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Occurrence and Prediction of Algal Blooms in Lake Taneycomo

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ABSTRACT

In summer 1988, Lake Taneycomo, Missouri, developed conspicuous algal blooms as a result of low inflow from an upstream hydropower reservoir and phosphorus loading from a point source. In multiple regression models, variation in total phosphorus concentration and an index of water residence time accounted for 78-85 percent of the variation in transparency, chlorophyll, and volatile suspended solids in surface water. Non-equilibrium conditions in this rapidly flushed lake led to rapid and predictable increases in algal standing crops during lulls in power generation.

Introduction

An important goal of applied limnology is to model factors regulating algal biomass and related water quality variables in individual lakes. These lake-specific models are used to make lake management decisions and judge their success. In large or complex water bodies, specific models are often developed for individual basins or embayments (Chapra and Robertson, 1977) rather than for the lake as a whole. In large reservoirs, a similar approach is necessary to account for longitudinal gradients in water quality that typically occur from the headwaters to the dam as a result of downlake changes in hydrology, morphology, and nutrient loading (Jones and Novak, 1981; Thornton et al. 1982; Knowlton and Jones, 1989; Kimmel et al. 1990).

The most variable reach in most reservoirs is the zone of transition between riverine areas near the headwaters and the lacustrine zone near the dam (Priscu et al. 1982; Thornton, 1990). Phytoplankton productivity and biomass in the transition zone may be several times more than in other areas of the lake (Soltero and Wright, 1975; Priscu et al. 1982; Whalen et al. 1985; Knowlton and Jones, 1989). The location and size of the transition zone, however, varies with inflow and lake stage (Priscu et al. 1982; Ford, 1990). In reservoirs with variable hydrology, the transition zone at different times may occur at virtually any point along the longitudinal axis or be absent altogether. This source of variation complicates efforts to construct water quality models of these systems.

Areas uplake from the transition zone are river-like and retain most of the water quality features of the inflowing stream. River water usually contains relatively low concentrations of phytoplankton relative to available nutrient supplies (Jones et al. 1984) because of high turbulence, short residence time, and low light. In serially impounded rivers, sedimentation of phytoplankton in upstream reservoirs is also important (Kimmel et al. 1990). Low ratios of phytoplankton to nutrients in inflowing water may be desirable from the standpoint of lake water quality but create the potential for rapid phytoplankton growth when this water moves into transitional areas. Headwater reaches may experience phytoplankton blooms during periods of low inflow when the transition zone extends uplake (Priscu et al. 1982; Whalen et al. 1985). Modeling the occurrence and magnitude of such blooms requires specific knowledge of the chemical, biological, and hydrologic features of the individual reservoir.

This paper describes the magnitude, duration, and location of algal blooms in Lake Taneycomo during summer 1988 and discusses the roles of water residence time, thermal stratification, ambient nutrient concentrations, and a nutrient point source in this dynamic reservoir.

Study Area

Lake Taneycomo was formed in 1913 by the closing of Ozark Beach Dam (36° 39.5'N 93° 7.5' W) on the White River near Forsyth, Missouri (Fig. 1). The dam has a spillway crest elevation of 214 m MSL and hydropower penstock inlets at about 208 m MSL. The lake comprises approximately 745 ha with a volume of 3.1×10^7 m^3 and extends about 37 km upstream to the base of Table Rock Dam (closed in 1958).

About 94 percent of the annual inflow to Lake Taneycomo results from hydropower releases at Table Rock Dam (U.S. Environ. Prot. Agency, 1977) which has an outlet approximately 42 m below the average lake surface (Knowlton and Jones, 1989). This inflow is usually between 4° and 12°C and enters Lake Taneycomo in pulses determined by demands on peaking power. Over the past 12 years, monthly total inflows to Lake Taneycomo have ranged over two orders of magnitude, from 1.2 percent to 128 percent of the lake volume per day.

Instantaneous discharge to Lake Taneycomo from Table Rock Dam ranges between a peak flow of about 450 m^3/s during periods of maximum power generation to a base flow of about 2.8 m^3/s when generation is curtailed. Maximum flow capacity of the turbines in Ozark Beach Dam (about 160 m^3/s) is considerably less than that of turbines in Table Rock Dam. Thus, during extended periods of high flow, much of the outflow from Lake Taneycomo occurs as surface discharge via the spillway.

Lake Taneycomo supports a valuable trout fishery (Weithman and Hass, 1984) and provides drinking water for the city of Branson and several surrounding communities. The lake also receives wastewater seepage from numerous septic tanks and effluent from Branson's municipal waste treatment plant. This plant is located about 20 km above Ozark Beach Dam and releases secondary treated wastewater at a rate of about 8800 m^3/s (about 0.03 percent of average lake volume) from an outlet pipe at the lake surface.

