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Limnological characteristics of Lake of the Ozarks, Missouri III: seasonal patterns in nutrients, chlorophyll and algal bioassays

Bruce D. Perkins and John R. Jones

Introduction

Summer sampling of Lake of the Ozarks began in 1976, and in Part I of the study JONES & NOVAK (1981) described a strong longitudinal gradient between the turbid, nutrient-rich headwaters and the lacusterine zone near the dam. In Part II, JONES & KAISER (1988) showed that P decreased and chlorophyll values rose after the impoundment of the Truman Reservoir upstream. Presumably conditions for algal growth were more favorable because of lower mean inorganic suspended solids. They also found a strong colinearity between inflow and various water quality variables; TP and suspended solids increased with inflow while salinity and Secchi declined. In this paper, we examine data from 1989–1991 and 1993 to determine hydrological and seasonal patterns in nutrients, suspended solids, transparency, chlorophyll and algal bioassays. We also compare seasonal patterns in this system with generally held theories on seasonality in lakes.

Site description and methods

Seasonal patterns were similar at all sites, but we are using data from sites 2 and 2.4 (Fig. 1), located at Bagnel Dam and 29 km uplake (JONES & KAISER 1988) to simplify the presentation and graphical representations (Table 1); the text features conditions at Site 2. Sampling frequency differed slightly between the two sites. Inflow was less than average during much of 1989 and all of 1991; in 1990 inflow exceeded the average during much of winter to early summer with below average values during the other periods, whereas 1992–1993 was marked by extreme inflow periods (Fig. 2). The average water residence time in the historical record is 5 months. During our study mean monthly residence time averaged 17 months with a maximum of 114 months and a minimum of 1.4 months.

Analytical methods were those of the APHA (1985) for non-volatile suspended solids (NVSS),

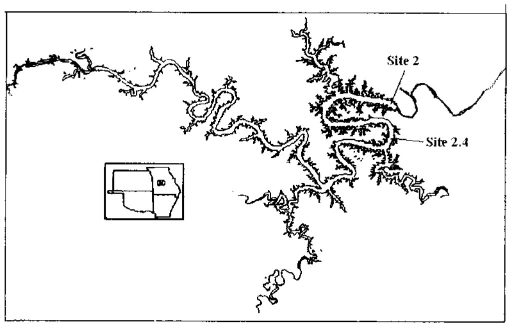

Fig. 1. Map of Lake of the Ozarks.

total phosphorus (TP) and nitrate + nitrite nitrogen (nitrate). Soluble reactive phosphorus (SRP) and ammonia nitrogen (NH_4-N) were analyzed as per STAINTON et al. (1977). Chlorophyll (Chl) was extracted in heated ethanol (SARTORY & GROBBELAAR 1984) and analyzed by fluorometry (KNOWLTON 1984). Total nitrogen (TN) was analyzed by second derivative spectroscopy following persulfate oxidation (CRUMPTON et al. 1992).

During 1989–1991, we conducted algal bioassays at Bagnel Dam after JONES et al. (1990). Treatments of unfiltered lake water in 10-L translucent polyethylene Cubitainers® were run in triplicate; control, nitrogen addition (150 µg L^{-1}), phosphorus addition (10 µg L^{-1}) and nitrogen plus phosphorus. Containers were incubated at one-half Secchi depth for 3–5 days. To determine light limitation additional containers were incubated at 1–3 × the Secchi depth. We interpreted results in terms of both initial Chl values and a one-way analysis of variance test among treatment responses, followed by a Tukey HSD procedure (SAS INSTITUTE INC. 1987). In some experiments we measured a 2- to 9-fold increase in Chl by containerizing algae within the photic zone, with no response or a modest secondary response to nutrients; these results were interpreted as indicating light limitation.

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Table 1. Mean annual values for TP (μg L^{-1}), TN (μg L^{-1}), CHL (μg L^{-1}), NVSS (mg L^{-1}) and Secchi (m) by site and year and mean, median, maximum and minimum values for all samples.

