described by Menzel and Corwin (1965). It should be emphasized that orthophosphate is reported as mg PO_4^{-3}/L and total phosphorus as mg P/L. Total Kjeldahl nitrogen was analyzed following the procedure given by the U.S. Environmental Protection Agency (1971) using a Kontes Micro-Kjeldahl Digestor and a Labconco Micro-Kjeldahl Distillation Apparatus.

Total residue and total volatile residue were determined gravimetrically as described in Standard Methods (APHA, 1981). A Mettler H10 Analytical Balance was used for the weighings. A Hach Model 2100A Turbidimeter was used to measure turbidity. True and apparent color were determined using the method outlined in Standard Methods (APHA, 1981). An International Clinical CL Centrifuge was used for centrifuging for true color.

Oil in the water was analyzed colorimetrically using the 1,1,1-Trichloroethane Extraction Method described by the Hach Company (1981). This method is modification of the Oil and Grease Extraction Method described in Standard Methods (APHA, 1981). A Bausch and Lomb Spectronic 70 Spectrophotometer was used with a standard curve prepared with crude oil from the Caddo-Pine Island oil field.

Sediments from the sediment-water interface were analyzed for oil and total organic content. Sediment samples were collected in October, March, and August at each station with an Ekman dredge. The method used for measuring the oil concentrations in the sediments was a colorimetric modification of the Oil and Grease Extraction Method described in Standard Methods (APHA, 1981). The method was adapted by shaking 1.00 g of wet sediment, 100.0 ml of distilled water and 35.0 ml of 1,1,2-trichloroethane in a separatory funnel for one minute. The mixture was then allowed to stand five minutes before withdrawing some of the 1,1,2-trichloroethane for analysis. The percent transmission at 450 nm was read for each sample using a Bausch and Lomb Spectronic 70 Spectrophotometer with 1,1,2-trichloroethane as the blank for the instrument. A standard curve was prepared with crude oil from the Caddo-Pine Island oil field. Another portion of each sediment sample was dried to find the percent water content. The water content of each sample was necessary to find the concentration of oil in each kg of dried sediment. The percent organic matter in the sediments was determined using a modification of the total volatile residue gravimetric procedure described in Standard Methods (APHA, 1981). The sediment sample was substituted for the water and the rest of the procedure was followed as outlined.

Statistical Methods

The physicochemical data were statistically analyzed with a Honeywell CP6 computer using the Statistical

Package for the Social Sciences (Nie et al., 1975). Yearly, monthly, seasonal, regional, and station means and standard deviations were calculated for all the parameters. The Student's t-statistic with pooled variance was used to test the means of the parameters of Station 1A and Station 1B for any significant differences. Pearson's correlation matrices were used to detect significant interactions between any two parameters both spatially and temporally. Spatial and temporal variations in the parameters were also examined using one-way analysis of variance. The model for one-way analysis of variance was given by Hicks (1973) as:

$$Y_{ij} = \mu + \tau_j + \varepsilon_{ij}$$

where:

Y_{ij} = the ith observation on the jth treatment

μ = overall mean response

τ_j = effect of the jth treatment

ε_{ij} = random error present in the ith observation on the jth treatment

and:

$j = 1, 2, \ldots, k$

k = number of treatments (seasons, stations, or regions)

$i = 1, 2, \ldots, n_j$

n_j = number observations per treatment (season, station, or region)

Duncan's Multiple Range Test was used in conjunction with each one-way analysis of variance to group the means with a 95% confidence level.

Two-way analysis of variance was used to detect any significant interaction between seasons and stations for all the parameters. The seasons were defined as the following: December, January, and February were winter; March, April, and May were spring; June, July, and August were summer; September, October, and November were fall. The model for two-way analysis of variance was given by Hicks (1973) as:

$$Y_{ijk} = \mu + A_i + B_j + AB_{ij} + \varepsilon_{k(ij)}$$

where:

μ = overall mean response

A_i = effect of ith treatment (season)

B_j = effect of jth treatment (station)

AB_{ij} = interaction between treatments A and B

$\varepsilon_{k(ij)}$ = random error associated with the kth observation of the ith treatment and jth treatment combination.

and:

$k = 1, 2, \ldots, n_{ij}$

n_{ij} = number of observations for ith season and jth station treatment combination

i = number of seasons

j = number of stations.

A stepwise discriminant analysis using all the parameters except depth, was used to group similar stations and to find the most discriminating parameters. Wilks' lambda was used as the criterion for the stepwise parameter selection. The model for discriminant analysis is briefly summarized as follows (Nie et al., 1975):

$$D_i = d_{i1}Z_1 + d_{i2}Z_2 + \dots + d_{ip}Z_p$$

where:

D_i = the score on discriminant function i

d = weighting coefficients

Z = standardized values of the p discriminating variables.

RESULTS

Yearly means, standard deviations, and ranges of each parameter for the entire study are summarized in Table 1. Figures 2-24 show the yearly station means for each parameter and the monthly means for each parameter. The physicochemical data from Caddo Lake are given in Appendices I-XIV.

Water Temperature, Dissolved Oxygen, and Phytoplankton Chlorophyll a

Water temperature ranged from 7° C at Stations 1, 2, 6, 7, and 9 on February 12, 1982 to 35° C at Stations 8 and 9 on July 19, 1982. The mean annual water temperature for Caddo Lake was 21° C and the standard deviation was 8° C. Stations 2 and 3 recorded the lowest yearly mean and Stations 8 and 9 had the highest (Figure 2).

The yearly mean for dissolved oxygen in the lake was 7.4 mg/L with a standard deviation of 3.0 mg/L. Dissolved oxygen varied from 0.1 mg/L at Station 1B on October 3, 1981 to 12.2 mg/L at Station 7 on February 12, 1982. The lowest annual mean was found at Station 3 and highest was at Station 7 (Figure 2). During August the lowest mean dissolved oxygen concentration was recorded, and

Table 1. Yearly means, standard deviations, and ranges for each parameter at Caddo Lake from October 3, 1981 to September 8, 1982.

Parameter	Mean	Standard Deviation	Minimum	Maximum
Water Temperature (^{o}C)	21	8	7	35
Dissolved Oxygen (mg/L)	7.4	3.1	0.2	12.2
Phytoplankton Chlorophyll <u>a</u> (μg/L)	7	6	1	23
Carbon Dioxide (mg/L)	8.6	7.0	0.0	42.0
Bicarbonate Alkalinity (mg/L)	35	13	13	80
pH	6.9	0.6	5.9	9.1
Conductivity (μmhos)	125	30	70	192
Chloride (mg/L)	26.4	9.3	14.5	60.0
Sodium (mg/L)	15.5	4.7	9.2	35.0
Secchi Disc Transparency (m)	1.0	0.3	0.5	1.9
Turbidity (NTU)	5.5	6.0	1.0	38.0
Apparent Color (APHA c.u.)	33	14	14	110
True Color (APHA c.u.)	21	9	6	48
Ammonium-Nitrogen (mg/L)	0.72	0.15	0.35	1.25
Nitrite-Nitrogen (μg/L)	4	2	< 2	15
Nitrate-Nitrogen (μg/L)	12	9	2	38
Total Kjeldahl Nitrogen (mg/L)	5.58	2.33	0.74	16.47
Orthophosphate (mg/L)	0.13	0.10	< 0.02	0.58
Total Phosphorus (mg P/L)	0.13	0.11	0.01	1.10

Table 1. (continued)

Parameter	Mean	Standard Deviation	Minimum	Maximum
Total Iron (mg/L)	0.38	0.50	< 0.02	2.62
Calcium (mg/L)	11	6	6	28
Sulfate (mg/L)	19.0	5.4	6.2	28.2
COD (mg/L)	14.9	5.3	5.6	48.0
BOD_5 (mg/L)	2.1	1.0	0.4	6.3
Total Residue (mg/L)	116	28	44	272
Total Volatile Residue (mg/L)	45	22	8	152
Oil in the Sediments (mg/kg dry weight)	26,615	22,956	757	67,873
Organic Matter in the Sediments (%)	12.6	6.8	2.3	30.2

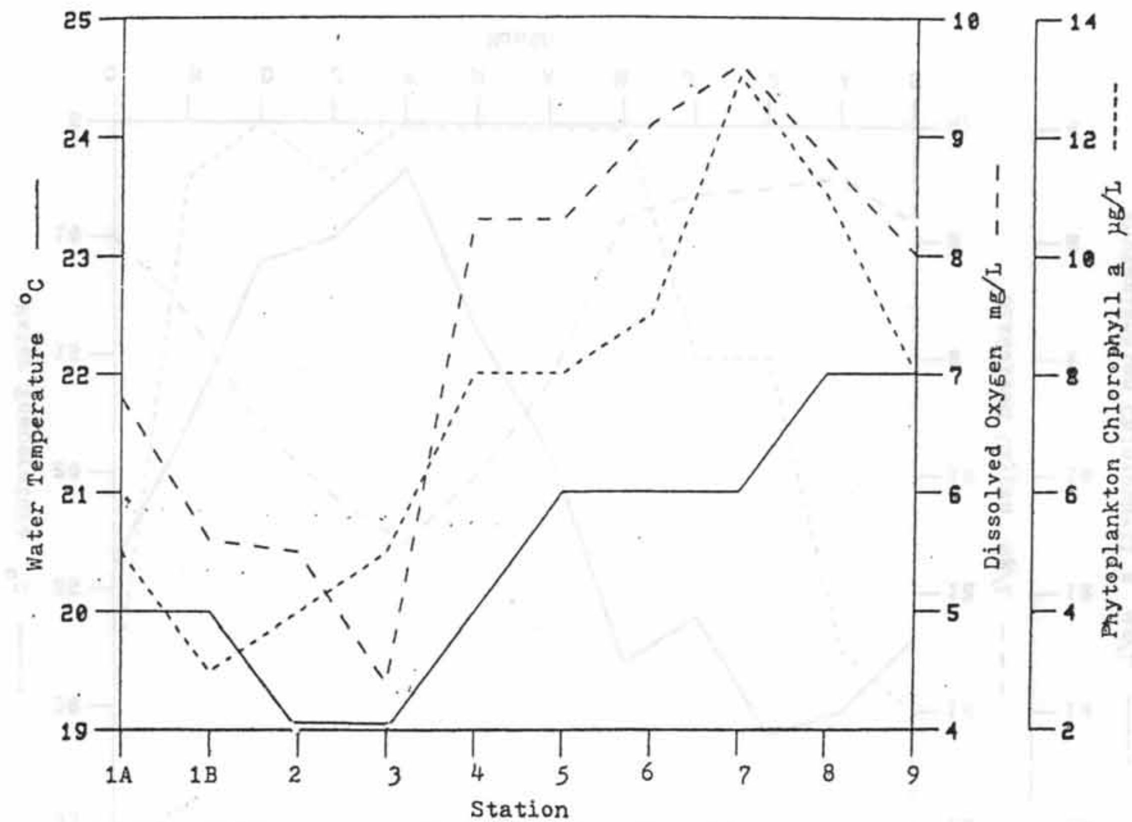


Figure 2. Mean water temperature, dissolved oxygen, and phytoplankton chlorophyll a for the sampling stations at Caddo Lake from October 3, 1981 to September 8, 1982.

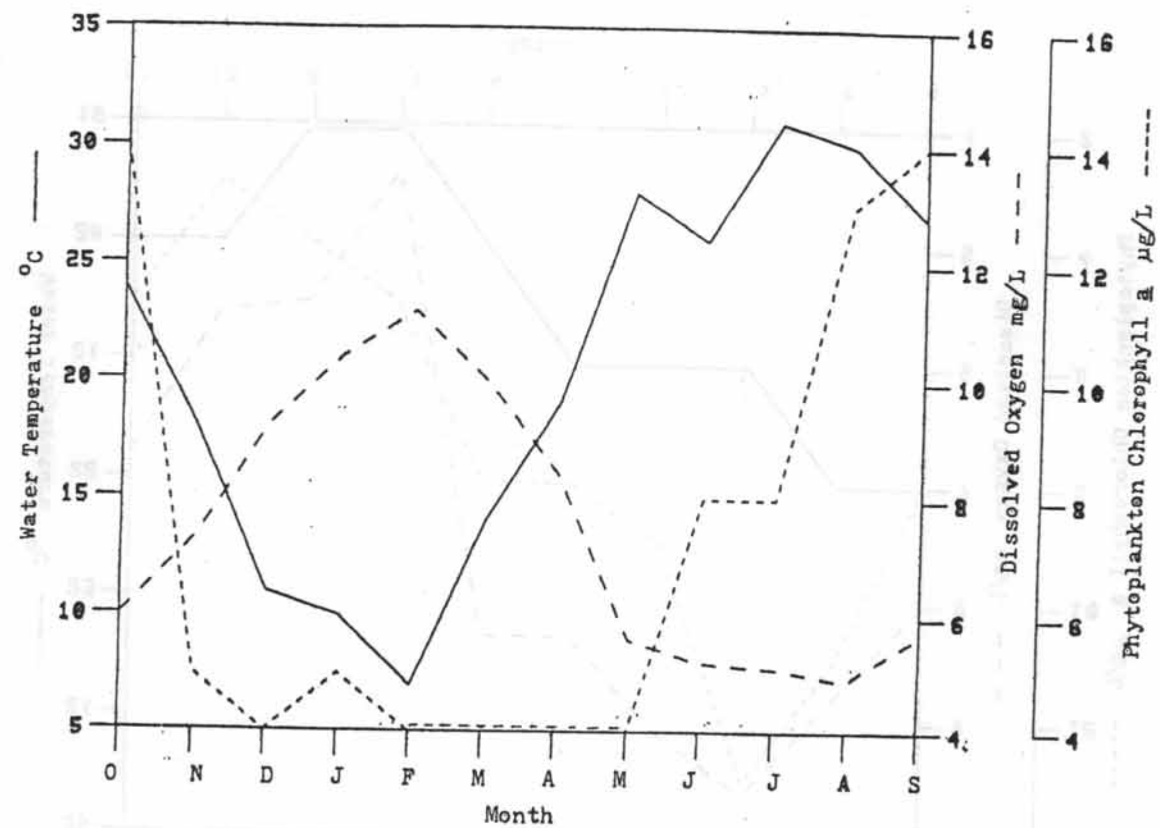


Figure 3. Monthly means for water temperature, dissolved oxygen, and phytoplankton chlorophyll a at Caddo Lake from October 3, 1981 to September 8, 1982.

the highest occurred in February (Figure 3).

Phytoplankton chlorophyll a ranged from 1 µg/L at many stations to 23 µg/L at Station 7 on October 3, 1981. The annual mean for the lake was 7 µg/L and the standard deviation was 6 µg/L. Station 2 had the lowest annual mean and Station 7 had the highest (Figure 2). Figure 3 shows the mean phytoplankton chlorophyll a to be lowest during the winter and spring and highest in the fall.

Carbon Dioxide, Bicarbonate Alkalinity, and pH

The yearly mean carbon dioxide concentration in Caddo Lake was 8.6 mg/L with a standard deviation of 7.0 mg/L. Carbon dioxide varied from 0.0 mg/L at Station 7 on August 13, 1982 to 42.0 mg/L at Station 3 on September 8, 1982. The yearly means were also lowest and highest at Stations 7 and 3 respectively. Stations 1A, 1B, 2, and 3 in the swamp region had the highest mean values as shown in Figure 4. Mean monthly values for carbon dioxide were lowest in January and highest in February (Figure 5).

Bicarbonate alkalinity ranged from 13 mg/L at Station 2 on February 12, 1982 to 80 mg/L at Station 3 on September 8, 1982. The yearly mean for the lake was found to be 35 mg/L with a standard deviation of 13 mg/L. Mean annual bicarbonate alkalinity was lowest at Stations 1A and 9 and highest at Station 3 (Figure 4). The

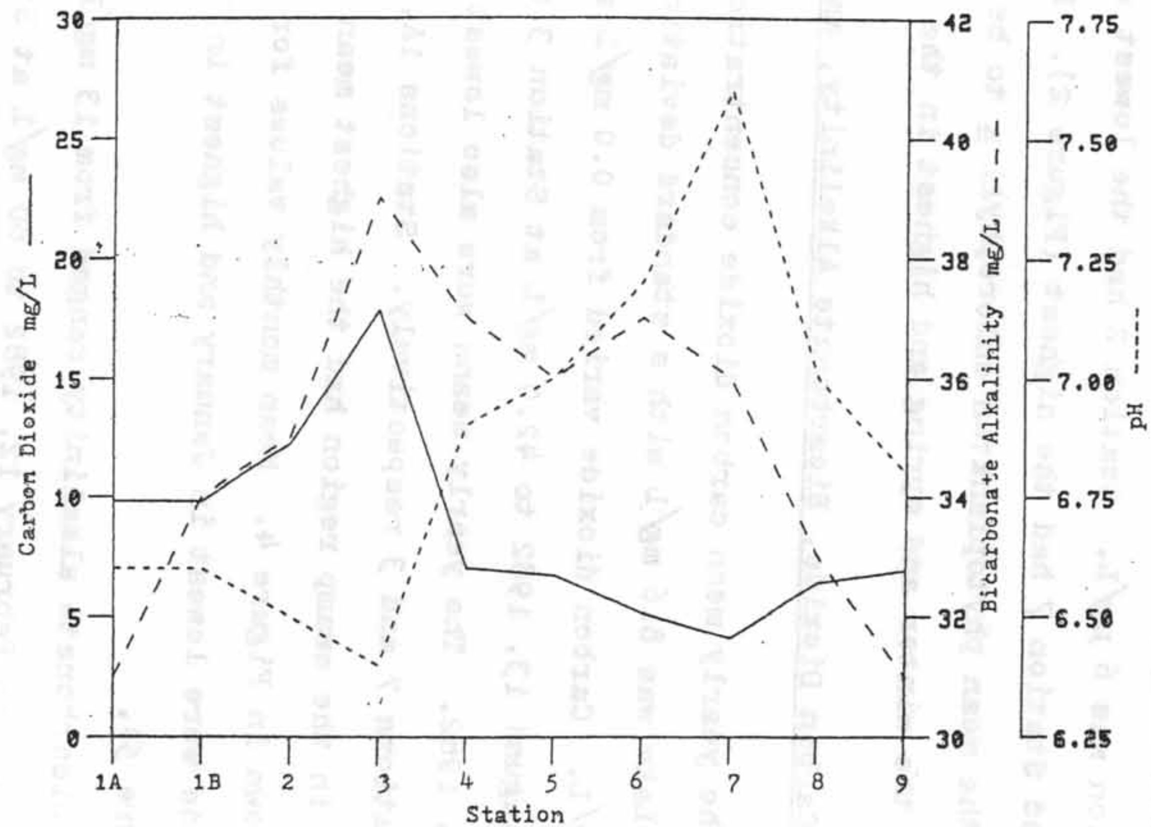


Figure 4. Mean carbon dioxide, bicarbonate alkalinity, and pH for the sampling stations at Caddo Lake from October 3, 1981 to September 8, 1982.

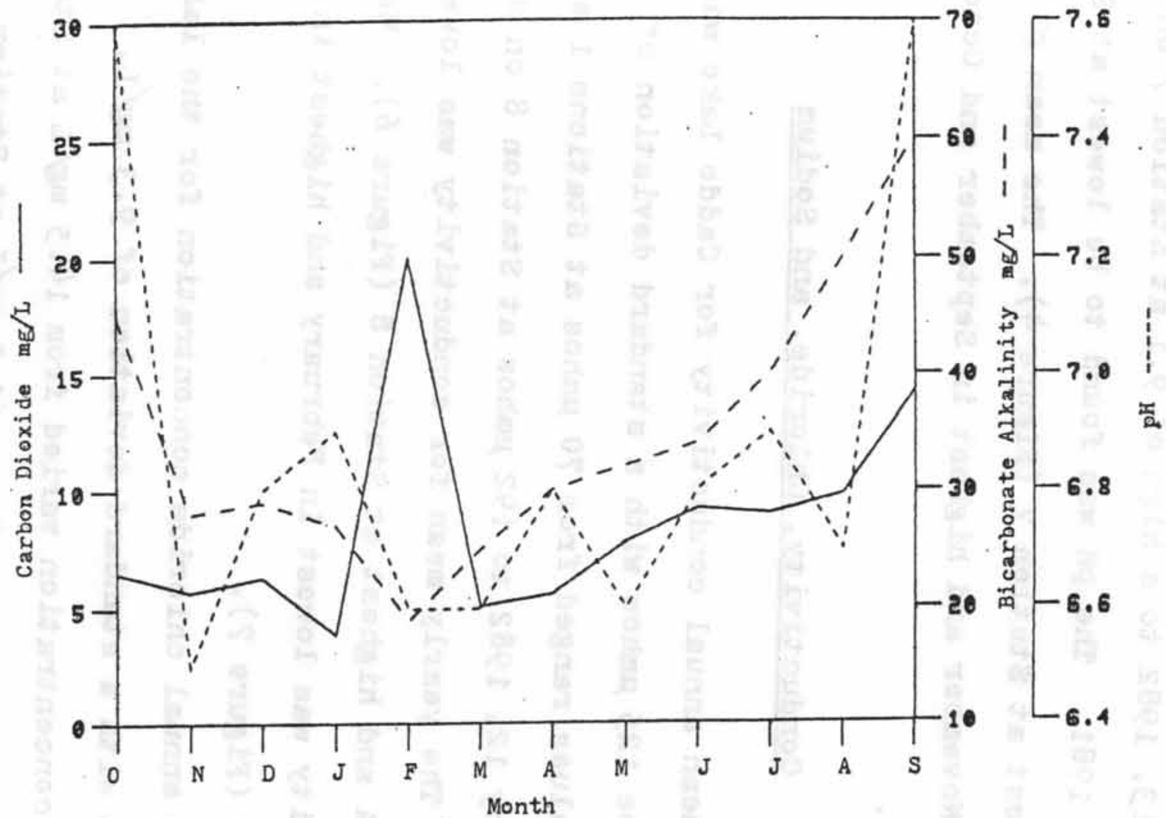


Figure 5. Monthly means for carbon dioxide, bicarbonate alkalinity, and pH at Caddo Lake from October 3, 1981 to September 8, 1982.

lowest monthly mean for the lake was recorded in February and the highest was in September (Figure 5).

The mean annual pH for the lake was 6.9, with a 0.6 standard deviation. The pH varied from 5.9 at Station 3 on August 13, 1982 to a high of 9.1 at Station 7 on October 3, 1981. The pH was found to be lowest at Station 3 and highest at Station 7 (Figure 4). The mean pH was lowest in November and highest in September and October (Figure 5).