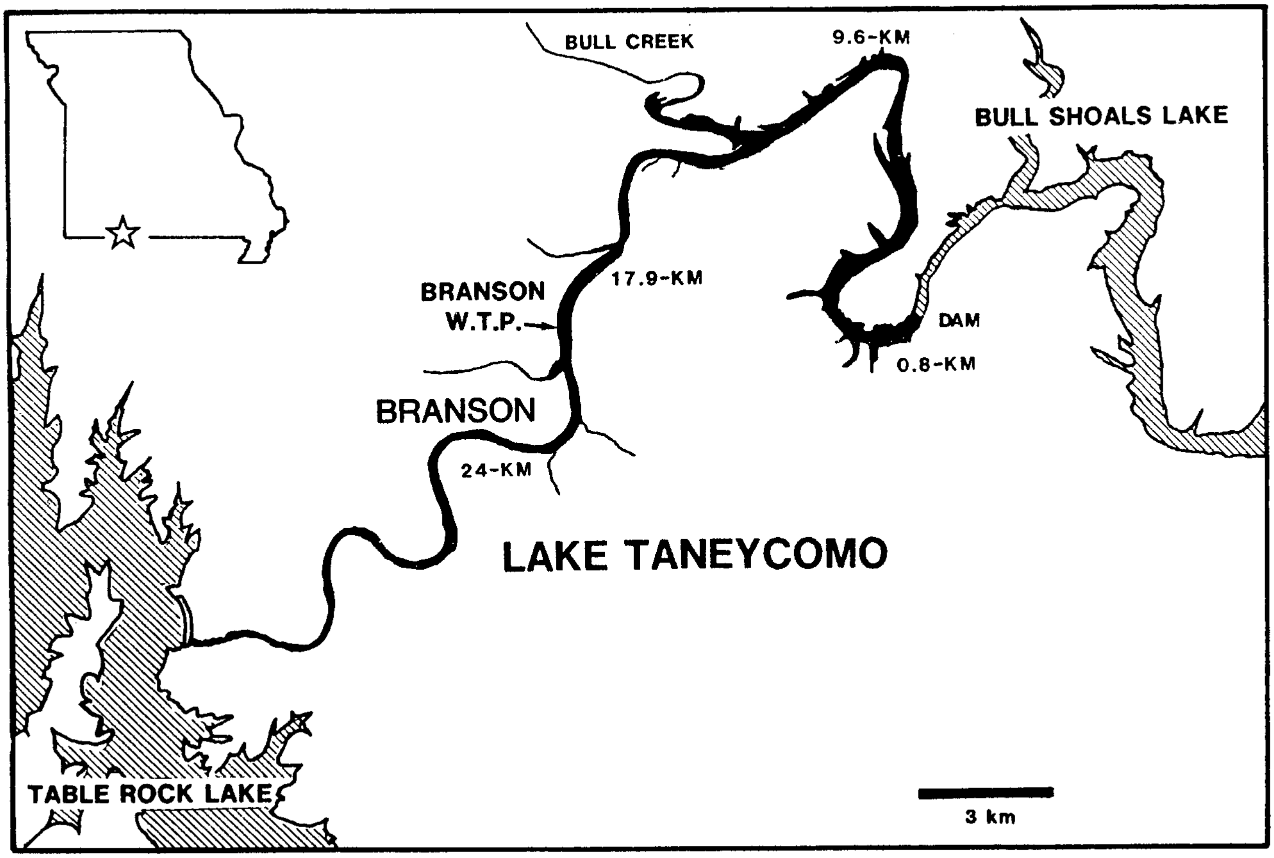

Figure 1.—Map of the study area. Branson municipal waste treatment plant is designated BMWTP.

Materials and Methods

We collected water quality data from Lake Taneycomo on 11 dates between May 16 and September 29, 1988. In routine collections, we took surface water samples (10 L), Secchi depths and temperature profiles (Montedoro–Whitney Model TC-5C resistance thermometer) at four locations in the lower 24 km of the lake (locations shown in Fig. 1). In the text, we refer to the sites by their distance uplake from Ozark Beach Dam (1-KM, 10-KM, 18-KM, and 24-KM).

In addition to routine collections, we took temperature profiles on 14 occasions at distances spaced 1.6 to 3.2 km along the lower 13-24 km of the lake. On June 20; July 7, 18, and 28; August 8 and 18, and September 1, we collected additional water samples (50 mL) at several discrete depths at the four routine sampling locations and analyzed for total phosphorus (TP) and *in vivo* chlorophyll fluorescence (IVCF – Turner Designs Model 10 fluorometer). Our collections on July 28, August 8 and 18, and September 1 included total phosphorus and IVCF profiles at up to four sites located between the usual sampling locations. On August 8, we took surface samples for total phosphorus and IVCF at 1.6 km intervals in the lower 21 km of the lake to record the effects of inflow from Table Rock Dam on wastewater distribution. We measured total phosphorus in the wastewater three times.

Water samples were processed on the lake shore by taking aliquots for total phosphorus and total nitrogen (TN). Samples (250 mL) for chlorophyll (CHL) were filtered through glass fiber filters (Gelman A-E). Precombusted (500°C) glass fiber filters (Whatman 934-AH) were used for gravimetric analyses of total, volatile and non-volatile suspended solids (TSS, VSS, and NVSS, respectively). Chlorophyll and suspended solids samples were frozen on desiccant up to a week prior to analysis. Filtrate from suspended solids samples was used for analysis of nitrate–nitrite (NO_3 + NO_2-N). All analyses from routine collections were done in triplicate.

Analysis of total phosphorus was performed following the molybdosilicate method of Murphy and Riley (1962) after persulfate digestion (Prepas and Rigler, 1982). Total nitrogen and nitrate–nitrite were determined following cadmium reduction (U.S. Environ. Prot. Agency, 1979). Samples for total nitrogen were digested prior to analysis (D'Elia et al. 1977). Chlorophyll was determined by fluorometry (Knowlton, 1984) after extraction in hot ethanol (Sartory and Grobbelaar, 1984). Chlorophyll values were corrected for pheopigment (Lorenzen, 1967). Suspended solids were determined according to Hoyer and Jones (1983).

