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Limnological characteristics of Lake of the Ozarks, Missouri[1]

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With 3 figures and 1 table in the text

Introduction

Lake of the Ozarks, located in the Ozark Highlands of westcentral Missouri, U. S. A., was formed in 1931 by the construction of Bagnell Dam on the Osage River. The lake, which extends up the Osage River Valley 145 km, and into the Gravois, Grand Glaize, and Niangua River Valleys (Fig. 1), has a shoreline development of 20.6, a surface area of 24,100 ha, a volume of 2.37×10^9 m^3, and a mean flushing rate of 3.4/yr. Water from Lake of the Ozarks is used for generating electricity and the inflow, outflow, and reservoir volumes vary among years depending upon rainfall and water use. This study was designed to describe the limnological characteristics of Lake of the Ozarks prior to the completion of Truman Lake, a mainstream reservoir located on the Osage River above Lake of the Ozarks.

Methods and materials

Six stations located along the major axis of the reservoir and in the minor arms (Fig. 1) were sampled between late June and early September 1976—1979. Water transparency was determined by using a 20-cm Secchi disk, and light extinction (η/m) (no filter) was measured using an underwater photometer.

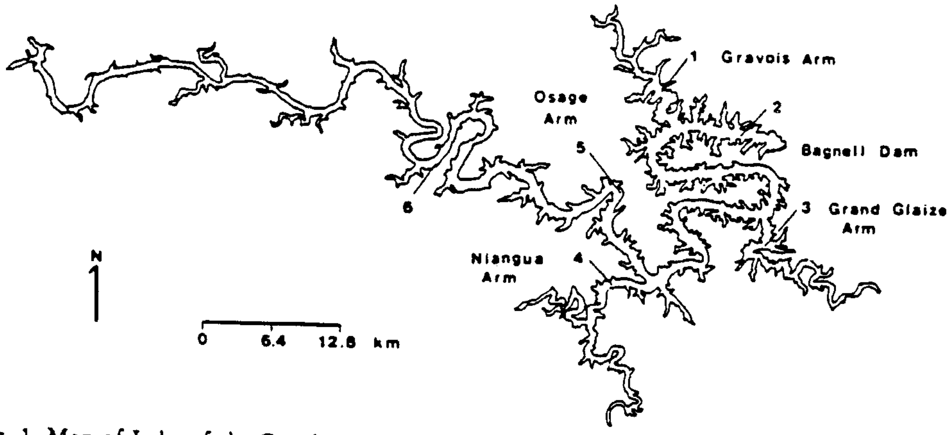

Fig. 1. Map of Lake of the Ozarks, Missouri, showing the location of sampling stations.

The following analyses were made on samples from the surface waters (0.5 m). Total phosphorus (TP) analyses (Murphy & Riley 1962) were made after a persulfate oxidation (Menzel & Corwin 1965). Dissolved total phosphorus (DTP) samples were filtered through

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0.45-μm membrane filter and treated as total phosphorus. Silica concentration was determined by using the molybdosilicate method (APHA 1976). Total and calcium hardness concentrations were determined by using a complexometric titration with EDATA (APHA 1976). Total alkalinity was determined by titration with 0.02 N sulfuric acid (APHA 1976). Chlorophyll *a* was extracted according to the methods of Yentsch & Menzel (1963) and calculated according to the equations of Parsons & Strickland (1963). A Radiometer pH meter (Model 26) was used to measure pH. Specific conductance was measured by a Radiometer Conductivity Meter (Model CDM Z e). A Hach Turbidimeter (Model 2100) was used to measure turbidity. In 1979 inorganic solids were measured gravimetrically (APHA 1976) by using glass fiber filters.

Data was analysed by using ANOVA with orthogonal comparisons ($P \leq 0.05$) (Statistical Analysis System 1979). Sample size and variance were within the limits established by Green (1979).