Site	Year	n	TP	TN	CHL	NVSS	Secchi
2	1989	35	21	425	8.1	1.5	2.4
	1990	47	37	704	15.9	2.8	1.4
	1991	23	20	552	14.0	2.4	1.9
	1993	21	41	773	15.4	3.0	1.7
	mean		30	602	12.8	3.4	1.8
	median		28	570	9.0	2.1	1.8
	max		90	1060	57.6	7.9	4.2
	min		11	290	1.9	0.1	0.4
2.4	1989	14	30	450	10.0	2.2	1.7
	1990	21	45	762	15.5	4.1	1.1
	1991	8	21	562	15.9	2.3	1.5
	1993	21	52	804	16.3	9.7	1.3
	mean		41	685	14.6	3.4	1.3
	median		38	670	11.4	2.9	1.2
	max		90	1100	41	10.2	3.8
	min		14	280	2.2	0.3	0.3

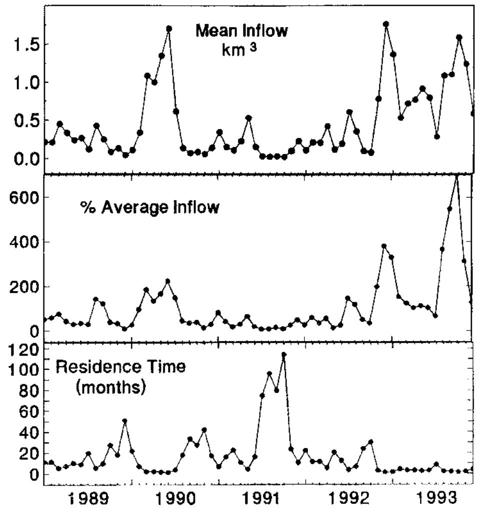

Fig. 2. Monthly mean inflow (km^3), monthly inflow expressed as a percentage of a particular month to the long-term average monthly inflow for that month, and monthly mean residence times.

Results

Nutrients, suspended solids, transparency and chlorophyll

Data from Lake of the Ozarks collected from May 1989 to August 1991 and from March to December 1993 demonstrated a strong temporal pattern in TP, TN, NVSS and Chl that was regulated by inflow and fall overturn. The amplitude and timing of changes in nutrients, solids and Chl over time were consistent at both sampling sites (Figs. 3a and 3b).

Sampling began in May 1989 when inflow was below average (Figs. 2 and 3a). Secchi was 4.2 m, which was the maximum observed during the study, and TP, TN, Chl and NVSS were at, or near, their yearly low which was about 50–70% of the overall mean for these variables (Table 1, Fig. 3a). In mid- to late May, inflow increased causing Secchi to decline to about 3 m but changes in the other variables were minor relative to the range for these values measured during the study (Table 1). Water residence time was about 10 months during summer 1989 (Fig. 2) and TP, Chl and Secchi values were quite stable; during this period TN decreased to the minimum value measured during the study (Table 1). Most variables responded somewhat to inflow in August 1989 but destratification in September caused larger increases and a decline in Secchi. Nitrate and ammonia were near detection limits during summer but increased with destratification (Fig. 4). Values of NVSS declined during fall and winter 1989–1990 but most variables were stable over this period of low inflow (Figs. 3a and 4).

Inflow increased sharply starting February 1990 (Fig. 2) and by mid-July the reservoir volume had been replaced some 2.5 times. There was a bimodal shape to this inflow pattern and this was reflected by bimodal increases during March–April and during June in all of our measurements, including dissolved nutrients (Figs. 3a and 4); nutrients exhibited two peaks of >60 μg L^{-1} TP and near 1000 μg L^{-1} TN; concurrent peaks in NVSS were >5 mg L^{-1}. Measurements during these events included the maximum TP, TN and NVSS values during the study. There were three Chl peaks – one in winter which preceded nutrient increases, and two peaks >30 μg L^{-1} which occurred as NVSS val-

