SEASONAL VARIATION IN THE TROPHIC STATE INDEX OF A SOUTHERN GREAT PLAINS RESERVOIR

By

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SEASONAL VARIATION IN THE TROPHIC STATE INDEX

OF A SOUTHERN GREAT PLAINS RESERVOIR

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PREFACE

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CHAPTER I

THE RESEARCH PROBLEM

Historically, reservoirs have been constructed for storing water for water supply, irrigation, flood control, power production, navigation, and recreation. The quality of water in reservoirs has become increasingly important because of increased demands associated with growth, development, and recreation.

Phytoplankton form the base of the food chain in reservoirs and are influenced by variables such as dissolved oxygen, light, nutrients, and temperature. Nuisance algal blooms, especially those of blue-green algae, interfere with the use of the reservoir by causing fish kills through depletion of dissolved oxygen, taste and odor problems in municipal and industrial water supplies, and esthetically displeasing shorelines. In addition, increased water treatment costs due to filter clogging and decreased recreational use may cause public concern.

Algae occur throughout North America and the United States. Silvey and Wyatt (1971) found the predominant types of algae occurring in lakes of the southwest to be greens, blue-greens, flagellates, and diatoms, and concluded that densities and species composition vary with season, nutrient content of the water body, and lake morphology. Algae are ideal to use as a basis for describing the ecological or trophic status of a lake due to their widespread distribution, correlation with other important biological and chemical parameters, and are of concern to the public.

Several investigators have attempted to develop indices of reservoir water quality using responses of algae as a measure of pertubation of aquatic ecosystems. Carlson (1977) proposed using a trophic state index (TSI) to predict the status of lakes. The TSI correlates relationships among phosphorus, algal blooms, chlorophyll _a_, and Secchi disc transparencies. The index has been used to classify waters, to predict trophic changes, and as a lake management tool.

Lake Carl Blackwell (LCB) was built in 1936 as part of the Federal Government Land Utilization Project primarily for recreation and water supply (Wilhm and Howick 1981). Cultivated areas in the upper reaches of the watershed, unprotected shorelines, and unimproved roads around the lake are subject to erosion. High winds mix the lake and continually resuspend fine bottom sediments, increasing lake turbidity. Nuisance algal blooms, taste, and odor problems have also been recorded. Because of these problems, the lake is being examined for possible restoration.

Prior to comparing the feasibility of various restoration techniques, it is necessary to define the trophic state. Thus, the objectives of the study were to measure and calculate the following in Lake Carl Blackwell:

1. The spatial and temporal variation in algal densities, chlorophyll _a_, phosphorus, and Secchi disc transparencies.
2. The trophic state index.

CHAPTER II

REVIEW OF THE LITERATURE

Introduction

Weber (1907) first used the term eutrophication to describe nutrient conditions influencing the flora of German peat bogs. Naumann (1919) redefined Weber's original works and related water types and phytoplankton of Swedish lakes in relation to transparency and color. Thienemann (1925) classified lakes as oligotrophic, eutrophic, and dystrophic. Oligotrophic lakes were characterized as deep, lacking nutrients, and having no phytoplankton blooms. Eutrophic lakes were characterized as being shallow and nutrient-rich with excessive phytoplankton blooms. Dystrophic lakes had humic or organic water.

For many years limnologists have studied the ecological classification of lakes and devised numerous trophic-state indices. Relationships among parameters such as dissolved oxygen, conductivity, phytoplankton production, pH, alkalinity, phosphorus, nitrogen, and turbidity have been used to determine trophic status. These parameters were used to indicate trends towards eutrophication of lakes in the Kashmir valley of the Himalayas (Kahn and Zutski 1980). Hutchinson (1973) noted that transparency and color are simple indicators of the nutrient condition of a lake if used with discretion. Chapra and Reckhow (1979) used phosphorus levels as indicators of eutrophication. Lakes with phosphorus levels greater than 50 μg/l were classed as eutrophic. Chlorophyll has also been used as an indicator of lake trophic status. Lakes with chlorophyll levels > 6 μg/l were classed as eutrophic and lakes with values < 5 μg/l were classed as oligotrophic (Jones et al. 1979). Carlson (1977) predicted the trophic state using the relationship between algal biomass measured as chlorophyll a, and phosphorus.

Secchi Disc-Chlorophyll Relationship

Cialdi (1886) used a white disc to estimate transparency in water. This work led to the development of the Secchi disc, which when lowered into the water disappears at approximately the region of transmission of 5% sunlight (Reid 1961). Beeton (1958) and Tyler (1968) report Secchi disc transparency can represent from 1 to 15% transmission. The theory and methods of use of the Secchi disc have been thoroughly discussed by Hutchinson (1957), Reid (1961), and Wetzel (1975). Although the Secchi disc is a useful instrument, problems exist that must be avoided if it is to yield useful information (Tyler 1968). Sources of error in Secchi disc measurements include passing the disc through the shadow of the boat, keeping the disc horizontal and the supporting cord vertical, and keeping the reflective surface of the disc at a known level of reflectance (Tyler 1968). Transmittance of the upper 100 m of the ocean water may differ greatly from that of the deeper water (Gilbert and Rue 1967). Both Wetzel (1975) and Hutchinson (1957) recommend lowering the disc from the shaded side of a boat.

Wetzel (1975) states that, "Secchi disc transparency is essentially a function of the reflectance of light from its surface and is therefore influenced by both absorption characteristics of the water and of its dissolved and particulate matter." Secchi disc transparency is sensitive to the number of particles scattering light and the visibility is more affected by the number of particles scattering light than by the chlorophyll content of the particles (Edmondson 1980). Attenuation of light is more closely related to the surface area of particles than to their volume, as demonstrated by Haffner and Evans (1974). Bannister (1974) reports Secchi disc transparencies are influenced by the intensity of light absorption and its nonphytoplankton components and the concentration of phytoplankton pigments.

Secchi disc transparency was also a parameter in Brezonik and Shannon's (1971) classification of lakes in north central Florida. Expressed as reciprocals, mean values for Secchi disc transparency ranged from 0.25 for oligotrophic waters to 1.72 for eutrophic waters. Secchi disc transparency was used to predict hypolimnetic oxygen deficits (Lasenby 1975; Cornett and Rigler 1980).

Chlorophyll concentrations greatly influenced Secchi disc depth at high concentrations, but depth is influenced significantly more by nonchlorophyll components at low concentrations (Lorenzon 1980). Oglesby and Schaffner (1975) noted similar effects if high concentrations of phytoplankton were present. Megard et al. (1980) contends that the Secchi disc becomes insensitive to changes of chlorophyll _a_ exceeding concentrations of 30 μg/l and loses resolution in lakes where algal populations are high.

Concentrations of photosynthetic pigments in natural waters vary with time and space. These pigments, especially chlorophyll _a_, provide estimates of phytoplankton biomass. Dillon and Rigler (1974) found chlorophyll to be a useful and simple estimator of phytoplankton standing crop and concluded that it is generally used more than cell number or cell volume counts for determining biomass. Relationships between phosphorus concentrations and chlorophyll a also exist and can be used to estimate algal biomass. Other investigators have correlated Secchi disc readings and chlorophyll a values (Lorenzen 1980).

Rodhe (1969) used annual phytoplanktonic productivity as an indicator of trophic status. Based on average annual rates of aquatic primary production using ^{14}C-testing, lakes were considered oligotrophic (7-25 g $C/m^2/yr$), naturally eutrophic (72-250 g $C/m^2/yr$), and polluted (350-700 g $C/m^2/yr$). Brezonik and Shannon (1971) used mean primary productivity (mg $C/m^3/h$) to classify lakes in north-central Florida. Lakes were classed as oligotrophic (1.3-5.8 mg $C/m^3/h$), mesotrophic (5.8-150.2 mg $C/m^3/h$), and eutrophic (150.2 mg $C/m^3/h$).

Phosphorus-Chlorophyll Relationship

Phosphorus was found to be the most important factor in lake eutrophication in northwestern Ontario (Shindler et al. 1971). A direct relationship exists between chlorophyll and phosphorus in many Japanese lakes (Sakamota 1966). Vollenweider (1968), Deevey (1972), and Schindler and Fee (1974) agree that phosphorus is the limiting factor in controlling the production and standing crops of phytoplankton. Chlorophyll a has been used as a measure of algal standing crop and correlated with phosphorus concentrations (Dillon and Rigler 1974). Total phosphorus correlates best with transparency when phosphorus is the major factor limiting growth (Carlson 1977). Correlations were poor during spring and fall overturns when algal production tended to be limited by temperature or light.