Daily flow records for the White River below Table Rock Dam were obtained from the U.S. Geological Survey at Rolla, Missouri. Hourly records of outflow from Table Rock Dam for selected dates were obtained from the U.S. Army Corps of Engineers. An estimate of average lake volume, corrected for recent sedimentation, was provided by the U.S. Geological Survey, Rolla, Missouri (W. Berkes, personal communication). Topographic maps and soundings made during the study were used to estimated the average volume of water uplake from each of the four routine sampling sites.

We used data on lake volume and hourly inflow from Table Rock Dam to estimate the length of time water had been in the lake prior to being collected (Sample Residence Time, SRT, in days). Assuming conditions of uniform plug flow, sample residence time would equal the length of pre-sampling time required for inflow to equal the volume uplake from the sampling site. However, plug flow conditions did not always occur during the study so we calculated a second index of sample residence time based on the difference in temperature ($\Delta T°$) between the surface layer (mean of the upper 2 m) at each sampling site and the temperature at the outlet depth in Table Rock Lake. Assuming that surface water warmed at a relatively uniform rate after entering the lake, values of $\Delta T°$ would be a function of residence time.

Results

Inflow and Thermal Stratification

During this study, daily outflow from Table Rock Dam ranged from 9.8 x 10^4 m^3/d on 27 July to 1.89 x 10^7 m^3/d on May 31. These inflows equaled 0.3 percent and 61.1 percent, respectively, of the average volume of Lake Taneycomo.

In comparison to inflows during 1976-1987, total inflow during the study period was 73 percent of average. Total inflows in May, June, July, August, and September were, respectively, 76 percent, 57 percent, 40 percent, 113 percent and 100 percent of average. Major power releases (>3 x 10^6 m^3/d) occurred almost daily in the first three weeks of May and August and through much of September, but were less frequent in June and July when there were seven periods of three to seven consecutive days without a major power release. Periods of more than three days without major power releases occurred only once in May (May 21-30), once in August (Aug. 26-31), and twice in September (Sept. 3-7 and 23-25).

During periods of high inflow in May, August and September, Lake Taneycomo was riverine throughout its length with most of the lake volume between 10°C and 15°C (Fig. 2a). The lake was strongly stratified, however, during low inflows from late May through July when surface temperatures often exceeded 25°C in the lower 10-20 km of the lake (Fig. 2b). Stratified areas of the lake were quite dynamic, however, and in most cases should be considered transitional rather than truly lacustrine.

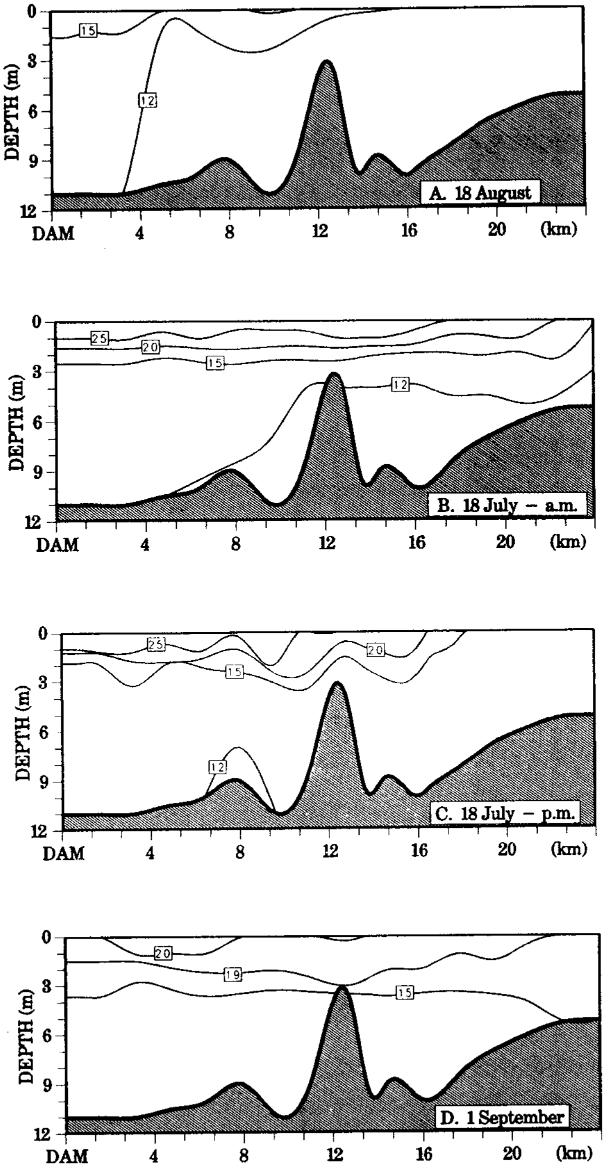

Figure 2. Representative temperature profiles (°C). (A) August 18, 8-11 a.m. (B) July 18, 9-12 a.m. before power release. (C) July 18, 5-7 p.m. during power release. (D) September 1, 8-11 a.m. Isotherms were interpolated from temperature profiles taken at 6-15 locations. Bottom profile was interpolated from cross channel soundings at 15 locations.