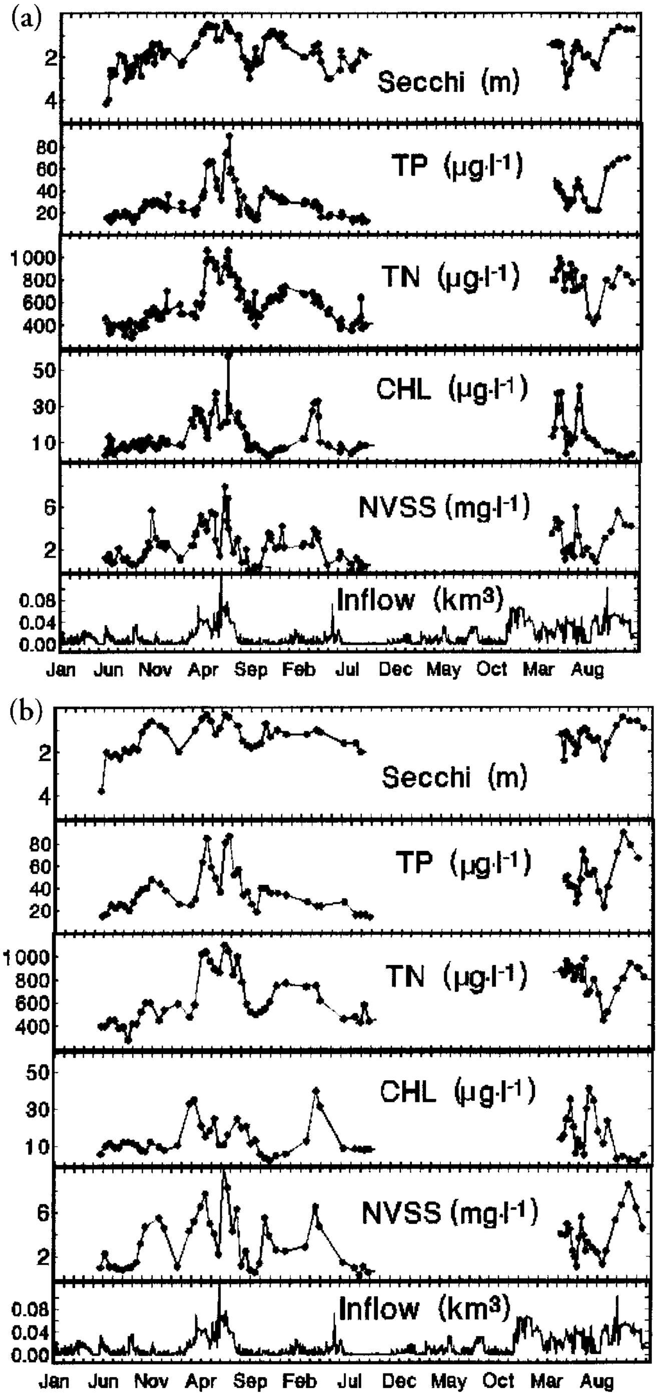

Fig. 3. Comparison of Secchi transparency, total phosphorus, total nitrogen, algal chlorophyll, non-volatile suspended solids and inflow for (a) site 2 and (b) site 2.4.

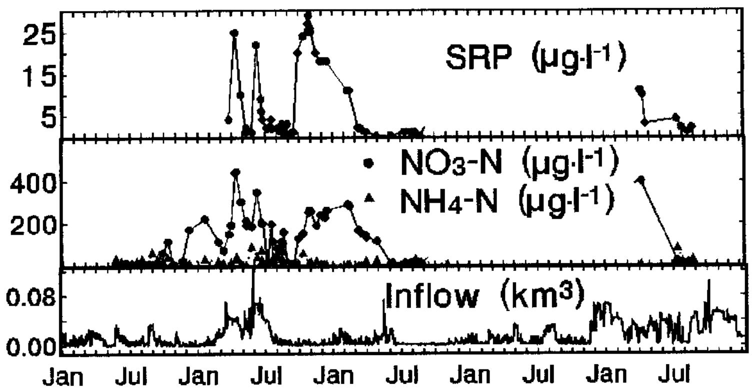

Fig. 4. Comparison of soluble reactive phosphorus, nitrate + nitrite nitrogen, ammonia nitrogen and inflow for site 2.

ues began to decline (Fig. 3a). By August, water residence time had increased to >20 months, resulting in a progressive decline in nutrients, Chl and NVSS and increasing Secchi values (Fig. 3a). The response to destratification mimicked 1989, with increases in TP, TN, NVSS, nitrate and SRP, shallower Secchi values and a decrease in Chl.

Inflow during winter 1990–1991 was somewhat less than in 1989–1990 and during this period there was a gradual decline in TP and TN that was abrupt immediately following the spring peak of about 30 µg L^{-1} Chl in March 1991; NVSS increased concurrently with Chl (Fig. 3a) and may represent diatom frustules within the seston. Secchi generally deepened over this period but shallowed in March with peak Chl. Secchi was the only variable showing a response to increased inflow in May. June–August 1991 was characterized by the smallest inflows recorded during this study; the measured variables generally declined and by August were near the minimum among our samples (Fig. 3a, Table 1).

Inflow during winter 1992–1993 was much greater than other years (Fig. 2), between November 1992 and January 1993 the reservoir volume was replaced >1.5 times, and the volume was replaced about twice during February–June 1993. Sampling began in April 1993; nutrients were greater than the overall mean for this study (Table 1) but less than during the high inflows of spring 1990 (Fig. 3a). From April until early May nutrients, Chl and NVSS gradually declined while Secchi transparencies deepened. Subsequent inflow increased TP, Chl and NVSS. Secchi also shallowed during this period, TN was variable but showed a general decline. Destratification in 1993 coincided with inflows some seven times that of typical fall levels (Figs. 2 and 3a). Nutrients and NVSS were near their maximum during this period and Chl declined to <2 µg L^{-1}, the minimum value in this data set. In fall 1993, we could not separate the influence of external inputs of nutrients and solids from internal regeneration during destratification.