Correlations have been used by several authors as a basis for developing predictive equations relating to trophic status. Vollenweider (1969, 1976) and Kirchner and Dillon (1975) developed equations to predict retention of phosphorus concentrations in lakes. A regression equation was used by Dillon and Rigler (1974) to predict the average summer chlorophyll concentrations from single measurements of phosphorus concentrations at spring overturn.

Trophic State Indices

Carlson (1977) developed a trophic state index using a single trophic criterion. The relationship among algal biomass, measured as chlorophyll a, phosphorus, and Secchi disc transparency was used because algal blooms are of concern to the public and Secchi disc readings are simple to make. The approach used by Carlson has distinct advantages over more traditional approaches. Instead of three categories, a large number exist along a continuum using the approach of Carlson. Trophic comparison among lakes is possible even if different variables are measured as long as data are available on chlorophyll a or phosphorus or Secchi disc.

Lorenzen (1980) and Megard et al. (1980) criticized the TSI developed by Carlson and suggested Secchi disc transparencies are affected by the attenuation of light by nonalgal substances present in the water column. Carlson (1980) explained that variation in his relationship was due to increases in the amount of chlorophyll per cell as total algal biomass increased, and cited work by Steele (1962) and Jorgensen (1969) as supporting evidence. He believes Secchi disc transparencies have limitations as estimators of algal biomass and recommends taking chlorophyll measurements for estimates of algal biomass.

CHAPTER III

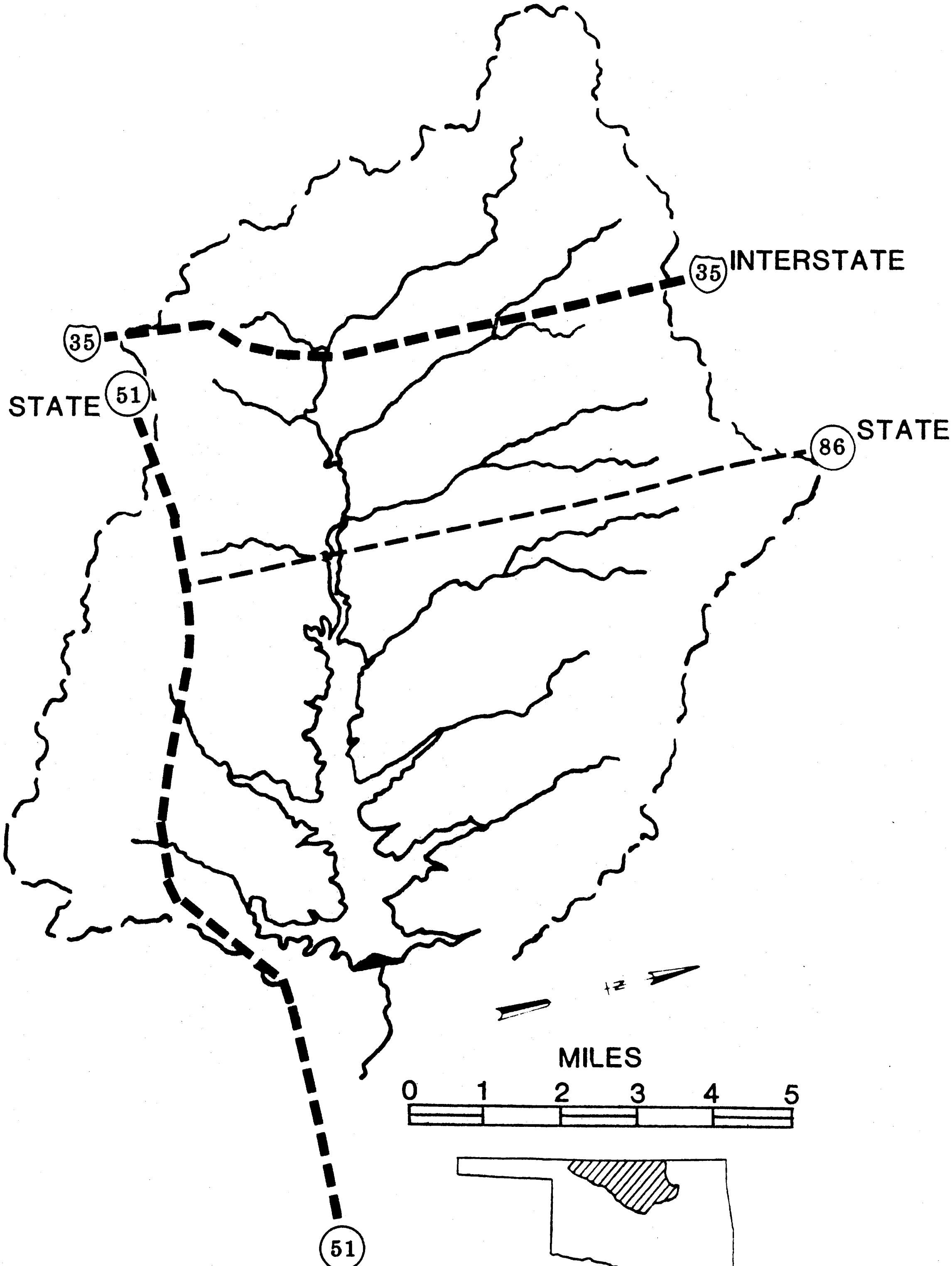
LAKE CARL BLACKWELL

Lake Carl Blackwell (LCB) is located in north-central Oklahoma, 14 km west of Stillwater on State Highway 51 in Township 19 N, Range 1W, Payne County. The lake was formed by impounding Stillwater Creek, a tributary of the Cimarron River (Figure 1). Construction of the dam was completed in 1938 (Oklahoma Department of Wildlife Conservation 1973). In 1945, the spillway elevation of 388.37 m msl, was later lowered to elevation 287.78 m msl due to structural faults of the dam. LCB is a multipurpose lake providing flood control, recreation, and municipal water supply for the city of Stillwater and surrounding communities.

Morphometric data for LCB at normal pool level are shown in Table 1. The lake has a classic dendritic pattern with a long main pool on an east-west axis and several smaller arms resulting in a long shoreline and high shoreline development (Figure 2). Maximum depth occurs immediately in front of the dam and large areas of shallow water exist in the upper reaches. Mean depth is 4.9 m. Since 1938 lake volume has decreased 15.2% due to sedimentation (Wilhm and Howick 1981).

The watershed of LCB encompasses about 15,000 ha in northwestern Payne and south-central Noble counties, Oklahoma. The geologic structure of the area is the Wellington formation, which is reddish-brown in color and composed primarily of fine-grained sandstone and mudstone.

Figure 1. Lake Carl Blackwell and watershed.