Results

Limnological characteristics

The most notable difference in water quality among the various areas of the reservoir (Table 1) was a longitudinal gradient of nutrient concentrations and water clarity (Secchi and light extinction). Depending upon the year, TP, silica and turbidity values were 2—10 times higher and water clarity was 3—4 times lower in the upper Osage Arm (Station 6) than near Bagnell Dam (Fig. 1). Values at stations 3, 4 and 5 were intermediate between these extremes. Differences in algal chlorophyll, alkalinity, hardness (total and calcium) and specific conductance values were less extreme but concentrations were generally greater in the upper Osage Arm.

The upper Osage Arm is the most riverine area within the reservoir, and flow from the turbid Osage River (drainage area ~ 30,000 km^2) dominates the limnological characteristics. Conditions are highly variable and dependent upon the annual hydrograph (Table 1). In contrast, processes acting upon impounded Osage River water as it passes through the reservoir — such as nutrient uptake by algae, sedimentation of particulate materials and dilution by minor tributaries — determine water quality at Bagnell Dam.

These differences in water chemistry and clarity between the upper Osage Arm (Station 6) and the main body of the reservoir (Stations 1—5) were significant in analyses by years (one way ANOVA). However, analyses of differences among stations and among years (two way ANOVA) showed a significant year-by-station interaction for most parameters. This interaction is caused by the relationship among stations varying among years. Also, there was more variation among samples within any given year at Station 6 than 1—5 (Table 1). Therefore, data from Station 6 was not included in subsequent analyses.

Water chemistry and clarity were significantly different among Stations 1—5 and among years (two way ANOVA). Chlorophyll *a* was the only parameter to show a significant year-by-station interaction. TP, TDP, silica, calcium hardness, and turbidity values were significantly greater and water clarity values were significantly lower at Station 5 than at Stations 1—4. Silica, alkalinity, and calcium hardness values were significantly lower at Stations 3 and 4 than at Stations 1 and 2. Therefore, the general trends in water quality among the stations were: first, for a station to be most similar to those nearest it; and, second for the similarity among stations to decrease with increasing distance from Bagnell Dam.

Table 1. Mean and standard error of the mean for various limnological parameters measured in the open water of Lake of the Ozarks during the summers 1976–1979.