The area and thickness of the epilimnion fluctuated widely in response to inflow. During major power releases, inflowing water typically pushed the uplake margin of the epilimnion 5-8 km downlake before forming an underflow current. The result was compression and thickening of the surface layer in downlake areas (compare Figures 2b and 2c). The latter effects were probably influenced by upwelling of the underflow currents near the dam and in a shallow zone in the lake basin just uplake from the mouth of Bull Creek (12 km above the Ozark Beach Dam). When power generation ended, the transition zone migrated back uplake at rates of about 100-300 m/d. These rebound migrations were augmented by inflow from Bull Creek (Fig. 1), the only unregulated tributary with continuous flow in summer 1988.

Lake Taneycomo also stratified during the six-day lull in power generation in late August. And by September 1, the upper 1-2 m of the lake had warmed to more than 19°C over a reach extending from Ozark Beach Dam to Branson (Fig. 2d). Inflow from Bull Creek probably increased the uplake expansion of the epilimnion during this period.

Sample Residence Time

Our estimates of sample residence time (SRT) based on plug flow calculations suggest that during the study we sampled water that had been in Lake Taneycomo from less than 1 to about 13 days. Water collected at site 24-KM was in the lake from 0.2 to 3.7 days and at site 1-KM, the range was from 2.6 to 12.8 days. Our second index of sample residence time, ΔT°, showed that during its passage through the lake the mean temperature of the surface layer increased 0.5 to 15°C over the inflow temperature. The relation between ΔT° and sample residence time is asymptotic with an inflection point at around four days (Fig. 3). Water that had been in the lake for less than four days was unstratified or weakly stratified and during this initial period, water in the surface layer warmed about 2°C/d (Fig. 3). Thereafter, the rate of warming slowed as surface temperatures reached maximum values of summer.

At sites where sample residence time was more than four days, the water column featured some thermal stratification. Underflow currents occurred at most if not all of these sites. Underflows violate

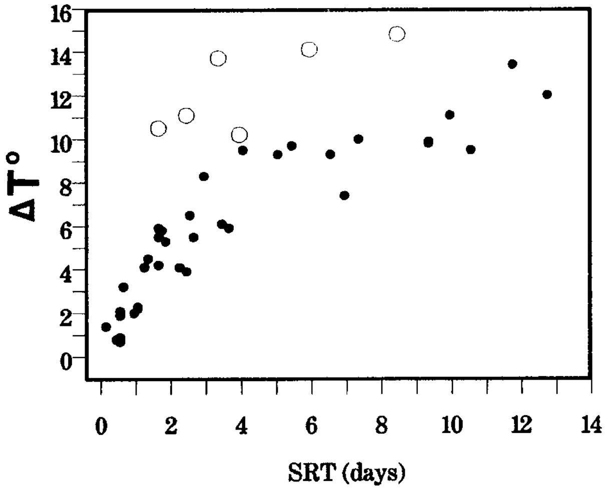

Figure 3.—Relation of ΔT° (°C) to sample residence time (days) for routine sampling sites. Open circles are data from sites 10-KM and 18-KM during the period of heavy stratification in June and July.

the assumption of plug flow and lead to negative biases in our estimates of sample residence time. Errors of this type were most severe at sites 10-KM and 18-KM during a period of strong stratification in June and July (open circles in Figure 3). These sites had vertical temperature gradients more than 1°C/m and underflows were obvious. The surface water at these sites would have been in the lake longer than estimated from our plug flow calculations of sample residence time. Comparing the relation of ΔT° to sample residence time for the sites with strongest stratification (open circles in Figure 3) to the same relation for other sites (solid circles in Figure 3) suggests that sample residence time for heavily stratified sites underestimated sample residence time by as much as 50 percent.

For sites with weak or no stratification, both ΔT° and sample residence time seem to provide a reasonable index of relative sample residence time. Because of the large potential bias in sample residence time values from heavily stratified sites, however, we used ΔT° data as an index of residence time in subsequent modeling efforts.

Nutrient Distribution and Dynamics

Nutrient and chlorophyll measurements suggest nitrogen did not limit algal growth during the study. Ratios of total nitrogen to total phosphorus in Lake Taneycomo averaged more than 30 and nitrate–nitrite was always more than 100 µg/L (Table 1). Nitrogen limitation is improbable in lakes with high total nitrogen:total phosphorus ratios (Forsberg and Ryding, 1980) and large concentrations of dissolved inorganic nitrogen (Morris and Lewis, 1988). Presumably, ammonia (not measured in this study) also contributed to the total pool of dissolved nitrogen. Also, chlorophyll was negatively related to total nitrogen and nitrate–nitrite in regression models (Table 2) but showed a strong positive relation to total phosphorus (TP) ($R^2 > 0.65$ — Table 2). Suspended organic matter, as measured by volatile suspended solids, showed similar trends (Table 2).

Phosphorus concentrations varied widely among locations, with depth, and over time during the study in response to inflow dynamics, thermal stratification, and phosphorus-loading from wastewater. At site 24-KM, total phosphorus ranged from 16 to 28 µg/L with an average of 19 µg/L (Table 1). Values at this site represent total phosphorus in the outflow of Table Rock Dam with minor increases from local sources. At sites downlake from the effluent, total phosphorus averaged 31 to 32 µg/L but individual samples ranged from 16 to 70 µg/L.

Variation in total phosphorus at downlake sites was mostly due to variability in the dilution and transport of wastewater within the lake. The effluent contained about 1,000 µg/L total phosphorus and, on average, amounted to 0.1 percent of total inflow to Lake Taneycomo. During major power releases the effluent was thoroughly mixed by water flowing past the plant discharge and had a minor effect on in-lake total phosphorus. For example, total phosphorus in surface samples taken during a power release on August 8 increased from 17 to 67 µg/L just downlake from the plant, but dropped to 23 µg/L 0.8 km downlake. Earlier that day, before the power release, total phosphorus was more than 800 µg/L 0.1 km downlake from the plant.