35
INTERSTATE
35
STATE
51
86
STATE
N
MILES
0
1
2
3
4
5
51

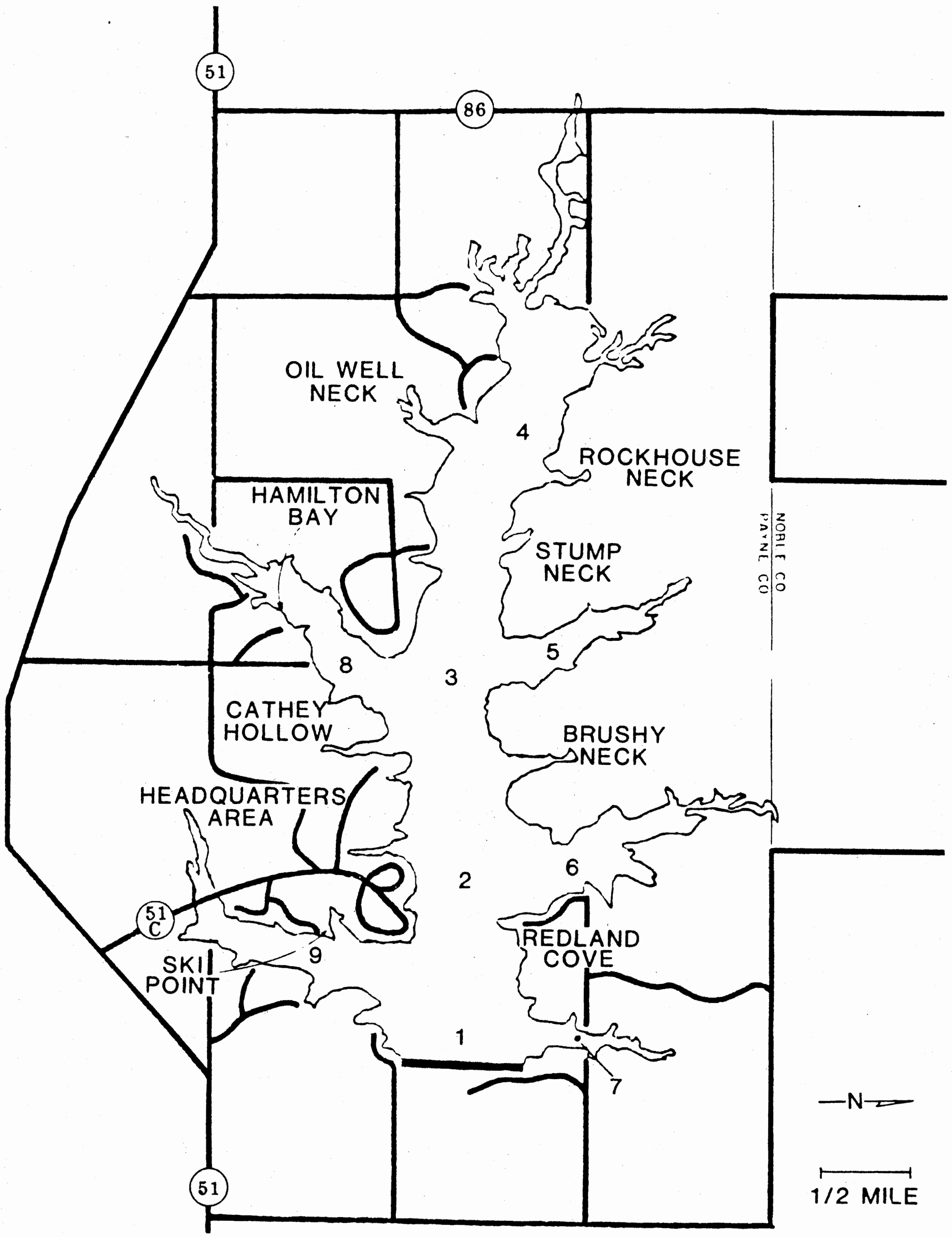
Table 1. Morphometric data for Lake Carl Blackwell.[a]

Surface area	13.52 km^2
Maximum depth	15 m
Mean depth	4.9 m
Volume	67.1 x 10^6 m^3
shoreline length[b]	88.5 km
Shoreline development[b]	6.8
Maximum length	8.28 km
Drainage area	193 km^2

[a]From Wilhm and Howick (1981).

[b]From Gomez and Grinstead (1973).

Figure 2. Sampling sites on Lake Carl Blackwell.


51
86
OIL WELL NECK
4
ROCKHOUSE NECK
HAMILTON BAY
STUMP NECK
NOBLE CO
PAYNE CO
5
8
3
CATHEY HOLLOW
BRUSHY NECK
HEADQUARTERS AREA
6
2
51 C
REDLAND COVE
9
SKI POINT
1
7
N
51
1/2 MILE

The color is reflected in the soil and in the water itself. Five major soil groups are found in the watershed; however, 88.4% of the watershed is made up of the Zaneis-Stoneburg-Renfrow and the Grainola-Lucein association (Payne County Conservation Dist. 1973; Wilhm and Howick 1981).

The watershed is located in the cross timbers region which Bailey (1976) describes as the Tall Grass Prairie Province. This region includes native grasslands, upland forests, and bottom-land forests. In grassland areas abused by over-grazing, cedars have become established. The LCB watershed is rural with no major developments such as housing or industry. Drilling for oil and gas reserves is occurring. Changes in the watershed are agricultural. In 1980, the amount of bottom-land forest had declined from 24% ot 9.1% and grassland had increased from 49.8% to 63% of the total land cover. Cropland had increased from 0.5% to 5.7% of the watershed (Wilhm and Howick 1981).

The area has long summers and short winters. Temperature ranges from -20.8°C to 47.5°C and mean annual rainfall is 83 cm and snowfall averages 17 cm (Oklahoma Water Resources Board 1972). Most of the precipitation falls in the spring and early summer as a result of thunderstorms of short duration. Long periods of drought occur and are often followed by excessive wet periods.

CHAPTER IV

METHODS AND MATERIALS

Field Procedures

All stations (Figure 2) were sampled monthly from late September 1980 to April 1982 and twice each month from May 1981 through September 1981. The sampling program was then extended to mid-November to obtain fall phytoplankton collections. Samples were collected on the following dates:

Fall 80	Winter 80-81	Spring 81	Summer 81	Fall 81
28 Sep	6 Dec	8 Mar	8 Jun	13 Sep
5 Oct	5 Jan	5 Apr	22 Jun	27 Sep
2 Nov	4 Feb	26 Apr	7 Jul	18 Oct
		11 May	20 Jul	15 Nov
		25 May	3 Aug	
			17 Aug	
			30 Aug	

Samples were collected at Station 1 from 0.5, 2, 5, 8, 11, and 14 m. Collections from 0.5 m were made at stations 2-9 and represented the upper mixing zone. All collections were made between 0855 and 1520 h CST. Weather conditions, percent cloud cover, and wind speed and direction were recorded at the beginning of each sample.

Temperature, pH, dissolved oxygen (DO) concentrations, and conductivity were measured with a Hydrolab model 4041 water quality monitoring system. Secchi disc transparencies were measured at each station in duplicate as described by Wetzel (1975). Water samples were collected using an acrylic plastic 8.3 liter capacity Van Dorn water sampler. Samples were preserved on ice and transported to Oklahoma State University for analysis of turbidity, suspended solids, and phosphorus (soluble reactive and total). Phytoplankton for determining algal densities and biomass were collected with a 28 μm mesh, 11.5 cm diameter Wisconsin plankton net drawn from the bottom to the top of the water column.

Laboratory Analysis

A Hach Model 16800 nephelometer was used to measure turbidity in NTU. The nephelometer was calibrated (Amco Standards International, Inc.) and the sample cuvette was oriented at the same position while calibrating and analyzing samples. All samples were well mixed and bubbles dispersed before readings were taken. Excessively turbid samples were diluted with distilled water, read, and the results multiplied by a dilution factor. Suspended solids were determined by a modification of procedures outlined in Standard Methods (1980). A 250 ml sample was filtered through a 0.22 m pore size, 47 mm diameter membrane filter and weighed on a Mettler balance to the nearest 0.0001 g. The filter was then oven dried at 60°C for at least 3 h, allowed to cool, and reweighed.

Total and soluble reactive phosphorus concentrations were determined by the molybdate blue procedure (EPA 1974). All analyses were performed by Dr. Dale Toetz's staff in conjunction with the Lake Carl Blackwell Clean Lakes Program. Total phosphorus was measured by adding 1 ml of H_2SO_4 solution and 0.4 g of ammonium persulfate to a 50 ml sample in a 125 ml Erlenmeyer flask. The sample was then boiled on a preheated hotplate for about 30 to 40 min and adjusted to a pH of

7±0.2 with NaOH. The sample was then allowed to cool and readjusted to 50 ml. Combined reagents described by EPA (1974) were then added and the sample thoroughly mixed. It was allowed to stand from 10-30 min and the color absorbance of each sample at 650 and 880 nm read on a spectrophotometer using a reagent blank as the reference solution. Soluble reactive phosphorus was measured in the same manner except the 50 ml sample was filtered through a phosphorus-free 0.45 μm pore size filter and the ammonium persulfate and heat omitted. Results were calculated by plotting a standard curve of the absorbance values of standards versus corresponding concentrations and sample values obtained directly from the standard curve.