Parameter	Station	N	1976	N	1977	N	1978	N	1979	1976–1979
Total Phosphorus mg/m^3	1	5	17.9 ± 1.1	9	34.3 ± 4.3	5	21.0 ± 0.9	9	21.8 ± 0.7	25.0 ± 1.8
	2	5	18.2 ± 1.1	12	46.9 ± 9.0	5	22.8 ± 1.5	9	21.7 ± 1.0	31.1 ± 4.1
	3	4	19.8 ± 1.1	9	39.3 ± 3.8	5	26.0 ± 1.2	9	27.2 ± 1.1	29.9 ± 1.9
	4	5	28.0 ± 2.3	9	53.0 ± 7.5	5	28.7 ± 3.9	9	26.4 ± 3.5	35.7 ± 3.5
	5	4	36.0 ± 5.3	12	71.5 ± 17.2	5	30.5 ± 1.2	9	57.0 ± 8.7	55.6 ± 7.7
	6	4	163.5 ± 57.8	12	103.9 ± 17.4	5	43.2 ± 6.8	9	70.9 ± 5.7	91.8 ± 11.8
Dissolved Total Phosphorus mg/m^3	1	5	10.8 ± 1.7	9	13.4 ± 1.3		–	9	6.9 ± 0.3	10.3 ± 0.9
	2	5	9.8 ± 1.3	9	19.8 ± 3.9		–	9	7.2 ± 0.3	12.7 ± 1.9
	3	4	9.2 ± 1.1	9	14.8 ± 1.7		–	9	9.9 ± 1.0	11.8 ± 1.0
	4	5	10.0 ± 1.5	9	18.1 ± 2.4		–	9	8.9 ± 0.6	12.7 ± 1.3
	5	4	13.5 ± 2.1	9	26.2 ± 4.4		–	9	23.9 ± 3.7	22.9 ± 2.5
	6		–	9	39.0 ± 7.1		–	9	29.5 ± 3.1	34.3 ± 3.9
Silica mg/l	1		–		–	3	2.1 ± 0.7	9	3.7 ± 0.6	3.3 ± 0.5
	2		–		–	3	2.1 ± 0.4	9	3.8 ± 0.6	3.4 ± 0.5
	3		–		–	3	7.6 ± 0.3	9	6.3 ± 0.7	6.6 ± 0.5
	4		–		–	3	8.2 ± 0.6	9	9.3 ± 0.8	9.0 ± 0.6
	5		–		–	3	9.1 ± 1.0	9	10.2 ± 2.4	9.9 ± 1.8
	6		–		–	3	8.7 ± 0.9	9	12.8 ± 2.5	11.8 ± 1.9
Total Alkalinity as mg/l CaCO$_3$	1	5	104.4 ± 2.5	9	100.7 ± 5.1	3	87.7 ± 2.8	9	90.2 ± 1.9	96.3 ± 2.3
	2	5	106.4 ± 1.7	9	89.1 ± 3.9	3	89.0 ± 2.1	9	94.8 ± 1.2	94.4 ± 1.9
	3	3	110.7 ± 0.9	9	97.9 ± 4.0	3	88.3 ± 2.6	9	97.0 ± 2.1	97.9 ± 2.0
	4	5	118.7 ± 3.5	9	103.7 ± 3.7	3	94.7 ± 4.0	9	98.8 ± 2.1	103.8 ± 2.2
	5	4	102.2 ± 4.5	9	95.0 ± 3.0	3	97.3 ± 8.2	9	90.3 ± 0.9	94.7 ± 1.7
	6	3	98.6 ± 2.2	9	103.3 ± 7.3	3	118.7 ± 6.4	9	95.1 ± 1.0	101.6 ± 3.1
Total Hardness as mg/l CaCO$_3$	1	5	139.4 ± 1.1	7	119.0 ± 6.2	3	84.3 ± 10.3	9	118.5 ± 1.2	118.7 ± 3.8
	2	5	140.0 ± 0.9	7	113.0 ± 6.0	3	85.3 ± 6.7	9	125.4 ± 2.7	119.8 ± 3.9
	3	3	136.0 ± 2.1	7	118.3 ± 6.2	3	86.0 ± 8.0	9	120.3 ± 2.0	117.1 ± 3.7
	4	5	143.8 ± 3.4	6	128.8 ± 5.9	3	85.7 ± 7.5	9	124.7 ± 1.5	124.8 ± 4.0
	5	4	126.7 ± 3.7	6	108.0 ± 6.9	3	101.7 ± 13.9	9	122.1 ± 2.0	116.3 ± 3.2
	6	4	124.7 ± 5.0	6	122.3 ± 9.9	3	105.7 ± 1.7	9	126.1 ± 1.2	122.0 ± 3.1
Calcium Hardness as mg/l CaCO$_3$	1	4	88.7 ± 1.6	7	83.4 ± 3.5	3	74.3 ± 10.3	9	83.1 ± 0.5	83.0 ± 1.7
	2	4	91.0 ± 1.5	7	82.4 ± 2.9	3	75.7 ± 6.8	9	87.9 ± 1.9	85.2 ± 1.7
	3	3	88.0 ± 1.1	7	86.3 ± 1.9	3	76.3 ± 8.2	9	88.8 ± 0.6	86.2 ± 1.4
	4	4	93.5 ± 0.3	6	94.2 ± 3.1	3	75.3 ± 6.9	9	93.5 ± 1.5	91.2 ± 1.9
	5	3	90.0 ± 3.0	6	87.5 ± 6.0	3	90.7 ± 12.4	9	93.3 ± 1.2	90.8 ± 2.3
	6		–	6	95.3 ± 4.2	3	95.0 ± 2.3	9	101.5 ± 2.3	98.4 ± 1.9
ph	1	3	7.54 ± 0.34	8	7.99 ± 0.14	3	8.58 ± 0.01	9	8.61 ± 0.18	8.25 ± 0.12
	2	3	7.45 ± 0.35	8	8.04 ± 0.08	3	8.59 ± 0.06	9	8.64 ± 0.08	8.27 ± 0.10
	3	2	7.53 ± 0.41	8	8.17 ± 0.08	3	8.61 ± 0.10	9	8.64 ± 0.09	8.37 ± 0.09
	4	3	7.67 ± 0.39	8	8.10 ± 0.10	3	8.72 ± 0.08	9	8.44 ± 0.07	8.26 ± 0.09
	5	3	7.78 ± 0.48	8	7.98 ± 0.17	3	8.64 ± 0.13	9	8.15 ± 0.12	8.11 ± 0.10
	6		–	8	7.85 ± 0.14	3	8.13 ± 0.20	9	7.71 ± 0.03	7.83 ± 0.07
Specific Conductance micromhos/cm 25C	1	4	287 ± 27	8	281 ± 12	4	243 ± 7	9	258 ± 4	268 ± 6
	2	4	285 ± 27	8	266 ± 9	4	246 ± 7	9	253 ± 3	261 ± 6
	3	3	299 ± 7	7	278 ± 9	4	227 ± 11	9	256 ± 4	263 ± 6
	4	4	280 ± 19	7	284 ± 5	4	234 ± 12	9	266 ± 4	268 ± 5
	5	3	284 ± 15	7	271 ± 16	4	262 ± 19	9	257 ± 4	266 ± 6
	6		–	6	290 ± 21	4	327 ± 8	9	272 ± 7	290 ± 9