Conductivity, Chloride, and Sodium

The mean annual conductivity for Caddo Lake was found to be 125 µmhos with a standard deviation of 30 µmhos. Values ranged from 70 µmhos at Stations 1 and 2 on February 12, 1982 to 192 µmhos at Station 8 on September 8, 1982. The yearly mean for conductivity was lowest at Station 1A and highest at Station 8 (Figure 6). Mean conductivity was lowest in February and highest in September (Figure 7).

Mean annual chloride concentration for the lake was 26.4 mg/L with a standard deviation of 9.3 mg/L. Chloride concentration varied from 14.5 mg/L at Stations 1A and 2 on June 26, 1982 to 60.0 mg/L at Station 9 on February 12, 1982. Station 1A had the lowest yearly mean and Station 8 had the highest (Figure 6). June had the lowest chloride concentration and January had the

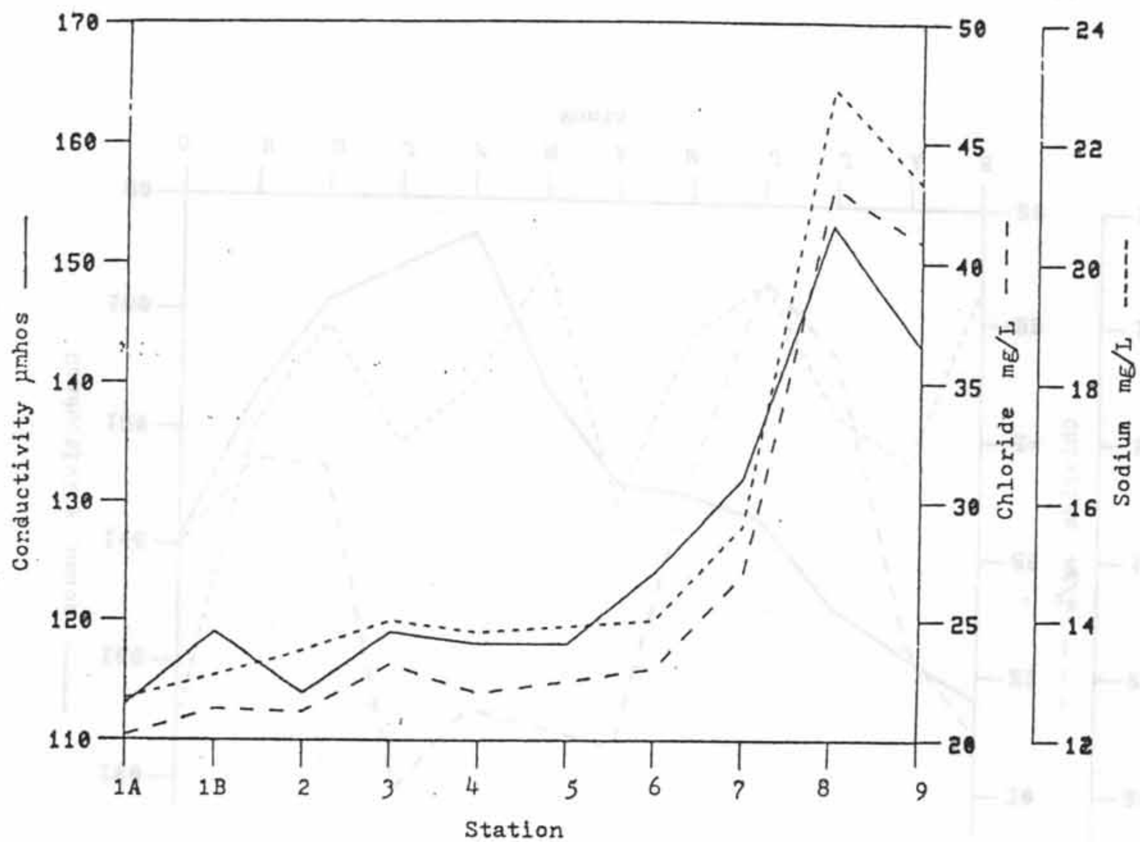


Figure 6. Mean conductivity, chloride, and sodium for the sampling stations at Caddo Lake from October 3, 1981 to September 8, 1982.

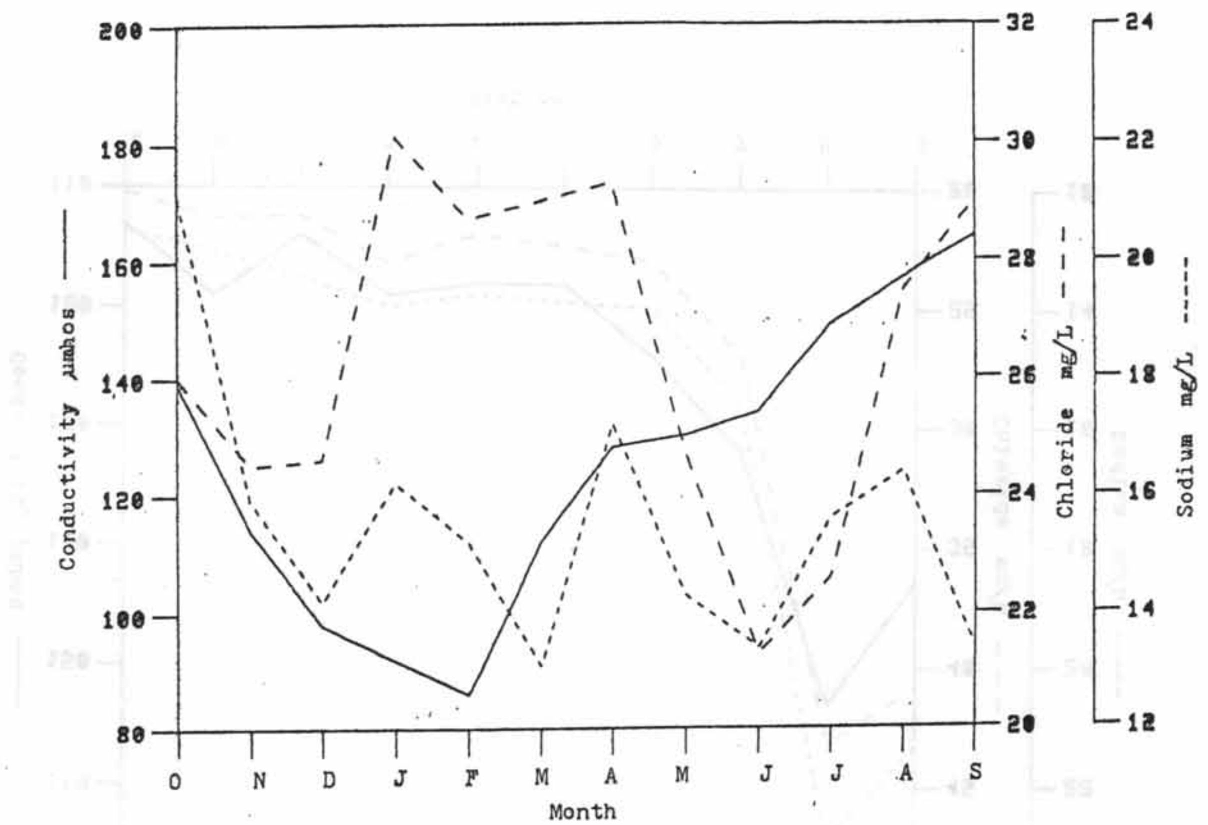


Figure 7. Monthly means for conductivity, chloride, and sodium at Caddo Lake from October 3, 1981 to September 8, 1982.

highest (Figure 7).

Sodium ranged from 9.2 mg/L at Station 1A on June 26, 1982 to 35.0 mg/L at Station 9 on October 3, 1981. The yearly mean for the lake was 15.5 mg/L with a standard deviation of 4.7 mg/L. Figure 6 shows that sodium concentrations were much higher at Stations 8 and 9 than at the rest of the stations. March had the lowest mean value and October had the highest (Figure 7).

Secchi Disc Transparency and Turbidity

Mean annual Secchi disc transparency for Caddo Lake was found to be 1.0 m with a standard deviation of 0.3 m. Secchi disc transparency varied from 0.5 m at many stations during the study, to 1.9 m at Station 4 on December 5, 1981. Station 7 had the lowest yearly mean and Station 4 had the highest (Figure 8). Mean Secchi disc transparency was lowest in September and October, and highest in January, March, and December (Figure 9).

Turbidity ranged from 1.0 NTU at Station 3 on July 19, 1982 to 38.0 NTU at Station 3 on August 13, 1982. The mean annual turbidity for the entire lake was 5.5 NTU with a standard deviation of 6.0 NTU. The lowest mean value was found at Station 4 and the highest was found at Station 3 (Figure 8). Mean turbidity was lowest in July and highest in February (Figure 9).

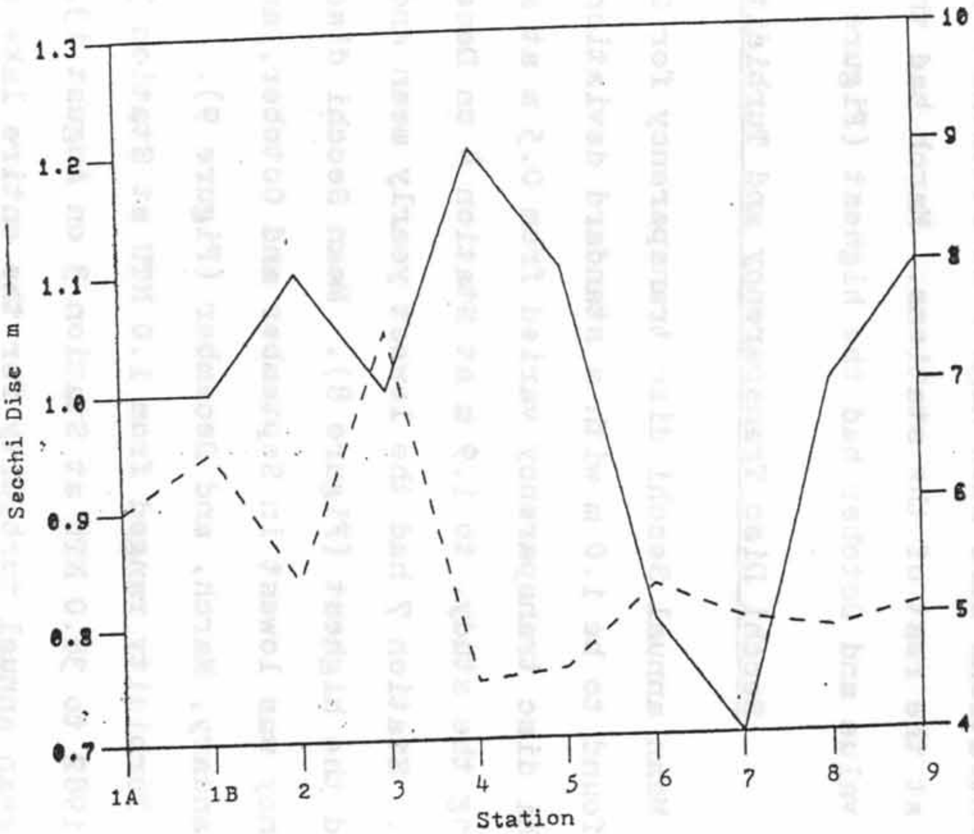


Figure 8. Mean Secchi disc transparency and turbidity for the sampling stations at Caddo Lake from October 3, 1981 to September 8, 1982.

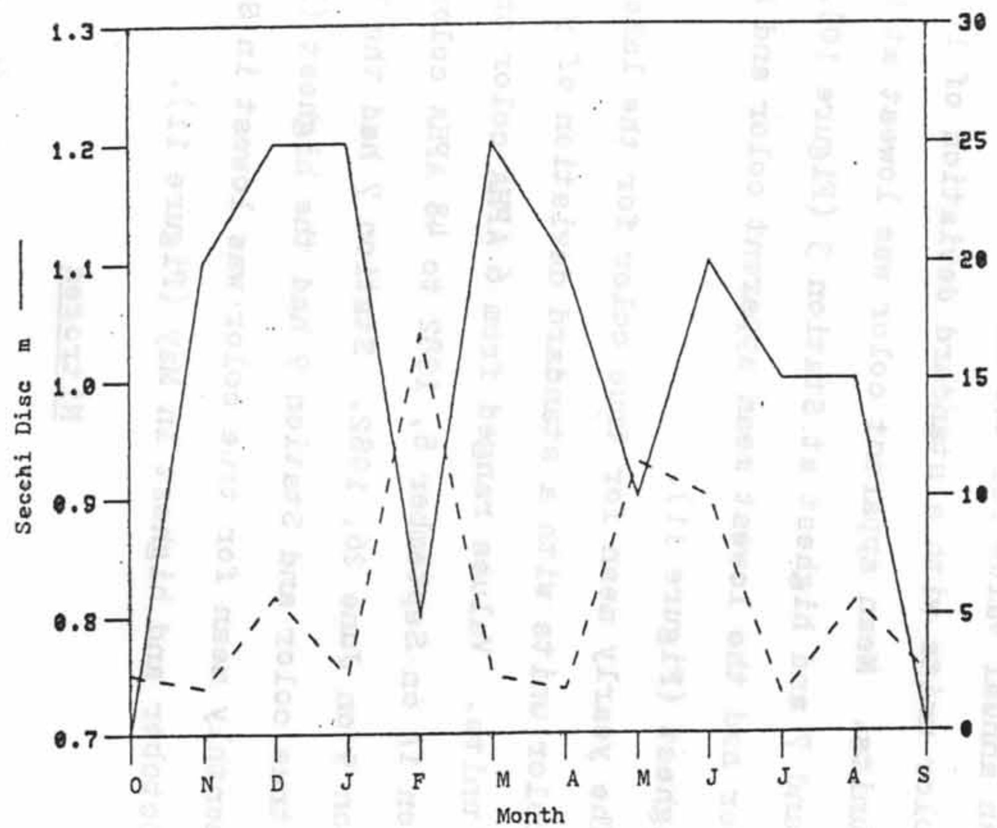


Figure 9. Monthly means for Secchi disc transparency and turbidity at Caddo Lake from October 3, 1981 to September 8, 1982.

Color

The apparent color of Caddo Lake varied from 14 APHA color units at Station 5 on December 5, 1981 to 110 APHA color units at Station 3 on August 13, 1982. The mean annual value for the lake was found to be 33 APHA color units with a standard deviation of 14 APHA color units. Mean apparent color was lowest at Stations 4, 5, and 7 and highest at Station 3 (Figure 10). December had the lowest mean apparent color and May had the highest (Figure 11).

The yearly mean for true color for the lake was 21 APHA color units with a standard deviation of 9 APHA color units. Values ranged from 6 APHA color units at Station 1A on September 8, 1982 to 48 APHA color units at Station 9 on June 26, 1982. Station 7 had the lowest mean true color and Station 9 had the highest (Figure 10). The monthly mean for true color was lowest in September and October and highest in May (Figure 11).

Nitrogen

Ammonium-nitrogen ranged from 0.35 mg/L at Stations 3, 4, and 7 on April 3, 1982 to 1.25 mg/L at Station 3 on August 13, 1982. The lake mean for the year was 0.72 mg/L with a standard deviation of 0.15 mg/L. Mean ammonium-nitrogen was lowest at Stations 4, 5, and 7 and

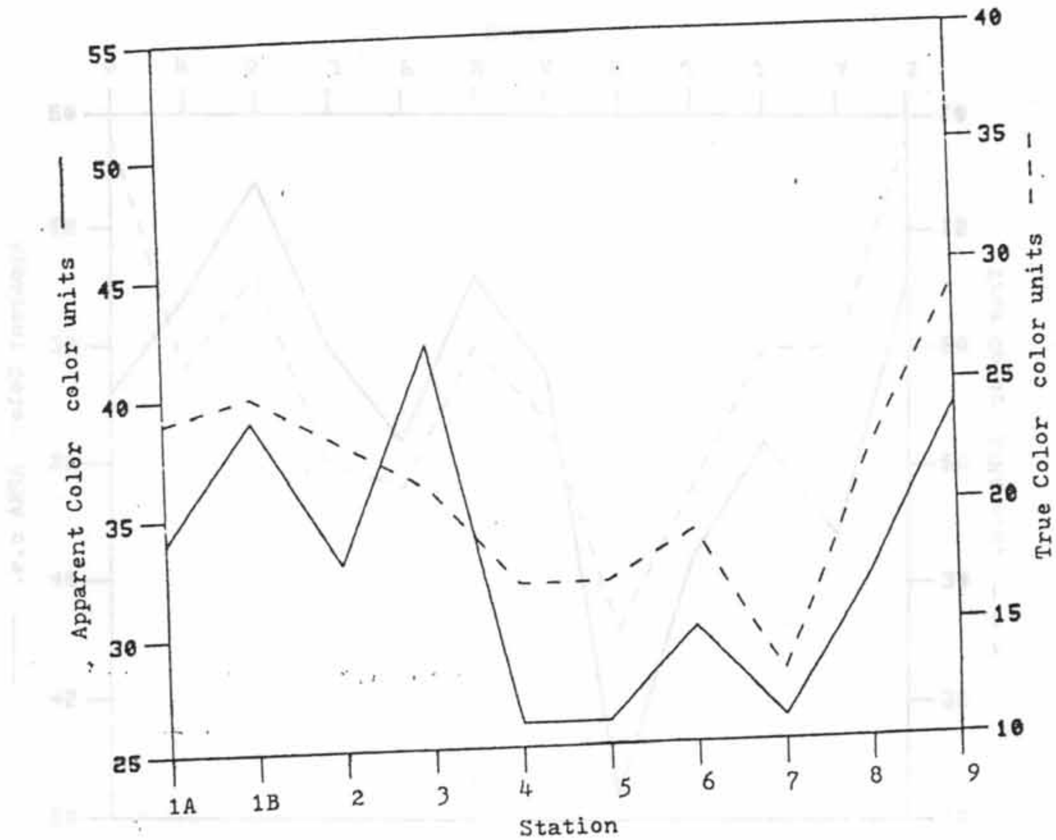


Figure 10. Mean apparent color and true color for the sampling stations at Caddo Lake from October 3, 1981 to September 8, 1982.

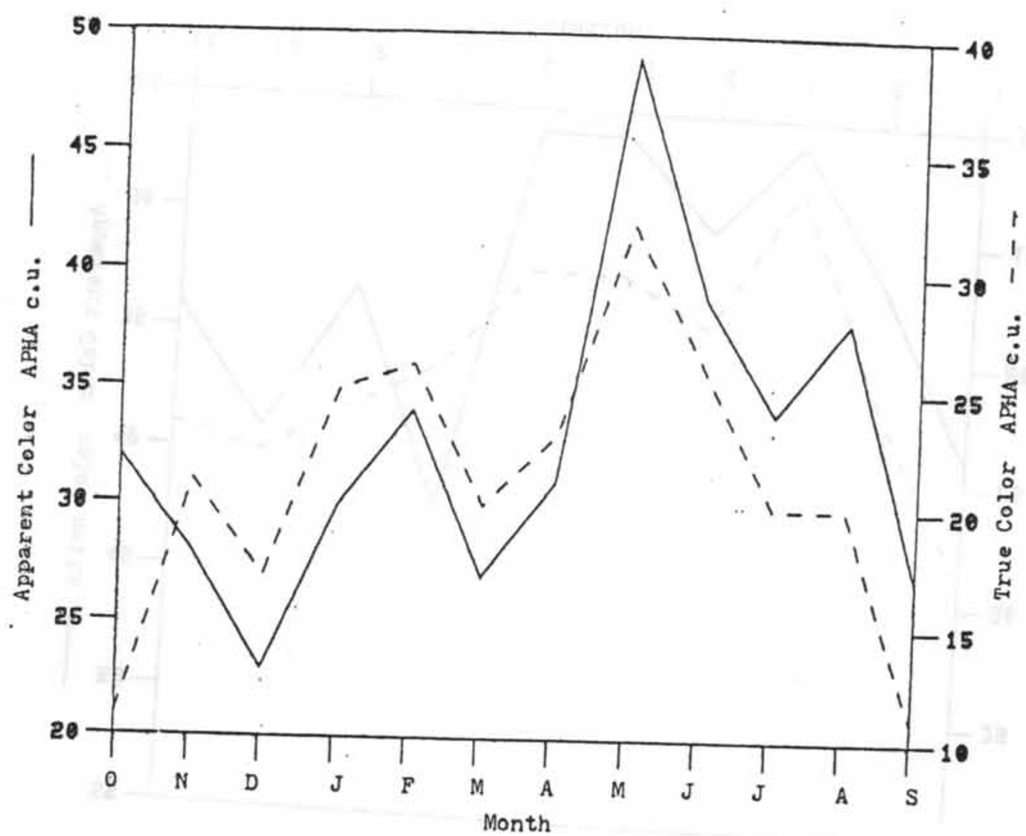


Figure 11. Monthly means for apparent color and true color at Caddo Lake from October 3, 1981 to September 8, 1982.

highest at Station 9 (Figure 12). The lowest mean value was found in April and the highest was found in September (Figure 13).

The yearly mean nitrite-nitrogen for Caddo Lake was 4 µg/L with a standard deviation of 2 µg/L. Values varied from <2 µg/L at many stations to 15 µg/L at Station 1A on August 13, 1982. Stations 3, 8, and 9 had the lowest mean and Station 1A had the highest (Figure 12). The lowest mean nitrite-nitrogen was in May and June and the highest was in February (Figure 13).

During the study, nitrate-nitrogen ranged from 2 µg/L at Station 3 on November 7, 1981 and February 12, 1982 and at Station 5 on September 8, 1982 to 38 µg/L at Station 4 on October 3, 1981. The yearly mean for the lake was 12 µg/L with a standard deviation of 9 µg/L. The yearly mean nitrate-nitrogen was lowest at Station 7 and highest at Station 5 (Figure 12). During March and August the lowest mean value occurred and in October the highest mean value was recorded (Figure 13).