Water samples were collected in the field and transported to the laboratory for immediate analysis of chlorophyll a in the manner described by Weber (1968) and Slack et al. (1973). The 1 liter sample was filtered through a 0.45 μm, 47 mm diameter membrane filter, at a vacuum less than 380 mm of mercury, about 15 psi, using an electric vacuum pump. The filter was rolled with the sample on the inside and placed in a ground-glass grinder tissue homogenizer. The filter was then covered with 2 to 5 ml of 90% aqueous acetone and 0.2 ml of saturated aqueous solution of magnesium carbonate and then macerated for about 1 min at 500 rpm. The sample was transferred to a 15 ml screw capped graduated centrifuge tube. The pestle and homogenizer were washed several times with 90% acetone and the total volume adjusted to 10 ml ± 0.1. The sample was allowed to steep approximately 12 h in the dark at 4°C and centrifuged for 10 min at 3,000 to 4,000 rpm. A set of five serial dilutions ranging in concentrations from 10 to 300 μg/l were prepared using a known concentration of chlorophyll a extract and the relative intensity values determined using a spectrophotofluorometer calibrated against a 90% acetone blank. Each sample was analyzed on an Aminco-Bowman Spectrophotofluorometer calibrated against the 90% acetone blank and relative intensity values determined at excitation and emission wavelengths of 430 and 663 nm. Chlorophyll a concentrations of the sample were determined as described by EPA (1973) in the following manner:

$$\text{mg chlorophyll } \underline{a}/\text{m}^3 = \frac{\text{Ca x volume of extract (liters)}}{\text{volume of grab sample (m}^3\text{)}}$$

where Ca = the concentrations in milligrams per liter of chlorophyll a in the extract.

A 10 ml sample for chlorophyll a determination was filtered through a 0.45 m pore size, 24 mm diameter membrane filter. During filtration a vacuum was less than 0.5 atmosphers to minimize cell damage. The filter was placed on a labeled microscope slide, allowed to dry, and cleared by adding a few drops of immersion oil. Slides were examined for algal identification and enumeration. Cell densities were determined by the method described by Slack et al. (1973) as follows:

$$\text{Phytoplankton} = \frac{\text{total cell count}}{\text{number of random grids x area of grid (mm}^2\text{)}} \text{ X } \frac{\text{effective filter area (mm}^2\text{)}}{\text{volume of filtered sample (ml)}}$$

Volumes were determined from Wetzel (1975) or by making optical measurements of 20 representative individuals of each major species or genera. The average volume (μm^3) was calculated and multiplied by the number of organisms per milliliter to determine the biomass of each major genera.

The slides were examined using the 100X (oil immersion) objective lens with 10X ocular. All cells appearing within 20 random grids on the filter were enumerated. Empty diatom frustules were not counted.

Statistical Methods

Data comparison was accomplished using the Statistical Analysis Systems (SAS) program (Barr et al. 1979). Since the data was not of a balanced design and without replication, a one-way analysis of variance (ANOVA) was performed for each parameter using the general linear models procedure. Sources of variation included the date, station, and depth. When the ANOVA indicated significance difference at the 95% confidence level, a Duncan's multiple range test was used to delineate the source of variation. As a measure of laboratory precision replicate samples from at least one station during each sampling period were analyzed.

CHAPTER V

RESULTS

Temperature

Water temperature in Lake Carl Blackwell varied with time, but not with station or depth. Temperature ranged from 2.9 to 29.2°C (Table 2). Surface temperatures (0.5 m) at Station 5 were slightly higher than those at other stations. The lake was thermally stratified from 8 June to 30 August 1981 with the thermocline forming between 8 and 11 m. Surface temperatures at Station 1 were slightly higher than those at lower depths (Table 3).

Oxygen

Dissolved oxygen (DO) concentrations varied significantly with date and depth. Surface DO concentrations ranged from 6.2 to 15.1 mg/l (Table 2). DO was considerably higher in winter than during other seasons. During thermal stratification DO was low in the hypolimnion from 11 to 14 m (Table 3).

pH

The pH in LCB varied with date and depth. Mean seasonal surface values ranged from 7.6 in fall to 8.4 in summer (Table 2). Values of pH were lower in the fall than in other seasons. In summer, values between 0 and 5 m varied from those at 8 and 11 m, and these values were

Table 2. Mean surface physicochemical concentrations in Lake Carl Blackwell.

	Sampling periods									
	Fall 1980		Winter 1980-81		Spring 1981		Summer 1981		Fall 1981	
Parameters	Range	$\bar{x}$	Range	$\bar{x}$	Range	$\bar{x}$	Range	$\bar{x}$	Range	$\bar{x}$
Temperature (°C)	12.8-21.7	19.1	2.9-4.2	5.6	9.1-21.1	16.8	23.1-29.2	26.9	11.6-25.7	19.7
Dissolved oxygen (mg/l)	7.9-10.8	8.8	12.4-15.1	13.2	7.7-10.1	9.2	6.2-9.5	7.5	8.1-10.6	9.2
pH	7.5-7.7	7.6	8.0-8.5	8.0	8.0-8.6	8.3	8.0-8.6	8.4	7.7-8.2	8.1
Turbidity (NTU)	21-32	27	6.5-20	14.5	24-27	41	21-81	43	29-57	37
suspended solids (mg/l)	8.44-17.92	14.08	4.64-14.20	9.96	3.48-35.32	16.08	3.2-42.2	15.5	2.5-22	15
Conductivity (μmhos)	406-477	452	409-437	419	409-474	453	434-615	509	415-439	430

Table 3. Mean vertical physicochemical concentrations in Lake Carl Blackwell.

Parameter	Season	0.5 m	2 m	5 m	8 m	11 m	14 m
Temperature (°C)	F (1980)	18.7	17.1	16.7	16.5	16.4	18.1
	W (1981)	5.6	5.6	5.5	5.5	5.5	5.4
	S (1981)	16.8	16.5	16.3	16.2	16.0	15.8
	S (1981)	26.7	26.7	26.2	25.2	22.2	20.3
	F (1981)	19.6	19.6	19.4	19.3	19.3	19.2
Dissolved oxygen (mg/l)	F (1980)	8.9	9.3	9.2	9.1	9.1	8.5
	W (1981)	13.2	13.1	13.1	13.1	13.1	13.0
	S (1981)	8.9	8.8	8.8	8.7	8.4	8.0
	S (1981)	7.8	8.1	7.8	6.5	1.9	0.5
	F (1981)	9.0	9.2	9.0	8.9	8.2	7.3
pH	F (1980)	7.7	7.9	7.9	7.9	7.9	7.9
	W (1981)	8.3	8.3	8.3	8.3	8.3	8.3
	S (1981)	8.4	8.3	8.3	8.3	8.2	8.1
	S (1981)	8.3	8.3	8.2	7.9	7.5	7.4
	F (1981)	8.0	8.0	8.1	8.1	7.9	7.9
Turbidity (NTU)	F (1980)	25	25	24	22	28	33
	W (1981)	18	17	17	18	19	20
	S (1981)	40	40	43	46	54	62
	S (1981)	27	29	32	64	98	123
	F (1981)	33	32	33	38	57	69
Suspended solids (mg/l)	F (1980)	13.44	13.32	14.62	14.52	15.66	29.98
	W (1981)	10.68	12.35	12.35	12.21	11.80	13.64
	S (1981)	14.97	16.14	14.45	16.78	21.21	23.85
	S (1981)	6.90	6.30	14.70	20.70	31.00	46.20
	F (1981)	11.30	12.00	10.00	12.70	20.80	31.90
Conductivity (μmhos)	F (1980)	433	416	418	417	417	429
	W (1981)	419	420	420	420	420	419
	S (1981)	455	456	456	456	455	455
	S (1981)	506	506	507	492	506	513
	F (1981)	431	431	432	431	431	431
Total phosphorus (μg/l)	F (1980)	32.8	33.8	32.5	32.5	33.3	28.3
	W (1981)	40.0	45.0	46.5	50.0	37.8	46.7
	S (1981)	28.0	19.3	24.5	33.3	28.4	29.2
	S (1981)	36.7	38.4	39.7	58.4	60.3	73.7
	F (1981)	46.0	40.0	41.0	68.0	80.0	94.0

Table 3. Continued.

Parameter	Season	0.5 m	2 m	5 m	8 m	11 m	14 m
Soluble reactive phosphorus (μg/l)	F (1980)	23.0	21.0	21.0	23.0	26.0	25.5
	W (1981)	25.3	26.0	29.3	29.0	31.0	34.0
	S (1981)	14.2	45.5	18.0	15.0	21.0	23.7
	S (1981)	13.1	10.9	13.1	15.8	30.8	38.6
	F (1981)	11.0	10.6	8.0	6.4	62.0	32.6
Chlorophyll *a* (μg/l)	F (1980)	5.23	4.63	2.87	3.37	2.72	3.73
	W (1981)	4.18	3.18	3.02	3.54	4.17	3.61
	S (1981)	5.21	4.31	3.87	4.08	3.67	4.09
	S (1981)	7.74	6.67	5.62	3.45	3.73	3.85
	F (1981)	6.63	5.52	4.44	4.51	5.07	5.52

different from those at 14 m (Table 3).

