THE RELATIONSHIPS AMONG PHOTOSYNTHETICALLY ACTIVE RADIATION, SECCHI DISC TRANSPARENCY, CHLOROPHYLL, AND PHOSPHORUS IN KEYSTONE LAKE

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PREFACE

I wish to thank my major advisor, Dr. Jerry Wilhm, for his guidance, assistance, and sense of humor during this study. Appreciation is also expressed to the other committee members, Dr. Sterling Burks, and Dr. Dale Toetz. Dr. John Carroll, Mr. Paul Mace, Ms. Jan Culbertson, Mr. Jim Staves, and Ms. Sandy Cobb helped with field collections and laboratory analysis. Their kind assistance is especially appreciated. A special thanks to my wife, Marcia, and son, Andrew, for their tolerance during my studies.

This study was part of a baseline water quality study conducted by the Tulsa District Corps of Engineers. It is part of a five-year plan to determine the existing water quality of all 34 Tulsa District impoundments.

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CHAPTER I

THE RESEARCH PROBLEM

Introduction

Knowledge of interrelationships among environmental parameters often enables predicting a critical factor which is difficult to measure based on levels of a second parameter which is easily measured. The Secchi disc is among the simplest and most commonly used limnological sampling devices. It allows rapid determination of the transparency of water, although the readings are influenced by refraction from the water surface and the coefficient of reflection of the disc surface (Tyler 1968). When properly used, the Secchi disc measure approximates the depth at which 20% of incident light remains (Lorenzen 1980).

Algal populations reduce the transparency of water by scattering and absorbing light waves. A correlation should exist between measurements of algae density or chlorophyll content and water transparency as estimated with the Secchi disc. Oglesby and Schaffner (1975) documented this relationship, but found drastic decreases in large chlorophyll concentrations produced only slight reductions in transparency.

A relationship exists between phosphorus and chlorophyll in lakes where phosphorus is the major factor limiting plant growth. Dillon and Rigler (1974) demonstrated this relationship using average summer chlorophyll concentrations and total phosphorus at spring overturn.

A similar correlation would be anticipated between Secchi disc transparency and total phosphorus in lakes where phosphorus is the limiting nutrient.

Carlson's Trophic State Index

Carlson (1977) obtained significant correlations for the relationships between Secchi disc transparency and concentration of chlorophyll and between Secchi disc depth and phosphorus. Because of concern that the commonly used trophic categories of oligotrophic and eutrophic waters were neither precise nor understood by laymen, Carlson proposed a trophic state index (TSI) using the above relationships. The TSI yields a number between 0 and 100 and can be calculated from Secchi disc depth, summer total phosphorus, or chlorophyll _a_ content.

The TSI was challenged by other authors (Lorenzen 1980; Megard et al. 1980) who believe absorption of light by silt and other non-chlorophyll containing particles varied significantly among lakes studied by Carlson. They stated that Carlson was unable to fit the Secchi disc-chlorophyll relationship to Beer's Law. Carlson contends this is a result of chlorophyll content per cell changing in response to differing light conditions; a phenomenon described by Steele (1962). Further criticism of the index (Edmondson 1980) resulted from the inherent inaccuracy of transparency measurements made with the Secchi disc. Besides increased values caused by non-chlorophyll turbidity, extreme care is required by the user to obtain accurate measurements. Tyler (1968) and Megard et al. (1980) recommend periodic calibration.

Purpose of the Study

Clarification of these objections could be accomplished using more accurate measurements of biologically produced turbidity and non-chlorophyll turbidity. Such a study could also be used as a test of the three methods of computing Carlson's trophic state index. Additionally, the influence of turbidity and conductivity on chlorophyll and Secchi disc transparency could be examined. Increased turbidity or salinity could alter species composition of algal populations and influence chlorophyll content.

The present study was conducted with the following objectives:

1. To measure the relationship between photosynthetically active radiation (400 to 700 nm wavelength), Secchi disc transparency, chlorophyll _a_, and phosphorus.
2. To evaluate the usefulness of Carlson's trophic state index.
3. To estimate the effect of turbidity and conductivity on Carlson's trophic state index.

CHAPTER II

LITERATURE REVIEW

Introduction

The Secchi disc is among the oldest limnological measuring devices; the first use dates to 1865 (Cialdi 1866). Measurements of Secchi disc depth approximate the point of 1 to 20% surface light penetration (Beeton 1958; Lorenzen 1978). Juday and Birge (1933) found the depth at which the Secchi disc could be observed varied little with disc size, but most investigators prefer a 20-cm diameter disc. Black and white markings gave Aberg and Rodhe (1942) a sharper end point. Specific instructions for use of the Secchi disc are provided by Hutchinson (1957) and Wetzel (1975). Tyler (1968) stated that the disc should not be viewed in the shadow of a boat.

Secchi Disc-Chlorophyll relationships

Transparency measurements made with a Secchi disc are influenced by two factors; the attenuation of light by the water and its non-chlorophyll components and the light absorption by phytoplankton (Bannister 1974). The relationship between these two factors is not uniform. Secchi disc depth is controlled by chlorophyll at high chlorophyll levels, while disc depth is controlled by non-chlorophyll turbidity at low chlorophyll levels (Lorenzen 1980). Furthermore, at high chlorophyll concentrations, even large reductions in chlorophyll produce little change in disc measurements (Rodhe 1965). Thus, the Secchi disc loses resolution where the greatest resolution is needed; in lakes where algal populations are high (Megard et al. 1980). This effect is greatest at chlorophyll concentrations above 30 mg/m^3 (Megard et al. 1980). The Secchi disc measures light reduction more from suspended particles than dissolved particles (Szczepanski 1968). Measurements are affected more by the number of particles scattering light than the chlorophyll content of the particles (Edmondson 1980). To provide measurements useful for the calculation of attenuation coefficients, Tyler (1968) states the reflectance of the disc must be known. Tyler (1968) and Carlson (1980) believe the Secchi disc is less precise than other methods of determining transparency.

A relationship exists between mean summer Secchi disc readings in lakes and the average summer concentration of chlorophyll a, but it is not applicable to lakes with high inorganic turbidity (Rast and Lee 1978). Secchi disc transparency was inversely correlated with color and concentration of seston by Wagner and Parker (1973). They were unable to separate the two factors in field observations.

Since anything affecting turbidity will affect Secchi disc depth (Edmondson 1980), transparency measurements made with a submarine photometer provide information more usable to limnologists. Dubinsky and Berman (1979) measured extinction coefficients of photosynthetically active radiation (PAR) by chlorophyll of 0.007. This value was 0.489 for water. Studies by Kirk (1975) showed extinction rates of chlorophyll a ranged from 0.006 to 0.018 and was dependent on the size and chlorophyll content of the cells and colonies. He also found organic materials absorb phtosynthetically active radiation and thus impede algal growth. Nonalgal light attenuation averaged 46% in studies by Hickman (1979). Robarts (1979) found a chlorophyll extinction coefficient of 0.529 in a Rhodesian lake. A strong correlation between volumetric rates of photosynthesis, chlorophyll, and nutrients was shown by Smith (1979), but these parameters were not strongly correlated with light transmission in a study by Brunskill et al. (1979). The differences in the results of these studies may be due to errors in field measurements. To obtain comparable results, Megard et al. (1979) measured PAR within 1.5 h of solar noon. This was necessary because attenuation coefficients showed the least variation with time near noon.

Although Oglesby and Schaffner (1975) document a relationship between Secchi disc transparency and chlorophyll content, some uncertainty exists in this relationship (Carlson 1980). Williams et al. (1978) found a negative correlation between Secchi disc transparency and chlorophyll _a_, but Spangler (1969) showed concentrations of chlorophyll _a_ were generally inversely related to euphotic zone depth at Keystone Lake. Welch (1952) believes light to be an influential factor in determining occurrence and distribution of chlorophyll in a lake. Tolstoy (1979) found chlorophyll _a_ is not always an adequate measure of phytoplankton volume at low concentrations.

Phosphorus-Chlorophyll Relationships

Phosphorus is the main nutrient controlling algae growth in many aquatic systems (Sawyer 1952). There exists a relationship between total phosphorus and algal productivity in many natural waters (Kramer et al. 1972). Algal growth rates were directly proportional to levels of dissolved phosphorus in laboratory studies (Maloney et al. 1971). A relationship exists between filtrable orthophosphate, total phosphorus, phytoplankton production, and light penetration (Dobbins and Boyd 1976; Lichtkoppler and Boyd 1977). Relationships between phosphorus and chlorophyll were found to be highly correlated (Verdulin 1977; Schindler 1978). These interrelationships have been used by numerous authors to develop predictive equations. Dillon and Rigler (1974) derived an equation allowing the prediction of average summer chlorophyll concentration from a single measurement of phosphorus at spring overturn. Williams et al. (1978) also found high linear correlations between phosphorus and mean chlorophyll a, especially when retention times exceeded 14 days. Nicholls and Dillon (1978) evaluated the various equations and found them similar. However, Scheider (1978) was unable to predict chlorophyll from phosphorus concentration in small lakes.

Trophic State Indices

Several authors have used facets of the Secchi disc-chlorophyll-phosphorus relationships to predict trophic status. Phosphorus levels above 50 mg/m^3 were associated with a 100% probability of a lake being eutrophic (Chapra and Reckhow 1979). Lakes with less than 5 mg/m^3 were classified as oligotrophic and those with more than 6 mg/m^3 of chlorophyll as eutrophic by Jones et al. (1979). A trophic state index which eliminated oligotrophic-eutrophic designations was proposed by Carlson (1977). He believed determination of trophic state was judgmental due to the reliance on species composition, shape of oxygen curve, or biomass and productivity measurements. Instead, Carlson used algal biomass as a single predictor since blooms were of interest to the public and algal biomass was correlated with Secchi disc measurements which are easy to make.

Carlson's trophic state index was criticized by some workers. Lorenzen (1980) believed the assumption that the attenuation of light by water was insignificant when compared to the attenuation by chlorophyll was wrong. Other authors (Megard et al. 1980) shared this view and felt Carlson should use a direct measurement of phytoplankton biomass rather than chlorophyll. Carlson (1980) believed variation in the data resulted from an increase in chlorophyll per cell as total algae biomass increased. He cited studies by Steele (1962) and Jorgensen (1969) as evidence, but admitted problems resulted from use of indices of biomass which do not measure algal biomass exclusively. Carlson (1979) also believed the attenuation of light by water somehow covaries with the attenuation by chlorophyll. The mechanism involved is unknown.