The difference in total phosphorus between site 24-KM (above the wastewater outfall) and site 18-KM (below the outfall) averaged 29 µg/L on days when sample residence time at the two sites differed by more than four days (n=3 dates). When this part

Table 1.—Means, standard deviations, minimums and maximums of water quality measurements made in summer 1988. Secchi depths (SD) are in meters, VSS and NVSS are in mg/L^1, and other variables are in µg/L^1.

SITE		SD	TP	TN	NO_3	VSS	NVSS	CHL
1-KM	mean	1.8	32	668	327	2.6	2.5	18.4
	std dev.	0.8	9	147	145	1.1	0.7	8.6
	min	1.2	21	500	130	0.7	1.2	2.2
	max	4.0	51	860	563	4.0	3.8	30.0
10-KM	mean	1.7	31	664	369	2.2	2.8	15.2
	std dev.	0.8	10	96	158	1.2	0.7	8.1
	min	1.0	16	470	130	0.7	1.6	3.8
	max	3.2	47	800	557	4.2	3.9	27.5
18-KM	mean	>3.0[1]	31	732	520	1.6	2.3	13.0
	std dev.	2.1	16	136	184	1.8	1.1	17.7
	min	1.0	16	550	230	0.2	0.7	0.6
	max	>6.7	70	890	750	5.5	4.3[2]	48.6
24-KM	mean	>4.7	19	838	646	0.3	1.2	1.4
	std dev.	0.6	4	130	78	0.2	0.9	0.9
	min	3.8	16	647	530	0.2	0.6	0.4
	max	>5.5	28	1010	770	0.7	3.6[2]	3.2

[1] The Secchi disk was sometimes visible to the bottom at sites 18-KM and 24-KM and Secchi depth was recorded as the depth of the water column.

[2] Maximum NVSS at sites 17.9 and 24 occurred on 18 July following a heavy rain that washed silt into the lake from Turkey Creek and other tributaries. In a surface sample collected at the mouth of Turkey Creek on that date NVSS = 47.4 mg/L^1.

Table 2.—Selected regression models based on 42 surface samples[1]. All models and individual coefficients were significant ($p < 0.05$).

MODEL	DEPENDENT VARIABLE	INDEPENDENT VARIABLE(S)	INTERCEPT	SLOPE(S)	R^2
1	CHL	TP	−12.636	0.894	0.73
2	CHL	TN	34.682	−0.031	0.14
3	CHL	NO_3-NO_2	32.147	−0.044	0.48
4	VSS	TP	−1.321	0.109	0.75
5	VSS	TN	4.257	−0.0036	0.13
6	VSS	NO_3-NO_2	4.14	−0.0054	0.50
7	CHL	ΔT^0	−4.010	2.291	0.59
8	VSS	ΔT^0	−0.416	0.300	0.69
9	TP	ΔT^0	14.943	1.807	0.40
10	Log_{10}SECCHI	Log_{10}CHL	0.669	−0.387	0.86
11	Log_{10}SECCHI	Log_{10}VSS	0.381	−0.504	0.88
12	Log_{10}SECCHI	Log_{10} T^0	0.860	−0.645	0.68
Multivariate Models:					
13	CHL	ΔT^0 TP	−13.636	1.127 0.644	0.81
14	VSS	ΔT^0 TP	−1.474	0.172 0.071	0.88
15	Log_{10}SECCHI	Log_{10} ΔT^0 Log_{10}TP	1.674	−0.440 −0.686	0.78

[1] One of the 43 original observations (18 August, site 18-KM) was omitted from the analyses because of the influence of a silt-laden inflow from Turkey Creek during a heavy rain.

of the lake was rapidly flushed (sample residence time difference less than two days), total phosphorus at the two sites usually differed less than 2 μg/L.

Our data show that wastewater can accumulate in the epilimnion resulting in large increases in total phosphorus. For example, on July 7 the epilimnion of Lake Taneycomo contained about 550 kg phosphorus at an average concentration of 51 μg/L (Fig. 4a). Given background concentrations (19 μg/L phosphorus), some 64 percent (350 kg) of this total was from the effluent and other local sources. This sum represents more than 80 percent of the phosphorus output from the treatment plant during the preceding period of stratification.

Temperature and total phosphorus profiles suggest that wastewater accumulated in the epilimnion by two mechanisms. The first occurred when the lake was stratified near Branson and the effluent, which was usually warmer than the receiving water, flowed directly into the epilimnion. This condition occurred several times during the study and is illustrated by data from September 1 (Fig. 4b). On this date elevated total phosphorus in the epilimnion near Branson extended several kilometers downlake and extended at least 1 km uplake from the plant, probably because of uplake expansion of the transition zone.