Turbidity

Secchi disc, turbidity (NTU), and suspended solids were measured to provide estimates of water clarity. Secchi disc transparency varied with time and station. Transparencies ranged from 23 to 130 cm. Secchi disc values were higher in winter than in summer (Figure 3). Summer values were higher than spring and fall values. Stations 4, 5, and 8 had lower Secchi disc values than other stations.

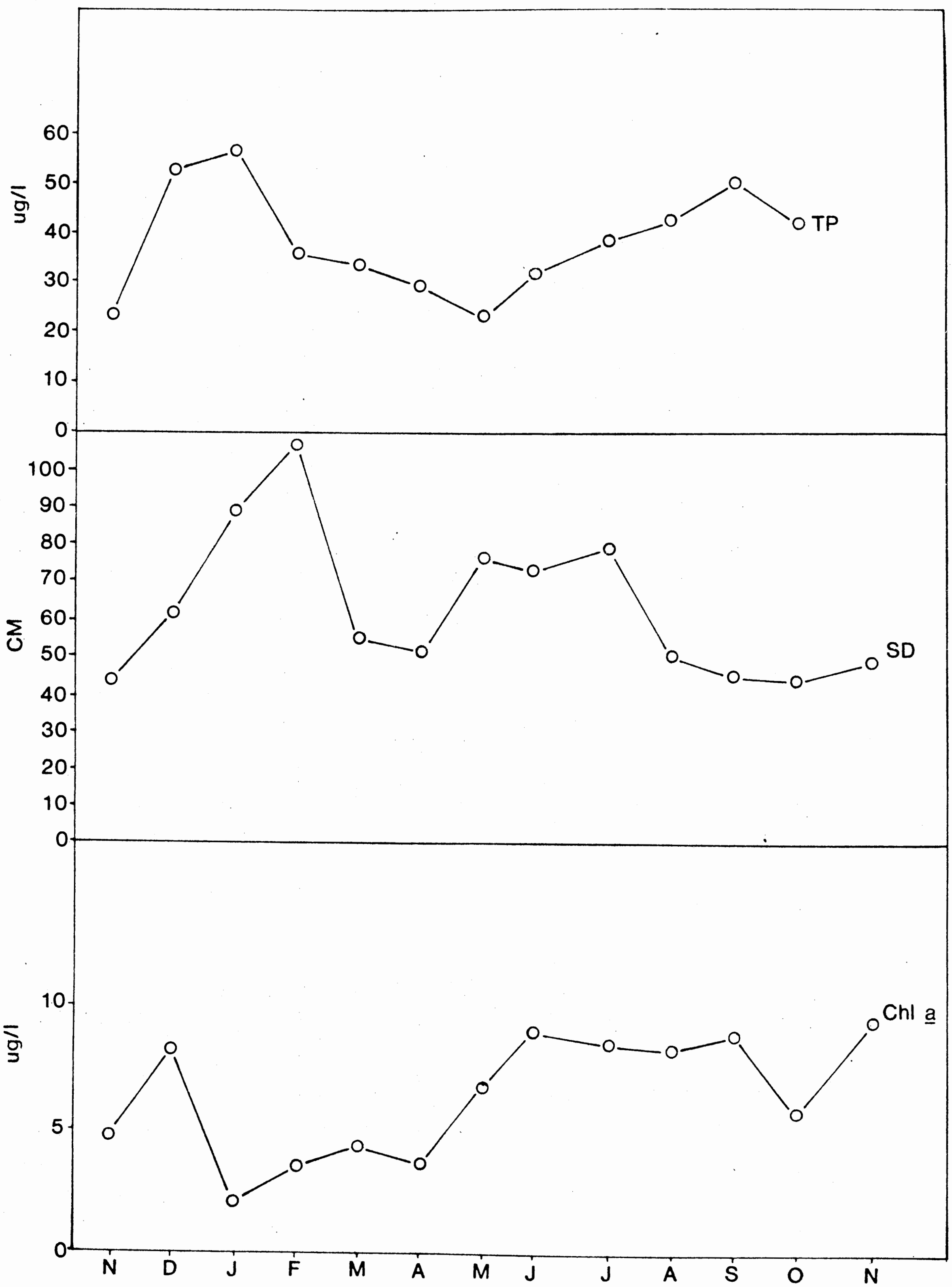
Turbidity and suspended solids are inversely related to Secchi disc transparency. Surface turbidity values ranged from 7 to 81 NTU (Table 2). No difference existed among stations. Turbidity varied with season, with the highest reading in summer and the lowest in winter. Turbidity was higher at 11 and 14 m than at other depths (Table 3).

Surface values for suspended solids ranged from 3.2 to 42.2 mg/l (Table 2) and varied with time and depth. Values for summer, fall, and spring were lower than values obtained in the winter. Values at 14 m were higher than those at 11 and 8 m and these values were higher than those at 5, 2, and 0.5 m (Table 3).

Conductivity

Mean surface conductivity values ranged from 406 to 615 μmhos/cm (Table 2). Mean surface readings varied over time but not by station. Higher values were recorded during the summer, while lower conductivities were found in the winter. Little variation existed among depths (Table 3).

Figure 3. Temporal variation in Secchi disc, chlorophyll a, and total phosphorus in Lake Carl Blackwell.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50
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10
0
ug/l
TP
100
90
80
70
60
50
40
30
20
10
0
CM
SD
10
5
0
ug/l
Chl a
N
D
J
F
M
A
M
J
J
A
S
O
N

Phosphorus

Mean total phosphorus (TP) surface concentrations ranged from 3.8 to 59 μg/l. Little differences existed among stations. Concentrations were higher in winter and summer than in spring (Figure 3). Values from 0.5 to 5 m were similar, while concentrations at 8, 11, and 14 m were higher. Mean soluble reactive phosphorus (SRP) values for 0.5 m ranged from nondetectible to 36 μg/l. Mean SRP concentrations were highest at Station 7 and lowest at Station 4. Soluble reactive phosphorus concentrations were generally higher in early winter and lower in later summer and spring (Figure 4).

Chlorophyll *a*

Chlorophyll *a* varied among dates and stations. Chlorophyll concentrations at 0.5 m ranged from 20.2 to 0.9 g/l. Stations 4, 5, and 8 were higher in chlorophyll *a* content than other stations (Figure 5). Higher concentrations occurred during the summer and fall (Figure 4). Surface concentrations were greater than other depths.

Phytoplankton

Twenty-two taxa were observed in 187 samples during the study (Table 4). All 22 taxa occurred in the summer, while 20 were collected in fall, 19 in spring, and 16 in winter. Two blue-green algae, *Aphanizomenon* and *Anabaena*, and one diatom, *Melosira*, comprised 99.6% of the total phytoplankton sample in the winter, 97% in the spring, 86% in summer, and 97.8% in the fall. *Aphanizomenon* was the dominant taxa in all seasons. *Anabaena* was the second most abundant species in the winter and summer, while *Melosira* was the second most abundant species

Figure 4. Temporal variation in algal density, biomass, and soluble reactive phosphorus in Lake Carl Blackwell.