CHAPTER III

THE STUDY AREA

Keystone Lake is a 10,520 ha impoundment located in Tulsa, Creek, Pawnee, and Osage counties of northeast Oklahoma. The dam is at Arkansas River mile 538.8 about 20 km west of Tulsa. The lake was designed and constructed by the U.S. Army Corps of Engineers for flood control, hydro-electric power generation, navigation releases, and recreation. Keystone Lake began flood control operations in September 1964, and commercial power generation began in the spring of 1968. The major tributaries of the lake are the Arkansas and Cimarron rivers, which join about 3 km above the dam. The two main arms have different water qualities. Morphometric data for Kaystone Lake are shown in Table 1.

Headwaters of the Arkansas River are in Colorado, near the Oklahoma-Kansas border. The river flows from northwest to southeast through the pasture and cropland of the Great Plains. Mean annual flow into Keystone Lake from the Arkansas River is about 2169 x 10^6 m^3 (Dover et al. 1968) which is 69% of the total inflow (Eley 1970). The Arkansas River receives industrial and municipal wastes from population centers upstream from Keystone Lake (OSHD 1980). The water is turbid and naturally high in calcium, magnesium, sulfate, and chloride.

The Cimarron River accounts for approximately 17% of the mean annual inflow to Keystone Lake (Eley 1970). The river originates in New Mexico and flows to the east-northeast through natural salt and gypsum

Table 1. Morphometric data for Keystone Lake.

Drainage area	577889 km^2
Surface area*	10520 ha
Volume*	817800 km^3
Mean depth*	7.7 m
Maximum depth*	22.9 m
Shoreline length*	531 km

*At maximum power pool (220 m MSL)

deposits in the Permian redbeds of western Oklahoma. The Cimarron River is generally free of industrial and municipal effluents and is relatively clear. However, the chloride content of the Cimarron River is 3 to 4 times greater than that of the Arkansas River (Kincannon 1979). These conditions result in haloclines in the lower portion of the lake and sharply defined areas of differing non-chlorophyll turbidty.

CHAPTER IV

MATERIALS AND METHODS

Introduction

Samples were collected monthly from March 1981, to October 1981. Sample days were chosen based on weather conditions that were typical for a given month. This eliminated large variations in data caused solely by aberrant weather.

Six stations were established at Keystone Lake (Figure 1), and a substation serving as a statistical replicate was situated approximately 100 m from each station. Station descriptions are shown in Table 2.

All data were collected for individual stations at approximately the same time relative to solar noon on each sample date. A 20-cm diameter Secchi disc with black and white markings was first lowered from the sunlit side of the boat and the Secchi disc transparency measured as the mean of two replicates.

Photometric Parameters

Photic zone depth, the depth at which 1% of the photosynthetically active radiation (photons in the 400 to 700 mm waveband) present at the surface remained, was determined using a Li-Cor Model LI-188B quantum submarine photometer (Li-Cor, Inc. Lincoln, NB) equipped with a Li-Cor LI-192SB sensor. The surface reading was taken at the air/water interface and all readings were integrated over 100 sec to minimize

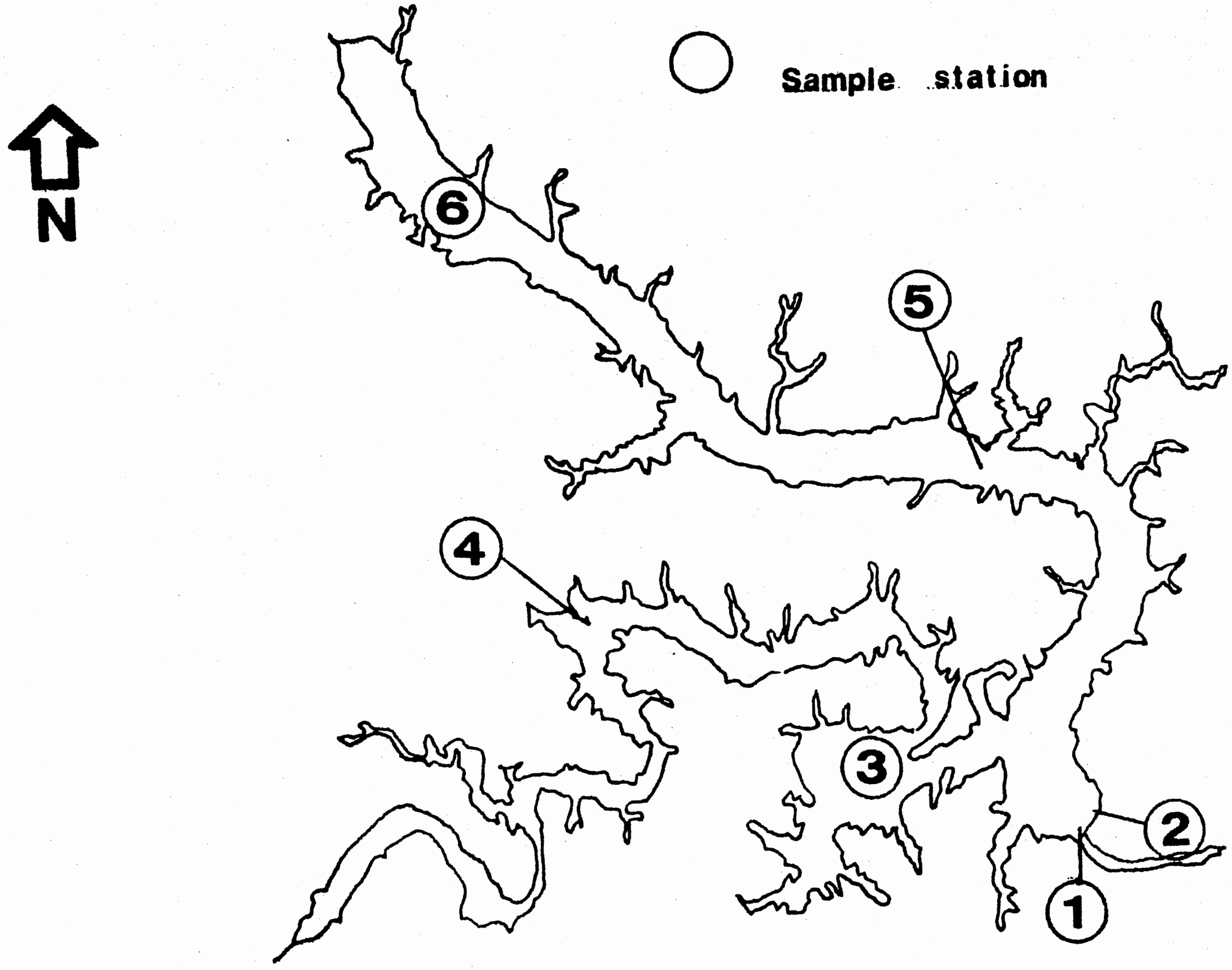

Figure 1. Map of Keystone Lake, Oklahoma.

Table 2. Locations of sample stations on Keystone Lake.

Station	Area*	River mile	Location
1	R	1	Southern-most of three hazard buoys located 40 m from the face of the dam.
2	R	1	Northern-most of three hazard buoys located 40 m from the face of the dam.
3	C	5	At the black channel marker just downstream from the mouth of Salt Creek Cove.
4	C	15	At the red channel marker west of Pawnee Cove Park.
5	A	8	At the red channel marker south of Walnut Creek Park.
6	A	16	At the black channel marker downstream from Osage Point.

*Main reservoir (R), Cimarron arm (C), Arkansas arm (A).

cloud and wave effects. Underwater measurements were corrected for immersion effect.

The photosynthetic photon flux density (PPFD), the number of photons in the 400 to 700 nm waveband incident per unit time on a unit surface, was measured with the photometer and sensor. Measurements, integrated over 100 sec and corrected for immersion effect, were made at the surface, midpoint, and bottom of the photic zone.

Photosynthetic photon flux fluence rate (PPFFR), which is the integral of PPFD at a point over all directions about the point, was measured at the surface, midpoint, and bottom of the photic zone. This is a measurement of both flat-plane and scattered light usable by algal populations. These readings were taken with the Li-Cor photometer equipped with a Li-Cor LI-193SB spherical sensor. Measurements were corrected for immersion effect and integrated over 100 sec.

Chemical Parameters

All water samples were collected with a 2.2 liter horizontal, Van Dorn bottle (Wildco, Saginaw, MI). Samples were placed in 1 liter plastic bottles, stored on ice, and analyzed within 24 h. Chlorophyll *a* measurements were made on 300 ml samples from the surface, midpoint, and bottom of the photic zone of each station. Algae in the samples was concentrated through a 0.45 porosity membrane filter (Gelman GA-6) and macerated to disrupt the cells. Samples were next steeped in about 7 ml of 90% aqueous acetone for 24 h in darkness at 4°C. The extract was then clarified by centrifuging at 500 g for 20 min. Chlorophyll *a* in the extract was computed based on the optical density of the extract at 663 nm measured on a Varian model 635 spectrophotometer. This was compared to a series of standards of pure chlorophyll a which were plotted against light absorbance. The concentration of chlorophyll a in the sample was obtained from this graph ($r=0.999$) and calculations made using the following formula (Environmental Progection Agency 1973):

$$\text{Chlorophyll } \underline{a} \text{ (mg/l)} = \frac{\text{sample conc (mg/l) x Volume of extract (l)}}{\text{Volume of sample (l)}}$$

Dissolved oxygen, temperature, pH, and specific conductance of the water at the surface, midpoint, and bottom of the photic zone was measured with a Hydrolab model 4014 (Hydrolab Corp., Austin, TX) water quality instrument. The instrument was calibrated prior to each sample trip.

A 30 ml subsample of water collected at the surface, midpoint, and bottom of the photic zone of each station was agitated and the turbidity determined on a Monitek Model 21 nephelometer (Monitek, Inc., Redwood City, CA). This instrument passes an intense, collimated beam of white light through the sample and the measurement is made at 90 degrees to this beam. The results are expressed in nephelometric turbidity units (NTU).