The second mechanism involved the accumulation of wastewater in unstratified water near Branson that was undergoing surface warming during lulls in power generation. Subsequent power releases moved this buoyant layer downlake where it was partly incorporated into the uplake margin of the epilimnion, causing an increase in total phosphorus content. Profiles taken on August 8 show two zones of elevated total phosphorus, one near the

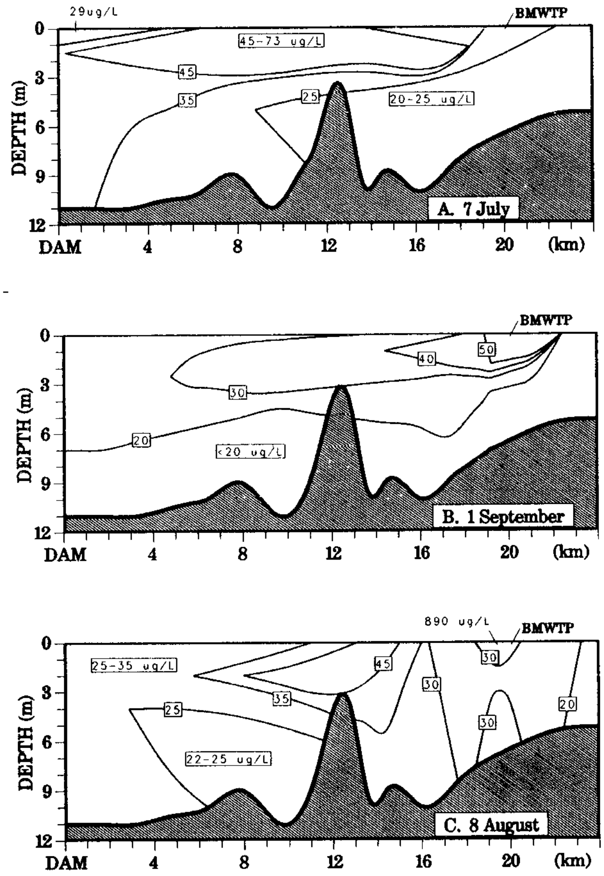

Figure 4.—Examples of the spatial distribution of total phosphorus (μg/L). (A) July 7. (B) September 1. (C) August 8. Isopleths were interpolated from total phosphorus profiles taken at 4-7 locations. Branson municipal waste treatment plant is designated BMWTP.

wastewater outfall, 19 km uplake from the dam, and another in a wedge of water extending from 5 to 10 km below the outfall (Fig. 4c). The high total phosphorus in the downlake zone probably accumulated near the outfall during a two-day period of base flow on August 5 to 6 and was pushed downlake by a small power release on August 7.

Distribution and Dynamics of Algal Biomass

Values of chlorophyll varied widely during the study fluctuating over time by as much as 48.0 µg/L at individual sites (Table 1). At site 24-KM, chlorophyll was usually less than 10 percent of the values found at sites downlake from the effluent (Table 1). Most of this spatial and temporal variation can be attributed to total phosphorus and residence time. Water released from Table Rock Lake comes from the tropholytic zone and contains few viable phytoplankton. Lake water collected less than 24 hours after entering Lake Taneycomo (sample residence time less than 1 days) contained, on average, less than 1.0 µg chlorophyll/L (n=8, range 0.4-1.6 µg/L). Values of chlorophyll subsequently increased with increasing residence time as indexed by ΔT° (Fig. 5a). Observed increases were presumably due to exponential growth of phytoplankton in response to increasing subsurface radiation and additions of total phosphorus from wastewater. When used together as independent variables in a multivariate regression, total phosphorus and ΔT° explain 80 percent of the variation in daily values of chlorophyll from individual sampling sites (Table 2).

The relation of chlorophyll to ΔT° in Figure 5a seems asymptotic. Maximum chlorophyll occurs above ΔT° more than 9°C, a value roughly corresponding to a residence time of five days (Fig. 3). The trend is similar when values of chlorophyll are normalized for differences in total phosphorus by conversion to chlorophyll:total phosphorus ratios (Fig. 5b). We suggest that phytoplankton in the surface layer of Lake Taneycomo grew to the limits set by available phosphorus within a few days. An equilibrium condition is seemingly reached in less than a week at chlorophyll:total phosphorus values of between 0.4 and 0.8.

Because of the rapid response of phytoplankton populations to increased total phosphorus and residence time, algal blooms developed quickly during the study. During extensive power generation in mid-August, for example, chlorophyll near Branson was less than 2 µg/L on August 18 and probably remained near this level until the subsequent lull in power generation beginning on August 26. By September 1, however, chlorophyll had increased to nearly 50 µg/L near Branson (Fig. 6a) in response to low inflows and the subsequent accumulation of total phosphorus from the effluent (Fig. 4b). A similar bloom (CHL=48.6 µg/L) occurred in mid-June near site 18-KM.