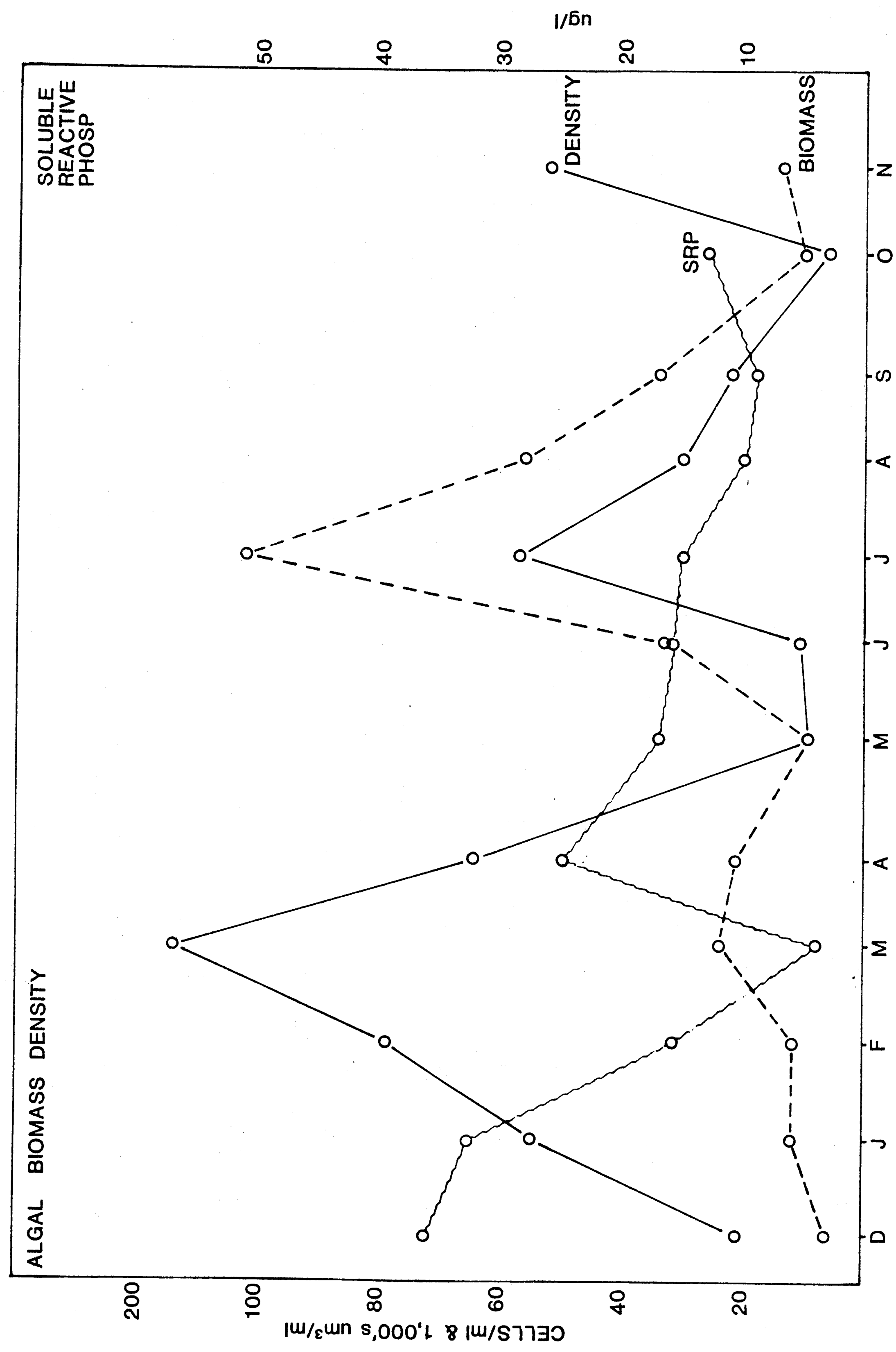

ALGAL BIOMASS DENSITY
SOLUBLE REACTIVE PHOSP
DENSITY
BIOMASS
SRP
CELLS/ml & 1,000's um³/ml
200
100
80
60
40
20
ug/l
50
40
30
20
10
D
J
F
M
A
M
J
J
A
S
O
N

Figure 5. Spatial variations in chlorophyll a and biomass in Lake Carl Blackwell.

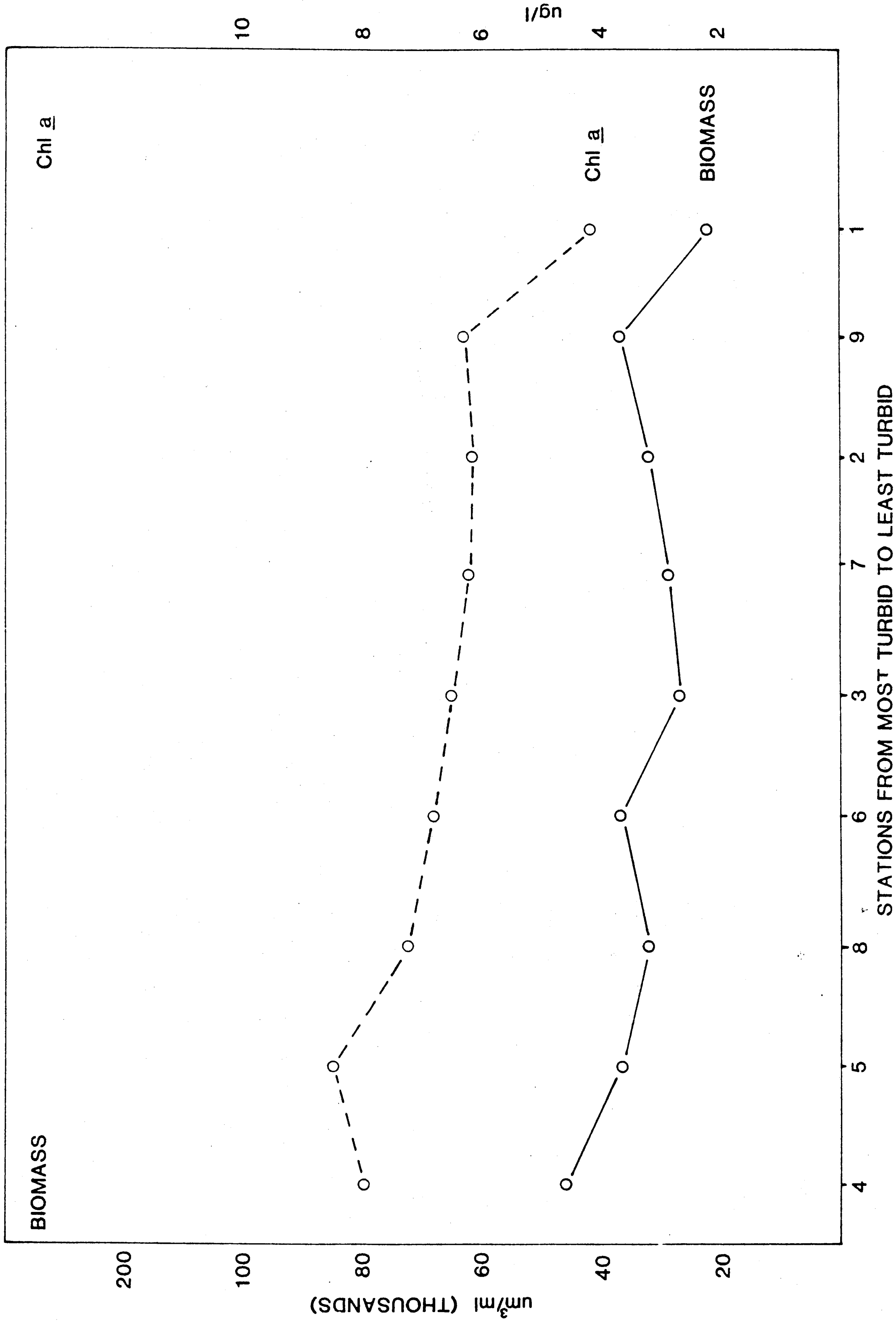

BIOMASS
Chl a
Chl a
BIOMASS
um³/ml (THOUSANDS)
200
100
80
60
40
20
ug/l
10
8
6
4
2
4
5
8
6
3
7
2
9
1
STATIONS FROM MOST TURBID TO LEAST TURBID

Table 4. Taxa collected in Lake Carl Blackwell.