Samples were collected at the surface, midpoint, and bottom of the photic zone at each station and analyzed for total phosphorus. Initial digestion followed the persulfate procedure of standard methods (APHA 1970). One ml of H_2SO_4 and about 0.4 g of ammonium persulfate was combined with 50 ml of the sample in an Erlenmyer flask. The covered flask was heated at 20 psi for 30 min in an autoclave and cooled. Sample volume was then adjusted to 50 ml with distilled water. Eight ml of an ascorbic acid and ammonium molybdate solution (APHA 1970) was pipeted into the sample and color was allowed to develop for 10 min. A Varian model 635 spectrophotometer, at a wavelength of 880 nm, was used with 10 cm lightpath cuvettes. The value obtained was compared to a curve developed from a series of standards and total phosphorus content determined.

Statistical Methods

Statistical comparisons were conducted using the Statistical Analysis Systems, Inc. computer programs (Barr et al. 1976). Data were arranged as an experiment with replication and individual analyses of variance performed for each parameter using the General Linear Models procedure. Sources of variation within each test included the date, station, and depth (except Secchi disc transparency and weather variables). When the analysis of variance indicated significant difference at the 95% confidence level, Duncan's multiple range test was used to locate where the variation lay within a source. The Stepwise procedure was used to obtain linear regression formulas to describe various relationships. It was also used to construct the multi-factor model. A significance level of 0.05 is used for all statistical tests throughout this report.

CHAPTER V

RESULTS OF THE STUDY

Phosphorus

Total phosphorus (TP) ranged from less than 3 to 66 mg/m^3 (Table 3). Stations in the upper reach of each arm had significantly more total phosphorus than in the lake and greater concentrations existed in the Arkansas River arm than in the Cimarron River arm (Fig. 2). Mean total phosphorus peaked at 29 mg/m^3 in March and declined through summer (Fig. 3). Concentrations increased in September and October. Total phosphorus did not vary significantly with depth.

Chlorophyll a

Significant difference in chlorophyll a levels existed by station and date. Significantly greater concentrations occurred at the upper station in both arms than at the lower stations (Fig. 3). Values were around 30 mg/m^3 at the upper stations and 18 mg/m^3 in the main pool. Concentrations exceeded 28 mg/m^3 in March and June and were less than 22 mg/m^3 in other months except October (Fig. 2). Although chlorophyll a decreased slightly with depth in the photic zone, the differences were not significant.

Table 3. Data collected in Keystone Lake from 26 March to 29 October 1981.

Parameter	Units	Number of samples	Mean	Range	SD
Water temp	C	267	22.5	11.3-31.3	5.9
PPFD	$\mu Es^{-1}m^{-2}$	237	375.5	1.1-1734.0	494.5
PPFFR	$\mu Es^{-1}m^{-2}$	162	508.2	3.5-2380.0	690.4
Photic zone	m	95	2.7	0.8-4.8	0.9
Secchi disc	m	95	0.9	0.3-1.5	0.3
Conductance	μmhos	267	2562	1300-3500	463
Dissolved Osygen	mg/l	267	8.7	4.3-14.4	1.7
pH	units	267	8.7	7.3-9.3	0.3
Total phosphorus	mg/m^3	267	14	2-66	10
Chlorophyll a	mg/m^3	267	23	3-65	13
Turbidity	NTU	267	7.3	1.7-24.0	5.4
Air temp	C	89	24.0	13.1-31.7	5.5
Cloud cover	%	89	25	0-100	27
Wind velocity	km/h	88	13	0-24	5.7
Wind direction	from N(0)	88	148	0-335	88
TSI-chlorophyll	units	95	69.0	53.2-79.3	4.9
TSI-phosphorus	units	95	39.0	27.4-63.2	8.3
TSI-Secchi disc	units	94	62.0	54.2-77.4	4.8
TSI-NTU	units	95	63.3	52.1-76.8	6.2

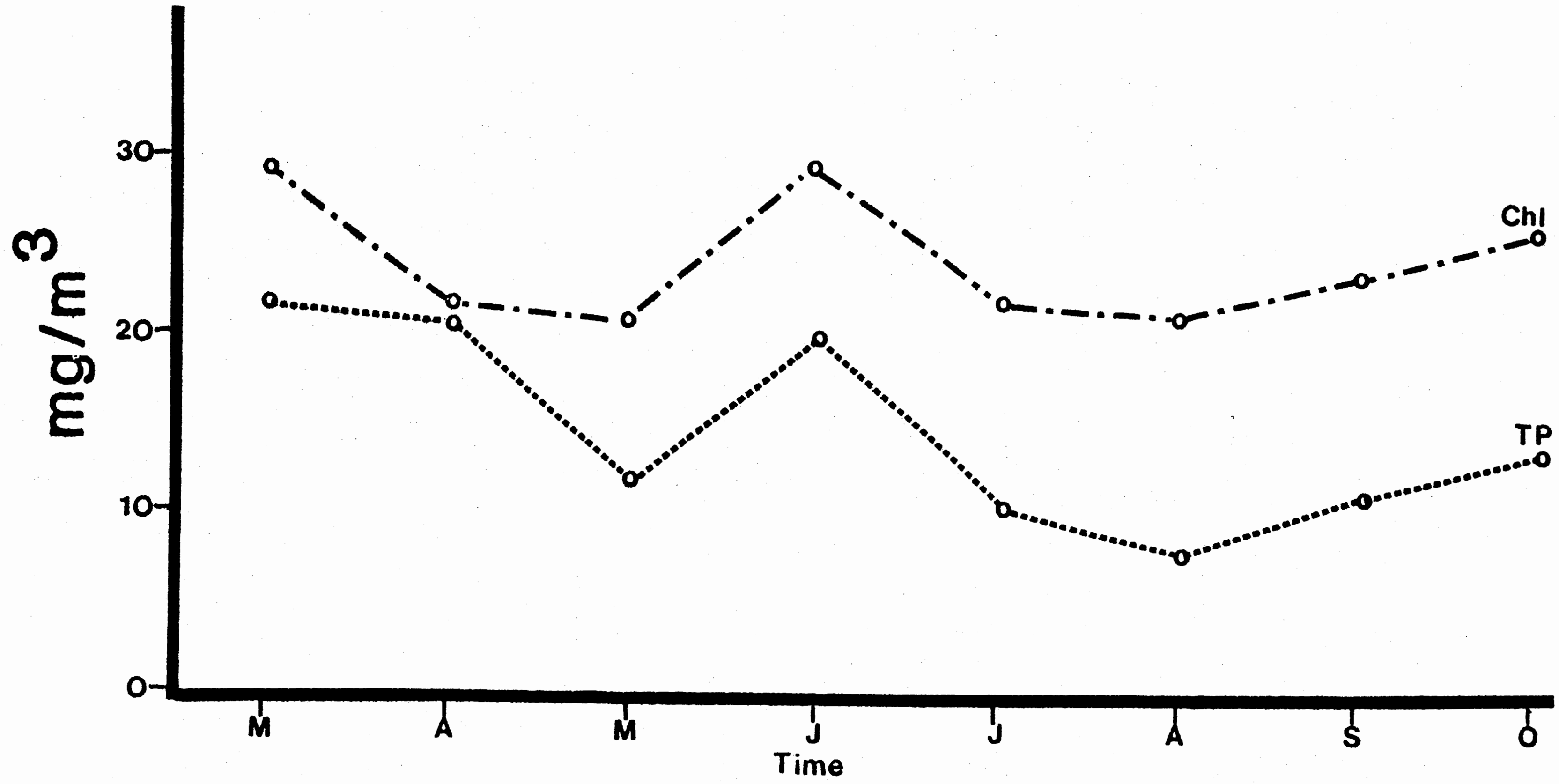

Figure 2. Temporal variation in total phosphorus and chlorophyll a in Keystone Lake.

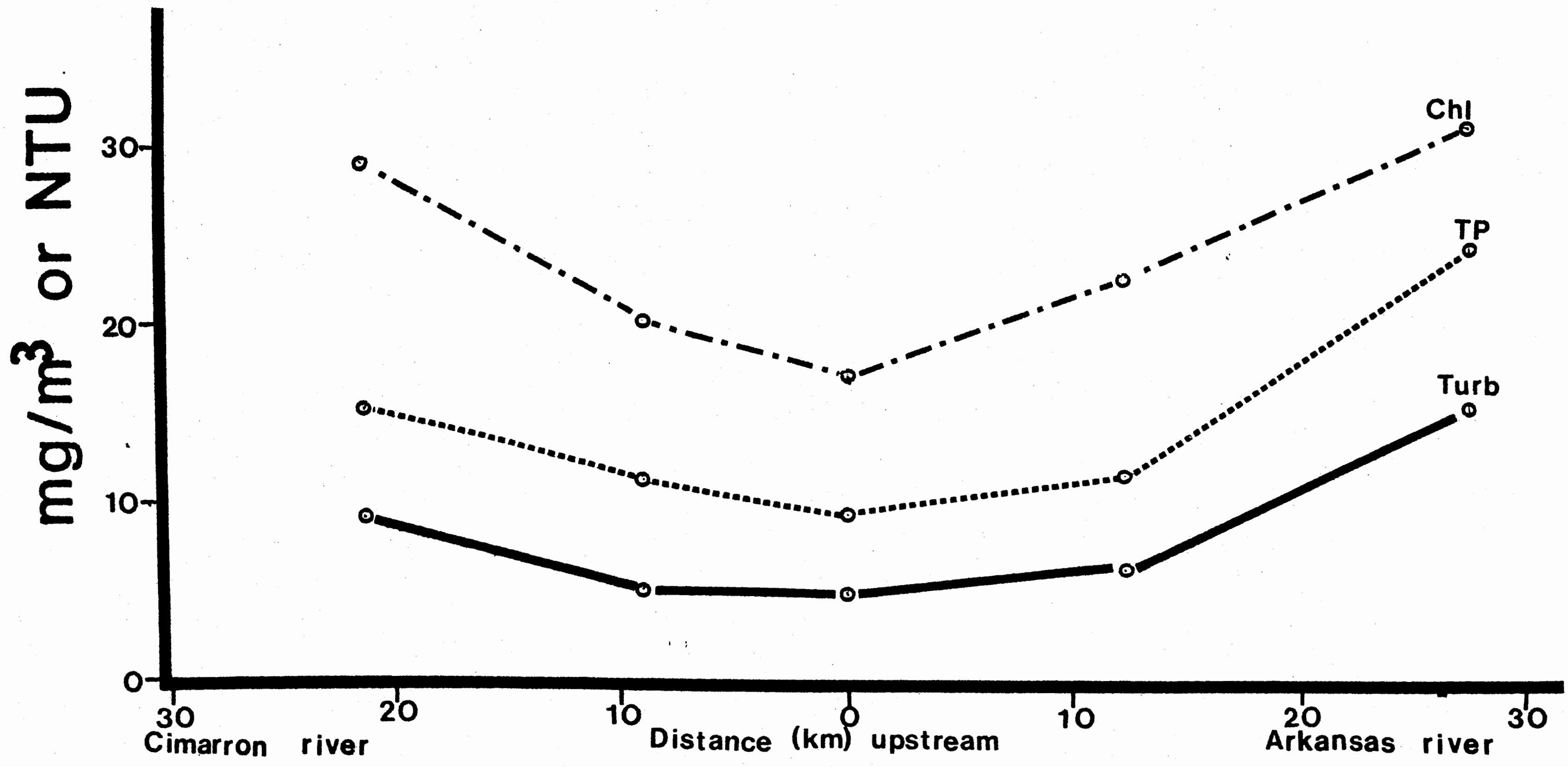

Figure 3. Spatial variation in total phosphorus, chlorophyll a, and turbidity in Keystone Lake.