Table 1. Continued

Parameter	Station	N	1976	N	1977	N	1978	N	1979	1976–1979
Turbitdity JTU	1	1	0.7	8	3.5 ± 1.2	5	1.8 ± 0.2	9	2.2 ± 0.4	2.5 ± 0.4
	2	1	1.2	8	7.4 ± 2.7	5	1.6 ± 0.2	9	2.2 ± 0.4	3.8 ± 1.1
	3		–	7	4.2 ± 1.1	5	2.7 ± 0.4	9	2.7 ± 0.3	3.2 ± 0.4
	4		–	7	5.8 ± 2.0	5	2.5 ± 0.5	9	6.9 ± 0.9	5.5 ± 0.8
	5		–	7	25.6 ± 14.3	5	2.6 ± 0.7	9	28.2 ± 8.0	21.2 ± 6.1
	6	4	32.6 ± 12.2	5	14.2 ± 7.5	5	5.6 ± 0.5	9	36.0 ± 6.0	24.0 ± 4.3
Secchi disk transparency m	1	5	3.0 ± 0.1	9	1.8 ± 0.3	3	2.0 ± 0.1	3	1.9 ± 0.2	2.2 ± 0.2
	2	5	3.0 ± 0.2	9	1.2 ± 0.2	3	2.1 ± 0.4	3	2.3 ± 0.3	2.0 ± 0.2
	3	4	2.4 ± 0.2	9	1.3 ± 0.1	4	1.7 ± 0.2	3	1.9 ± 0.1	1.7 ± 0.1
	4	5	1.8 ± 0.1	9	1.2 ± 0.2	4	1.6 ± 0.2	3	1.1 ± 0.1	1.4 ± 0.1
	5	4	1.5 ± 0.4	9	1.0 ± 0.2	4	1.5 ± 0.2	3	0.8 ± 0.3	1.2 ± 0.1
	6	4	0.4 ± 0.2	9	0.6 ± 0.1	4	0.6 ± 0.1	3	0.4 ± 0.1	0.5 ± 0.1
Chlorophyll *a* mg/m^3	1	5	3.9 ± 0.3	8	11.8 ± 1.8	3	13.3 ± 2.6	9	15.3 ± 1.4	11.8 ± 1.1
	2	5	3.2 ± 0.3	8	13.1 ± 1.5	3	11.8 ± 0.4	9	10.4 ± 0.9	10.5 ± 0.9
	3	4	5.4 ± 0.9	8	16.9 ± 2.1	3	16.0 ± 1.4	9	13.8 ± 1.5	14.0 ± 1.1
	4	5	10.5 ± 2.5	8	24.1 ± 4.7	3	13.5 ± 0.3	9	11.8 ± 1.3	15.8 ± 1.9
	5	4	13.5 ± 4.0	8	15.1 ± 2.6	3	11.7 ± 2.5	9	9.2 ± 1.3	12.6 ± 1.4
	6	4	16.7 ± 3.0	8	16.3 ± 2.4	3	15.2 ± 2.1	9	9.8 ± 2.1	14.2 ± 1.3
Light extinction η/m	1	5	0.57 ± 0.08	11	0.87 ± 0.15	3	0.98 ± 0.13	3	0.95 ± 0.26	0.83 ± 0.09
	2	5	0.53 ± 0.03	11	1.56 ± 0.41	3	0.71 ± 0.11	3	0.76 ± 0.25	1.10 ± 0.23
	3	5	0.81 ± 0.12	11	1.25 ± 0.24	3	1.43 ± 0.16	3	0.82 ± 0.10	1.12 ± 0.13
	4	5	0.94 ± 0.23	10	1.48 ± 0.32	3	1.04 ± 0.04	3	1.55 ± 0.13	1.29 ± 0.17
	5	3	1.01 ± 0.10	8	2.15 ± 0.32	3	1.15 ± 0.18	3	3.25 ± 0.98	1.97 ± 0.37
	6	1	2.65 –	10	3.96 ± 0.55	3	1.97 ± 0.30	3	6.07 ± 1.65	3.91 ± 0.51