Chlorophyta	Euglenophyta	Pyrrhophyta	Chrysophyta	Cyanophyta
Eudorina	Euglena	Glenodenium	Melosira	Anabaena
Pandorina		Ceratium	Fragilaria	Aphanizomenon
Oocystis			Synedra	Microcystis
Botryococcus			Gyrosigma	
Pediastrum			Navicula	
Closterium			Cosinodiscus	
Staurastrum				
Ankistrodesmus				
Kirchnerella				

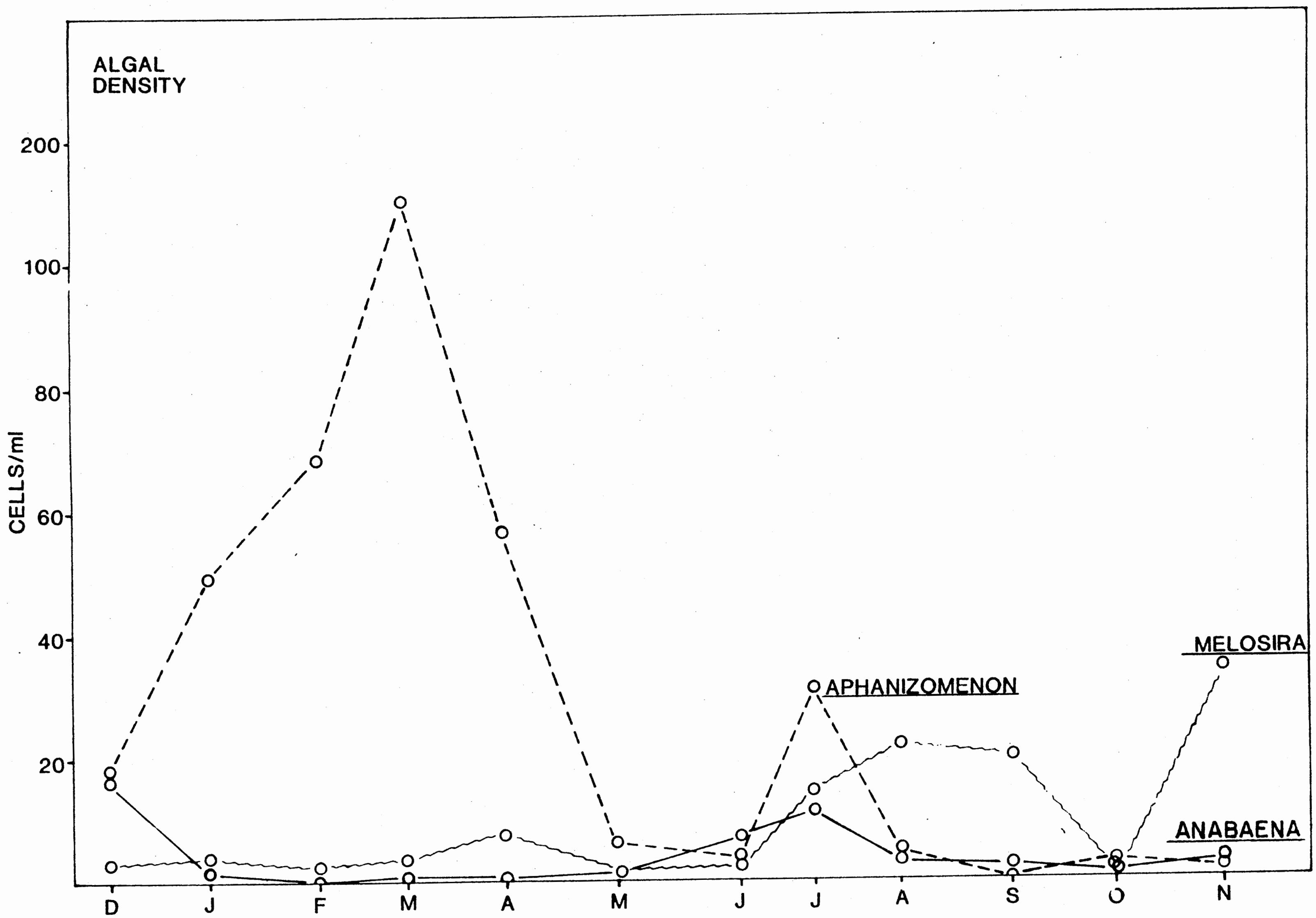
in spring and fall (Figure 6).

Phytoplankton densities varied with time and station. Higher densities occurred in early spring and summer, while lower densities existed in late spring and fall (Figure 4). Mean algal densities ranged from 25.2 cells/ml at Station 1 to 52.5 cells/ml at Station 9. Higher densities were found at stations in protected arms of the lake, while lower densities were found in the main pool stations.

Biomass

Biomass estimates ranged from a mean of 5.8 to 10.5×10^4 μm^3/ml. Biomass remained relatively low from December through May then increased abruptly, reaching the maximum value on 7 July 1981 (Figure 5). Minimum biomass occurred at Station 1 and maximum at Station 4. Generally, stations in the arms had greater biomass than stations in the main pool.

Figure 6. Mean seasonal occurrence of major phytoplankton in Lake Carl Blackwell.


ALGAL
DENSITY
CELLS/ml
200
100
80
60
40
20
D
J
F
M
A
M
J
J
A
S
O
N
APHANIZOMENON
MELOSIRA
ANABAENA

CHAPTER VI

DISCUSSION

Algal Density and Community Structure

The number of dominant algal genera in LCB appears to be decreasing. Eight genera were common in 1940-41 (Leonard 1950), four in 1949-50 (Leonard 1950), four in 1971-72 (Faust 1973), and only three genera in the present investigation. There has been an increase in dominance by blue-green algal species, which may indicate eutrophication. Seasonal variation was also reported in the various studies. Leonard (1950) reported peak algal abundance in November and April of 1940-41 and in February 1949-50. Peak algal production occurred in June and September of 1971 and in May of 1972 (Faust 1973). In the present study, the major peak in algal production occurred in March, with smaller peaks occurring in July and November (Figure 6).

Between 1972 and 1975, 815 lakes were sampled as part of EPA's National Eutrophication Survey (EPA 1975). _Aphanizomenon_ was the most abundant in the fall, while _Anabaena_ was dominant in the summer and _Melosira_ in the spring. In the present investigation, _Aphanizonmenon_ was the most common in all seasons.

Algal Density vs Biomass

Increases in algal densities were accompanied by increases in biomass. Seasonal variation in algal density and biomass were similar in May, but biomass was disproportionally high in July, August, and September. The higher biomass during the summer resulted from the appearance of *Microcystis*, a blue-green algae that comprised only 1% of the samples but had an extremely large cell volume. By October, *Microcystis* had disappeared and biomass declined.

Secchi Disc, Total Phosphorus, and Chlorophyll *a*

Phosphorus (TP) is frequently cited as the limiting factor to production of phytoplankton in lakes (Edmondson 1970; Bachman and Jones 1974; Schindler 1974). Phosphorus may not be the primary factor limiting algal production in LCB (Faust 1973). In the present study, no significant difference ($p > .05$) existed among seasons in total phosphorus concentrations despite large differences in algal densities and biomass.

Soluble reactive phosphorus (SRP) is more readily available than TP for algal use. Seasonal increases and decreases in algal densities were accompanied by corresponding decreases and increases in SRP concentrations. While the relationship between phosphorus and algal density is more apparent using SRP than TP, no significant difference ($p > .05$) existed among seasons in SRP concentrations despite large differences in algal densities and biomass. Soluble reactive phosphorus was lowest in March, which also coincided with the period of highest algal densities. While March values for SRP were low, the fact that concentrations remained available for algal uptake indicate that phosphorus is not limiting in LCB.

A strong relationship between chlorophyll *a* and total phosphorus has been described by Sakamoto (1966), Dillon and Rigler (1974), Jones and Bachman (1976), and Carlson (1977). Carlson's equation is as follows:

$$\ln \text{chl } a = -1.06 + 1.45 \ln \text{TP} \quad (n = 43,\ r = 0.85)$$

A regression developed for LCB resulted in:

$$\ln \text{Chl } a = 1.83 - .031 \ln \text{TP} \quad (n = 12,\ r = 0.14)$$

The positive slope of Carlson's regression line indicates increases in chlorophyll a occur at a faster rate than increases in TP concentrations. The slope of the regression line for the LCB equation indicates that increases in chlorophyll a are not occurring at a faster rate than increases in TP and suggests TP is not a factor limiting chlorophyll concentrations.

The relationship between light and chlorophyll a have been examined at LCB. A previous investigation reported chlorophyll a concentrations to begin increasing from winter levels in June, peak in July, decline, and increase again in mid September (Toetz et al. 1977). Similar temporal trends were noted during the present study (Figure 3). Chlorophyll a content was found to be greater at 0.5 m than at other depths, which is indicative of light limiting conditions. Generally, the more turbid stations also had the highest mean annual chlorophyll a content and algal biomass. This contrast could be the result of phytoplankton adapting to turbid conditions and producing more chlorophyll. Chlorophyll a per cell has been found to increase in certain species as light decreased (Steele 1962; Jorgensen 1969). Jewson and Taylor (1978) found similar conditions in Irish lakes and attributed it to differences in lake mixing. Stations in Lake Erne were found to have similar chlorophyll a content despite differences in euphotic zone depth and algal concentrations.