Light Penetration

The depth at which 1% of the surface light remained varied significantly with both station and date. Stations at the lower end of the lake had a deeper mean photic zone depth, about 3.5 m, than other stations. The upper portions of the two arms had the shallowest photic zone depths, with the Arkansas River arm shallower than the Cimarron arm (Fig. 4). Mean photic zone depth of about 3.6 m was not significantly different in March and May. Mean values in July, August, and September averaged about 2.7 m (Fig. 5).

Secchi disc transparency varied significantly by both station and date. Stations at the lower end of the lake had the largest mean Secchi transparency, about 1.1 m (Fig. 4). Intermediate Secchi values, avaeraging around 0.9 m, were found at stations in the lower part of the main arms. Stations in the Cimarron River arm had greater Secchi values than similar stations in the Arkansas River arm. The greatest Secchi depths occurred in August and May (Fig. 5).

Although photosynthetic photon flux density (PPFD) did not vary significantly by station, significant variation by date and depth occurred. The insignificant variation by station indicates measurements were not affected by sample time. By date, PPFD followed the seasonal trend of solar incident angle. The maxima of 454 $\mu Es^{-1}m^{-2}$ occurred in June. Each region of the photic zone was significantly different in PPFD. Mean value at the surface was 876 $\mu Es^{-1}m^{-2}$, decreasing to 81 $\mu Es^{-1}m^{-2}$ at the midpoint of the photic zone and 18 $\mu Es^{-1}m^{-2}$ at the bottom of the photic zone.

Photosynthetic photon flux fluence rate (PPFFR) was closely related to PPFD and also varied significantly by date and depth. PPFFR peaked

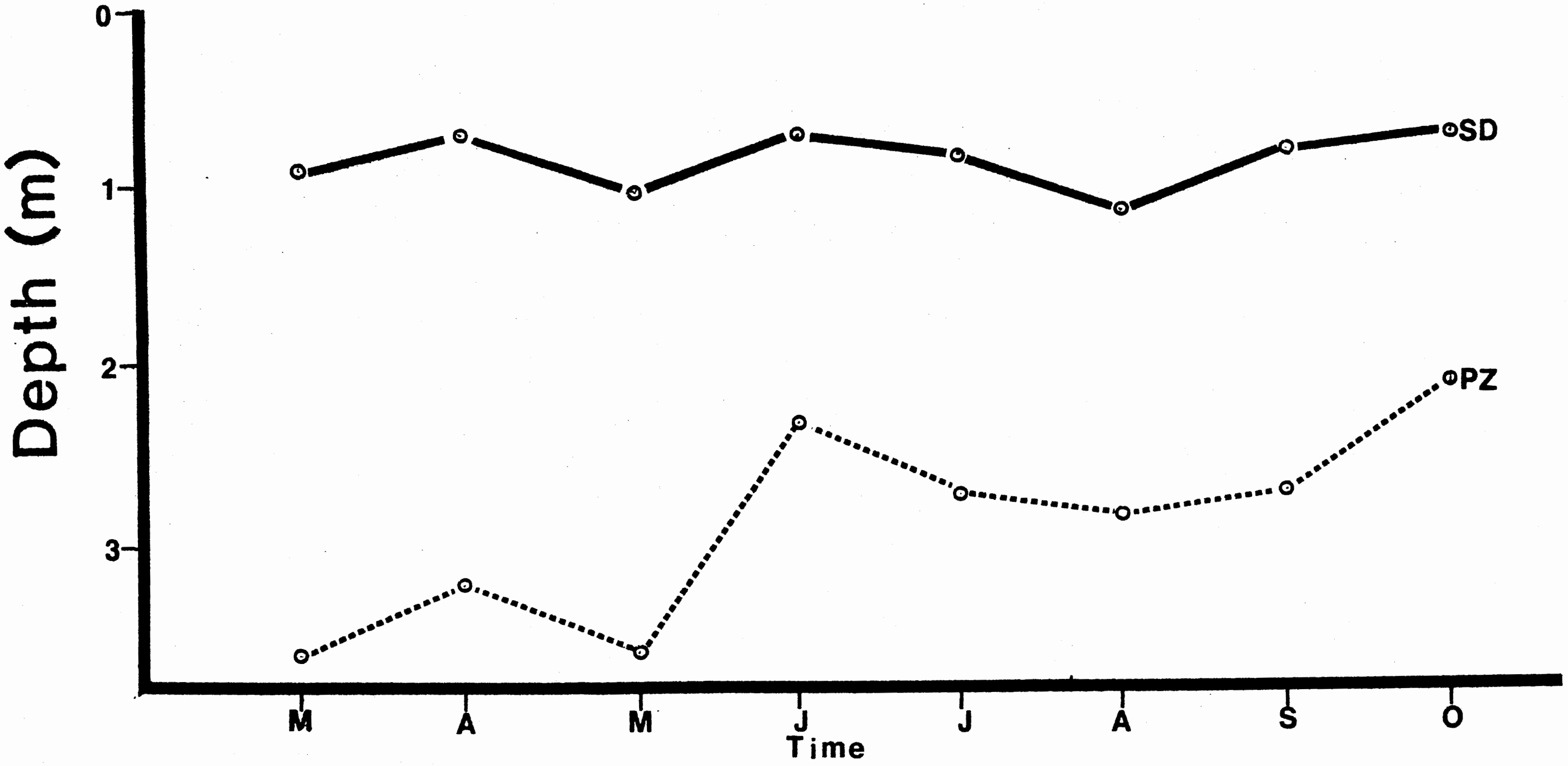

Figure 4. Temporal variation in Secchi disc transparency and photic zone in Keystone Lake.

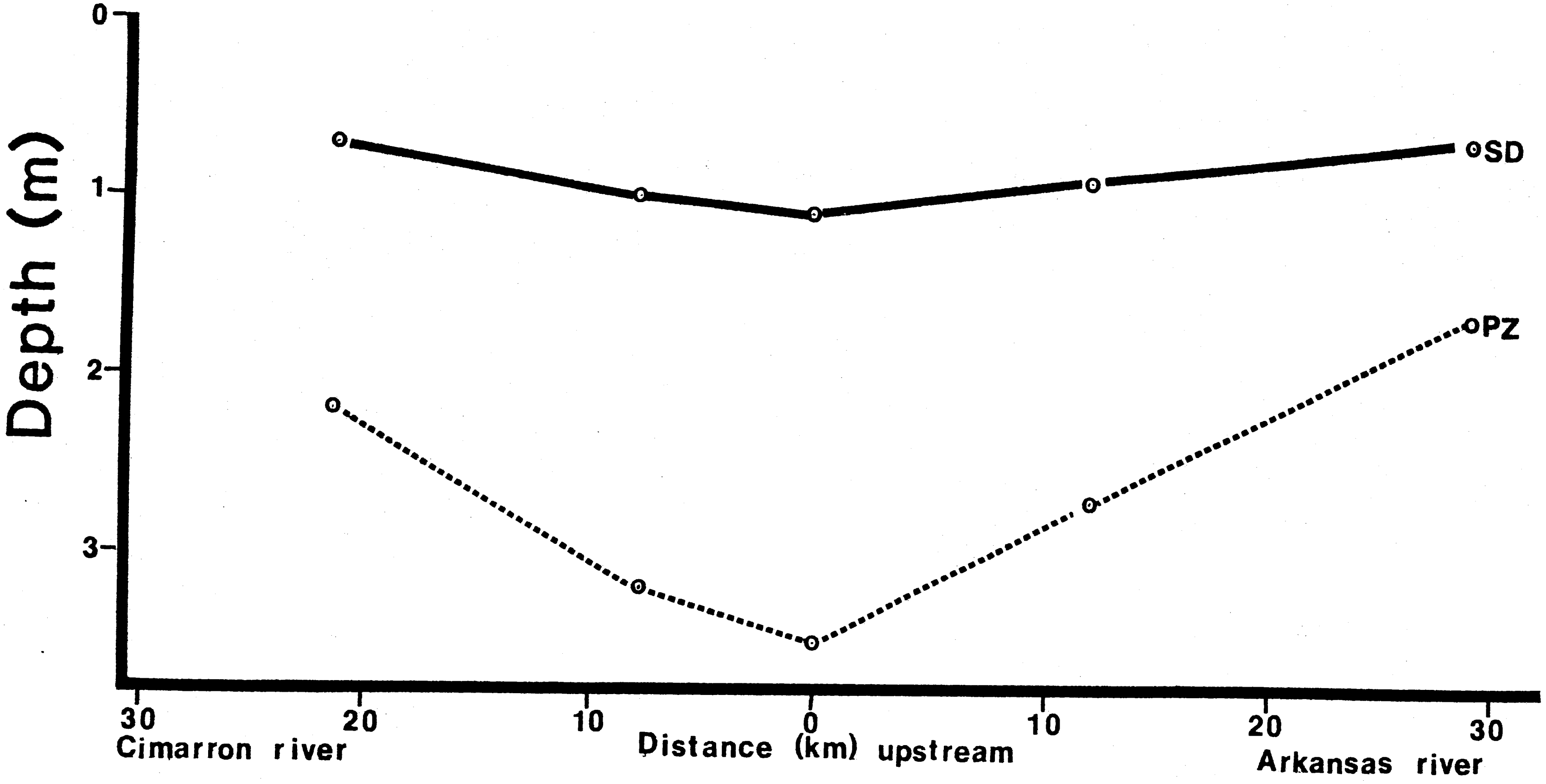

Figure 5. Spatial variation in Secchi disc transparency and photic zone in Keystone Lake.

at 671 $\mu Es^{-1}m^{-2}$ in June and was similar to the seasonal trend of the solar incident angle. PPFFR was significantly different in each of the three regions of the photic zone. Surface measurements averaged 1350 $\mu Es^{-1}m^{-2}$, midpoint values averaged 155 $\mu Es^{-1}m^{-2}$, and the mean PPFFR was 20 $\mu Es^{-1}m^{-2}$ at the bottom of the photic zone.