The yearly mean total Kjeldahl nitrogen for Caddo Lake was 5.58 mg/L with a standard deviation of 2.33 mg/L. Total Kjeldahl nitrogen varied from 0.74 mg/L at Station 1A on February 12, 1982 to 16.47 mg/L at Station 7 on October 3, 1981. The yearly mean for Station 9 was the lowest and the mean for Station 3 was highest (Figure 14). Figure 15 shows that in February the lowest

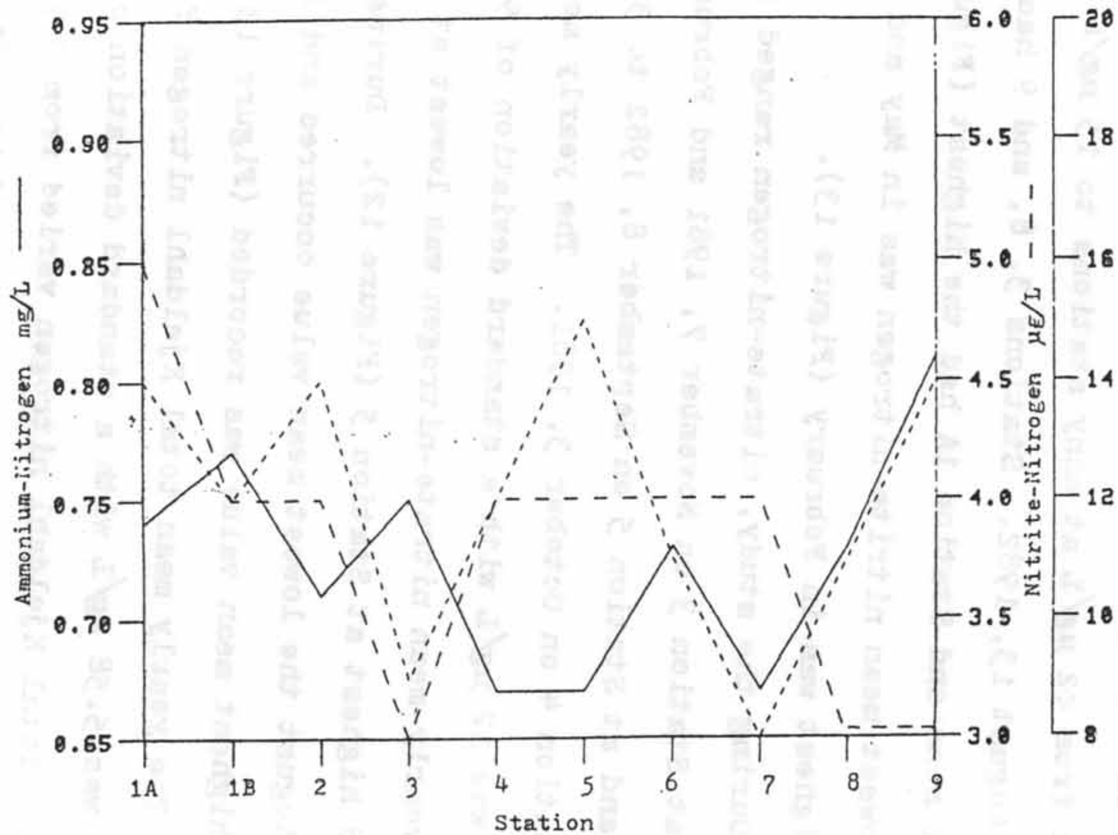


Figure 12. Mean ammonium-nitrogen, nitrite-nitrogen, and nitrate-nitrogen for the sampling stations at Caddo Lake from October 3, 1981 to September 8, 1982.

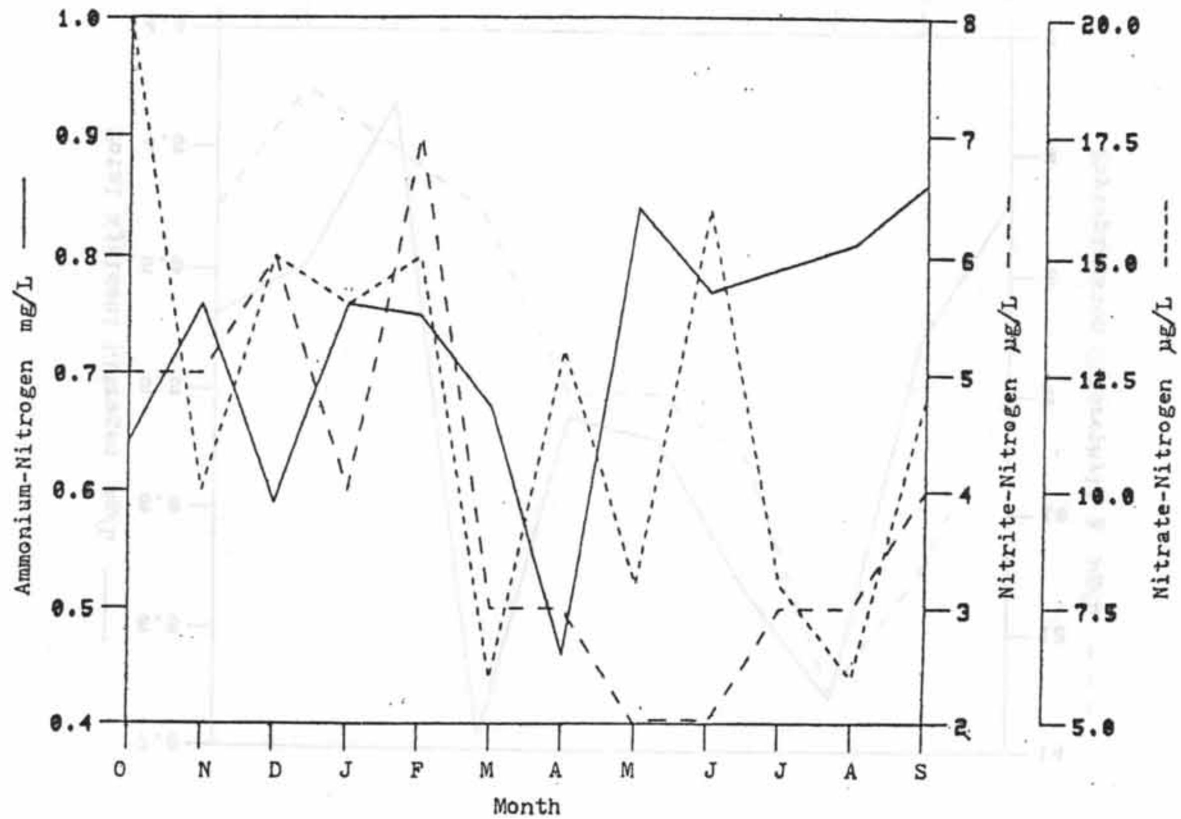


Figure 13. Monthly means for ammonium-nitrogen, nitrite-nitrogen, and nitrate-nitrogen at Caddo Lake from October 3, 1981 to September 8, 1982.

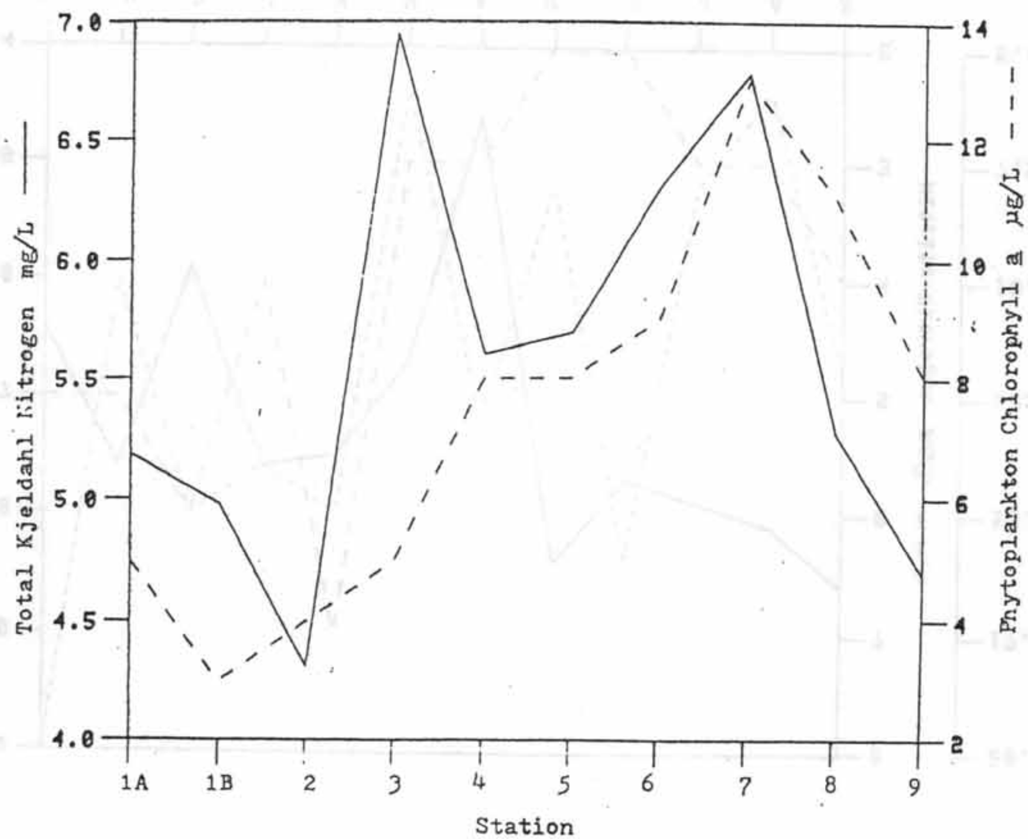


Figure 14. Mean total Kjeldahl nitrogen and phytoplankton chlorophyll a for the sampling stations at Caddo Lake from October 3, 1981 to September 8, 1982.

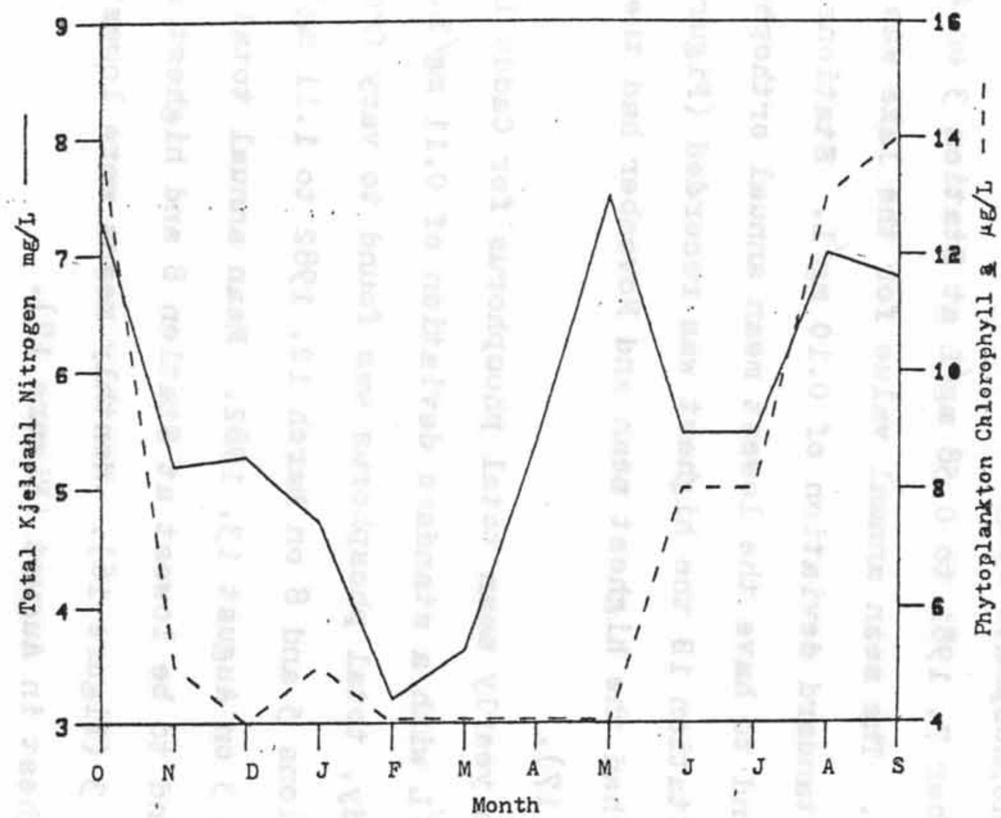


Figure 15. Monthly means for total Kjeldahl nitrogen and phytoplankton chlorophyll a at Caddo Lake from October 3, 1981 to September 8, 1982.

mean value occurred and in October the highest was recorded.

Phosphorus

Orthophosphate ranged from <0.02 mg/L at Station 7 on November 7, 1981 to 0.58 mg/L at Station 3 on August 13, 1982. The mean annual value for the lake was 0.13 mg/L with a standard deviation of 0.10 mg/L. Stations 7 and 8 were found to have the lowest mean annual orthophosphate and at Station 1B the highest was recorded (Figure 16). October had the highest mean and November had the lowest (Figure 17).

The yearly mean total phosphorus for Caddo Lake was 0.13 mg/L with a standard deviation of 0.11 mg/L. During the study, total phosphorus was found to vary from 0.01 at Stations 5 and 8 on March 12, 1982 to 1.11 mg/L at Station 3 on August 13, 1982. Mean annual total phosphorus was found to be lowest at Station 8 and highest at Station 3 (Figure 16). Monthly means were lowest in March and highest in August (Figure 17).

Iron, Calcium, Zinc, and Sulfate

Total iron ranged from <0.02 mg/L at many of the stations during the period of the study to 2.62 mg/L at Station 8 on May 23, 1982. The yearly mean for the lake was 0.38 mg/L with a standard deviation of 0.50 mg/L.

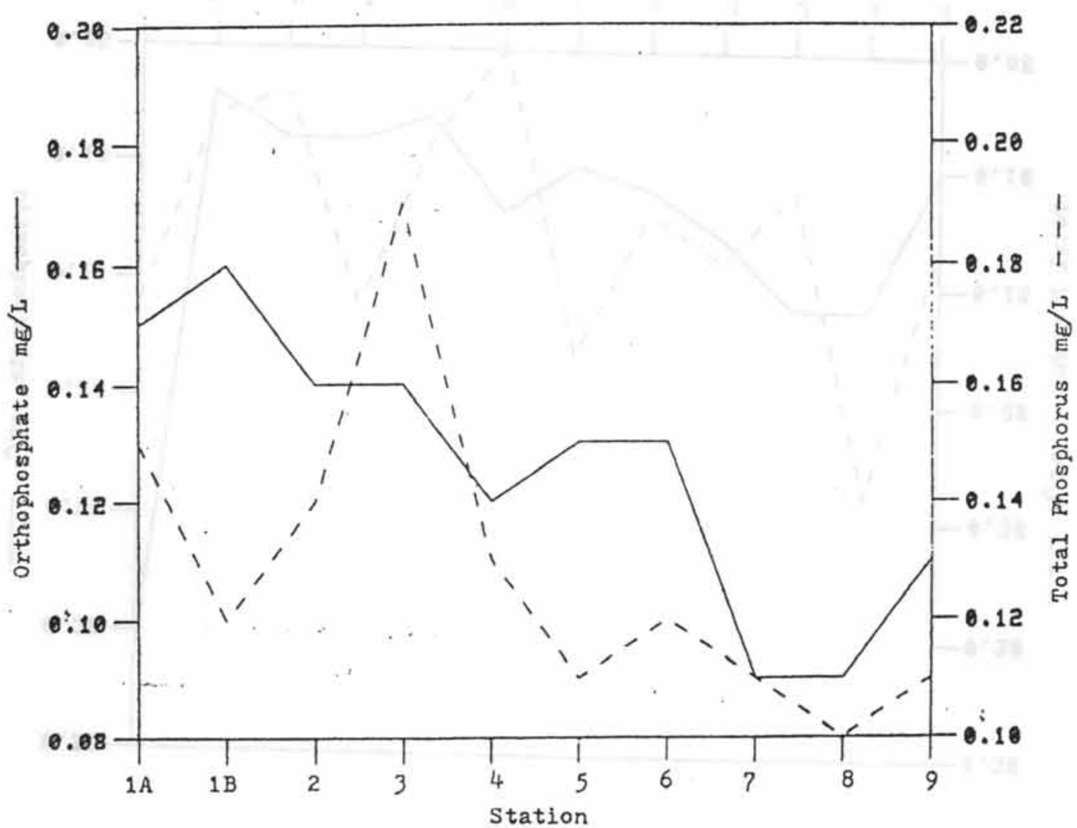


Figure 16. Mean orthophosphate and total phosphorus for the sampling stations at Caddo Lake from October 3, 1981 to September 8, 1982.

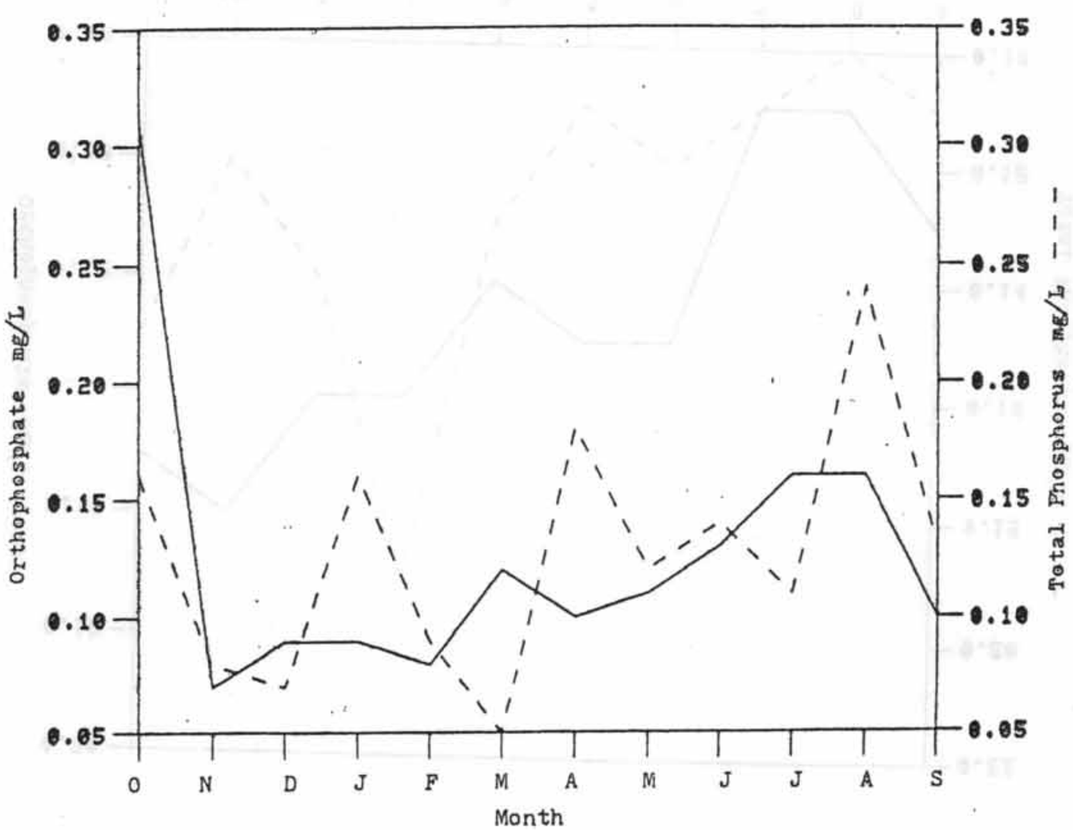


Figure 17. Monthly means for orthophosphate and total phosphorus at Caddo Lake from October 3, 1981 to September 8, 1982.

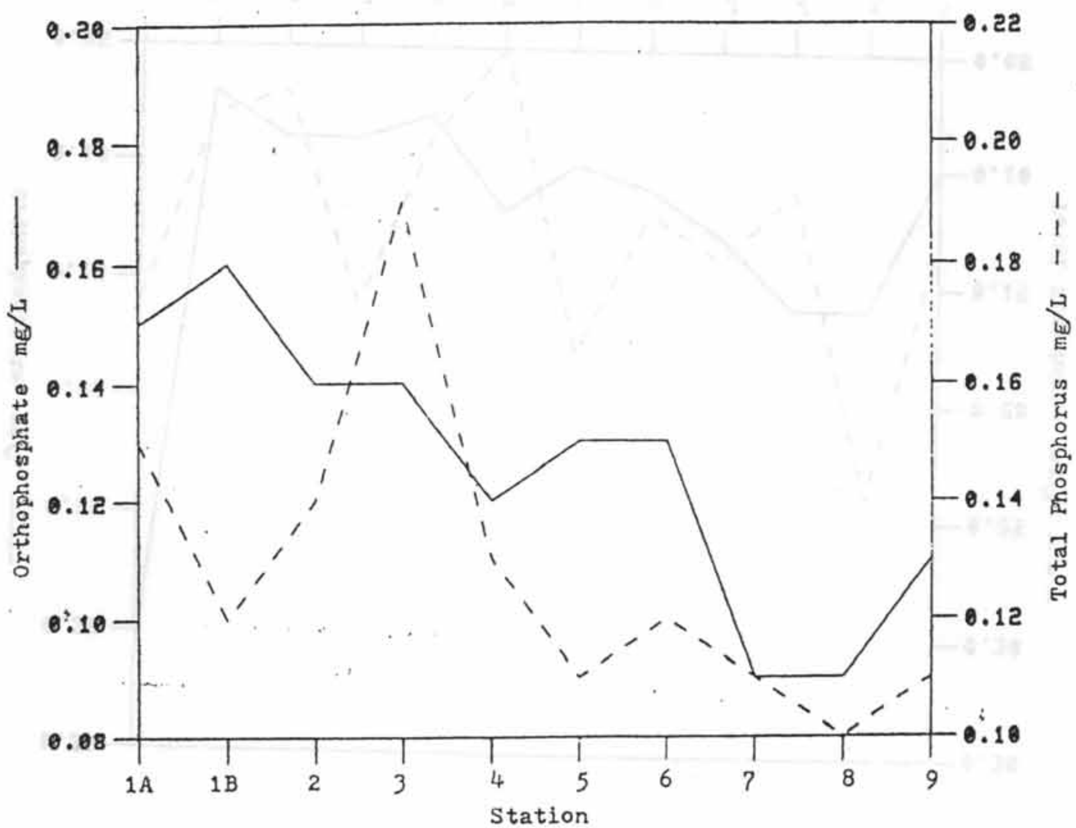


Figure 16. Mean orthophosphate and total phosphorus for the sampling stations at Caddo Lake from October 3, 1981 to September 8, 1982.