The relationship between Secchi disc transparency and chlorophyll a has been described by a number of investigators (Edmondson 1970; Bachman and Jones 1974; Carlson 1977). Carlson's equation for Secchi disc and chlorophyll a is as follows:

$\ln$ (Secchi disc) = 2.04 - 0.68 $\ln$ (Chl a) (n = 147, r = 0.93).

A regression equation expressing this relationship for LCB is:

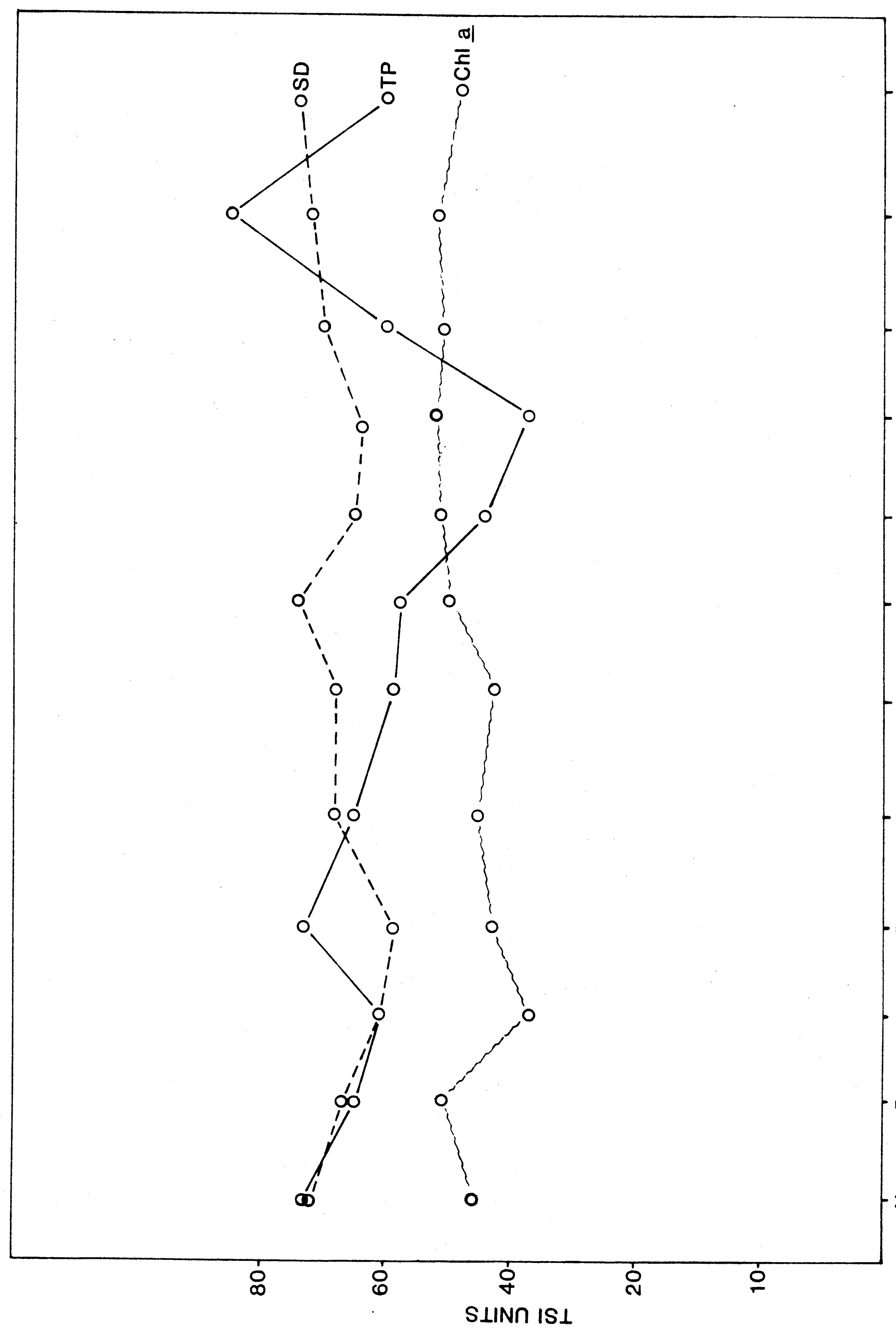
$\ln$ (Secchi disc) = -0.06 - 0.29 $\ln$ (Chl a) (n = 13, r = 0.41).

Correlation between these parameters for LCB are low (r = 0.41) compared to Carlson's (r = 0.93). Light attenuation in LCB is mostly due to non-chlorophyll containing particles. Low correlations between chlorophyll a and Secchi disc due to these particles have been noted by others (Bannister 1974; Lorenzen 1980). In turbid conditions relationships between Secchi disc and chlorophyll a must be examined closely since light attenuation may be caused by substances other than algae.

Trophic State Index

Carlson (1977) developed a Trophic State Index (TSI) based on the relationship among phosphorus, chlorophyll a, and Secchi disc. The TSI can be computed from any of the three parameters and should be approximately the same regardless of the parameter chosen. Carlson generated a single number to fit into a numerical scale ranging from 0 to 100 with major trophic divisions at 10 unit increments. Mean annual TSI values computed for LCB were 68 for Secchi disc, 49 for chlorophyll a, and 56 for total phosphorus. Seasonal TSI values calculated for LCB are shown in Figure 7. Values generated from the different methods of calculation were all significantly different from each other ($p > .05$).

Figure 7. Temporal variation in Carlson's TSI for Lake Carl Blackwell.


SD
TP
Chl a
TSI UNITS
80
60
40
20
10
N
D
J
F
M
A
M
J
J
A
S
O

Consequently, the trophic state for LCB on any given season may vary by as much as two trophic divisions, depending upon which parameter is used to calculate the TSI. Carlson recommended calculation of the index for more than one parameter to serve as a check on methodology and assumptions regarding relationship among parameters. Clearly, LCB violates some of the assumptions.

Carlson conducted his work on natural lakes where relationships among Secchi disc, chlorophyll a, and total phosphorus relate well because turbidity was chiefly due to algae and phosphorus limited algal abundance. However, his assumptions underlying the relationship between these parameters has been critized (Edmondson 1980; Lorenzen 1980; Megard et al. 1980). These relationships do not hold for impoundments or reservoirs such as LCB where transparency depth is limited by interference from non-algal particles. Carlson recognized that Secchi disc transparency could give false values in highly colored lakes but concluded that its advantages outweighed its disadvantages.

Use of the total phosphorus TSI developed by Carlson is based on the assumption that phosphorus is the major limiting factor. In LCB, phosphorus is probably not the major limiting factor and its use as an indicator of trophic state is unwise. Carlson found that trophic state indices calculated from Secchi disc transparencies usually approximated those calculated from chlorophyll a. This was not the case in LCB where the derived Secchi disc value more nearly equated the diurnal value for TP. The TSI value calculated from chlorophyll a probably provides a more accurate index of the trophic state of LCB than either phosphorus of Secchi disc. While it is neither simple nor inexpensive to derive TSI values from chlorophyll a estimates, it appears to provide a more reasonable index for calculating trophic state in a highly colored or turbid lake.

CHAPTER VII

SUMMARY AND CONCLUSIONS

1. Limnological data were collected from Lake Carl Blackwell, Oklahoma to measure the spatial and temporal variation in algal densities, chlorophyll *a*, phosphorus, Secchi disc transparencies, and to calculate trophic state.

2. A total of 22 algal taxa was observed during the study. *Aphanizomenon*, *Anabaena*, and *Melosira* were the most abundant genera in all seasons.

3. In LCB turbidity from non-algal particles, not phosphorus, was probably the primary limiting factor for algal production.

4. It is not possible to predict adequately chlorophyll *a* from Secchi disc measurements due to light attenuation from non-chlorophyll *a* particles.

5. The trophic state index developed by Carlson was of limited usefulness at LCB. Seasonal TSI values computed for Secchi disc, chlorophyll *a*, and total phosphorus were found to be significantly different and could vary by as much as two trophic divisions. The basic assumptions formulated by Carlson correlating the relationship of these parameters do not hold true in LCB because of interference from nonchlorophyll particles.

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