Turbidity varied significantly by station and date, but not by depth. The clearest water, with a turbidity around 3.8 NTU, occurred near the dam (Fig. 3). Stations in the upper ends of the two arms had significantly greater turbidity than other stations with the upper Arkansas River arm most turbid. The Arkansas River arm stations, with mean turbidity of 5.5 and 14.6 NTU, were more turbid than similar stations in the Cimarron arm, which averaged 3.9 and 10.1 NTU. The clearest water occurred in September and May.

In Situ Measurements

Conductivity showed singificant difference by station and date, but not by depth. Mean conductivity was 2992 μmhos/cm in the Cimarron arm and 2183 μmhos/cm in the Arkansas River arm. Stations in the main body of the lake were intermediate in conductance. Average values ranged from 2061 μmhos/cm in March to 3191 μmhos/cm in May.

Water temperature varied significantly by station, date, and depth. Values ranged from 11.3 to 31.3°C during the study. Stations in the Arkansas River arm were significantly warmer than those in the Cimarron River arm, averaging 23.1 and 22.2°C, respectively. Stations in the main lake were coolest.

Dissolved oxygen varied significantly by station, date, and depth. The greatest mean dissolved oxygen, about 9.0 mg/l, was found at the upper stations in the Cimarron River arm and in the lower Arkansas River. Variations among other stations were not significant. The trend by date was similar to water temperature. Cooler months had higher mean dissolved oxygen concentrations. Values ranged from 10.4 mg/l in March and October to 6.8 mg/l in August. The lowest level in the photic zone had a mean dissolved oxygen of 8.1 mg/l.

The pH varied significantly with station, date, and depth. the Cimarron River arm, with a mean pH of 8.8, was significantly higher than the Arkansas River stations, which averaged 8.5. The main body of the reservoir was intermediate in pH. pH was lowest in August through October and highest in July. The deepest strata in the photic zone had significantly lower pH than other depths.

Physical Factors

Weather variables followed the expected trends. Air temperature varied by station and date, ranging from 13.1 to 31.7°C. The correlation with station is an indication that efforts to sample stations at approximately the same time of day were successful. Rain and cloud cover varied significantly only by date. Wind speed, which was as high as 24 km/h and direction did not vary significantly by station or date.

CHAPTER VI

ECOLOGICAL RELATIONSHIPS

Secchi Disc-Chlorophyll a Relationship

A graph of Secchi disc transparency versus chlorophyll a (Fig. 6) is similar to one by Carlson (1977). The graph illustrates how large changes in chlorophyll a result in only small changes in Secchi disc readings. In Keystone Lake, where the minimum and maximum Secchi disc values differed by only 1.2 m, the Secchi disc lacked the sensitivity required to predict accurately chlorophyll a concentration. Although Megard et al. (1980) believed this loss of sensitivity was most pronounced at chlorophyll concentrations above 30 mg/m^3, concentrations of chlorophyll between 2 and 66 mg/m^3 in Lake Keystone failed to provide adequate correlations with Secchi disc transparency.

The inclusion of larger Secchi disc values allowed Carlson (1977) to identify a non-linear component in the Secchi disc-chlorophyll a relationship. His log-log transformation resulted in the following equation:

$$\ln SD = 2.04 - 0.68 \ln Chl \quad (n=147,\ r=0.93).$$

The same regression for the data from Keystone Lake produced:

$$\ln SD = 0.39 - 0.18 \ln Chl \quad (n=94,\ r=0.26).$$

The latter correlation was significant but not usable for predictive purposes; untransformed data yielded a slightly greater correlation (r=0.35). This discrepancy in correlation between Carlson's equations

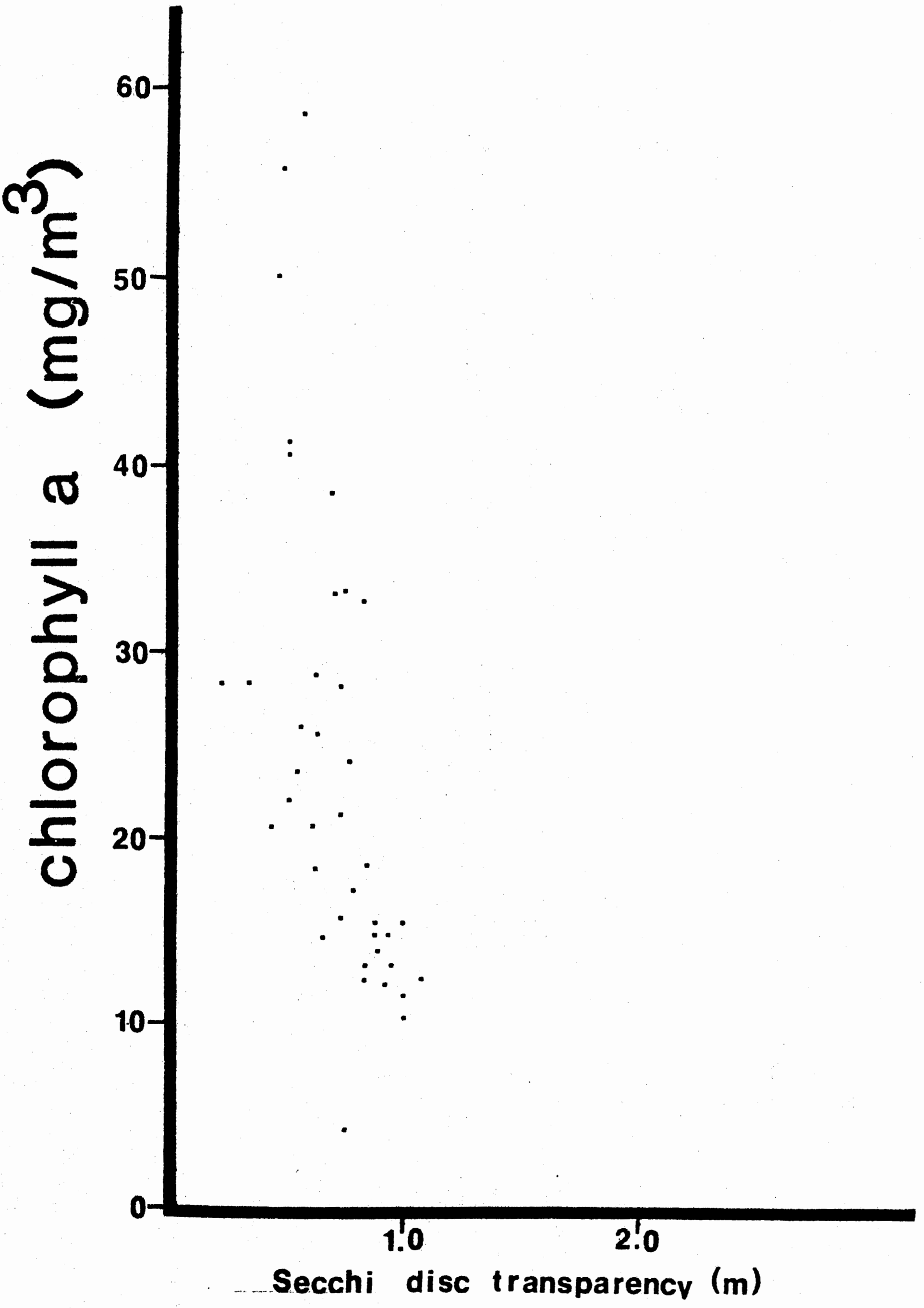

Figure 6. Relationship between Secchi disc transparency and chlorophylla in Keystone Lake.

and this study has been noted in other comparisons of natural lakes versus artificial impoundments (Taylor et al. 1979, 1980), and this has been attributed to higher non-chlorophyll turbidity generally associated with artificial lakes. The attenuation of light by these particles disrupts the theoretical direct linear relationship between transmission of light in water and chlorophyll a. Measurements of transparency made with a Secchi disc are poorly suited to establishing relationships since the non-chlorophyll turbidity scatters light as it travels to the disc and again as it is reflected from the disc towards the user.

Secchi Disc Versus Other Transparency Measurements

Two alternate methods of measuring turbidity and their relationship to chlorophyll a were evaluated. These methods, the submarine photometer and nephelometric turbidity measurements, lack the ease and economy of Secchi disc measurements. However, the photometer measures the light after only one trip through the water column and resembles a laboratory spectrophotometer in function. The turbidimeter measures the light scattered by all particles in the sample.

Photosynthetic photon flux fluence rate (PPFFR) provided more accurate measurements of photic zone than PPFD, since the scattered light measured by PPFFR is usable by phytoplankton (Combs 1977). The true photic zone, as measured by PPFFR, exceeded the value from PPFD measurements by 8 to 21%. The ratio of PPFD to PPFFR indicates the amount of light diffusion in the environment and thus is an indication of light scattering particles. For a collimated beam at normal incident angle the measurements are equal; while for perfectly difuse radiation, the PPFFR is four times the PPFD (McCree 1981). At Keystone Lake, the mean PPFD:PPFFR ranged from 1.5 at the surface to 2.4 at the bottom of the photic zone. The deviation from unity at the surface resulted from atmospheric diffusion, while the increased ratio at the bottom can be attributed to particles in the water column. Water diffused light more in the Arkansas River arm than in the Cimarron River arm. The least diffusion occurred in the main lake.