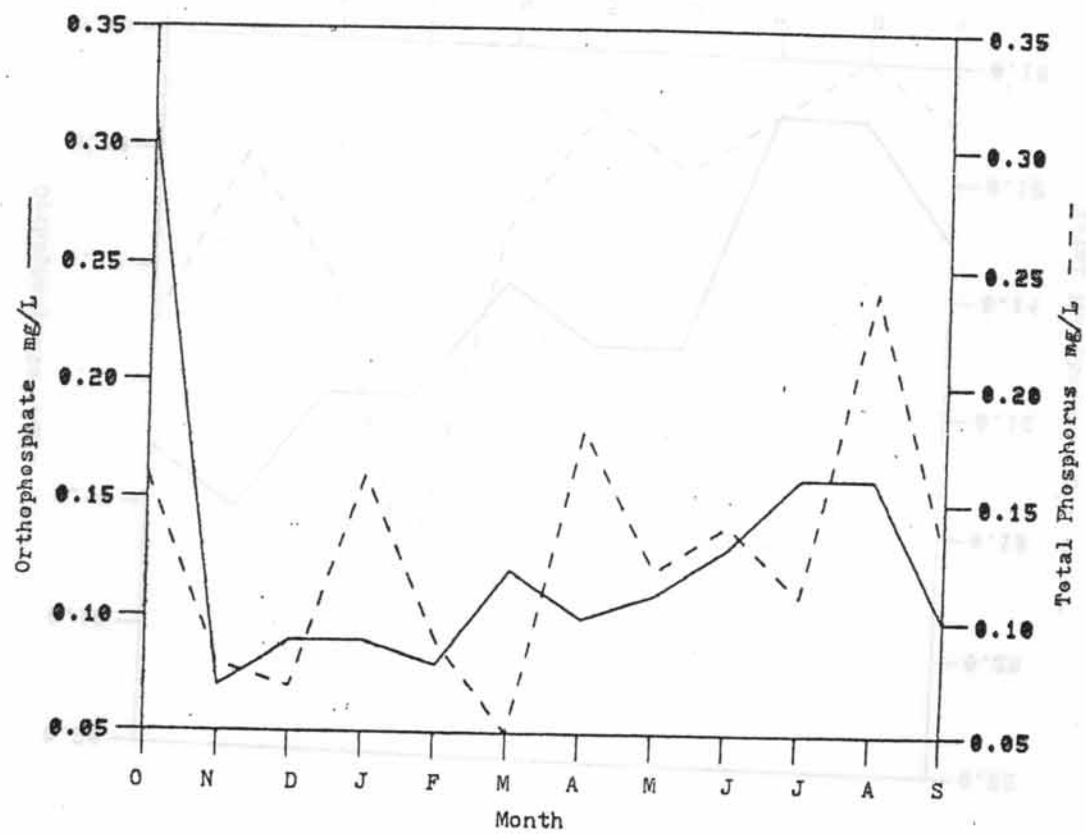


Figure 17. Monthly means for orthophosphate and total phosphorus at Caddo Lake from October 3, 1981 to September 8, 1982.

Figure 18 shows that iron concentrations were lowest at Station 7 and highest at Station 3. During September the lowest monthly mean was recorded and October was found to have the highest (Figure 19).

The mean annual calcium concentration at Caddo Lake was 11 mg/L with a standard deviation of 6 mg/L. Calcium varied from 6 mg/L at Station 9 on September 8, 1982 to 28 mg/L at all the stations except 1B on July 19, 1982. Yearly means were lowest at Station 1B and highest at Station 3 (Figure 18). Figure 19 shows that calcium values were lowest in the winter and highest in July.

October 3, 1981 was the only time the water was analyzed for zinc. Concentrations were very low ranging from 0.01 mg/L at Station 1B to 0.05 mg/L at Station 9. Mean zinc concentration during October was 0.03 mg/L with a standard deviation of 0.01 mg/L.

Sulfate concentration ranged from 6.2 mg/L at Station 9 on December 5, 1981 and August 13, 1982 to 28.2 at Station 2 on March 12, 1982 and Station 1A on July 19, 1982. The annual mean concentration for Caddo Lake was found to be 19.0 mg/L with a standard deviation of 5.4 mg/L. Figure 18 shows that Station 8 and 9 had much lower mean sulfate concentrations than the rest of the stations. Monthly means were lowest in December and highest in March (Figure 19).

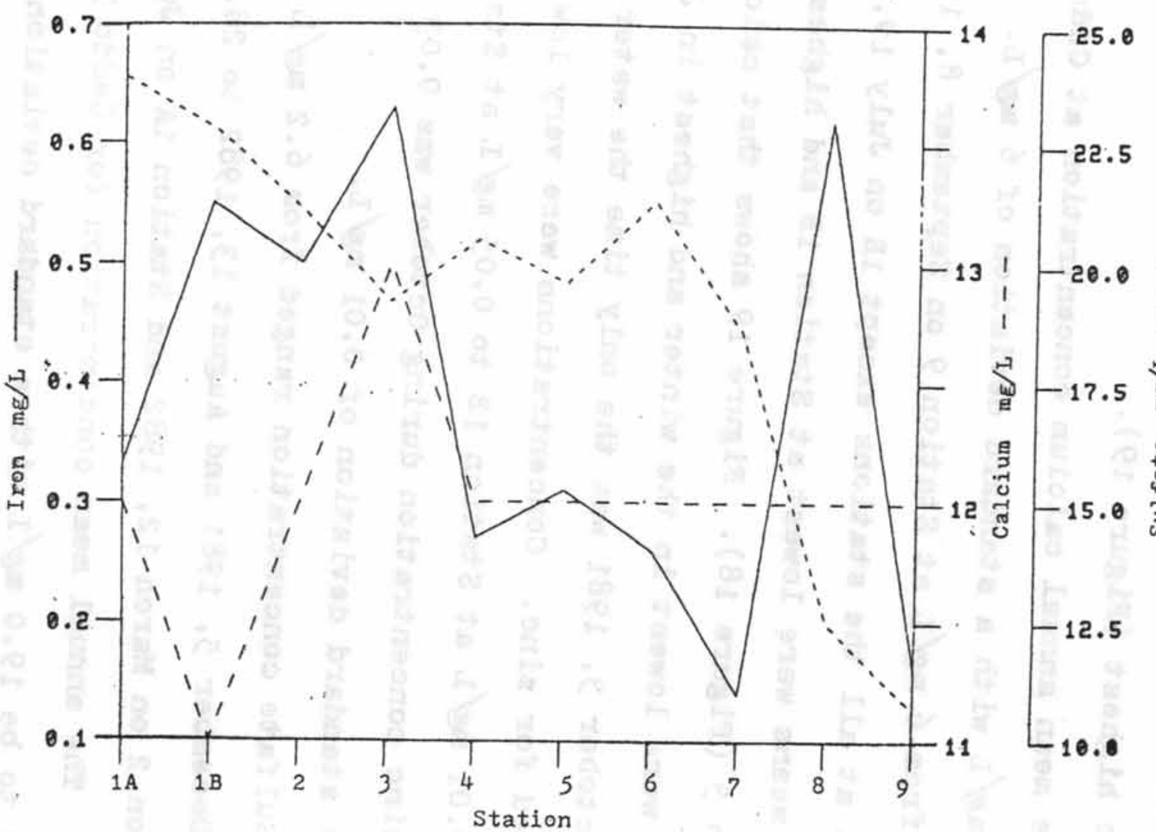


Figure 18. Mean iron, calcium, and sulfate for the sampling stations at Caddo Lake from October 3, 1981 to September 8, 1982.

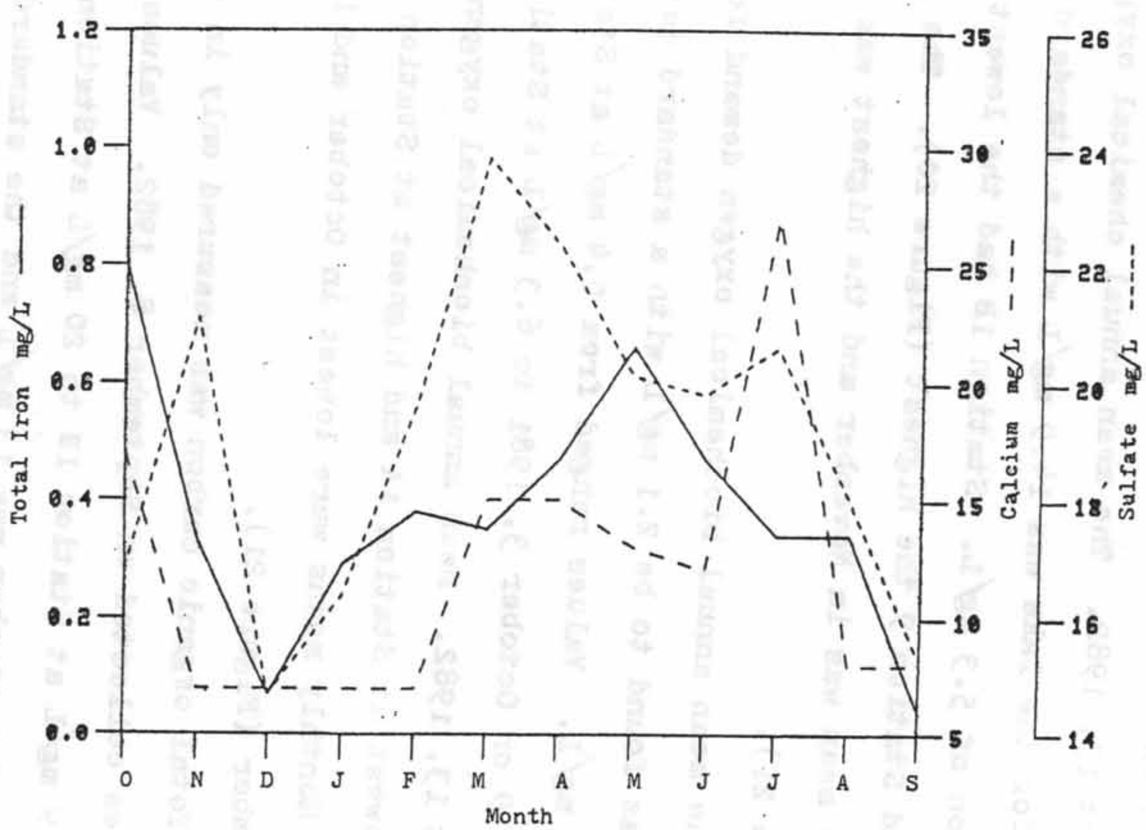


Figure 19. Monthly means for total iron, calcium, and sulfate at Caddo Lake from October 3, 1981 to September 8, 1982.

Chemical Oxygen Demand, Biochemical Oxygen Demand, Total Organic Carbon, and Oil

Chemical oxygen demand varied from 5.6 mg/L at Station 3 on November 7, 1981 to 48.0 mg/L at Station 3 on August 13, 1982. The mean annual chemical oxygen demand for the lake was 14.9 mg/L with a standard deviation of 5.3 mg/L. Station 1B had the lowest yearly mean and Station 9 the highest (Figure 20). The lowest monthly mean was in November and the highest was August (Figure 21).

The mean annual biochemical oxygen demand for Caddo Lake was found to be 2.1 mg/L with a standard deviation of 1.0 mg/L. Values ranged from 0.4 mg/L at Stations 4, 8, and 9 on October 3, 1981 to 6.3 mg/L at Station 3 on August 13, 1982. Mean annual biochemical oxygen demand was lowest at Station 1A and highest at Station 3 (Figure 20). Monthly means were lowest in October and highest in September (Figure 21).

Total organic carbon was measured only in the water samples collected on September 8, 1982. Values ranged from 9 mg/L at Station 1B to 20 mg/L at Station 5. The mean for September was 13 mg/L and the standard deviation was 3 mg/L.

Oil in the water was analyzed from a surface sample at Station 8 on February 12, 1982. The water was found

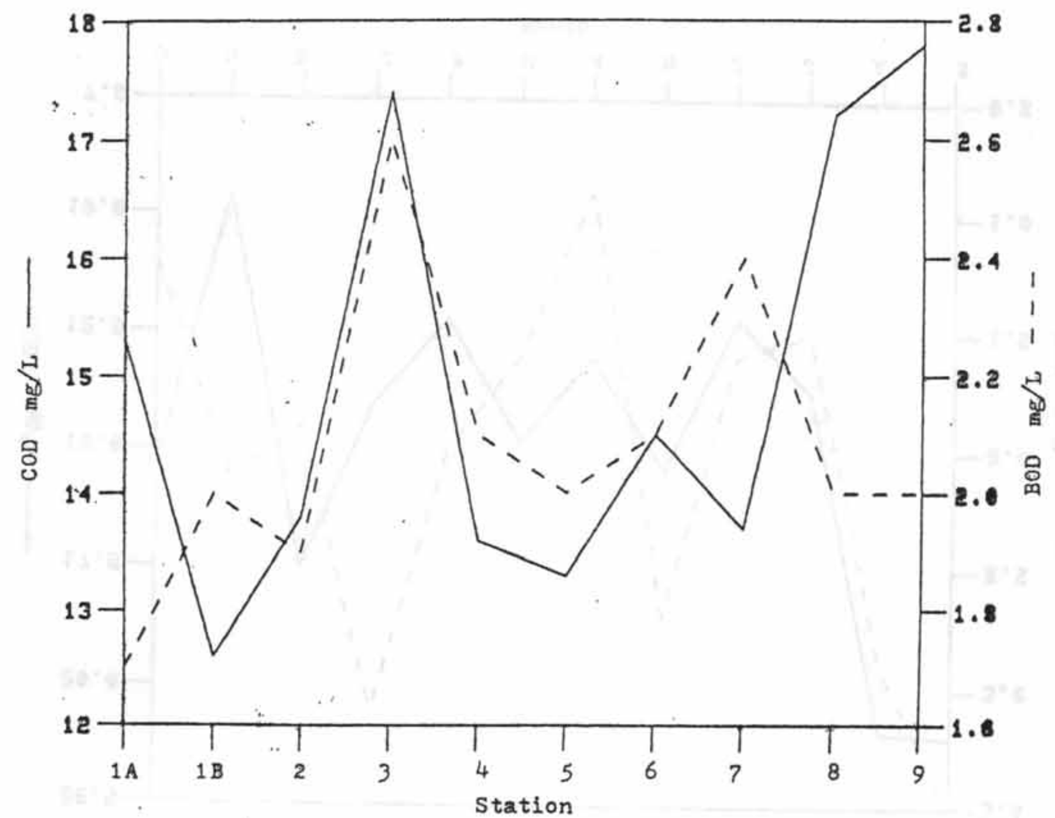


Figure 20. Mean COD and BOD_5 for the sampling stations at Caddo Lake from October 3, 1981 to September 8, 1982.

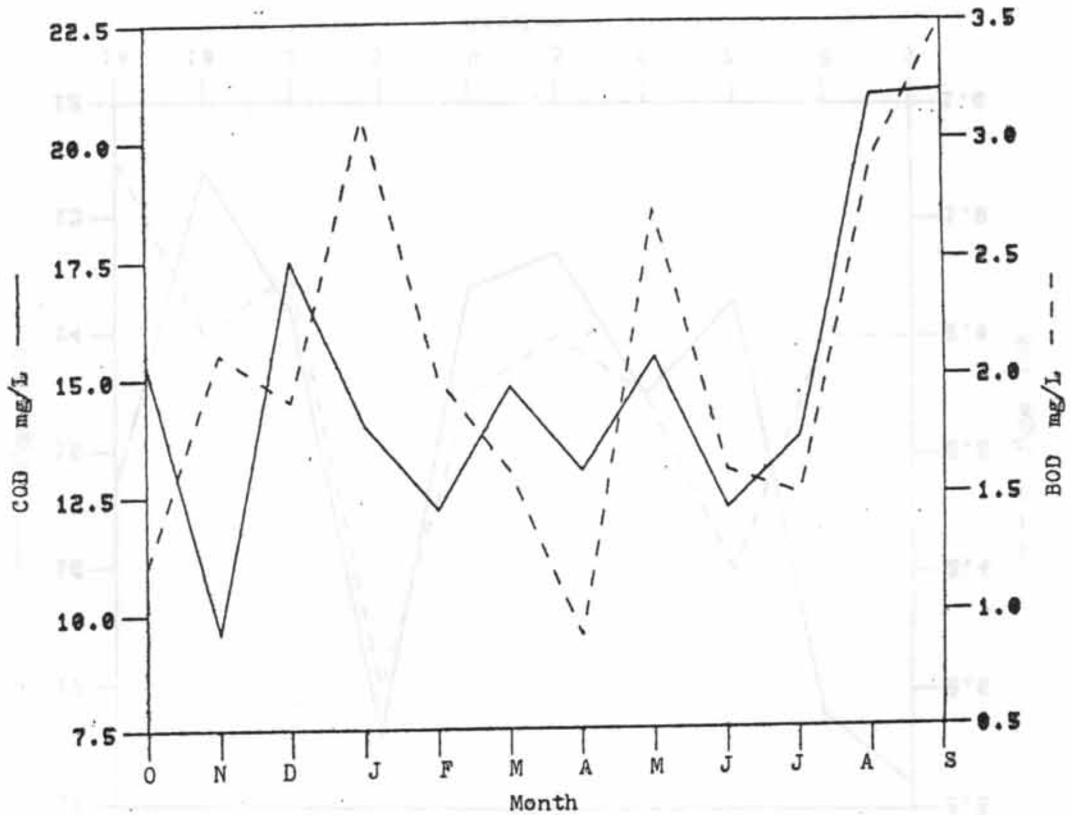


Figure 21. Monthly means for COD and BOD_5 at Caddo Lake from October 3, 1981 to September 8, 1982.

to have 2400 mg of crude oil per liter.

Residue

The yearly mean for total residue in Caddo Lake was 116 mg/L with a standard deviation of 28 mg/L. Total residue ranged from 44 mg/L at Station 5 on February 12, 1982 to 272 mg/L at Station 3 on August 12, 1982. Station 4 had the lowest mean value and Station 9 had the highest (Figure 22). Figure 23 shows that the monthly means were lowest in the winter and highest in the fall.

Total volatile residue varied from 8 mg/L at Station 1B on January 9, 1982 to 152 mg/L at Station 3 on August 13, 1982. The yearly mean value for the lake was 45 mg/L with a standard deviation of 22 mg/L. The lowest annual mean for total volatile residue was found at Station 1A and the highest was at Station 6 (Figure 22). Monthly means were lowest in the winter and highest in the summer (Figure 23).

Sediments

The mean concentration of oil found in the sediments during the study was 26,615 mg oil/kg of dried sediments; the standard deviation was 22,956 mg oil/kg (of dried sediment). Values ranged from 757 mg oil/kg (of dried sediment) at Station 2 on October 3, 1981 to 67,873 mg oil/kg (of dried sediment.) Figure 24 shows that yearly

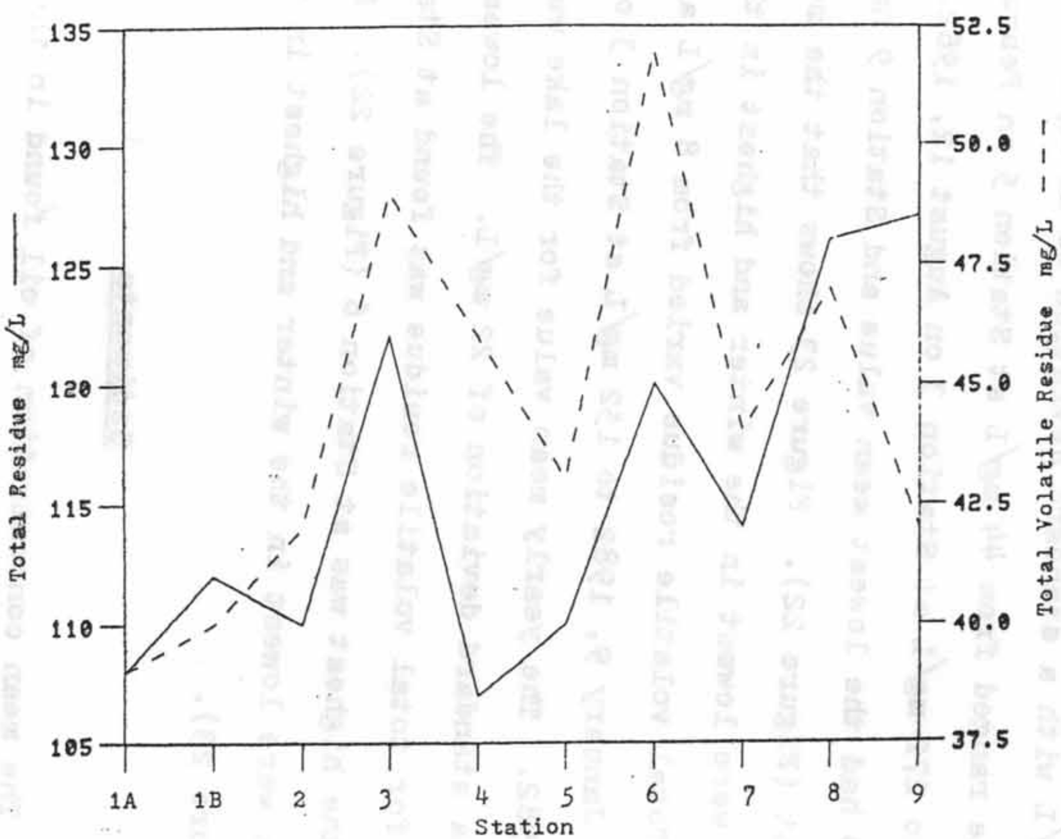


Figure 22. Mean total residue and total volatile residue for the sampling stations at Caddo Lake from October 3, 1981 to September 8, 1982.