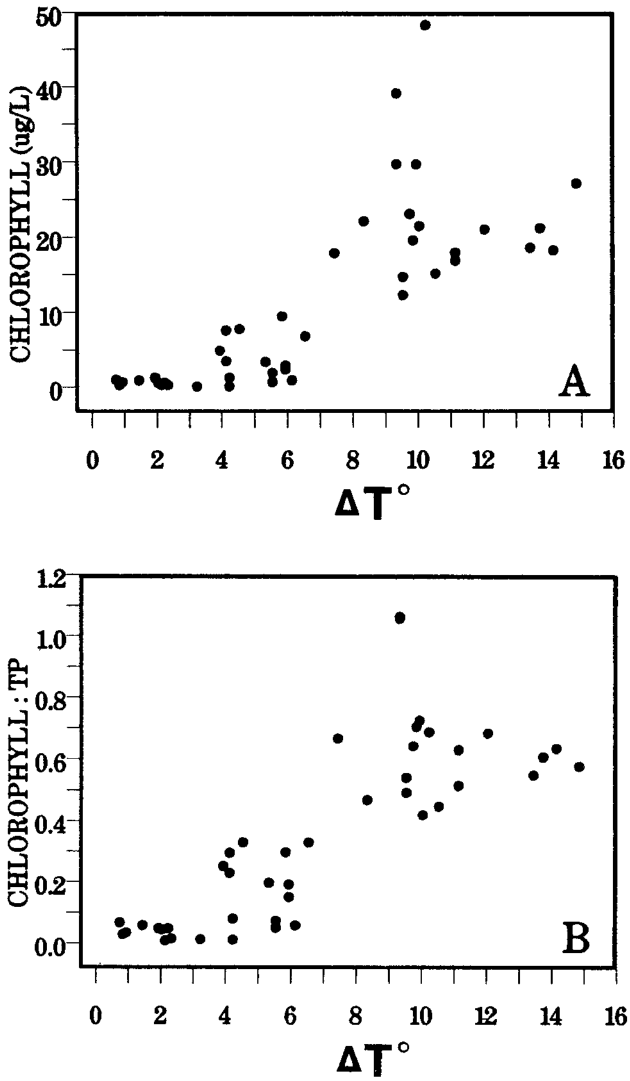

Figure 5.—Relation to ΔT° of (A) chlorophyll (µg/L) and (B) chlorophyll:total phosphorus.

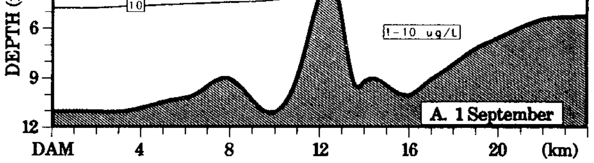

Figure 6.—Spatial distribution of chlorophyll (µg/L) on September 1. Isopleths were interpolated from IVCF profiles taken at 6 locations and converted to µg/L chlorophyll *a* by comparison of IVCF and chlorophyll *a* values from surface water samples.

Transparency and Seston Composition

Water transparency in Lake Taneycomo is controlled principally by phytoplankton abundance. Inflow from Table Rock Dam contains little suspended matter and is exceptionally transparent when compared to most surface waters in the Midwest. At site 24-KM, concentrations of total seston (volatile suspended solids + non-volatile suspended solids) averaged 1.5 mg/L and a Secchi disk was visible to the bottom (4-5.5 m) except when heavy rains washed large quantities of silt into the lake (August 18).

At downlake sites, Secchi depths varied from 1.0 m to more than 6 m in response to variations in algal biomass. In regression models (excluding data affected by local rains), variation in chlorophyll and volatile suspended solids each accounted for more than 85 percent of the variation in Secchi depth (Fig. 7; Table 2). As with chlorophyll, transparency was closely related to residence time. Secchi depths declined from more than 5 m to less than 2 m in about four days (ΔT°= <8°C).

Extreme differences in phytoplankton abundance between riverine and transitional areas of the lake created sharp contrasts in transparency, especially in the reach near Branson. On several occasions transparency differed by at least threefold between the uplake and downlake ends of the reach bordering the city. These large differences in transparency over a short distance were apparent to recreationists who frequently remarked about water clarity to personnel conducting this survey. During June and July when the downlake reach was stratified, the surface water was noticeably cloudy and it exhibited a greenish-brown cast—a sharp contrast to the limpid water in unstratified areas uplake. Complaints about similar conditions in 1987 were the main impetus for this study.

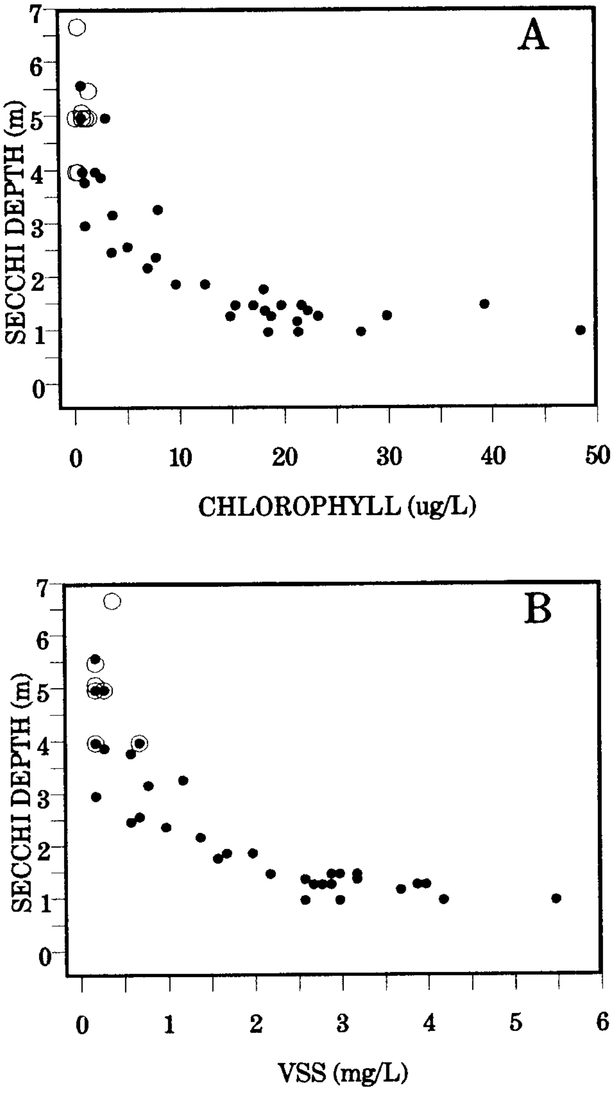

Figure 7.—Relation of Secchi depth (m) to: (A) chlorophyll (μg/L) and (B) volatile suspended solids (mg/L). Open circles show observations where transparency was underestimated because the Secchi disk was visible to the bottom.