When mean values are plotted by station or date, a good correlation exists between Secchi disc transparency and photic zone measurements made with the submarine photometer (Fig. 4 and 5). The relative insensitivity of the Secchi disc as a measure of light penetration is especially obvious in the more turbid, upper river arms. In general, Secchi disc depth represented 30 to 50% of the photic zone depth as measured by PPFD. This is much less than the ability to approximate the photic zone depth attributed to the Secchi disc by Lorenzen (1978) and Beeton (1958). Individual Secchi disc values were correlated with photic zone depth by the following equation:

$$SD = 0.438 + 0.053\ PZ\ (n=94,\ r=0.61).$$

Photic zone (PZ) measurements, although inherently more accurate than Secchi disc readings, were not well correlated with either phosphorus or chlorophyll a. The following equations describe these relationships at Keystone Lake:

$$PZ = 10.84 - 0.123\ \text{Phos}\ (n=94,\ r=0.36),\ \text{and}$$

$$PZ = 11.95 - 0.123\ \text{Chlor}\ (n=94,\ r=0.44).$$

Neither formula benefited greatly from log or log-log transformations. Obviously, some factor prevents the relationship between photic zone and phosphorus or chlorophyll a from functioning as it does in natural lakes.

Near surface measurements of nephelometric trubidity (Turb) were well correlated with Secchi disc (SD) and photic zone measurements. The correlations were described by:

$$\text{Turb} = 16.44 - 1.05\ \text{PZ}\ (n=94,\ r=0.67),\ \text{and}$$

$$\text{Turb} = 18.7 - 13.03\ \text{SD}\ (n=94,\ r=0.72).$$

Turbidity and total phosphorus had a greater correlation than Secchi disc and phosphorus or photic zone and phosphorus. The calculated regression formula was:

$$\text{Turb} = 2.07 - 0.36\ \text{Phos}\ (n=94,\ r=0.67).$$

Chlorophyll a was only slightly correlated with nephelometric turbidity. The regression formula,

$$\text{Turb} = 3.33 + 0.36\ \text{Chlor}\ (n=94,\ r=0.35),$$

was improved somewhat (r=0.44) by log-log transformation. Other studies of Southern Great Plains reservoirs (Harris and Silvey 1940; Spangler 1969) failed to correlate chlorophyll and turbidity.

Thus, nephelometric turbidity measurements are a good replacement for either Secchi disc transparency or photic zone. Turbidity readings also gave good correlation with total phosphorus, but were poorly related to chlorophyll a. The relatively high correlation of turbidity to phosphorus is an indication the turbidity results from particles to which the phosphorus is adsorbed. The slight correlation between turbidity or phosphorus and chlorophyll a shows that phosphorus must be associated with non-algal particles.

Effect of Inflow

Lake Keystone was not phosphorus limited soon after impoundment (Eley 1970). The present study did not attempt to determine limiting nutrients; however, the nitrogen to phosphorus ratio of a lake can be used as an indication of limiting nutrients. Lakes with nitrogen:phosphorus ratios greater than 15:1 are considered phosphorus limited (Sawyer 1969). According to data from the Oklahoma State Department of Health (1980) the nitrogen:phosphorus ratio in this segment of the Arkansas River greatly exceeds 15:1, and it appears Keystone Lake is now phosphorus limited. The same particles which transport phosphorus into the aquatic system also reduce the photic zone depth. It is probable that high turbidity during large inflows temporarily prevent algal densities from increasing in response to the phosphorus associated with the inflows. Therefore, the factor limiting algal growth may change from being phosphorus limitation to light limitation depending on inflow rates.

An examination of flow data for the Arkansas and Cimarron rivers (Corps of Engineers, unpublished) immediately above Lake Keystone reveals the importance of flow to the lake. Although flows in the two tributaries were significantly different, they generally followed a similar trend. An exception to this occurred in September, when flows in the Cimarron River increased while flows in the Arkansas River decreased. Turbidity in each arm was significantly correlated with flow. As expected, total phosphorus also was significantly correlated with flow in the major tributaries. Chlorophyll a concentrations followed the trend of inflows so long as inflow was not excessive. When the maximum inflow rate in the 25 days before sampling exceeded about

5000 cfs, chlorophyll a concentrations dropped dramatically in that arm. This may have been influenced by increased turbidity.

Carlson's Trophic State Index

The trophic state index advocated by Carlson (1977) was calculated for each sample date and station. Calculations were made using three key parameters; Secchi disc, chlorophyll a, and total phosphorus. By date, the phosphorus method of calculation yielded significantly different values (Fig. 7). Although calculations based on the three parameters followed a similar temporal pattern, the values based on chlorophyll a followed the pattern less precisely. The phosphorus based figures were about 30 to 40% lower than the other methods and had a greater standard deviation (Table 3). All three methods generally followed the pattern of inflows, except for a decrease in trophic state index during May when flows increased. The reason for this is unknown.

A plot of the three forms of trophic state index by station (Fig. 8) showed all three methods followed a similar spatial trend. The more turbid stations in the upper arms gave higher trophic state indices. The phosphorus method produced significantly lower values.

It appears Calson's trophic state index contains several flaws which negate its usefulness in artificial lakes. The relationships among Secchi disc, chlorophyll a, and total phosphorus are not strong in Keystone Lake or in many other reservoirs (Jones and Bachmann 1976; Canfield and Bachmann 1981). Calson and his critics (Lorenzen 1980; Megard et al. 1980) recognized his inability to fit his data to Beer's law and attributed this to attenuation of light by non-chlorophyll particles. Carlson believed the ease and inexpense of Secchi disc

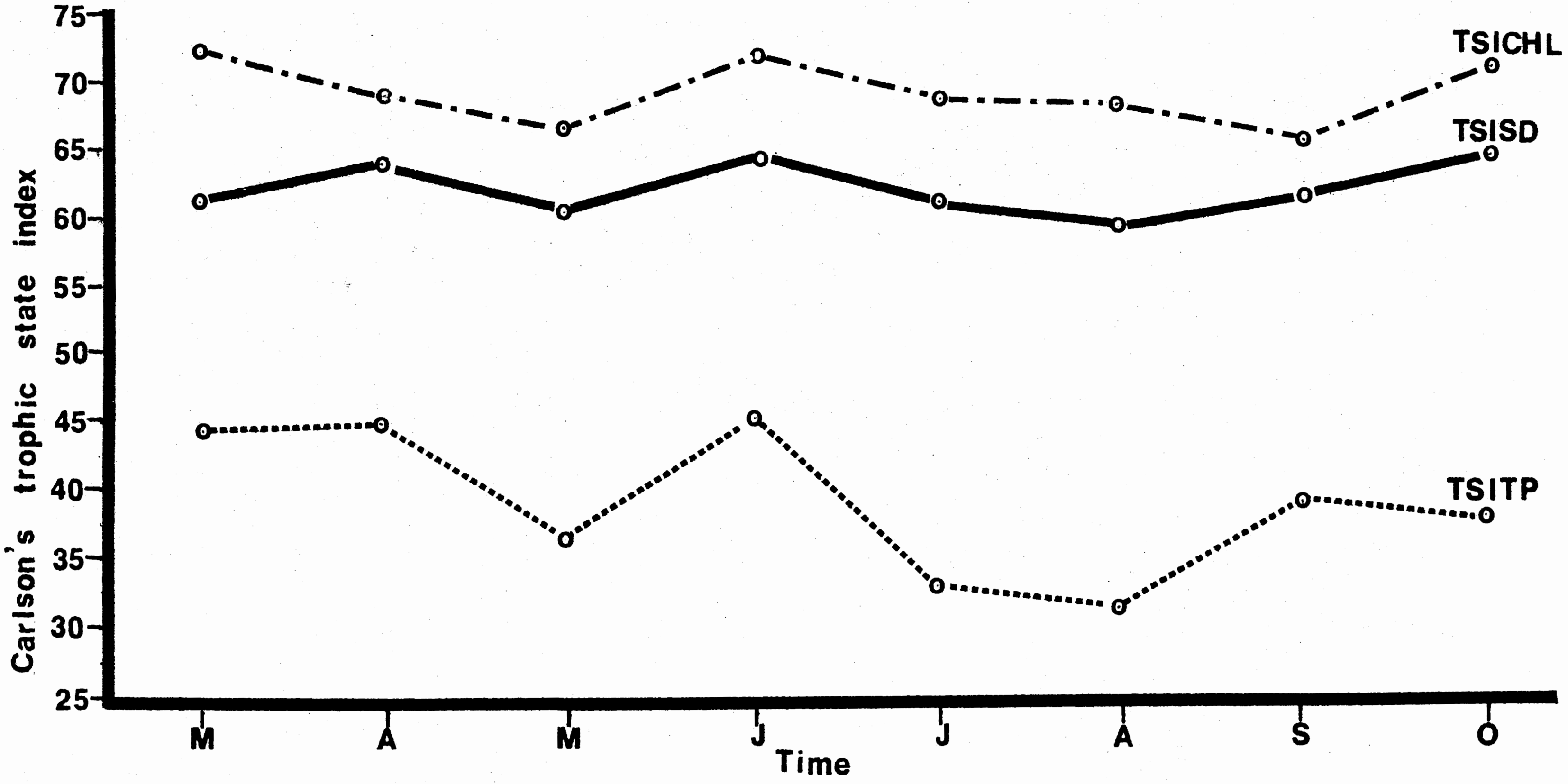

Figure 7. Temporal variation in the three methods of calculating Carlson's trophic state index.