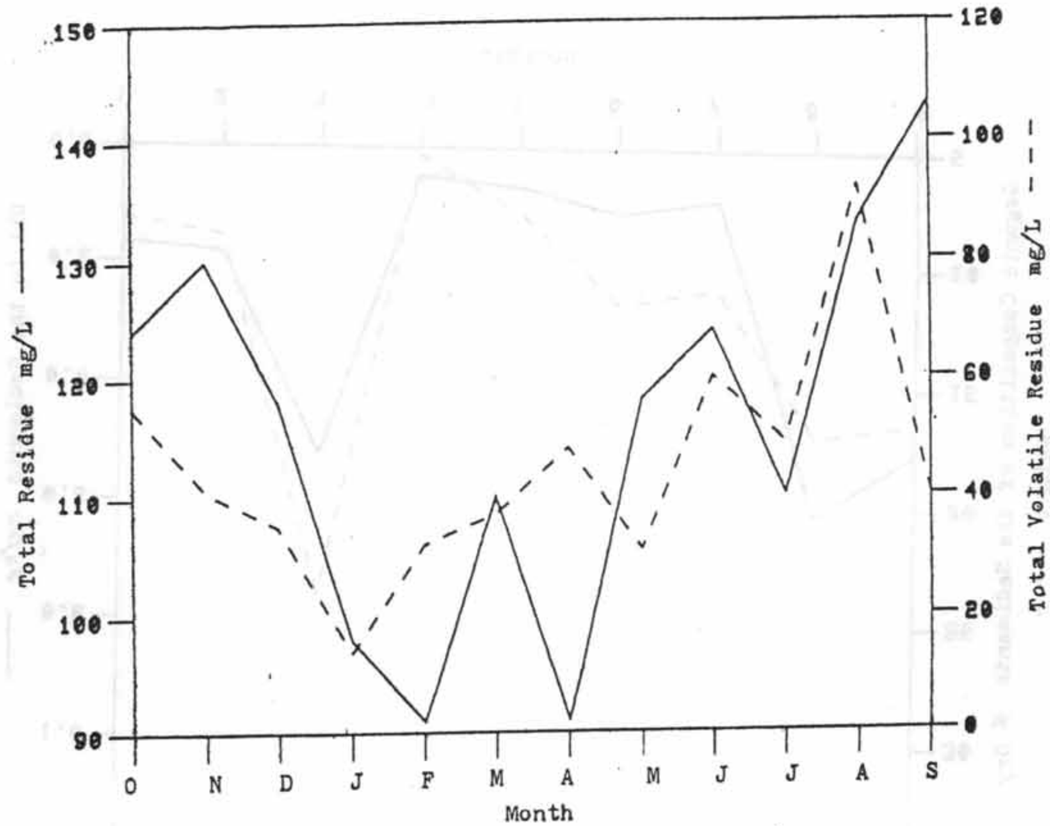


Figure 23. Monthly means for total residue and total volatile residue at Caddo Lake from October 3, 1981 to September 8, 1982.

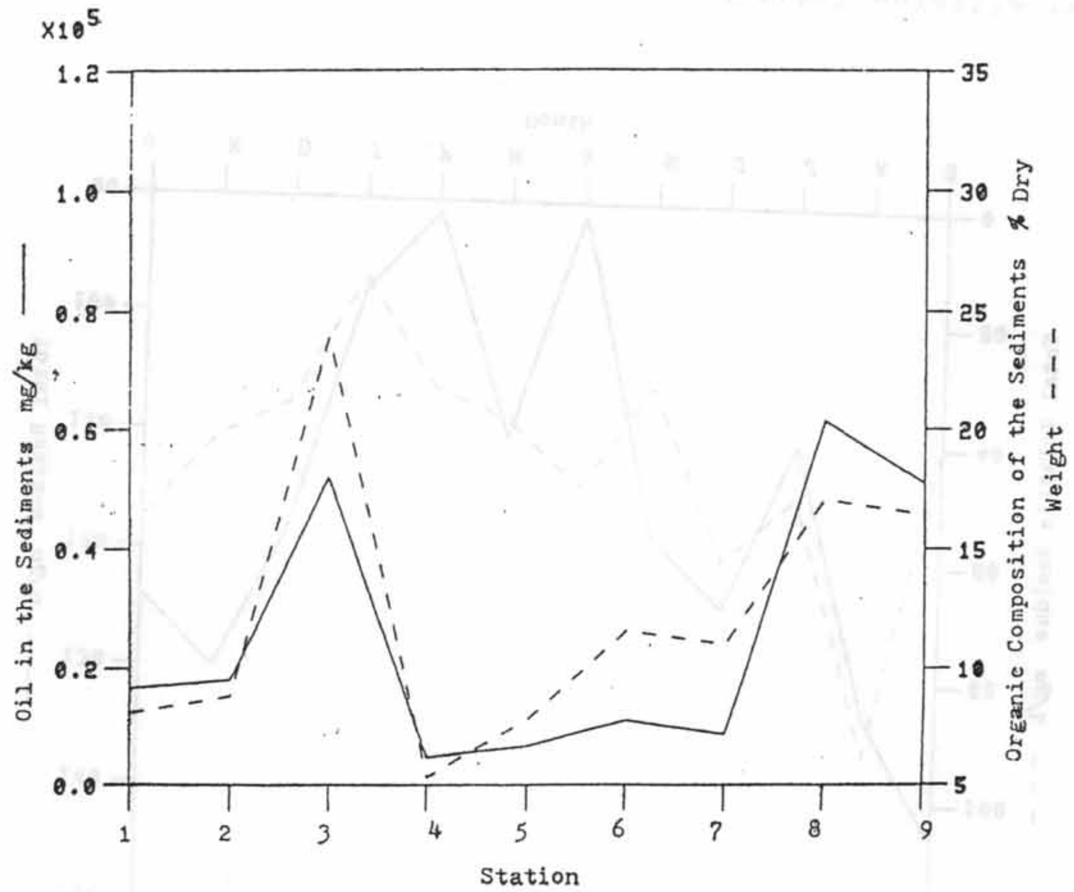


Figure 24. Mean oil in the sediments and organic composition of the sediments for the sampling stations at Caddo Lake from October 3, 1981 to August 13, 1982.

mean values were lowest at Station 4 and highest at Station 8.

The organic content of the sediments varied from 2.3% at Station 2 on October 3, 1981 to 30.2% at Station 3 on August 13, 1982. Mean organic content was 12.6% with a standard deviation of 6.8%. The lowest mean value was found at Station 4 and the highest at Station 3 (Figure 24).

DISCUSSION

The sampling stations used in this study were established to represent three regions of Caddo Lake. Stations 1A, 1B, 2, and 3 were in the Swamp Region. Stations 4, 5, 6, and 7 were in the Open Water Region. Stations 8 and 9 were in the Oil-Producing Region. These three regions are used frequently in the following discussion.

Ellis (1941) states that the physicochemical conditions of lakes are more stable than reservoirs. This was not found to be true for Caddo Lake. Variations in the parameters were large as indicated by the standard deviations and ranges reported in Table 1. It is well-known that physicochemical instability is inherent in lakes as shallow as Caddo Lake (Wetzel, 1983).

Thermal Stratification and Mixing

Because of its shallow depth, Caddo Lake was essentially isothermic with respect to depth for the entire study. Only during June and July at Stations 7, 8, and 9 did weak thermal stratification develop. Earlier studies by Fuss (1959), Geagan and Allen (1961), and Shampine (1971) also reported the absence of any prolonged stratification in Caddo Lake.

Although wind is important in mixing lakes, sheltering by bald cypress and other aquatic macrophytes appeared to reduce mixing, especially in the Swamp Region. However, turbulent inflow from Cypress Bayou kept the water at Station 1 well mixed even though it was the deepest sampling station. T-tests (with pooled variances) for every parameter detected no significant differences at the 95% confidence level between Stations 1A and 1B on a seasonal or yearly basis.

Spatial and Temporal Variations in Physicochemical Characteristics

High turbidity was found throughout Caddo Lake in December, February, May, and June. This could be attributed to the suspension of lake sediments by wind action and suspended material carried in by tributaries after heavy rainfall. The months with elevated turbidity sometimes produced values five-times greater than the preceding month. High turbidity can probably occur anytime in the lake and be widespread because of the shallowness of the lake, however because of low hydraulic retention time and perhaps the low pH, the turbidity quickly subsides.

Many parameters were found to be significantly correlated with the occurrence of elevated turbidity. High carbon dioxide, color, and ammonium-nitrogen were especially notable. Total phosphorus, apparent color, and COD were directly correlated with low turbidity. Table 2 compares the correlations of several parameters with high and low turbidity.

Table 2. Comparison of Pearson's correlation coefficients for several parameters with turbidity during high and low turbidity months.

Parameter	High Turbidity		Low Turbidity	
	r	P	r	P
Ammonium-nitrogen	0.60	< 0.001	0.44	< 0.001
True Color	0.59	< 0.001	0.20	0.035
Apparent Color	0.58	< 0.001	0.77	< 0.001
Carbon Dioxide	0.58	< 0.001	0.32	0.002
Total Iron	0.32	0.024	0.51	< 0.001
Total Phosphorus	0.22	0.089	0.86	< 0.001
Phytoplankton Chlorophyll *a*	-0.31	0.027	0.11	0.161
COD	-0.28	0.088	0.65	< 0.001
Total Residue	-0.28	0.038	0.62	< 0.001
Total Volatile Residue	-0.16	0.166	0.47	< 0.001

Boats powered by large outboard motors were observed on several occasions to cause considerable disturbance of the sediments. This probably accounts for the extremely high turbidity at Station 3 in August since it was close to a shallow boat lane.

On a seasonal basis, significantly lower turbidity values were found to occur during the fall compared with the other seasons (Figure 25). Turbidity was generally

Figure 25. Duncan's Multiple Range Test for seasonal turbidity means (NTU) at Caddo Lake.

F = 5.81 P = 0.0010

Winter	Summer	Spring	Fall
8.5	5.7		
	5.7	5.3	
			2.4

higher in the Swamp Region during the study, even though this variation was not found to be statistically significant.

Light penetration as measured by Secchi disc transparency was reduced by turbidity. Table 3 shows a significant inverse correlation between Secchi disc depth and turbidity during the months of high turbidity.

Table 3. Pearson's correlation coefficients for Secchi disc transparency with turbidity and phytoplankton chlorophyll a during high turbidity and low turbidity.

	High Turbidity	Low Turbidity
Secchi Disc Transparency with Turbidity	r = -0.67 P 0.001	r = -0.13 P = 0.145
Secchi Disc Transparency with Phytoplankton Chlorophyll a	r = -0.01 P = 0.196	r = -0.69 P 0.001

When turbidity was low, phytoplankton cells caused the reduction in Secchi disc transparency as indicated by the high inverse correlation between phytoplankton chlorophyll a and Secchi disc transparency. Figure 26 shows that Station 7 had significantly lower Secchi disc transparency than the rest of the sampling stations with the exception of Station 6. Stations 6 and 7

Figure 26. Duncan's Multiple Range Test for annual Secchi disc transparency means (m) for the sampling stations at Caddo Lake.

F = 3.23 P = 0.0027

4	2	5	9	8	1	3		
1.2	1.1	1.1	1.1	1.0	1.0	1.0	6	
			1.1	1.0	1.0	1.0	0.8	7
							0.8	0.7

had lower values because they consistantly had high phytoplankton populations as indicated by high chlorophyll a concentrations.

The mean water temperature of Caddo Lake was found to be significantly different during all the seasons (Figure 27). The shallowness of the water allowing rapid heating and cooling could be responsible for this seasonal variation.

There were marked physicochemical differences between the areas dominated by macrophytes and those areas that are in open water. Decaying vegetation was the most influential factor on the physicochemistry of the water in the Swamp Region. Dense stands of bald cypress (*Taxodium distichum*), American lotus (*Nelumbo lutea*), and duckweed

Figure 27. Duncan's Multiple Range Test for water temperature means (°C) during each season at Caddo Lake.

$F = 131.85$ $P < 0.0001$

Summer	Fall	Spring	Winter
29	23	21	9

(Lemna sp.) added immense amounts of organic matter to the water during their yearly cycle. A good example of this prolific growth was seen at Station 3 where macrophytes completely covered the surface from June through October.

Mean dissolved oxygen at Caddo Lake was highest in the winter, and significant seasonal differences in dissolved oxygen were found during the other seasons as well (Figure 28). As microbial oxidation accelerated

Figure 28. Duncan's Multiple Range Test for seasonal dissolved oxygen means (mg/L) at Caddo Lake.

$F = 25.80$ $P < 0.0001$

Winter	Spring	Fall	Summer
10.3	8.0	6.3	5.1

in warmer temperatures, dissolved oxygen in the Swamp Region dropped to a low level. In the Open Water and Oil-Producing Regions, however, oxygen levels remained fairly high during the warmer months (Figure 29). A two-way analysis of variance found this season-station interaction to be significant (Table 4).

Table 4. Two-way analysis of variance for dissolved oxygen with seasons and stations at Caddo Lake.

Source	Sum of Squares	D.F.	Mean Squares	F Ratio	P
Season	455.938	3	151.979	53.631	0.001
Station	333.016	9	37.002	13.057	0.001
Interaction	123.554	27	4.576	1.615	0.052
Error	226.705	80	2.834		

A one-way analysis of variance was used to analyze yearly dissolved oxygen means for the regions of Caddo Lake. This analysis showed that dissolved oxygen in the Swamp Region during the warmer months was low enough to cause the yearly mean to be significantly lower than the means for the Open Water and Oil-Producing Regions (Figure 30). Even though the lake was isothermic there was still a slight decrease in dissolved oxygen with increasing depth in the warmer months.

Fall and summer phytoplankton chlorophyll a means were significantly higher than those for spring and winter (Figure 31). This pattern indicated the absence of a spring phytoplankton bloom and summer lag that is often

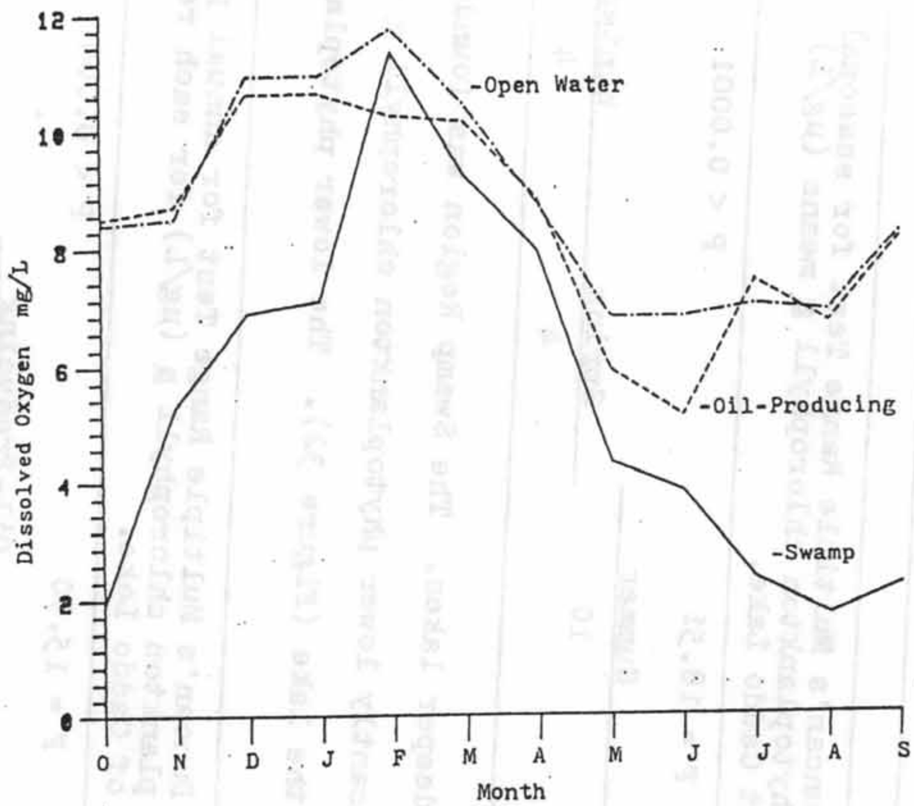


Figure 29. Monthly means for dissolved oxygen for the regions of Caddo Lake from October 3, 1981 to September 8, 1982.

Figure 30. Duncan's Multiple Range Test for annual dissolved oxygen means (mg/L) for each region of Caddo Lake.

$F = 19.14$ $P < 0.0001$

Open Water	Oil-Producing	Swamp
8.8	8.4	5.6

Figure 31. Duncan's Multiple Range Test for seasonal phytoplankton chlorophyll a means (µg/L) at Caddo Lake.

$F = 18.51$ $P < 0.0001$

Fall	Summer	Spring	Winter
11	10	4	4

observed in deeper lakes. The Swamp Region was found to have significantly lower phytoplankton chlorophyll a than the rest of the lake (Figure 32). The lower phytoplankton

Figure 32. Duncan's Multiple Range Test for annual phytoplankton chlorophyll a (µg/L) for each region of Caddo Lake.

$F = 15.90$ $P < 0.0001$

Open Water	Oil-Producing	Swamp
10	9	4

population in the Swamp Region was probably due to the shading by macrophytes.

Mean annual carbon dioxide was significantly higher in the Swamp Region than in the Open Water and Oil-Producing Regions (Figure 33). Aerobic decomposition

Figure 33. Duncan's Multiple Range Test for yearly carbon dioxide means (mg/L) for each region of Caddo Lake.

$F = 14.75$ $P < 0.0001$

Swamp	Oil-Producing	Open Water
12.4	6.6	5.7

of large amounts of organic matter was the likely source of most of this carbon dioxide. The high concentration of carbon dioxide contributed to the Swamp Region being the most acidic region due to the formation of carbonic acid (Figure 34). High carbon dioxide was also found

Figure 34. Duncan's Multiple Range Test for annual pH means for the regions of Caddo Lake.

$F = 22.28$ $P < 0.0001$

Open Water	Oil-Producing	Swamp
7.2	6.9	6.5

throughout the lake during the months of elevated turbidity.

Carbon dioxide concentration was reduced at stations with high phytoplankton chlorophyll a because of the high rate of assimilation by phytoplankton during photosynthesis. The removal of carbon dioxide lowered the carbonic acid level which raised the pH and bicarbonate alkalinity at these stations. The pH was significantly higher in the fall than during any of the other seasons (Figure 35).

Figure 35. Duncan's Multiple Range Test for seasonal pH means at Caddo Lake.

	F = 6.47		P < 0.0001
Fall	Summer	Winter	Spring
7.2	6.8	6.8	6.7

The pH was highly correlated with phytoplankton chlorophyll a (r = 0.71) and followed a similar seasonal pattern. Bicarbonate alkalinity was found to be significantly higher in the fall and summer (Figure 36). Bicarbonate alkalinity

Figure 36. Duncan's Multiple Range Test for seasonal bicarbonate alkalinity means (mg/L) at Caddo Lake.

	F = 25.06		P < 0.0001
Fall	Summer	Spring	Winter
45	41	29	25

rose in the summer due to the high pH at the open water stations and formation of bicarbonate ions in their buffering reactions. Another possible source of bicarbonate alkalinity in the Swamp Region could have been the formation of ammonium bicarbonate during anaerobic bacterial respiration in the sediments (Wetzel, 1983). Carbonate alkalinity was found only once during the study; it was at Station 7 on August 13, 1982 when the pH was 8.4. The concentration was only 10 mg/L. The low alkalinity during winter and spring provided very little buffering capability. On a yearly basis the alkalinity was fairly low at Caddo Lake, but this is common for surface waters in this region (U.S. Geological Survey, 1981). No significant spatial variation was detected for bicarbonate alkalinity.

Total volatile residue was highest in the summer and lowest in the winter (Figure 37). This may be due to

Figure 37. Duncan's Multiple Range Test for seasonal means of total volatile residue (mg/L) at Caddo Lake.

F = 28.20   P < 0.0001

Summer	Fall	Spring	Winter
67	45	39	27

increased dissolved organic matter. Since turbidity was lowest in the fall and summer, particulate organic matter was also probably low and therefore did not account for much of the increase in total volatile residue.

Total residue increased significantly during the fall and summer months (Figure 38). Dissolved matter was

Figure 38. Duncan's Multiple Range Test for seasonal total residue means (mg/L) at Caddo Lake.

$F = 9.37$ $P < 0.0001$

Fall	Summer	Spring	Winter
132	122	106	102

probably responsible for this rise since turbidity was low during this time. The rise of calcium (Figure 39), sulfate (Figure 47), and bicarbonate (Figure 36) contributed to that trend. The increase of these ions caused conductivity to rise significantly during the summer and fall (Figure 40). Bicarbonate alkalinity and conductivity

Figure 39. Duncan's Multiple Range Test for seasonal calcium means (mg/L) at Caddo Lake.

$F = 16.59$ $P < 0.0001$

Summer	Spring	Fall	Winter
16	14	11	7

Figure 40. Duncan's Multiple Range Test for seasonal conductivity means (μmhos) at Caddo Lake.

$F = 37.78$ $P < 0.0001$

Summer	Fall	Spring	Winter
147	139	123	93

were strongly correlated ($r = 0.64$). Conductivity was also highly correlated with phytoplankton chlorophyll a ($r = 0.60$).

Significant seasonal variation was detected for BOD (Figure 41). The data indicate that BOD remained

Figure 41. Duncan's Multiple Range Test for seasonal BOD_5 means (mg/L) at Caddo Lake.

$F = 6.18$ $P = 0.0007$

Fall	Winter		
2.8	2.3	Summer	
		2.0	Spring
		2.0	1.7

high through the winter. This could be attributed to the winter die-back of aquatic macrophytes (and possibly plankton) and the subsequent increase in the amount of detritus. Carpenter et al. (1979) found that dissolved organic matter from macrophytes have an important role in raising BOD. This situation was expected to cause elevated BOD values in the Swamp Region, but no significant spatial differences were detected.

The TOC results for September 1982 were as high as TOC values found in organically enriched rivers such as the Trinity River near Dallas, Texas (U.S. Geological Survey, 1982).

One of the most striking features of Caddo Lake was the highly colored water. Apparent color ranged as high as 110 APHA color units and true color as high as 48 APHA color units. True and apparent color were significantly higher in the Swamp and Oil-Producing Regions (Figures 42 and 43). Color in lake water is caused mostly by dissolved

Figure 42. Duncan's Multiple Range Test for yearly true color means (color units) for the regions of Caddo Lake.

$F = 11.019$ $P < 0.0001$

Oil-Producing	Swamp	Open Water
25	23	17

Figure 43. Duncan's Multiple Range Test for yearly apparent color means (color units) for the regions of Caddo Lake.

$F = 6.903$ $P = 0.0015$

Swamp	Oil-Producing	Open Water
37	36	27

organic matter (Wetzel, 1983), in this case from decomposing vegetation in the watershed and in the Swamp Region of the lake. True color was found to be lowest in the fall when turbidity was lowest (Figure 44). Figure 45 shows significant seasonal variation in apparent color that differs some what from true color.