All parameters except silica were significantly different among years (Table 1). TP values were lowest and water clarity was greatest in 1976, a drought year. A major flood in 1977 resulted in the greatest TP and turbidity values and the lowest water clarity values during the study. Annual differences in runoff have previously been shown to account for differences in the TP concentration and transparency of lakes from year to year (Jones & Bachmann 1975). Differences in the concentration of conservative ions (specific conductance, alkalinity, and hardness) among years are also a function of the annual hydrograph, and their concentrations are generally higher during base flow periods and lower during spates than at normal flow.

Algal biomass and water clarity

Algal populations are nearly uniform and, in most areas of the reservoir, algal chlorophyll bears the same average relationship to TP concentrations as has been found in natural lakes (Jones & Bachmann 1976) (Fig. 2). Certain data from the Osage Arm (Stations 5 and 6), however, lie at or below the 95 % confidence limits for this relationship. Given the average measured TP concentrations of 50 to 200 mg/m^3 at these stations, the average yield of algal chlorophyll is 9—36 % of the expected values. These data agree with N. Crisp (1977) who found that on individual sampling dates about 25 % as much chlorophyll *a* is produced per unit of TP in the Osage Arm as is produced in natural lakes. The ratio of chlorophyll-to-phosphorus from the regression line in Fig. 2 increases from 0.5 at 50 mg/m³ TP to 1.0 at 200 mg/m³ TP. For those data below the confidence limit in Fig. 2 this ratio ranges from 0.08 to 0.2. Nitrogen limitation of phytoplankton growth does not explain this low yield of chlorophyll per unit of TP. The ratio of nitrogen-to-phosphorus was greater than 11 (based upon unpublished N values from 1978 and 1979 which ranged from 350—1000 mg/m³ depending upon year and station), which exceeds the ratio of these materials in aquatic plant tissues (Vallentyne 1974).

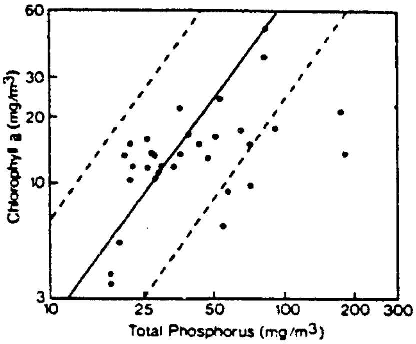

Fig. 2. Relationship between average summer chlorophyll a concentrations and TP concentrations for Stations 1—6 in Lake of the Ozarks. Data from N. Crisp (1977) and Cunningham (1979) are also included. The line and confidence limits represent the regression calculated for these variables in 143 natural lakes covering a broad range of trophic states (Jones & Bachmann 1976).