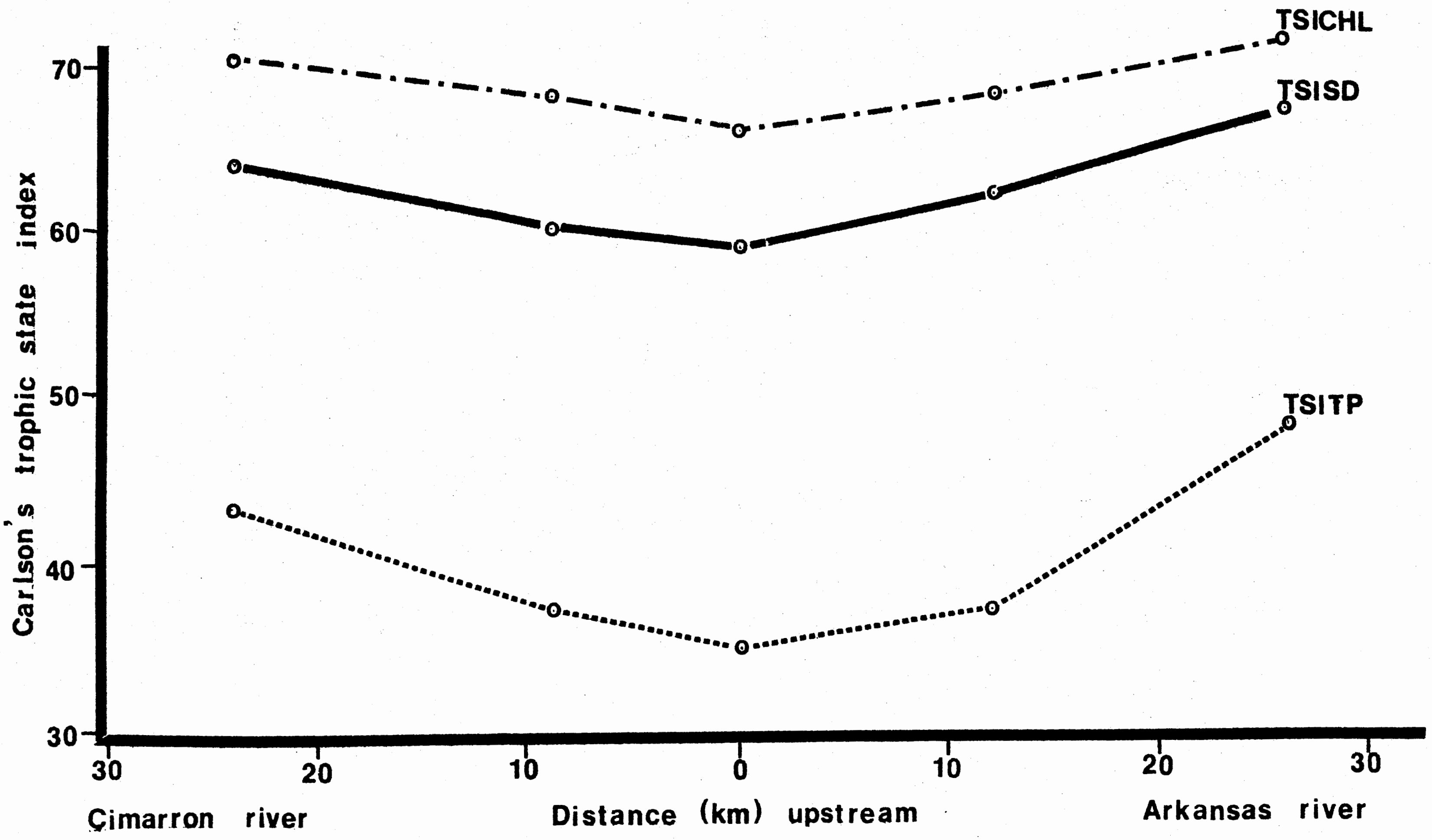

Figure 8. Spatial variation in the three methods of calculating Carlson's trophic state index.

measurements outweighed the disadvantages of inaccuracy, and noted Secchi disc usually provided a trophic state index value similar to the value derived from chlorophyll. This was the case at Keystone Lake. Probably limitations of the Secchi disc, such as lack of sensitivity and large variation among users, more than offset its supposed advantages.

Trophic state index values obtained from phosphorus readings were significantly different from the chlorophyll and Secchi disc methods. The phosphorus index at Keystone Lake provides an interesting contrast to Carlson's (1977) Minnesota lakes. Phosphorus trophic state index was generally the larger of the three forms in the Minnesota lakes, while at Keystone Lake it was the lowest. Carlson praised the phosphorus calculations for their relative stability; yet, at Keystone Lake these readings were the most variable. Apparently, most of the phosphorus in Carlson's natural lakes was associated with the living cells of chlorophyll bearing plants. In Keystone Lake, it is probable most phosphorus is associated with inorganic particulate matter washed into the lake from the watershed. Another supposed advantage of the phosphorus method was its ability to provide a meaningful value during seasons when algal biomass was far below potential maximum (Carlson 1977). However, if phosphorus is limiting, it is not apparent why algal biomass would not be at a maximum.

Light attenuation by non-chlorophyll particles was more important than that by chlorophyll particles in Keystone Lake. Therefore, the addition of such factors to Carlson's trophic state index might make the index more applicable to artificial lakes. Carlson (1977) originally used Secchi disc because it gave a good correlation with algal biomass. Algal blooms are of concern to the public. Nusiance algal blooms are unknown in many turbid lakes such as Keystone, and it is not apparent whether Secchi disc or chlorophyll a calculations of Carlson's index accurately describe such situations. Since phosphorus is limiting in many reservoirs, the phosphorus related trophic state index should be retained. However, due to the failure of Carlson's phosphorus index to give values similar to the other two parameters, another method of calculation should be considered. Photic zone measurements were rejected as an alternate method of calculation since they were poorly correlated with phosphorus. Nephelometric turbidity measurements were strongly related to light penetration and phosphorus, the two limiting factors at Keystone Lake.

The addition of nephelometric turbidity to Carlson's index was accomplished by setting a 0 value of the index equal to 200 NTU. This is full scale deflection on the Monitek Model 21 turbidimeter, and it is doubtful that this value would ever be exceeded. The maximum index value of 100 represents 0.01 NTU; exceedingly clear water. The formula used was:

$$\mathrm{TSI(NTU)} = 10[6-2(\ln 2) + \ln \mathrm{NTU}].$$

The calculation of trophic state index using Secchi disc transparency, chlorophyll, and turbidity is show in Table 4.

Calculation of the trophic state index for the Keystone Lake data gave values which were not significantly different than those obtained for the chlorophyll a and Secchi disc methods. It appears this turbidimetric method of calculation might be an appropriate indicator of trophic state in artificial lakes.

Table 4. Carlson's trophic state index with calculation by nephelometric turbidity.

TSI (units)	Secchi disc (m)	Near surface chlorophyll *a* (mg/m^3)	Near surface nephelometric turbidity (NTU)
0	64	0.04	0.01
10	32	0.12	0.03
20	16	0.34	0.08
30	8	0.94	0.2
40	4	2.6	0.6
50	2	6.4	1.5
60	1	20	4
70	0.5	56	11
80	0.25	154	30
90	0.12	427	81
100	0.062	1183	200

A Model of the Relationships

The maximum R^2 improvement technique of the Statistical Analysis System, Inc. Stepwise Procedure (Barr 1976) was used to construct a multivariate model of several variables. These variables were maximum flow in the 25 days preceeding sampling, Secchi disc transparency, photic zone depth, chlorophyll a, total phosphorus, and nephelometric turbidity. Various models were attempted with each parameter in turn designated as the dependent variable and modeled against the remaining factors. The significance level for inclusion of a parameter into the model was 0.15. Stations were separated into three groups; main pool, lower arms, and upper river arms. Each of the three groups was modeled individually. Measurements of all parameters except flow were made at previously described stations. Flow measurements for all models were made at Corps of Engineers gaging stations near Perkins, Oklahoma for the Cimarron River and Ralston, Oklahoma for the Arkansas River.

When used as dependent variables, flow and phosphorus were correlated only with turbidity in the upper river stations. The relationship of these parameters to the remaining variables was so weak ($r < 0.35$) they could not be used by the modeling technique. This reinforces the importance of flows and the phosphorus containing particulate matter washed into Keystone Lake.

The modeling procedure found chlorophyll a weakly ($r=0.44$) related only to Secchi disc transparency in the upper river arms. Secchi disc transparency for these sites could be described by a three factor model consisting of turbidity, chlorophyll a, and photic zone and the correlation was relatively strong ($r=0.62$).

The most highly correlated multivariate model obtained was for turbidity in the upper stations:

$$\text{Turb} = 10.68 + 0.202\ \text{Phos} - 0.603\ \text{PZ} + 0.005\ \text{Flow} - 0.753\ \text{SD}\ (n=40,\ r=0.79).$$

Almost 70% of the sensitivity of this model resulted from the inclusion of phosphorus and flow. As expected, chlorophyll _a_ values could not be used for this model.

Models for lower arm and main pool stations were generally similar but less correlated. Flow provided considerably less sensitivity in those models.

CHAPTER VII

SUMMARY

1. Monthly measurements of limnological parameters were made at three depths in the photic zone for six stations at Keystone Lake, Oklahoma. The object was to determine the relationship between photosynthetically active radiation, Secchi disc transparency, chlorophyll _a_, and total phosphorus. The usefulness of Carlson's trophic state index was also evaluated.

2. Maximum chlorophyll _a_, total phosphorus, and turbidity all occurred in the upper reaches of the two main arms. Spatial and temporal trends were similar for these parameters.

3. It was not possible to predict adequately chlorophyll _a_ from Secchi disc readings due to interference by non-chlorophyll turbidity.

4. Secchi disc depth represented 30 to 50% of the photic zone as determined by PPFD values. The true photic zone, measured by PPFFR was around 10% greater than indicated by PPFD measurements.

5. Photic zone measurements were well correlated with Secchi disc transparency. They were poorly correlated with phosphorus and chlorophyll _a_ values.

6. Nephelometric turbidity was strongly correlated with photic zone depth, Secchi disc transparency, and total phosphorus, but not with chlorophyll _a_. It appears phosphorus at Keystone Lake is associated primarily with non-algal particles.

7. Keystone Lake is generally phosphorus limited. When peak inflows exceed about 5000 cfs, the main arms become light limited for a period of time.

8. Carlson's trophic state index was of limited usefulness at Keystone Lake due to the weak relationship among parameters such as chlorophyll _a_ and Secchi disc depth.

9. A modification of Carlson's trophic state index, using nephelometric turbidity, provided values similar to those derived from chlorophyll _a_ and Secchi disc measurements.

10. A multivariate model was constructed that adequately described turbidity in the upper reaches of Keystone Lake. A similar model for the lower areas of the lake was less precise.

LITERATURE CITED

ABERG, B., AND W. RODHE. 1942. Uber die Millieufaktorenin e. niger sudschwedischen Seen. Symb. bot. upsaliens. 5(3): 256.

AMERICN PUBLIC HEALTH ASSOCIATION. 1960. Standard methods for the examination of water and wastewater. 11th ed., Amer. Publ. Health Assoc., Washington, D. C. 874 p.

BANNISTER, T. T. 1974. Production equations in terms of chlorophyll concentration, quantum yield, and upper limit to production. Limnol. Oceanogr. 19: 1-12.

BARR, A. J., J. H. GOODNIGHT, J. P. SALL, AND J. T. HELWIG. 1976. A user's guide to SAS 76. SAS Institute Inc., Raleigh, North Carolina. 329 p.

BEETON, A. M. 1958. Relationship between Secchi disc readings and light penetration in Lake Huron. Trans. Am. Fish. Soc. 87: 73-79.