Significantly higher sulfate concentrations were found

Figure 44. Duncan's Multiple Range Test for seasonal true color means (color units) at Caddo Lake.

$F = 9.397$ $P < 0.0001$

Spring	Winter	Summer	Fall
25	23	22	
			14

Figure 45. Duncan's Multiple Range Test for seasonal apparent color means (color units) at Caddo Lake.

$F = 2.899$ $P < 0.0001$

Summer	Spring	Winter	Fall
37	35		
	35	29	29

in the Swamp Region compared with the other two regions (Figure 46). The release of sulfur compounds during microbial decomposition of organic matter could explain the higher sulfate in the Swamp Region. The mean annual sulfate value for the Oil-Producing Region was much lower than the other two regions. High sulfate concentrations normally associated with oil and brine were not found.

Sulfate was found to be significantly greater in the spring than in the winter and fall, but not significantly greater than the summer (Figure 47). This seasonal pattern with a spring peak is similar to the pattern that Mann (1958) found in shallow ponds. The spring peak can be attributed to oxidation of sulfide compounds in the sediments.

Figure 46. Duncan's Multiple Range Test for annual sulfate means (mg/L) for the regions of Caddo Lake.

$F = 56.09$ $\qquad$ $P < 0.0001$

Swamp	Open Water	Oil-Producing
21.8	20.0	11.6

Figure 47. Duncan's Multiple Range Test for seasonal sulfate means (mg/L) at Caddo Lake.

$F = 5.90$ $\qquad$ $P = 0.0009$

Spring	Summer	Fall	Winter
22.0	19.4		
	19.4	17.8	16.9

Total iron was extremely variable with respect to both month and station, ranging from <0.02 mg/L to 2.62 mg/L. The reducing environments of the sediments and organic iron complexes could be the reason for the higher values found in the Swamp and Oil-Producing Regions (Figure 48).

Figure 48. Duncan's Multiple Range Test for yearly total iron means (mg/L) for the regions of Caddo Lake.

$F = 3.20$ $\qquad$ $P = 0.0443$

Swamp	Oil-Producing	Open Water
	0.39	
	0.39	0.25

East Texas soils are known to have high levels of iron

(Godfrey et al., 1973) and are probably the original source of the iron.

According to Wetzel (1983), aquatic macrophytes are the primary sources of nitrogen and phosphorus for some lakes. There is some evidence that this is true for Caddo Lake. Relatively high levels of total phosphorus were found in Caddo Lake compared to orthophosphate concentrations. This indicates that much of the phosphorus is organically bound. Detritus, living cells, and humic acids could be the source of this phosphorus. Since Station 1A and 1B had the highest annual means, water from Cypress Bayou would also have to be considered a major source of phosphorus.

The highest total phosphorus and orthophosphate concentrations were generally found in the Swamp Region during the fall when large amounts of leaf litter and aquatic vascular plants were decomposing. Mean annual orthophosphate was found to be significantly higher in the Swamp Region than in the Oil-Producing Region as shown in Figure 49. There was also a significant decrease in orthophosphate during winter (Figure 50). Spatial and seasonal differences in total phosphorus were not found to be statistically significant. Total phosphorus was found to be highly correlated with turbidity (r = 0.86) and apparent color (r = 0.68) when the four months of very

Figure 49. Duncan's Multiple Range Test for yearly orthophosphate means (mg/L) for each region of Caddo Lake.

F = 2.48 P = 0.0880

Swamp	Open Water	Oil-Producing
0.15	0.12	
	0.12	0.10

Figure 50. Duncan's Multiple Range Test for seasonal orthophosphate means (mg/L) at Caddo Lake.

F = 3.81 P = 0.0120

Fall	Summer	Spring	Winter
0.16	0.15	0.11	
		0.11	0.09

high turbidity were excluded. This indicates that much of the phosphorus was tied up in living cells and detritus.

Mean annual ammonium-nitrogen was highest in the Oil-Producing and Swamp Regions (Figure 51). Decomposition

Figure 51. Duncan's Multiple Range Test for yearly ammonium-nitrogen means (mg/L) for the regions of Caddo Lake.

F = 3.12 P = 0.0478

Oil-Producing	Swamp	Open Water
0.77	0.74	
	0.74	0.68

of organic matter was probably the source of the ammonium-nitrogen in those two regions. Microbial oxidation presumably lowered the concentration in the well oxygenated Open Water Region.

Ammonium-nitrogen was found to be highest in summer and fall (Figure 52). This seasonal pattern has been

Figure 52. Duncan's Multiple Range Test for seasonal ammonium-nitrogen means (mg/L) at Caddo Lake.

F = 5.12 P = 0.0024

Summer	Fall	Winter	Spring
0.79	0.75		
	0.75	0.70	
		0.70	0.65

observed previously in East Texas reservoirs (Almquist, 1977; Smith, 1979). Ammonium-nitrogen was highly correlated ($r = 0.62$) with apparent color.

Total Kjeldahl nitrogen followed a seasonal pattern similar to ammonium-nitrogen with the highest values in the fall and summer (Figure 53). Station 3 had the highest

Figure 53. Duncan's Multiple Range Test for seasonal total Kjeldahl nitrogen means (mg/L) at Caddo Lake.

F = 4.62 P = 0.0044

Fall	Summer	Spring	Winter
6.43	5.97	5.51	
		5.51	4.39

values probably due to the amount of detritus in the water. Most of the other stations with high total Kjeldahl nitrogen were located in the Open Water Region. High values at those stations could be attributed to their large phytoplankton populations as indicated by high phytoplankton chlorophyll a values.

Nitrate-nitrogen and nitrite-nitrogen values exhibited no significant spatial variation. Seasonal variation, however, was found to be significant. Both were highest in the winter and lowest during spring (Figures 54 and 55).

Figure 54. Duncan's Multiple Range Test for seasonal nitrite means (µg/L) at Caddo Lake.

$F = 12.44$ $P < 0.0001$

Winter			
5	Fall		
	4	Summer	Spring
		3	3

Figure 55. Duncan's Multiple Range Test for seasonal nitrate means (µg/L) at Caddo Lake.

$F = 3.25$ $P = 0.024$

Winter	Fall	Summer	
15	14	10	Spring
		10	9

The drop in nitrate could be attributed to its rapid uptake by aquatic macrophytes, plankton, and bacteria during spring growth.

Effects of Off-Shore Oil Industry

The physicochemical limnology of Caddo Lake was found to be affected by the off-shore oil industry in several ways. The Oil-Producing Region was found to have significantly higher sodium (Figure 56), chloride (Figure 57), and conductivity (Figure 58) than the other regions of the lake. This strongly suggests pollution by oil brine, however, high calcium and sulfate concentrations usually associated with brine were not present.

Figure 56. Duncan's Multiple Range Test for yearly sodium means (mg/L) for the regions of Caddo Lake.

$F = 59.23$ $P < 0.0001$

Oil-Producing	Swamp	Open Water
22.1	14.3	13.3

Figure 57. Duncan's Multiple Range Test for yearly chloride means (mg/L) for the regions of Caddo Lake.

$F = 143.32$ $P < 0.0001$

Oil-Producing	Open Water	Swamp
42.0	23.6	21.5

Figure 58. Duncan's Multiple Range Test for yearly conductivity means (µmhos) for the regions of Caddo Lake.

$F = 10.73$ $P = 0.0001$

Oil-Producing	Open Water	Swamp
148	123	116

Oil slicks resulting from oil spills, were occasionally found during the study. A large oil slick greater than 1000 m^2 was observed on February 12, 1982 at Station 8. A surface sample was found to have 2400 mg/L of oil. The presence of an oily scum on the shore and vegetation indicated that spills were fairly common. The Oil-Producing Region had a significantly higher yearly mean COD than the rest of the lake (Figure 59). It is possible

Figure 59. Duncan's Multiple Range Test for yearly COD means (mg/L) for the regions of Caddo Lake.

$F = 3.86$ $P = 0.0240$

Oil-Producing	Swamp	Open Water
17.5	14.8	13.8

that oil in the water caused this difference.

Oil in the sediments was significantly higher in the Oil-Producing Region than the Swamp and Open Water Regions (Figure 60). It is very likely that oil spills and leakages over the months and years have contributed to the accumulation of oil in the sediments in James Bayou. The Texas Water Quality Board (1977) also reported high oil concentration in the sediments of James Bayou. The higher oil concentrations in the sediments at Stations 8 and 9 were reflected in the analysis for total organic composition with values generally higher in the Oil-Producing Region (Figure 61). Organic matter was found to be high in the sediments of the Swamp Region as well. This was probably due to decaying plant material in the region.

Figure 60. Duncan's Multiple Range Test for yearly oil in the sediments means (mg oil/kg dried sediment) for the regions of Caddo Lake.

$F = 19.45$ $P < 0.0001$

Oil-Producing	Swamp	Open Water
56,089	28,801	10,238

Figure 61. Duncan's Multiple Range Test for yearly organic composition means (% dry weight) for the regions of Caddo Lake.

$F = 5.26$ $P = 0.0127$

Oil-Producing	Swamp	Open Water
18.24	13.60	
	13.60	8.92

Concentrations of zinc as high as 170 mg/kg have been found in the sediments of Caddo Lake (Texas Water Quality

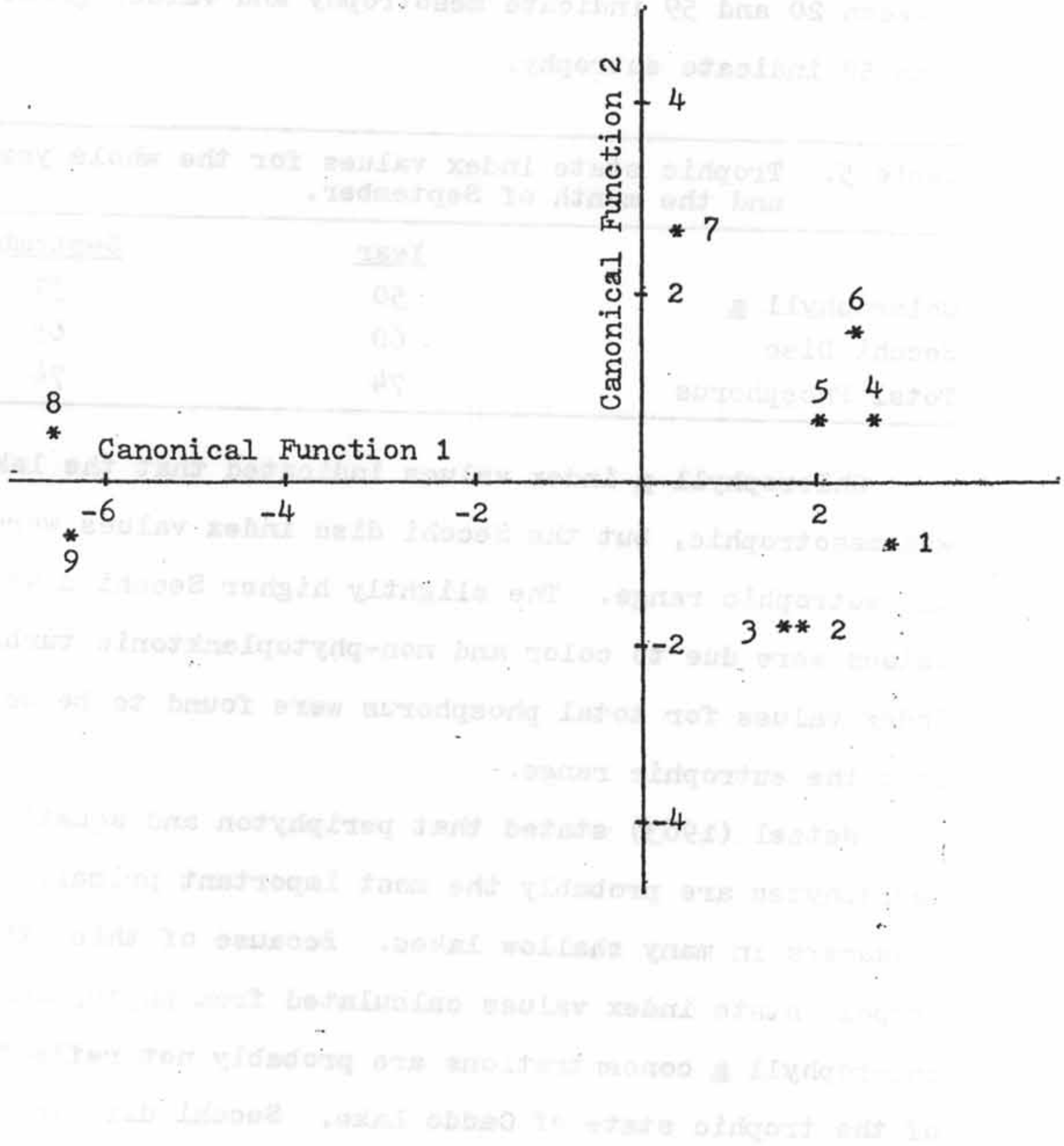
Board, 1977), however, water samples collected in October 1981 had very low levels of zinc.

A discriminant analysis was done on the nine sampling stations (Stations 1A and 1B were combined) for the whole year. A plot of the station centroids with respect to the first and second canonical functions divided the stations into two distinct groups (Figure 62). The stations representing the Oil-Producing Region were widely separated from the rest of the stations along the first canonical function. The most discriminating parameter was chloride and the next most discriminating parameter was sulfate. Dissolved oxygen was mostly reponsible for the slight separation between the stations of the Swamp and Open Water Regions along the second canonical function. This analysis emphasizes the physicochemical dissimilarity of the Oil-Producing Region and suggests that oil-related activity was having an effect on the water chemistry of the James Bayou region of the lake.

Trophic State

The trophic state index developed by Carlson (1977) was used to estimate the trophic condition of Caddo Lake. Trophic state index values were calculated for the annual means of phytoplankton chlorophyll a, Secchi disc transparency, and total phosphorus. Index values were also calculated for the means of the above parameters for

Figure 62. Discriminant analysis for the sampling stations at Caddo Lake. Plot of station centroids by canonical functions 1 and 2 ($P < 0.0001$).



September, since this month had the highest mean phytoplankton chlorophyll a value and lowest mean Secchi disc value recorded during the study period. The results of these calculations are given in Table 5. Index values between 20 and 59 indicate mesotrophy and values greater than 59 indicate eutrophy.

Table 5. Trophic state index values for the whole year and the month of September.

	Year	September
Chlorophyll a	50	57
Secchi Disc	60	65
Total Phosphorus	74	74

Chlorophyll a index values indicated that the lake was mesotrophic, but the Secchi disc index values were in the eutrophic range. The slightly higher Secchi disc values were due to color and non-phytoplanktonic turbidity. Index values for total phosphorus were found to be well into the eutrophic range.

Wetzel (1963) stated that periphyton and aquatic macrophytes are probably the most important primary producers in many shallow lakes. Because of this, the trophic state index values calculated from phytoplankton chlorophyll a concentrations are probably not reflective of the trophic state of Caddo Lake. Secchi disc transparency and total phosphorus might be better indicators of trophic conditions where there is an abundance of floating and emergent macrophytes.

Nutrient concentrations have been used extensively to estimate trophic state. Mackenthun (1973) found that total phosphorus levels greater than 0.1 mg/L could cause eutrophic conditions; Caddo Lake had 0.13 mg/L. Another indication of the eutrophic state of the lake was the high concentration of nitrogen that was found. Lee (1970) suggested that eutrophic conditions are likely to occur when ammonium-nitrogen plus nitrate-nitrogen exceeds 0.3 mg/L; Caddo Lake had 0.73 mg/L.

Based on the physicochemical data from this study and the criteria given here, Caddo Lake should be classified as eutrophic.

Water Quality

The U.S. Environmental Protection Agency (1976) and the Texas Department of Water Resources (1981) have established standards for good water quality. The results of this study are compared with those standards in Table 6. Yearly parameter means at Caddo Lake were in compliance with all of the standards, indicating good water quality. However, variations from the standards were found in some samples. Dissolved oxygen just below the water surface was 0.6 mg/L at Station 3 on August 13, 1982 and the yearly

Table 6. Water quality standards and the corresponding yearly means for those standards at Caddo Lake from October 3, 1981 to September 8, 1982.

Parameter	Yearly Mean for Caddo Lake	Texas Dept. of Water Resources (1981)	U.S. Environmental Protection Agency (1976)
Dissolved Oxygen	7.4 mg/L	> 5.0 mg/L *	> 5.0 mg/L *
Temperature	21° C	<32° C *	<32° C *
pH	6.9	6.0-8.5 *	6.5-9.0 *
Alkalinity	35 mg/L	----	> 20 mg/L *
Total Iron	0.38 mg/L	----	< 1.00 mg/L *
Sulfate	19.0 mg/L	< 50.0 mg/L **	----
Chloride	26.4 mg/L	< 100.0 mg/L **	----
Oil	occasional	none visible	none visible

* Grab sample.
** Yearly mean.

mean for this station was 4.4 mg/L. From April through October the monthly means for dissolved oxygen in the Swamp Region were less than the 5.0 mg/L standard. Water temperature exceeded the 32° C standard in July and August apparently due to natural processes in the lake.

The pH often fell below the lower limit of 6.5 set by the U.S. Environmental Protection Agency. Only once, however, did the pH drop below the minimum of 6.0 set by the Texas Department of Water Resources; it was 5.9 at Station 3 on August 13, 1982. The upper limits of these pH standards were exceeded at Station 7 on October 3, 1982 with a value of 9.1 and at Stations 5 and 6 on September 8, 1982 with values of 8.6 and 8.7, respectively.

Alkalinity dropped below the minimum recommended level of 20 mg/L (set by the EPA) at Stations 1A, 1B, 2, 3, 4, 8, and 9 during the month of February of 1982. Total iron exceeded the EPA standard of 1.00 mg/L many times but with much variability in respect to date and station. The highest total iron value found was 2.62 mg/L at Station 8 on May 24, 1982. Values greater than 1.00 mg/L are known to be toxic to many forms of aquatic life (U.S. Environmental Protection Agency, 1976). The occasional presence of an oily scum on the water and on aquatic macrophytes near Station 8 and 9 was a violation of both sets of standards.

CONCLUSIONS

1. The shallowness of Caddo Lake prevented any prolonged thermal stratification, because of this the lake was easily mixed and turbidity was sometimes very high.
2. The Swamp Region had the lowest dissolved oxygen, pH, and phytoplankton chlorophyll a values along with the highest carbon dioxide and sulfate concentrations.
3. The Oil-Producing Region had the highest chloride, sodium, conductivity, and COD values for the water samples and the highest concentrations of oil in the sediments.
4. Most of the parameters exhibited significant seasonal variations. Particularly notable were the low phytoplankton chlorophyll a values in the spring indicating the lack of a spring phytoplankton bloom.
5. High phosphorus and nitrogen concentrations indicated that Caddo Lake is eutrophic.
6. Based on water quality standards established by the Texas Department of Water Resources (1981) and the U.S. Environmental Protection Agency (1976), the water quality of Caddo Lake was fairly good. Low dissolved oxygen in the Swamp Region was the principle water quality problem.

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APPENDIX I. Water temperature, dissolved oxygen, and conductivity profiles for the sampling stations at Caddo Lake from October 3, 1981 to September 8, 1982.