We hypothesize that the chlorophyll-to-phosphorus ratio is reduced in the upper Osage Arm, in part, because of high concentrations of inorganic solids. C. Crisp (1977) found a strong positive correlation between turbidity and TP in the Osage River above Lake of the Ozarks and found acid-extractable P associated with the suspended sediments. In laboratory studies using these sediments as a P source 20—50 % less algal biomass was produced than with an equal concentration of DTP (Cunningham 1979). We found turbidity averaged 3.3 JTU for those data points within the confidence limits in Fig. 2 and 24.8 JTU for those data outside this relationship. In 1979, inorganic solids averaged 19.4 mg/l in the upper Osage Arm and 2.4 mg/l at the other stations. These solids most likely bind P, thus making it unavailable to algae and in addition limit algal growth by reducing light penetration.

Another hypothesis is that because of the riverine conditions in this area of the reservoir there is insufficient residence time for the algal biomass to respond to the TP; whereas by the time these waters reach Bagnell Dam, the algal biomass has responded to the available nutrients. A similar phenomenon has been reported for Iowa rivers (Burkholder-Crecco & Bachmann 1979). However, we lack the time-series data to determine the effect of high concentrations of inorganic solids and water residence time on algal growth in the upper Osage Arm.

Water clarity was also reduced at those stations with high inorganic solids (Fig. 3). The clarity of most natural lakes during the summer is determined by the magnitude of the algal bloom. Most Secchi disk transparency and chlorophyll data from Lake of the Ozarks fit the empirical relationship between these variables (Fig. 3). Those data from the upper Osage Arm with low algal chlorophyll levels, however, lie below the confidence limits for this relationship. In 1979, inorganic solids within the reservoir were negatively correlated with transparency (r =

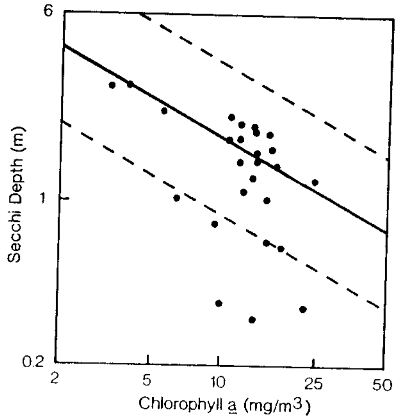

Fig. 3. Relationship between average summer SECCHI disk transparency and chlorophyll *a* concentrations for Stations 1—6 in Lake of the Ozarks. Data from N. CRISP (1977) are also included. The line and confidence limits represent the regression calculated for these variables for lake data from the literature (JONES & BACHMANN 1978).

-0.86, $N = 6$, $P < 0.05$). This indicates that the concentration of inorganic solids rather than algal biomass is the major factor determining water clarity at these stations.

Discussion

By conventional criteria (SAKAMOTO 1966; VOLLENWEIDER 1968; LIKENS 1975) Lake of the Ozarks ranges from mesotrophic to eutrophic depending upon the year, the area of the reservoir, and the parameter used to estimate trophic status. Trophic status generally increases with increasing distance from Bagnell Dam. The concentrations of TP in the main body of the reservoir (18—53 mg TP/m^3 depending upon station and year) are generally below the 30 mg TP/m^3 which is set as the upper limit of the mesotrophic range for this parameter, while in the upper Osage Arm TP concentrations (30—163 mg/m^3) are generally characteristic of eutrophic conditions. In contrast, concentrations of algal chlorophyll throughout the reservoir (3—24 mg/m^3) are characteristic of mesotrophic conditions. Chlorophyll *a* values in the upper Osage Arm are less than would be expected given the TP concentrations because of high inorganic solids and the riverine conditions in this region of the reservoir. For this reason, the general characteristics of trophic status developed by using data from natural lakes should be applied with caution to turbid reservoirs.

Data collected in this study represent the water quality in Lake of the Ozarks prior to the closure of Truman Dam and filling of Truman Lake (which occurred in December 1979). Because of differences in water quality among stations and among years these data should be used with caution in interpreting the effect of Truman Lake on the limnological characteristics of Lake of the Ozarks.

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