BRUNSKILL, G. J., D. W. SCHINDLER, S. E. M. ELLIOTT, AND P. CAMPBELL. 1979. The attenuation of light in Lake Winnipeg, Canada waters. Can. Fish. Mar. Serv. Manuscr. Rep. 0(1522): i-v, 1-79.

CANFIELD, D. E., AND R. W. BACHMANN. 1981. Prediction of total phosphorus concentrations, chlorophyll a, and Secchi depths in natural and artifical lakes. Can. J. Fish. Aquatic Sci. 38: 414-423.

CARLSON, R. E. 1977. A trophic state index for lakes. Limnol. Oceanogr. 22: 361-369.

_______. 1979. A review of the philosophy and construction of trophic state indices, p. 1-52. In T. Maloney [ed.], Lake and reservoir classification systems. USEPA Ecol. Res. Ser. EPA 600/3-79-074.

_______. 1980. More complications in the chlorophyll-Secchi disk relationship. Limnol. Oceanogr. 25:379-382.

CHAPRA, S. C., AND K. H. RECKHOW. 1979. Expressing the phosphorus loading concept in probalistic terms. J. Fish. Res. Bd. Can. 36: 225-229.

CIALDI, A. 1866. Sul moto ondoso del mare e su le correnti de esso specialmente auguelle littorali, 2nd ed. p. 258-288. Cited in ONI Transl. A-665, p. 1, Hydrographic Office, 1955.

COMBS, W. S. 1977. The measurement and prediction of irradiances available for photosynthesis by phytoplankton in lakes. Ph.D. thesis, Univ. Minn., Minneapolis. 87 p.

DILLON, P. J., AND F. H. RIGLER. 1974. The phosphorus-chlorophyll relationship in lakes. Limnol. Oceanogr. 19: 767-773.

DOBBINS, D. A., AND C. E. BOYD. 1976. Phosphorus and potassium fertilization of sunfish ponds. Trans. Am. Fish. Soc. 105: 536-540.

DUBINSKY, Z., AND T. BERMAN. 1979. Seasonal changes in spectral composition of downwelling radiance in Lake Kinneret (Israel). Limnol. Oceanogr. 24: 652-663.

EDMONDSON, W. T. 1980. Secchi disk and chlorophyll. Limnol. Oceanogr. 25: 378-379.

ELEY, R. L. 1970. Physicochemical limnology and community metabolism of Keystone reservoir, Oklahoma. Ph.D. thesis, Okla. State Univ., Stillwater. 240 p.

ENVIRONMENTAL PROTECTION AGENCY. 1973. Biological field and laboratory methods for measuring the quality of surface waters and effluents. USEPA Env. Monit. Ser., EPA 670/4-73-001.

HARRISS, B. B., AND J. K. G. SILVEY. 1940. Limnological investigations on Texas reservoir lakes. Ecol. Monogr. 10: 111-143.

HICKMAN, M. 1979. Seasonal succession, standing crop and determinants of primary productivity of the phytoplankton of Ministik Lake, Alberta, Canada. Hydrobiologia. 64: 105-122.

HUTCHINSON, G. E. 1957. A treatise on limnology. Vol. 1. Wiley and Sons, New York. 1015 p.

JONES, J. R., AND R. W. BACHMANN. 1976. Prediction of phosphorus and chlorophyll levels in lakes. J. Water Pollut. Contr. Fed. 48: 2176-2182.

JORGENSEN, E. G. 1969. The adaptation of plankton algae. 4. Light adaptation in different algae species. Physiol. Plant. 22: 1307-1315.

JUDAY, C., AND E. A. BIRGE. 1933. The transparency, the color and the specific conductance of the lake waters of northeastern Wisconsin. Trans. Wis. Acad. Sci. Arts Lett. 28: 205-259.

KINCANNON, D. F. 1979. A water quality study on Lake Keystone, Arkansas and Cimarron River, Oklahoma. U.S. Army Corps of Eng. Mimeogr. 189 p.

KIRK, J. T. 1975. A theoretical analysis of the contribution of algal cells to the attenuation of light within natural waters. 2. Sperical cells. New Phytol. 75: 21-36.

KRAMER, J. R., S. E. HERBES, AND H. E. ALLEN. 1972. Phosphorus: Analysis of water, biomass, and sediment, p. 51-104. In J. R. Kramer and H. E. Allen [eds.], Nutrients in natural waters. J. Wiley and Sons, New York.

LASENBY, S. C. 1975. Development of oxygen deficits in 14 southern Ontario lakes. Limnol. Oceanogr. 20: 993-999.

LICHTOKOPPLER, F., AND C. E. BOYD. 1977. Phosphorus fertilization of sunfish ponds. Trans. Am. Fish. Soc. 106: 634-636.

LORENZEN, M. W. 1978. Phosphorus models and eutrophication, p. 31-50. In R. Mitchell [ed.], Water pollution microbiology, V. 2. Wiley and Sons, New York.

________. 1980. Use of chlorophyll-Secchi disc relationships. Limnol. Oceanogr. 25: 371-372.

MALONEY, T. E., W. E. MILLER, AND T. SHIROYAMA. 1971. Algae responses to nutrient additions in natural waters. I. Laboratory analyses, p. 134-140. In G. E. Likens [ed.], Nutrients and eutrophication. Allen Press, Lawrence.

MCCREE, K. J. 1981. Photosynthetically active radiation. p. 82-111. In O. L. Lange, P. Nobel, B. Osmond, and H. Zeigler [eds.], Physiological plant ecology, V. 12A. Encyclopedia of plant physiology. Springler-Verlag, New York.

MEGARD, R. O., W. S. COMBS, JR., P. D. SMITH, AND A. S. KNOLL. 1979. Attenuation of light and daily integral rates of photosynthesis attained by planktonic algae. Limnol. Oceanog. 24: 1038-1050.

_______, J. C. SETTLES, H. A. BOYER, AND W. S. COMBS, JR. 1980. Light, Secchi disk and trophic states. Limnol. Oceanogr. 25: 373-377.

NICHOLS, K. H., AND P. J. DILLON. 1978. An evaluation of phosphorus-chlorophyll-phytoplankton relationships for lakes. Int. Revue ges Hydrobiol. 63: 141-154.

OGLESBY, R. T., AND W. R. SCHAFFNER. 1975. The response of lakes to phosphorus, p. 23-57. In K. S. Porter [ed.], Nitrogen and phosphorus-food production, waste and the environment. Ann Arbor Sci., Ann Arbor, MI. 217 p.

OKLAHOMA STATE DEPARTMENT OF HEALTH. 1980. 305(b) Technical report for Oklahoma. OSDH Env. Health Svcs., Oklahoma City. 129 p.

REST, W., AND G. F. LEE. 1978. Summary analysis of the North American (U.S. portion) OECD eutrophication project: Nutrient loading - lake response relationships and trophic state indices. U.S. EPA report EPA-600/3-78-008. Corvallis Environmental Research Lab., Corvallis, OR. 454 p.

ROBARTS, R. D. 1979. Underwater light penetration, chlorophyll a and primary production in a trophical African lake (Lake McIlwaine, Rhodesia). Arch. Hydrobiol. 86: 423-444.

RODHE, W. 1965. Standard correlations between pelagic photosynthesis and light, p. 365-382. In C. R. Goldman [ed.], Primary productivity in aquatic environments. Mem. 1st Ital. Idrobiol., 18 Suppl., Univ. Calif. Press, Berkeley.

SAWYER, C. N. 1952. Some new aspects of phosphates in relation to lake fertilization. J. Poll. Contr. Fed. 24: 768-777.

________. 1969. Basic concepts of eutrophication, p. 103-129. In G. W. Cox [ed.], Readings in conservation ecology. Meridith, Inc., New York.

SCHEIDER, W. A. 1978. Applicability of phosphorus budget models to small Precambrian lakes, Algonquin Park, Ontario. J. Fish. Res. Bd. Can. 35: 300-304.

SCHINDLER, D. W. 1978. Factors regulating phytoplankton production and standing crop in the World's freshwaters. Limnol. Oceanogr. 23. 318 p.

SPANGLER, F. L. 1969. Chlorophyll and carotenoid distribution and phytoplankton ecology in Keystone Reservoir, Tulsa, Oklahoma. Ph.D. thesis, Okla. State Univ., Stillwater. 61 p.

STEELE, J. H. 1962. Environmental control of photosynthesis in the sea. Limnol. Oceanogr. 7: 137-150.

SMITH, V. H. 1979. Nutrient dependence of primary productivity in lakes. Limnol. Oceanogr. 24: 1051-1064.

SZCZEPANSKI, A. 1968. Scattering of light and visibility in water of different types of lakes. Pol. Arch. Hydrobiol. 15: 51-77.

TAYLOR, W. D., L. R. WILLIAMS, S. C. HERN, AND V. W. LAMBOU. 1979. Phytoplankton water quality relationship in U.S. lakes, Part VII: Comparison of some new and old indices and measurements of trophic state. EPA 600/3-79-079. USEPA, Las Vegas, NV. 51 p.

________, V. W. LAMBOU, L. R. WILLIAMS, AND S. C. HERN. 1980. Trophic state of lakes and reservoirs. TR-E-80-3, Waterways Experiment Station, Vicksburg, MS. 15 p.

TOLSTOY, A. 1979. Chlorophyll a in relation to phytoplankton volume in some Swedish lakes. Arch. Hydrobiol. 85: 133-151.

TYLER, J. E. 1968. The Secchi disc. Limnol. Oceanogr. 13: 1-6.

VERDULIN, J. O. 1977. A simple equation relating total phosphorus to chlorophyll concentration in lakes. Proc. Int. Assoc. Theo. Appl. Limn.

WAGNER, J. F., AND M. PARKER. 1973. Primary production and limiting nutrients in a small subalpine Wyoming lake. Trans. Am. Fish. Soc. 102: 698-706.

WELCH, P. S. 1962. Limnology. McGraw-Hill, Inc., New York. 538 p.

WETZEL, R. G. 1975. Limnology. W. B. Saunders Co., Philadelphia, PA. 743 p.

WILLIAMS, L. R., V. W. LAMBOU, S. C. HERN, AND R. W. THOMAS. 1978. Relationships of productivity and problem conditions to ambient nutrients: National eutrophication survey findings for 418 eastern lakes. USEPA Ecol. Res. Ser. EPA-600/3-78-002.

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