October 3, 1981

Depth m	Temp. °C	O_2 mg/L	Cond. µmhos	Temp. °C	O_2 mg/L	Cond. µmhos
	Station 1			Station 2		
S	24	3.3	130	23	3.5	132
1	24	3.6	130	23	2.6	132
2	24	3.4	133	23	1.6	132
3	24	2.5	133			
4	24	0.2	142			
5	24	0.1	147			
6	24	0.1	149			
	Station 3			Station 4		
S	23	1.5	130	24	9.4	120
1	22	1.5	130	23	8.2	120
	Station 5			Station 6		
S	25	9.0	125	25	8.9	125
1	25	8.7	122	25	7.8	125
2				24	4.6	125
	Station 7			Station 8		
S	25	9.3	125	26	9.4	175
1	25	9.0	129	26	9.1	175
2	25	6.6	129	26	2.0	177
	Station 9					
S	26	8.5	180			
1	25	7.8	180			
2	25	3.0	185			

APPENDIX I. (continued)

November 7, 1981

Depth m	Temp. °C	O_2 mg/L	Cond. µmhos	Temp. °C	O_2 mg/L	Cond. µmhos
	Station 1			Station 2		
S	16	6.7	100	16	6.1	98
1	16	6.6	100	16	5.1	99
2	16	6.4	100			
3	16	6.4	100			
4	16	6.4	100			
5	16	6.3	100			
	Station 3			Station 4		
S	15	3.5	94	19	8.1	99
1	15	3.0	91	18	7.6	99
	Station 5			Station 6		
S	19	7.9	100	19	9.1	100
1	19	7.6	100	19	8.8	99
2				19	8.4	99
	Station 7			Station 8		
S	20	10.1	105	20	9.6	175
1	19	10.0	105	19	9.3	175
2	18	9.5	105	18	8.4	170
	Station 9					
S	19	8.4	164			
1	19	8.1	165			
2	18	8.0	165			

APPENDIX I. (continued)

December 5, 1981

	Station 1			Station 2		
Depth m	Temp. °C	O_2 mg/L	Cond. µmhos	Temp. °C	O_2 mg/L	Cond. µmhos
S	11	7.1	90	10	7.1	89
1	11	6.9	90	10	7.0	90
2	11	6.7	91	10	6.9	90
3	11	6.7	92			
4	11	6.7	93			
5	11	6.7	93			
6	11	6.7	95			
7	11	6.7	95			
8	11	6.7	96			
	Station 3			Station 4		
S	9	6.9	82	10	10.5	87
1	9	6.9	82	10	10.3	88
	Station 5			Station 6		
S	11	11.0	87	11	11.0	88
1	11	10.9	87	11	10.8	88
2				11	10.6	88
	Station 7			Station 8		
S	11	11.8	95	12	11.2	134
1	11	11.6	95	12	11.0	136
2	11	11.5	94	11	10.5	139
	Station 9					
S	12	10.4	138			
1	11	10.1	138			
2	11	10.0	139			

APPENDIX I. (continued)

January 9, 1982

	Station 1			Station 2		
Depth m	Temp. °C	O_2 mg/L	Cond. µmhos	Temp. °C	O_2 mg/L	Cond. µmhos
S	10	10.0	81	9	10.2	85
1	10	10.0	82	9	9.8	91
2	10	10.0	87			
3	10	9.8	89			
4	10	9.6	90			
5	10	9.6	90			
	Station 3			Station 4		
S	8	9.6	85	10	11.5	88
1	8	8.5	86	10	11.5	89
	Station 5			Station 6		
S	10	10.6	89	10	11.2	84
1	10	10.4	89	10	10.8	85
2				10	10.2	85
	Station 7			Station 8		
S	10	11.4	92	11	11.0	121
1	10	11.0	94	11	10.6	121
2	10	10.9	94	11	10.6	121
	Station 9					
S	11	10.6	108			
1	11	10.6	105			
2	11	10.0	105			

APPENDIX I. (continued)

February 12, 1982

	Station 1				Station 2		
Depth m	Temp. °C	O_2 mg/L	Cond. µmhos		Temp. °C	O_2 mg/L	Cond. µmhos
S	7	11.8	70		7	11.4	71
1	7	11.6	70		7	11.2	70
2	7	11.6	71		7	11.2	72
3	7	11.4	72				
4	7	11.4	73				
5	7	11.4	75				
	Station 3				Station 4		
S	8	11.5	71		8	11.0	71
1	8	11.0	71		8	11.1	71
	Station 5				Station 6		
S	8	11.6	72		7	11.8	71
1	8	11.6	73		7	11.8	72
2					7	11.7	73
	Station 7				Station 8		
S	8	12.2	92		8	10.3	133
1	7	12.1	93		8	10.3	133
2	7	12.1	95		8	10.2	140
	Station 9						
S	7	10.2	136				
1	7	10.1	137				
2	7	10.0	137				

APPENDIX I. (continued)

March 12, 1982

	Station 1			Station 2		
Depth m	Temp. °C	O_2 mg/L	Cond. µmhos	Temp. °C	O_2 mg/L	Cond. µmhos
S	13	10.0	100	14	9.5	102
1	12	10.0	100	13	9.4	102
2	12	10.2	100	13	9.2	102
3	12	10.2	101			
4	12	10.4	102			
5	12	10.4	102			
6	12	10.4	104			
	Station 3			Station 4		
S	16	8.1	110	16	9.9	112
1	15	7.1	110	15	10.0	112
	Station 5			Station 6		
S	15	10.4	110	16	10.2	110
1	15	10.2	110	15	10.2	110
2				15	10.4	111
	Station 7			Station 8		
S	14	11.0	115	16	10.1	130
1	14	11.1	116	16	10.2	130
2	14	11.2	117	15	10.2	130
S	16	10.0	130			
1	16	10.0	130			
2	15	10.0	135			

APPENDIX I. (continued)

April 3, 1982

Depth m	Temp. °C	O_2 mg/L	Cond. µmhos	Temp. °C	O_2 mg/L	Cond. µmhos
	Station 1			Station 2		
S	18	8.6	115	18	7.6	120
1	18	8.6	116	18	8.0	120
2	18	8.7	118			
3	18	8.9	120			
4	18	9.0	120			
5	18	8.9	121			
6	18	8.9	122			
	Station 3			Station 4		
S	20	6.2	122	20	8.6	125
1	19	6.2	122	19	8.6	129
	Station 5			Station 6		
S	20	8.4	123	20	8.7	128
1	19	8.4	125	20	8.8	128
2				20	8.8	129
	Station 7			Station 8		
S	20	9.0	168	21	8.7	136
1	20	9.0	160	20	9.0	130
2	19	9.1	160	19	9.3	130
	Station 9					
S	21	8.5	129			
1	20	8.6	126			
2	20	8.8	126			

APPENDIX I. (continued)

May 23-24, 1982

Depth m	Temp. °C	O_2 mg/L	Cond. µmhos	Temp. °C	O_2 mg/L	Cond. µmhos
	Station 1			Station 2		
S	27	5.9	110	26	4.8	112
1	27	5.8	111	26	4.8	112
2	27	5.5	112	26	4.0	113
3	27	5.3	115			
4	27	5.5	115			
5	27	5.5	115			
6	27	5.3	116			
7	27	5.3	116			
	Station 3			Station 4		
S	27	4.5	138	29	6.4	120
1	25	1.3	145	27	6.4	120
	Station 5			Station 6		
S	28	7.2	126	29	8.5	145
1	27	5.4	120	29	8.2	143
	Station 7			Station 8		
S	31	7.7	158	32	7.8	135
1	31	7.0	160	31	6.5	135
2	31	7.0	161	29	1.8	135
	Station 9					
S	32	7.0	139			
1	30	5.3	135			
2	29	1.9	134			

APPENDIX I. (continued)

June 26, 1982

	Station 1			Station 2		
Depth m	Temp. °C	O_2 mg/L	Cond. µmhos	Temp. °C	O_2 mg/L	Cond. µmhos
S	25	4.8	105	25	3.4	113
1	25	4.7	105	25	3.4	115
2	25	4.7	108	25	3.5	117
3	25	4.6	108			
4	25	4.6	109			
5	25	4.5	110			
6	25	4.6	110			
7	25	4.6	110			
8	25	5.0	112			
	Station 3			Station 4		
S	25	2.5	136	28	7.8	143
1	24	1.5	153	26	5.4	135
	Station 5			Station 6		
S	27	5.4	133	30	7.6	150
1	26	5.1	132	28	7.5	147
2				28	7.2	147
	Station 7			Station 8		
S	31	9.0	159	30	8.4	159
1	28	9.1	153	28	5.9	166
2	27	7.7	152	26	1.5	135
	Station 9					
S	30	7.4	143			
1	26	4.2	144			
2	25	3.0	93			

APPENDIX I. (continued)

July 19, 1982

Depth m	Station 1 Temp. °C	O_2 mg/L	Cond. µmhos	Station 2 Temp. °C	O_2 mg/L	Cond. µmhos
S	31	6.2	149	30	2.0	148
1	31	5.6	150	30	1.8	149
2	30	1.7	149	30	1.4	150
3	30	1.1	149			
4	29	0.9	149			
5	29	0.7	150			
6	29	0.6	150			
	Station 3			Station 4		
S	29	0.9	148	31	4.8	145
1	27	0.7	150	30	4.2	145
	Station 5			Station 6		
S	31	6.1	145	31	8.4	150
1	31	6.2	145	31	8.3	155
	Station 7			Station 8		
S	33	9.1	160	35	8.0	165
1	32	9.1	160	35	7.8	161
2	32	8.3	160	33	3.0	150
	Station 9					
S	35	7.7	125			
1	34	7.0	130			
2	33	3.0	130			

APPENDIX I. (continued)

August 13, 1982

	Station 1			Station 2		
Depth m	Temp. °C	O_2 mg/L	Cond. µmhos	Temp. °C	O_2 mg/L	Cond. µmhos
S	31	5.3	145	30	2.1	149
1	31	5.0	150	30	1.0	150
2	31	2.3	150	29	0.2	160
3	31	0.3	150			
4	30	0.3	150			
5	28	0.2	165			
6	28	0.2	175			
	Station 3			Station 4		
S	29	0.6	150	30	6.4	150
1	27	0.3	165	30	4.5	152
	Station 5			Station 6		
S	30	6.4	150	31	8.2	170
1	30	6.5	150	31	7.8	170
	Station 7			Station 8		
S	31	9.2	150	33	7.8	180
1	31	8.9	155	32	7.2	180
2	31	7.9	155	32	6.1	180
	Station 9					
S	32	6.8	150			
1	31	6.1	150			
2	31	5.0	160			

APPENDIX I. (continued)

September 8, 1982

Depth m	Temp. °C	O_2 mg/L	Cond. µmhos	Temp. °C	O_2 mg/L	Cond. µmhos
	Station 1			Station 2		
S	28	3.4	152	26	2.0	150
1	28	3.2	153	26	1.4	151
2	28	3.2	156	25	1.3	151
3	28	3.2	158			
4	28	3.2	160			
5	28	3.1	160			
6	28	3.1	160			
	Station 3			Station 4		
S	25	1.1	152	28	8.8	162
1	25	2.0	155	26	8.5	160
	Station 5			Station 6		
S	27	8.8	166	28	9.5	175
1	26	8.5	165	27	8.4	170
2				26	7.3	170
	Station 7			Station 8		
S	29	9.3	170	31	9.2	192
1	27	6.7	160	28	8.1	192
2	26	6.4	160	28	5.8	192
	Station 9					
S	30	8.4	175			
1	28	8.1	172			
2	27	7.5	175			

APPENDIX II. Physicochemical data for the sampling stations at Caddo Lake on October 3, 1981.

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Secchi disc (m)	1.3	---	1.3	0.5	0.5	0.5	0.6	0.5	0.7	0.8
Bicarb. alk. (mg/L)	40	50	50	56	50	46	44	40	42	36
CO_2 (mg/L)	6.5	6.5	9.5	18.5	4.5	5.0	4.0	3.5	3.0	3.5
pH	7.0	6.9	6.9	6.6	7.8	8.0	7.8	9.1	7.9	7.5
Phytoplankton chlorophyll <u>a</u> (µg/L)	11	3	5	5	20	22	19	23	18	17
PO_4^{-3} (mg/L)	0.31	0.43	0.06	0.08	0.38	0.35	0.36	0.55	0.26	0.27
NH_4^+-N (mg/L)	0.61	0.48	0.56	0.75	0.72	0.66	0.64	0.72	0.61	0.64
NO_2^--N (µg/L)	4	4	4	< 2	9	4	4	6	4	6
NO_3^--N (µg/L)	21	21	28	30	38	4	13	< 2	28	17
Turbidity (NTU)	1.3	1.9	1.4	4.1	3.4	3.4	3.8	3.2	2.0	1.9
Apparent color (APHA c.u.)	21	30	24	58	36	33	36	40	24	21
True color (APHA c.u.)	8	12	12	14	10	11	14	10	10	11
Total phosphorus (mg/L)	0.18	0.14	0.23	0.10	0.13	0.16	0.18	0.19	0.13	0.14

APPENDIX II. (continued)

Parameter	Stations									
	1A	1B	2	3	4	5	6	7	8	9
Total iron (mg/L)	0.55	1.34	0.71	2.40	0.63	0.55	0.63	0.27	0.50	0.40
SO_4^{-2} (mg/L)	25.3	24.8	18.2	12.0	13.5	10.6	14.8	14.8	20.1	14.2
Cl^- (mg/L)	19.5	21.0	22.0	23.0	22.5	23.5	22.5	23.0	39.0	43.5
COD (mg/L)	---	---	---	---	---	---	---	---	---	---
BOD_5 (mg/L)	0.8	1.6	3.2	2.0	0.4	1.2	0.8	0.8	0.4	0.4
Total Kjeldahl nitrogen (mg/L)	3.72	4.71	5.80	7.44	4.41	10.02	8.23	16.47	7.44	4.86
Total residue (mg/L)	104	104	104	132	108	104	108	132	152	196
Total volatile residue (mg/L)	60	52	68	40	64	36	52	52	80	44
Ca^{+2} (mg/L)	20	15	15	20	15	15	15	15	20	20
Na^+ (mg/L)	12.0	16.0	18.0	20.0	19.0	19.0	19.0	19.0	34.0	35.0
Zn^{+2} (mg/L)	0.03	0.01	0.03	0.04	0.03	0.01	0.02	0.02	0.03	0.05

APPENDIX III. Physicochemical data for the sampling stations at Caddo Lake on November 7, 1981.

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Secchi disc (m)	1.0	---	1.2	1.2	1.3	1.3	1.1	0.8	1.2	1.1
Bicarb. alk. (mg/L)	25	25	25	30	24	25	26	36	32	30
CO_2 (mg/L)	5.8	6.5	8.0	8.0	6.0	5.3	3.8	2.5	3.8	7.0
pH	6.4	6.4	6.3	6.2	6.5	6.5	6.8	7.3	6.4	6.5
Phytoplankton chlorophyll <u>a</u> (µg/L)	1	1	3	5	3	5	7	13	8	8
PO_4^{-3} (mg/L)	0.10	0.10	0.12	0.06	0.08	0.08	0.04	< 0.02	0.08	0.04
NH_4^+-N (mg/L)	0.77	0.86	0.75	0.72	0.77	0.77	0.72	0.69	0.69	0.83
NO_2^--N (µg/L)	6	< 2	2	6	8	6	4	4	4	4
NO_3^--N (µg/L)	11	6	6	2	9	11	4	13	21	13
Turbidity (NTU)	3.2	3.1	2.2	1.3	1.6	1.9	1.7	2.2	1.4	1.5
Apparent color (APHA c.u.)	39	36	34	24	24	24	26	23	20	27
True color (APHA c.u.)	30	30	26	18	20	20	15	12	15	22
Total phosphorus (mg/L)	0.09	0.09	0.07	0.07	0.09	0.07	0.10	0.07	0.08	0.09

APPENDIX III. (continued)

Parameter	Stations									
	1A	1B	2	3	4	5	6	7	8	9
Total iron (mg/L)	0.33	0.12	0.13	1.01	0.12	1.15	0.10	0.08	0.10	0.12
SO_4^{-2} (mg/L)	26.0	23.6	24.8	21.1	24.8	23.6	24.2	17.2	12.5	13.6
Cl^- (mg/L)	17.5	18.5	17.5	16.5	16.0	17.5	16.5	22.5	53.0	49.0
COD (mg/L)	12.8	7.2	7.2	5.6	9.6	6.4	8.0	9.6	17.6	12.0
BOD_5 (mg/L)	1.6	1.9	1.6	2.0	2.2	2.3	2.1	2.6	2.3	2.5
Total Kjeldahl nitrogen (mg/L)	1.49	6.00	1.84	5.31	9.42	6.35	5.16	8.53	4.86	2.88
Total residue (mg/L)	136	132	124	120	72	148	132	124	140	168
Total volatile residue (mg/L)	40	40	40	40	28	48	56	44	28	48
Ca^{+2} (mg/L)	7	7	7	7	7	7	7	7	7	7
Na^+ (mg/L)	13.0	14.0	13.0	12.0	12.0	12.0	13.0	14.0	30.0	26.0

APPENDIX IV. Physicochemical data for the sampling stations at Caddo Lake on December 5, 1981.

Parameter	Stations 1A	1B	2	3	4	5	6	7	8	9
Secchi disc (m)	0.8	---	1.6	1.0+	1.9+	1.7+	1.0	0.8	1.0	1.4
Bicarb. alk. (mg/L)	30	28	28	36	30	30	28	27	27	26
CO_2 (mg/L)	7.0	7.0	9.3	10.8	5.0	5.0	5.0	4.0	5.0	5.0
pH	6.4	6.4	6.5	6.4	6.8	7.2	7.0	7.4	7.0	6.6
Phytoplankton chlorophyll a (µg/L)	1	1	1	2	2	3	3	12	12	4
PO_4^{-3} (mg/L)	0.12	0.06	0.12	0.10	0.08	0.10	0.10	0.04	0.08	0.10
NH_4^--N (mg/L)	0.80	0.86	0.61	0.45	0.43	0.40	0.48	0.53	0.69	0.66
NO_2^--N (µg/L)	9	6	8	8	2	8	8	2	<2	2
NO_3^--N (µg/L)	16	11	17	24	15	9	24	6	<6	23
Turbidity (NTU)	9.1	9.4	6.2	2.9	2.9	3.3	5.7	7.0	7.7	4.7
Apparent color (APHA c.u.)	29	29	22	17	17	14	21	19	27	34
True color (APHA c.u.)	22	22	17	14	14	11	14	12	19	26
Total phosphorus (mg/L)	0.09	0.07	0.05	0.05	0.07	0.09	0.09	0.07	0.05	0.09

APPENDIX IV. (continued)

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Total iron (mg/L)	0.06	0.06	0.03	0.10	0.03	0.03	0.10	0.06	0.12	0.10
SO_4^{-2} (mg/L)	17.2	17.2	17.2	13.6	16.5	16.0	17.7	16.5	8.5	6.2
Cl^- (mg/L)	19.0	20.0	20.0	19.5	18.5	17.5	19.0	20.5	44.5	47.0
COD (mg/L)	20.8	18.4	20.8	16.0	16.8	12.8	16.0	15.2	20.0	18.4
BOD_5 (mg/L)	1.9	2.2	2.3	2.0	1.6	1.7	2.3	2.2	1.7	1.4
Total Kjeldahl nitrogen (mg/L)	7.64	4.27	4.41	6.20	4.71	5.51	6.00	5.51	3.97	4.41
Total residue (mg/L)	112	116	116	108	108	120	104	108	140	144
Total volatile residue (mg/L)	24	36	32	40	32	40	28	32	44	44
Ca^{+2} (mg/L)	7	7	7	7	7	7	7	7	7	7
Na^+ (mg/L)	12.0	11.5	11.5	11.5	11.0	11.5	11.0	12.0	24.5	25.5

APPENDIX V. Physicochemical data for the sampling stations at Caddo Lake on January 9, 1982.

	Stations									
Paramter	1A	1B	2	3	4	5	6	7	8	9
Secchi disc (m)	1.3	---	1.0+	1.2+	1.2+	1.5+	0.6	0.8	1.3	1.6
Bicarb. alk. (mg/L)	26	28	26	25	35	27	30	24	23	22
CO_2 (mg/L)	5.0	4.8	3.5	4.5	3.0	4.3	3.5	2.5	3.3	5.0
pH	6.9	6.9	6.7	6.7	7.0	7.0	7.0	7.1	7.0	6.9
Phytoplankton chlorophyll a (µg/L)	2	1	2	3	3	3	8	11	13	3
PO_4^{-3} (mg/L)	0.10	0.12	0.08	0.16	0.08	0.16	0.08	0.02	0.04	0.10
NH_4^--N (mg/L)	0.75	0.77	0.77	0.72	0.66	0.72	0.95	0.69	0.75	0.77
NO_2^--N (µg/L)	2	4	4	4	2	4	4	6	2	8
NO_3^--N (µg/L)	23	4	4	13	6	21	21	19	6	24
Turbidity (NTU)	2.8	3.0	2.6	2.3	1.5	1.5	4.0	4.1	1.5	1.5
Apparent color (APHA c.u.)	39	42	34	29	20	25	38	24	25	27
True color (APHA c.u.)	34	34	31	21	19	24	27	14	20	24
Total phosphorus (mg/L)	0.21	0.10	0.16	0.14	0.20	0.25	0.16	0.16	0.10	0.16

APPENDIX V. (continued)

Parameter	Stations									
	1A	1B	2	3	4	5	6	7	8	9
Total iron (mg/L)	0.18	0.22	0.13	0.18	0.03	0.13	0.80	0.10	0.91	0.20
SO_4^{-2} (mg/L)	27.7	18.8	16.5	13.0	16.0	16.5	21.1	16.0	8.5	9.5
Cl^- (mg/L)	26.5	27.5	28.0	28.0	24.0	25.0	22.5	30.5	46.5	42.5
COD (mg/L)	15.2	9.6	14.4	10.4	11.2	12.8	15.2	9.6	17.6	24.0
BOD_5 (mg/L)	3.0	3.8	2.2	3.0	2.8	3.1	2.9	3.6	3.4	3.1
Total Kjeldahl ntirogen (mg/L)	6.35	5.70	1.98	7.09	5.31	4.27	4.71	7.44	2.13	2.13
Total residue (mg/L)	104	104	108	88	96	84	100	88	108	96
Total volatile residue (mg/L)	16	8	16	12	12	12	20	20	16	12
Ca^{+2} (mg/L)	7	7	7	7	7	7	7	7	7	7
Na^+ (mg/L)	15.0	15.0	15.5	14.5	14.0	14.0	13.0	15.5	25.0	20.0

APPENDIX VI. Physicochemical data for the sampling stations at Caddo Lake on February 12, 1982.

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Secchi disc (m)	0.7	---	0.8	0.8	0.7	0.8	0.7	0.7	1.2	0.5
Bicarb. alk. (mg/L)	15	14	13	16	19	24	27	22	19	16
CO_2 (mg/L)	14.8	18.3	20.0	19.5	23.5	18.0	17.0	14.5	23.5	20.5
pH	6.5	6.9	6.6	6.5	6.7	6.6	6.7	6.8	6.4	6.2
Phytoplankton chlorophyll a (µg/L)	3	3	3	3	3	3	4	9	3	1
PO_4^{-3} (mg/L)	0.08	0.10	0.10	0.06	0.04	0.06	0.10	0.04	0.06	0.12
NH_4^+-N (mg/L)	0.72	0.66	0.66	0.77	0.77	0.77	0.75	0.66	0.72	0.98
NO_2^--N (µg/L)	6	9	8	6	6	8	9	8	4	4
NO_3^--N (µg/L)	11	16	17	2	11	24	8	17	< 4	35
Turbidity (NTU)	13.0	15.0	17.0	18.0	19.0	17.0	17.0	14.0	15.0	25.0
Apparent color (APHA c.u.)	30	30	32	36	36	32	32	25	29	62
True color (APHA c.u.)	24	24	25	29	25	24	25	15	24	45
Total phosphorus (mg/L)	0.09	0.09	0.09	0.09	0.12	0.09	0.07	0.09	0.09	0.08

APPENDIX VI. (continued)

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Total iron (mg/L)	0.68	0.13	0.73	0.08	0.80	0.10	0.06	0.10	0.85	0.27
SO_4^{-2} (mg/L)	21.7	21.7	21.1	22.3	21.7	23.6	21.1	18.8	11.2	13.0
Cl^- (mg/L)	18.5	19.5	17.5	21.5	20.5	20.5	21.0	29.5	58.0	60.0
COD (mg/L)	12.0	9.6	13.6	13.6	10.4	12.0	10.4	10.4	12.8	16.8
BOD_5 (mg/L)	1.9	2.3	2.0	2.0	1.8	1.1	2.1	2.6	2.2	2.1
Total Kjeldahl nitrogen (mg/L)	0.74	1.04	5.01	3.82	3.27	3.72	4.41	4.12	3.82	2.13
Total residue (mg/L)	72	100	88	52	80	44	96	88	132	160
Total volatile residue (mg/L)	24	32	32	28	--	32	40	16	32	48
Ca^{+2} (mg/L)	7	7	7	7	7	7	7	7	7	7
Na^+ (mg/L)	11.0	11.0	11.0	11.0	11.0	11.5	11.0	16.0	28.0	30.0
Oil (mg/L)	--	--	--	--	--	--	--	--	>2400	--

APPENDIX VII. Physicochemical data for the sampling stations at Caddo Lake on March 12, 1982.