Discussion

The transition zone in reservoirs is the intersection between riverine and lacustrine environments and may be remarkably productive. In the transition zone of Lake Mohave on the lower Colorado River, Priscu et al. (1982) measured areal photosynthetic rates more than 5 g C/m^2/d some of the highest photosynthetic rates ever observed in a lake. In this study, data from August–September are consistent with a community doubling rate of about 1/d in the transition zone near Branson. Such high rates are more typical of laboratory cultures than natural communities (Reynolds, 1984).

Several factors probably contribute to the high primary productivity of reservoir transition zones. Among these are improved underwater irradiance and reduced turbulence. Also, competition is probably minimal within the sparse initial phytoplankton community as is grazing by microinvertebrates. And nutrients are present in large quantities relative to existing algal biomass. For example, in Lake Taneycomo ratios of chlorophyll:total phosphorus at recently flushed sites (sample residence time < 2 d) averaged 0.07 (n=15), less than one sixth the average for other Missouri lakes (x=0.45, n=323; University of Missouri, unpublished data). Low ratios of chlorophyll to nutrients are probably typical of the inflows to many reservoirs (Priscu et al. 1982; Soballe and Threlkeld, 1985; Knowlton and Jones, 1989).

These findings suggest that the predictability of algal growth in Lake Taneycomo and similar transitional lakes may be greater than expected from lakes and reservoirs with longer residence times. Rapid flushing keeps the phytoplankton community in a continual state of disequilibrium through most of the year. Water in uplake areas is continually replaced by inflow containing a low ratio of algal biomass to available nutrients in a situation much like a chemostat (Kimmel et al. 1990). The initial growth of the phytoplankton community may be little affected by factors such as nutrient stress, zooplankton grazing, and interspecific competition that complicate the dynamics of phytoplankton in established communities in equilibrium with their surroundings (Tilman et al. 1982).

Two factors regulating chemostat algal cultures, nutrient concentrations and water renewal rate may have a predictable influence on algal biomass in reservoir transition zones. Regression models developed in this study show a good fit (R^2 more than 75 percent) between indices of phytoplankton abundance (chlorophyll, volatile suspended solids, Secchi depth) and a pair of independent variables: ΔT°, a surrogate for water residence time, and total phosphorus, a measure of nutrient availability. These results are based on observations from one season only and need to be confirmed by additional data. Nonetheless, our results are consistent with the idea that simple empirical relations may provide useful predictions about algal biomass in rapidly flushed lakes (Soballe and Threlkeld, 1985; Uttormark and Hutchins, 1985).

Management Implications

The most obvious effect of algal blooms in Lake Taneycomo is aesthetic. Inflows to the lake are exceptionally transparent by regional standards. Most lakes in Missouri have average Secchi depths less than 1.5 m (Univ. Mo., unpubl. data). Transparency in headwater areas of Lake Taneycomo would probably average nearly five times that amount if the water column were deep enough to obtain measurements. Algal blooms during this study reduced water clarity by several fold to values quite typical of many Missouri lakes. Whether such blooms have economic consequences is unknown.

If algal blooms become conspicuous when they reduce transparency to less than 2 m, we predict that conspicuous blooms will occur in any part of the lake where residence time exceeds about four days in summer (Model 12, Table 2). Our predictions of residence time are still tentative for periods of low and variable flow. However, conspicuous blooms probably will occur in areas downlake from Branson following any extended period without frequent power releases.

Historic power generation schedules show that periods with four or more consecutive days without major power releases (maximum daily inflow less than 3.6×10^6 m^3) occurred 3 to 10 times annually during the period May–September, 1976-87. These low flow periods lasted as long as 20 days. If we assume that conspicuous blooms developed during low flow periods and continued until power releases resumed, then conspicuous blooms occurred in the lake an average of about 19 days each summer.

Based on our regression models, we suggest that reducing phosphorus-loading from the treatment plant by diversion or phosphorus-removal would slow the onset and reduce the severity of algal blooms in Lake Taneycomo. As demonstrated in Models 13 and 15 (Table 2), the average phosphorus concentration (19 µg/L phosphorus) at site 24-KM can accelerate growth of phytoplankton to more than 8 µg chlorophyll/L in about one week ($\Delta T^{\circ} = 9^{\circ}C$, Fig. 3) and reduce Secchi depth to less than 2.5 m. Inflow of wastewater sufficient to double in-lake total phosphorus would more than double algal biomass during this period and reduce transparency to less than 2.0 m. Also, doubling total phosphorus would shorten the time required to conspicuously reduce transparency.

Conspicuous summer algal blooms could be completely avoided in Lake Taneycomo if flushing rates were sufficient to maintain completely riverine conditions in the lake. Blooms could also be reduced in magnitude and frequency by removing phosphorus from the wastewater. Alternatively, the effluent could be diverted away from the lake or routed to the lake bottom in order to minimize its accumulation in surface water. The cost-benefit ratio of these measures is unknown. Because Lake Taneycomo is a unique and valuable resource (e.g., Weithman and Hass, 1984), additional study should be done on the aesthetic, economic, and recreational impact of algal blooms and on cost effective management solutions.

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