Seasonal patterns

To generalize about seasonal patterns in Lake of the Ozarks we normalized the data (after MARSHALL & PETERS 1989) by expressing each variable as a percentage of the mean (Table 1) and displayed the data in box plots, irrespective of year (Fig. 5). This presentation shows that P values were greater than the mean during spring, variable during early summer, declined thereafter to a seasonal low in late summer and increased to greater than the mean during fall destratification. Nitrogen showed a similar pattern. Non-volatile suspended solids were low in late winter and late summer with higher values during spring inflow and fall destratification. Chlorophyll showed a sharp increase in Febru-

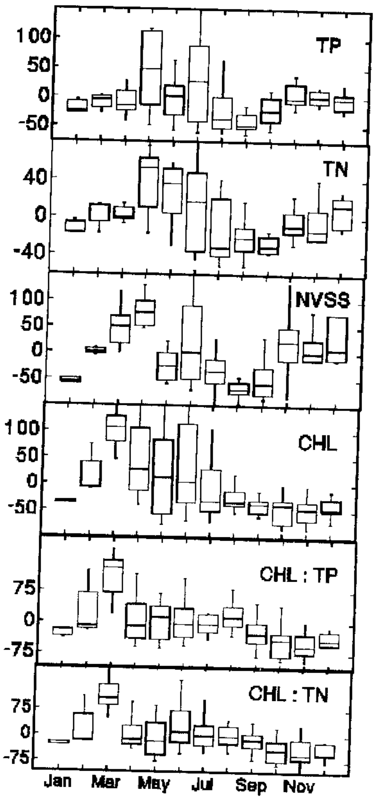

Fig. 5. Box plots of TP, TN, NVSS, Chl, Chl:TP ratio and Chl:TN ratio by month normalized over the sample period by month.

ary, and a spring maximum in March; thereafter, Chl values were variable but showed a general decline into late summer and a further decline with fall destratification. The yield of Chl per unit of the major plant nutrients (ratios of Chl/TP and Chl/TN) also show maximums in February and March, and a decline with destratification.

Nutrient bioassays

Nutrient bioassays at the dam showed a response to nutrients and light that varied seasonally (Fig. 6); P limitation was prevalent in spring, N limitation was common during summer and in 1989 when inflow was moderate, light limitation was measured each fall and during a turbid, nutrient-rich period in spring 1990 (Fig. 3a) and no limitation was measured in winter and during an algal bloom in June 1990 (Fig. 3). Concurrent limitation (response to simultaneous additions of N and P) and reciprocal limitation (response to either N or P) were only measured during mid-summer.

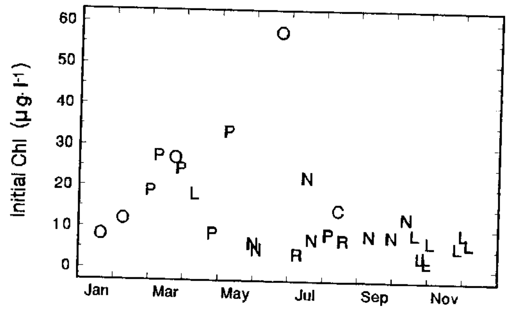

Fig. 6. Response of algal bioassays at Bagnel Dam coded at the initial Chl concentration of the experiment. Categories of phytoplankton limitation follow MORRIS & LEWIS (1988): no limitation (O); P limitation (P); N limitation (N); concurrent limitation (C, stimulation only by simultaneous additions of N and P); reciprocal limitation (R, stimulation by addition of either N or P) and light limitation (L).

On four occasions during fall turnover we conducted bioassays at multiple depths (Fig. 7), when the mixing zone exceeded the photic zone. In each case, there was a sharp increase in Chl (2- to 9-fold) that diminished with depth, and only minor secondary responses to nutrient amendments. We interpret this result as light limitation. In chambers where we measured a response to light, the proportion of phaeopigment within the Chl measurement declined relative to the initial condition; this suggests that Chl was of higher quality as a result of being held within the photic zone. Phaeopigments are being used in this comparison as a general measure of the well-being of the algal community.