Parameter	Stations									
	1A	1B	2	3	4	5	6	7	8	9
Secchi disc (m)	1.2	---	1.3	1.3+	1.3	1.2	1.2	0.8	0.8	1.3
Bicarb. alk. (mg/L)	20	24	20	22	28	30	30	24	28	23
CO_2 (mg/L)	5.5	5.8	5.3	7.0	5.5	5.0	4.8	2.8	4.3	4.8
pH	6.5	6.5	6.4	6.3	6.7	6.7	6.7	6.8	6.6	6.4
Phytoplankton chlorophyll _a_ (µg/L)	3	3	4	3	3	4	3	13	3	3
PO_4^{-3} (mg/L)	0.06	0.20	0.08	0.12	0.08	0.10	0.08	0.08	0.10	0.25
NH_4^+-N (mg/L)	0.69	0.75	0.66	0.61	0.64	0.72	0.75	0.58	0.66	0.61
NO_2^--N (µg/L)	< 2	< 2	4	< 2	4	4	4	4	< 2	2
NO_3^--N (µg/L)	< 6	< 6	4	6	2	13	4	< 4	< 6	6
Turbidity (NTU)	2.7	2.7	2.5	2.2	2.3	2.4	2.1	3.1	2.7	2.5
Apparent color (APHA c.u.)	34	29	27	25	22	25	22	24	32	27
True color (APHA c.u.)	27	20	20	20	17	19	17	14	25	22
Total phosphorus (mg/L)	0.05	0.08	0.05	0.08	0.04	0.01	0.07	0.05	0.01	0.10

APPENDIX VII. (continued)

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Total iron (mg/L)	0.77	0.85	0.13	0.18	0.10	0.08	0.71	0.45	0.10	0.10
SO_4^{-2} (mg/L)	25.4	27.7	28.2	24.2	26.0	25.4	26.0	26.0	14.1	14.8
Cl^- (mg/L)	23.5	24.0	23.5	26.0	25.0	25.0	25.0	29.5	44.0	44.0
COD (mg/L)	15.2	14.4	13.6	14.4	15.2	14.4	16.8	15.2	14.4	14.4
BOD_5 (mg/L)	1.8	1.7	1.7	1.8	1.8	1.6	1.4	1.7	1.2	1.3
Total Kjeldahl nitrogen (mg/L)	4.27	1.24	1.04	1.24	4.56	4.27	4.41	5.16	4.56	5.51
Total residue (mg/L)	108	116	96	104	112	92	100	124	128	116
Total volatile residue (mg/L)	40	48	28	32	44	36	28	36	36	44
Ca^{+2} (mg/L)	20	20	15	15	15	10	20	10	10	10
Na^+ (mg/L)	13.0	13.0	13.0	12.0	12.0	11.0	11.0	13.0	16.0	17.0

APPENDIX VIII. Physicochemical data for the sampling stations at Caddo Lake on April 3, 1982.

	Stations									
Paramter	1A	1B	2	3	4	5	6	7	8	9
Secchi disc (m)	1.1	---	1.4+	1.1+	1.2	1.2	1.0	0.8	1.2	1.2
Bicarb. alk. (mg/L)	30	28	30	30	32	30	32	31	28	32
CO_2 (mg/L)	5.5	7.3	7.5	10.0	5.5	5.0	3.5	2.8	4.0	5.0
pH	6.8	6.8	6.7	6.5	6.8	6.8	7.0	7.0	6.9	6.9
Phytoplankton chlorophyll <u>a</u> (µg/L)	3	3	3	4	4	4	5	9	6	3
PO_4^{-3} (mg/L)	0.29	0.22	0.12	0.04	0.08	0.08	0.06	0.04	0.04	0.04
NH_4^+-N (mg/L)	0.45	0.56	0.48	0.35	0.35	0.48	0.56	0.35	0.45	0.53
NO_2^--N (µg/L)	< 2	6	< 2	< 2	4	2	2	2	2	< 2
NO_3^--N (µg/L)	6	33	15	< 6	13	30	6	< 6	< 6	< 6
Turbidity (NTU)	2.3	2.4	1.9	1.2	1.5	2.2	2.6	2.1	1.6	1.3
Apparent color (APHA c.u.)	34	39	32	27	25	27	29	17	32	45
True color (APHA c.u.)	27	29	25	22	19	19	19	8	24	36
Total phosphorus (mg/L)	0.42	0.23	0.19	0.13	0.16	0.16	0.16	0.10	0.08	0.13

APPENDIX VIII. (continued)

Parameter	Stations									
	1A	1B	2	3	4	5	6	7	8	9
Total iron (mg/L)	0.29	0.22	1.50	0.13	1.08	0.35	0.33	0.12	0.27	0.38
SO_4^{-2} (mg/L)	25.4	26.0	24.2	22.9	24.8	24.2	26.0	26.0	11.9	11.2
Cl^- (mg/L)	25.0	27.0	26.5	28.0	28.5	27.5	25.5	29.5	39.0	36.5
COD (mg/L)	15.2	9.6	8.0	16.0	13.6	12.0	12.8	8.8	12.8	20.8
BOD_5 (mg/L)	1.1	1.2	0.9	1.2	0.8	0.8	0.8	0.8	0.5	0.8
Total Kjeldahl nitrogen (mg/L)	4.86	6.20	7.09	7.24	4.86	5.80	4.86	4.27	4.27	4.56
Total residue (mg/L)	100	100	96	80	92	100	100	76	80	84
Total volatile residue (mg/L)	44	48	52	44	40	48	48	48	52	60
Ca^{+2} (mg/L)	15	15	15	15	15	15	15	15	15	15
Na^+ (mg/L)	16.0	16.0	17.0	16.0	17.5	17.0	17.5	17.5	19.5	18.0

APPENDIX IX. Physicochemical data for the sampling stations at Caddo Lake on May 23-24, 1982.

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Secchi disc (m)	1.0	---	0.9	1.0	1.2	0.9	0.8	0.7	1.0	1.0
Bicarb. alk. (mg/L)	30	32	28	32	28	30	36	36	40	24
CO_2 (mg/L)	8.5	7.0	12.0	17.0	7.0	6.5	3.5	5.0	5.3	5.8
pH	6.4	6.4	6.3	6.2	6.5	7.0	6.6	7.2	6.6	6.5
Phytoplankton chlorophyll <u>a</u> (µg/L)	1	1	2	3	4	8	5	11	5	4
PO_4^{-3} (mg/L)	0.14	0.12	0.16	0.12	0.08	0.06	0.20	0.06	0.10	0.06
NH_4^+-N (mg/L)	0.89	0.89	0.83	0.86	0.80	0.75	0.83	0.69	0.80	1.07
NO_2^--N (µg/L)	< 2	< 2	< 2	< 2	4	2	4	< 2	< 2	< 2
NO_3^--N (µg/L)	< 6	< 6	< 6	< 6	4	28	4	< 6	< 6	< 6
Turbidity (NTU)	15.0	16.0	12.0	10.0	11.0	9.0	12.0	8.0	14.0	8.0
Apparent color (APHA c.u.)	55	62	48	51	42	36	51	21	66	58
True color (APHA c.u.)	42	39	36	29	29	24	34	11	36	42
Total phosphorus (mg/L)	0.14	0.18	0.12	0.12	0.13	0.10	0.10	0.05	0.13	0.09

APPENDIX IX. (continued)

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Total iron (mg/L)	0.13	1.55	1.34	0.38	0.20	0.13	0.13	0.06	2.62	0.08
SO_4^{-2} (mg/L)	23.6	23.6	24.2	17.7	22.3	19.4	22.9	20.4	14.8	11.9
Cl^- (mg/L)	18.0	17.5	18.5	25.0	21.5	25.5	23.0	31.5	32.0	34.0
COD (mg/L)	18.4	15.2	16.0	19.2	14.4	11.2	14.4	10.4	18.4	16.0
BOD_5 (mg/L)	2.3	2.1	2.1	3.1	2.3	3.1	3.3	3.5	2.8	2.8
Total Kjeldahl nitrogen (mg/L)	10.81	7.44	7.64	7.64	7.09	5.70	6.50	8.43	7.44	6.20
Total residue (mg/L)	108	112	128	124	108	120	116	120	124	116
Total volatile residue (mg/L)	36	24	28	28	32	24	44	32	28	32
Ca^{+2} (mg/L)	7	10	15	15	10	15	15	15	15	10
Na^+ (mg/L)	11.5	11.0	12.0	15.0	12.5	15.5	13.0	17.0	18.0	17.5

APPENDIX X. Physicochemical data for the sampling stations at Caddo Lake on June 26, 1982.

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Secchi disc (m)	0.6	---	1.0	1.1+	1.5+	1.5+	1.0	1.1	1.2	1.0
Bicarb. alk. (mg/L)	30	30	30	27	33	36	40	38	40	32
CO_2 (mg/L)	10.0	9.5	11.0	25.0	6.0	10.0	5.0	2.5	5.8	7.0
pH	6.5	6.5	6.4	6.3	6.9	6.6	7.0	8.2	7.0	6.7
Phytoplankton chlorophyll <u>a</u> (µg/L)	4	3	3	1	10	7	10	11	16	13
PO_4^{-3} (mg/L)	0.22	0.18	0.14	0.22	0.12	0.14	0.14	0.04	0.04	0.06
NH_4^+-N (mg/L)	0.95	0.98	0.77	0.75	0.61	0.66	0.61	0.58	0.77	0.98
NO_2^--N (µg/L)	4	2	2	< 2	2	2	2	2	< 2	< 2
NO_3^--N (µg/L)	28	23	37	< 6	23	23	< 6	6	< 6	< 6
Turbidity (NTU)	17	18	13	6	6	9	7	7	7	10
Apparent color (APHA c.u.)	62	71	42	27	17	29	21	19	42	62
True color (APHA c.u.)	36	42	32	20	9	19	9	9	34	48
Total phosphorus (mg/L)	0.13	0.14	0.12	0.12	0.12	0.12	0.14	0.16	0.14	0.18

APPENDIX X. (continued)

Parameter	Stations									
	1A	1B	2	3	4	5	6	7	8	9
Total iron (mg/L)	0.29	1.30	0.16	0.42	0.12	1.12	0.12	0.10	0.89	0.18
SO_4^{-2} (mg/L)	20.4	22.3	22.9	22.9	22.9	22.3	24.2	19.4	11.9	8.5
Cl^- (mg/L)	14.5	15.0	14.5	20.0	19.5	18.0	20.5	25.0	35.5	30.5
COD (mg/L)	10.4	10.4	14.4	10.4	9.6	12.0	10.4	12.8	12.8	19.2
BOD_5 (mg/L)	1.2	1.2	1.2	2.3	2.0	1.5	1.6	1.6	1.8	1.8
Total Kjeldahl nitrogen (mg/L)	4.12	5.31	1.84	8.68	5.51	4.56	7.44	6.00	6.00	5.16
Total residue (mg/L)	128	108	124	132	152	144	140	104	108	96
Total volatile residue (mg/L)	52	52	64	72	72	76	96	44	44	24
Ca^{+2} (mg/L)	10	10	10	15	10	10	10	15	15	15
Na^+ (mg/L)	9.2	10.0	10.5	13.0	14.0	12.5	14.0	16.0	19.0	16.0

APPENDIX XI. Physicochemical data for the sampling stations at Caddo Lake on July 19, 1982.

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Secchi disc (m)	0.9	---	0.8	1.0	1.2	1.2	1.0	0.7	1.0	1.0
Bicarb. alk. (mg/L)	35	32	42	44	50	46	42	40	37	34
CO_2 (mg/L)	7.5	9.0	11.3	22.5	10.0	8.0	4.5	3.5	6.0	7.5
pH	6.7	6.6	6.5	6.2	6.7	6.8	7.4	8.1	7.1	6.8
Phytoplankton chlorophyll <u>a</u> (µg/L)	9	6	3	2	9	8	11	12	13	8
PO_4^{-3} (mg/L)	0.08	0.10	0.29	0.10	0.20	0.18	0.27	0.10	0.12	0.12
NH_4^+-N (mg/L)	0.77	0.77	0.83	0.86	0.75	0.69	0.72	0.69	0.86	0.95
NO_2^--N (µg/L)	6	< 2	< 2	< 2	< 2	< 2	4	< 2	< 2	< 2
NO_3^--N (µg/L)	11	< 6	< 6	< 6	< 6	< 6	21	< 6	< 6	< 6
Turbidity (NTU)	2.1	2.2	2.0	1.0	1.1	1.3	1.5	2.1	1.3	1.5
Apparent color (APHA c.u.)	25	32	45	58	28	24	24	24	34	48
True color (APHA c.u.)	15	17	21	21	19	15	15	12	24	36
Total phosphorus (mg/L)	0.12	0.09	0.23	0.09	0.16	0.05	0.05	0.16	0.10	0.08

APPENDIX XI. (continued)

Parameter	Stations									
	1A	1B	2	3	4	5	6	7	8	9
Total iron (mg/L)	0.58	0.63	1.04	0.13	< 0.02	< 0.02	0.03	0.02	0.89	< 0.02
SO_4^{-2} (mg/L)	28.2	27.1	22.9	23.6	20.4	20.4	21.7	18.2	11.9	11.2
Cl^- (mg/L)	18.5	20.0	19.0	21.0	19.5	20.5	22.0	24.5	34.0	27.0
COD (mg/L)	12.8	12.0	11.2	18.4	9.6	12.8	10.4	13.6	17.6	18.4
BOD_5 (mg/L)	0.9	1.3	1.5	2.1	2.6	1.0	1.0	1.9	1.1	1.4
Total Kjeldahl nitrogen (mg/L)	4.41	5.51	5.80	7.44	5.70	6.20	5.70	1.98	6.70	5.01
Total residue (mg/L)	104	116	108	116	112	100	120	112	112	96
Total volatile residue (mg/L)	36	40	48	60	64	36	52	44	52	56
Ca^{+2} (mg/L)	28	20	28	28	28	28	28	28	28	28
Na^+ (mg/L)	15.0	14.5	14.5	15.5	15.0	15.0	15.0	17.0	19.5	15.5

APPENDIX XII. Physicochemical data for the sampling stations at Caddo Lake on August 13, 1982.

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Secchi disc (m)	1.3	---	1.3	1.0	1.3	1.0	0.6	0.6	1.0	1.0
Bicarb. alk. (mg/L)	40	60	60	68	55	54	52	40	40	34
CO_2 (mg/L)	10.5	13.5	16.5	29.0	5.5	6.0	4.5	0.0	6.8	5.5
pH	6.5	6.3	6.2	5.9	6.7	6.6	7.4	8.4	6.6	6.5
Phytoplankton chlorophyll a (μg/L)	12	6	8	12	16	13	16	16	15	17
PO_4^{-3} (mg/L)	0.12	0.22	0.18	0.58	0.14	0.12	0.04	0.08	0.06	0.08
NH_4^+-N (mg/L)	0.69	0.83	0.75	1.25	0.66	0.66	0.80	0.92	0.77	0.80
NO_2^--N (μg/L)	15	< 2	2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
NO_3^--N (μg/L)	10	< 6	6	< 6	< 6	< 6	< 6	< 6	< 6	< 6
Turbidity (NTU)	1.4	1.9	1.8	38.0	1.4	1.7	3.1	3.6	1.8	1.5
Apparent color (APHA c.u.)	17	34	24	110	24	23	39	42	32	32
True color (APHA c.u.)	11	22	15	32	15	12	32	19	20	19
Total phosphorus (mg/L)	0.13	0.14	0.19	1.11	0.18	0.12	0.13	0.13	0.13	0.12

APPENDIX XII. (continued)

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Total iron (mg/L)	0.08	0.12	0.02	2.48	0.12	0.03	0.06	0.35	0.12	< 0.02
SO_4^{-2} (mg/L)	26.0	22.3	19.4	21.1	20.4	17.2	17.7	17.2	12.5	6.2
Cl^- (mg/L)	20.0	23.5	23.5	24.5	22.5	23.5	27.5	27.5	48.0	34.5
COD (mg/L)	20.0	16.0	13.6	48.0	15.2	16.0	21.6	20.0	18.4	20.0
BOD_5 (mg/L)	1.5	2.3	1.7	6.3	2.3	1.9	2.7	3.6	3.0	3.4
Total Kjeldahl nitrogen (mg/L)	6.52	6.52	3.98	13.45	6.52	6.03	8.96	6.23	5.53	6.37
Total residue (mg/L)	100	112	96	272	108	108	172	148	120	96
Total volatile residue (mg/L)	64	76	64	152	80	84	112	120	112	56
Ca^{+2} (mg/L)	8	8	7	9	8	8	9	7	9	7
Na^+ (mg/L)	14.5	14.5	14.5	15.5	15.0	15.5	17.5	16.5	22.0	18.0

APPENDIX XIII. Physicochemical data for the sampling stations at Caddo Lake on September 8, 1982.

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Secchi disc (m)	1.0	---	1.0	0.5	0.7	0.7	0.5	0.5	0.7	0.7
Bicarb. alk. (mg/L)	56	56	66	80	60	56	55	72	40	60
CO_2 (mg/L)	21.3	21.8	33.0	42.0	3.0	2.5	2.0	5.0	5.5	6.0
pH	6.7	6.7	6.6	6.5	8.2	8.6	8.7	8.2	8.1	7.6
Phytoplankton chlorophyll *a* (ug/L)	9	8	11	13	16	15	19	20	18	15
PO_4^{-3} (mg/L)	0.16	0.12	0.18	0.08	0.08	0.10	0.06	0.06	0.10	0.02
NH_4^+-N (mg/L)	0.75	0.77	0.83	0.89	0.86	0.80	0.92	0.92	0.96	0.96
NO_2^--N (ug/L)	4	< 2	6	< 2	< 2	6	4	< 2	6	< 2
NO_3^--N (ug/L)	21	6	19	< 6	6	2	13	6	26	15
Turbidity (NTU)	1.7	1.8	2.0	3.0	2.8	2.4	3.2	4.0	2.5	1.8
Apparent color (APHA c.u.)	23	30	27	36	25	23	25	36	23	23
True color (APHA c.u.)	6	12	10	14	11	11	8	14	10	12
Total phosphorus (mg/L)	0.17	0.13	0.17	0.14	0.12	0.12	0.13	0.12	0.10	0.08

APPENDIX XIII. (continued)

	Stations									
Parameter	1A	1B	2	3	4	5	6	7	8	9
Total iron (mg/L)	< 0.02	< 0.02	0.03	0.10	0.03	< 0.02	0.03	0.02	0.06	< 0.02
SO_4^{-2} (mg/L)	19.9	18.2	14.1	16.5	16.5	16.5	17.7	12.5	12.5	8.5
Cl^- (mg/L)	22.0	21.5	24.0	25.5	26.0	26.0	30.5	29.5	44.0	41.0
COD (mg/L)	16.0	16.0	19.2	19.2	24.0	24.0	23.2	24.8	27.2	16.0
BOD_5 (mg/L)	2.0	1.8	2.7	3.5	4.6	4.6	4.5	4.2	4.1	2.9
Total Kjeldahl nitrogen (mg/L)	7.24	5.80	5.31	7.84	5.80	5.80	9.37	7.24	6.50	7.09
Total residue (mg/L)	124	124	132	136	140	160	148	148	168	152
Total volatile residue (mg/L)	32	24	36	44	36	48	52	44	44	36
Ca^{+2} (mg/L)	7	8	8	9	9	10	8	8	8	6
Na^+ (mg/L)	10.5	10.5	11.5	12.0	13.0	12.5	13.0	14.0	19.0	17.5
TOC (mg/L)	12	9	11	11	11	20	10	15	16	13

APPENDIX XIV. Oil in the sediments and organic matter in the sediments of the sampling stations at Caddo Lake on October 3, 1981, March 12, 1982, and August 13, 1982.

October 3, 1981

Station	mg oil/kg dried sediment	% organic matter dry wt.
1	17,023	9.32
2	757	2.30
3	31,606	14.03
4	5,333	6.89
5	5,917	7.37
6	18,190	9.93
7	2,046	9.91
8	66,556	19.38
9	44,856	13.92

APPENDIX XIV. (continued)

March 12, 1982

Station	mg oil/kg dried sediment	% organic matter dry wt.
1	10,359	6.84
2	39,820	12.91
3	60,606	27.51
4	5,316	4.54
5	4,994	7.46
6	16,757	12.81
7	23,474	12.71
8	49,751	18.96
9	40,069	16.08

APPENDIX XIV. (continued)

August 13, 1982

Station	mg oil/kg dried sediment	% organic matter dry wt.
1	22,283	8.08
2	13,249	11.20
3	63,510	30.18
4	3,356	4.54
5	8,527	8.48
6	15,898	12.00
7	13,048	10.40
8	67,427	21.78
9	67,873	19.32

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by

AUGUST ALAN HARTUNG, B.S.S.S.

Presented to the Faculty of the Graduate School of
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ABSTRACT

The physicochemical limnology of Caddo Lake, Texas and Louisiana was studied for one year. Twenty-nine parameters were investigated at nine sampling stations in the lake from October 1981 to September 1982. Caddo Lake is a large, shallow, natural lake with an extensive swamp region and a large-scale off-shore oil industry.

Prolonged thermal stratification was absent due to the shallowness of the lake. The swamp region had the lowest dissolved oxygen, pH, and phytoplankton chlorophyll a values along with the highest concentrations of carbon dioxide and sulfate. The oil-producing region had the highest chloride, sodium, conductivity, and COD values in the water samples and the highest concentrations of oil in the sediments. Most of the parameters exhibited significant seasonal variations.

The lake was found to be eutrophic, and low dissolved oxygen in the swamp region was the principle water quality problem.

VITA

August Alan Hartung was born at Mather Air Force Base, California on September 24, 1958, son of George Harley Hartung and Martha Viola Hartung. After graduating from Klein High School in Spring, Texas in May 1978, he entered Stephen F. Austin State University in Nacogdoches, Texas in September 1978. He received a Bachelor of Science degree with a major in environmental science in May 1981.

In June 1981 he entered the Graduate School of Stephen F. Austin State University to begin work on a Master of Science degree with a major in biology. He was married to Belinda Gaye Boyd on July 18, 1981. From September 1981 to May 1983 he was a graduate teaching assistant in the Department of Biology. During the summer of 1982 he worked as a water chemist on a research grant received from Bay Chemical Corporation, Corpus Christi, Texas. He is a member of Alpha Chi National Honor Society, Sigma Xi Scientific Research Society, and the Texas Academy of Science.

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