Discussion

This study extends the finding of JONES & KAISER (1988) – that nutrients, suspended solids and transparency are responsive to hydrology – to seasons other than summer. Reservoir water

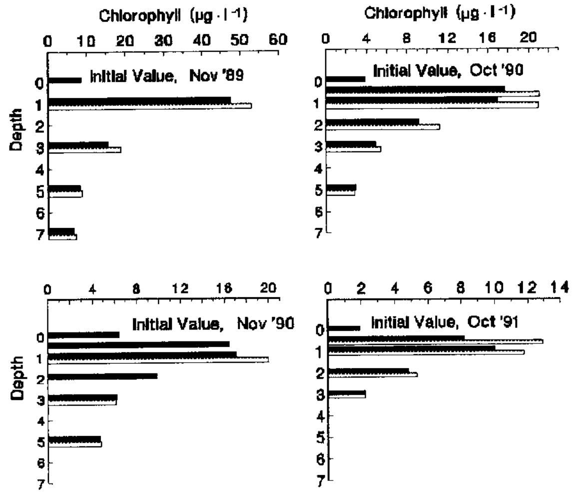

Fig. 7. Response of nutrient stimulation experiment to depth and nutrient addition. Solid bar represents control, open bar represents addition of both nitrogen and phosphorus.

was more nutrient-rich and turbid during periods of extreme inflow in 1990 and 1993 than during low inflow periods in 1989 and 1990 (Figs. 3a and 4). When the reservoir was rapidly flushing, we have experimental evidence that algal biomass was light- rather than nutrient-limited. Light limitation also occurred each fall, shortly after the breakdown of thermal stratification. Phosphorus limitation was measured in spring and N limitation was common in late summer when TN was often at a seasonal low (Fig. 5) and dissolved nutrients were near detection levels (Fig. 4). Averages of TP, TN and Chl from this study (Table 1, JONES & KNOWLTON 1993) show that the lacustrine zone of Lake of the Ozarks is eutrophic.

The seasonal pattern for TP and TN in Lake of the Ozarks depicted in Fig. 5 is an average over the period of our study. Within any given year, seasonal patterns in these elements can be modified by extremes in inflow, above or below the mean (Fig. 3a). Data from additional hydrologic conditions would help determine modal conditions within this reservoir. There were similarities between these patterns and those in Mark Twain Reservoir in northern Missouri, sampled within the same time frame (KNOWLTON & JONES 1995). In Mark Twain, nutrients responded to inflow and destratification and remained high throughout winter, with declines in spring and summer. Light limitation of phytoplankton was also prevalent in that waterbody (KNOWLTON & JONES 1995, 1996).

The onset of a protracted spring bloom in February and subsequent Chl decline in summer matches the phenology for eutrophic lakes described by MARSHALL & PETERS (1989). The fall bloom, considered characteristic of the seasonal cycle of phytoplankton in temperate lakes, however, was absent in Lake of the Ozarks during this study (Fig. 5). Within our data set the Chl/TP ratio averaged 0.43 and this is considered an overall high response to P (WALKER 1985), and a value typical of Missouri reservoirs (JONES & KNOWLTON 1993). During fall destratification Chl/TP values were below average and in several cases ≤0.13, the cutpoint identifying a low response to phosphorus. Light limitation was shown by our bioassays in 1990 and 1993 and by the product of Secchi × Chl; values were <6 and these are thought to indicate that turbidity dominated conditions favorable to light limitation and low nutrient response by phytoplankton (WALKER 1985). The lack of a fall bloom seems tied to the onset of deep mixing during destratification and concurrent increases in NVSS (Fig. 3a) even in 1989 and 1990 when inflows during fall were minimal. Increases in NVSS may represent the mixing in fall of turbid inflows that entered the lake during stratification as an inter- or underflow and were present in the profundal waters near the dam. We hypothesize that this mechanism contributes to light limitation and the lack of a fall bloom in Lake of the Ozarks. Other studies in Missouri have shown that interflows are common, and that timing of turbid, nutrient-laden inflows relative to stratification can control the loading of sediment and nutrients to surface water downlake (KNOWLTON & JONES 1995). High ratios of Chl/TP and Chl/TN during the vernal maximum (Fig. 5) may be the result of an algal community adapted to low temperatures and light (PICK et al. 1984). Our goal is to further evaluate these seasonal patterns in Lake of the Ozarks and other Missouri reservoirs.

Acknowledgments

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Authors' address:

B. D. PERKINS, J. R. JONES, School of Natural Resources, 302 Anheuser Busch Natural Resources Bldg., University of Missouri, Columbia, MO 65211-7240, U.S.A.