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Authors: C.H. Ward, J.M. King, and William G. Characklis

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Chemical and Algal Studies of Urban Lakes

C. H. WARD, J. M. KING, AND W. G. CHARACKLIS

Departments of Biology and Environmental Science and Engineering, Rice University, Houston, Texas 77001

A lake system was studied for a 3-yr period to determine changes in nutrient concn and algal populations associated with increasing urbanization of a watershed. Low flow concn of nitrogen, phosphorus, and suspended solids were high in early phases of urbanization. During storm events, massive quantities of dissolved and particulate material were transported to the lake by surface runoff. Fifty algal species were identified from the lake and dominance of species composition shifted from euglenoids to green algae. Euglenoids usually dominated algal cell numbers and biomass, while diatoms and blue-green algae alternated as codominants. Algal biomass was relatively low, thus algae were minor components of suspended solids and carbon loads of the lake. Regression analyses indicated that no single measured variable was responsible for changes in algal standing crops. However, theoretical evaluations of nutrient limitations and algal bioassays indicated that nitrogen and phosphorus were primary limiting nutrients in the lake, while turbidity was the primary limiting factor for algal growth.

INTRODUCTION

Urbanization often causes detrimental changes in surface-water quality. Concentrations of dissolved and particulate solids may be several times higher in surface runoff from urban reas than from relatively undisturbed watersheds (Keup 1968; Stewart 1968; Sylvester 961; Wiebel et al. 1964). Increased nutrients in urban drainage may accelerate eutrophiation of receiving waters and lead to excessive growths of aquatic flora. Thus, urban unoff is a major nonpoint pollution source and requires proper management to minimize mpact on surface waters.

Such a water resource plan was developed for a new community, The Woodlands, ocated in southeastern Texas. Development strategies were designed to maximize benefits of water resources to the community, while minimizing impact of urbanization on receiving waters. Preexisting swales and creeks transport storm-water runoff, and large, open areas llow infiltration of runoff water into the soil. Wet weather ponds and variable volume akes are used for storm-water storage.

A lake system (Lake Harrison) in The Woodlands was monitored to assess changes in nutrient levels and algal populations associated with increasing urbanization of a watershed. Lake Harrison was studied from time of construction until major land disturbance in its drainage area was terminated. This paper reports data from this 3-yr study.

MATERIALS AND METHODS

Description of study area and Lake Harrison. The Woodlands encompasses 7,194 ha of pine-hardwood forest approx. 56 km north of Houston, Texas. This planned community will be developed over a 25-yr period, beginning September 1972. Residential areas will

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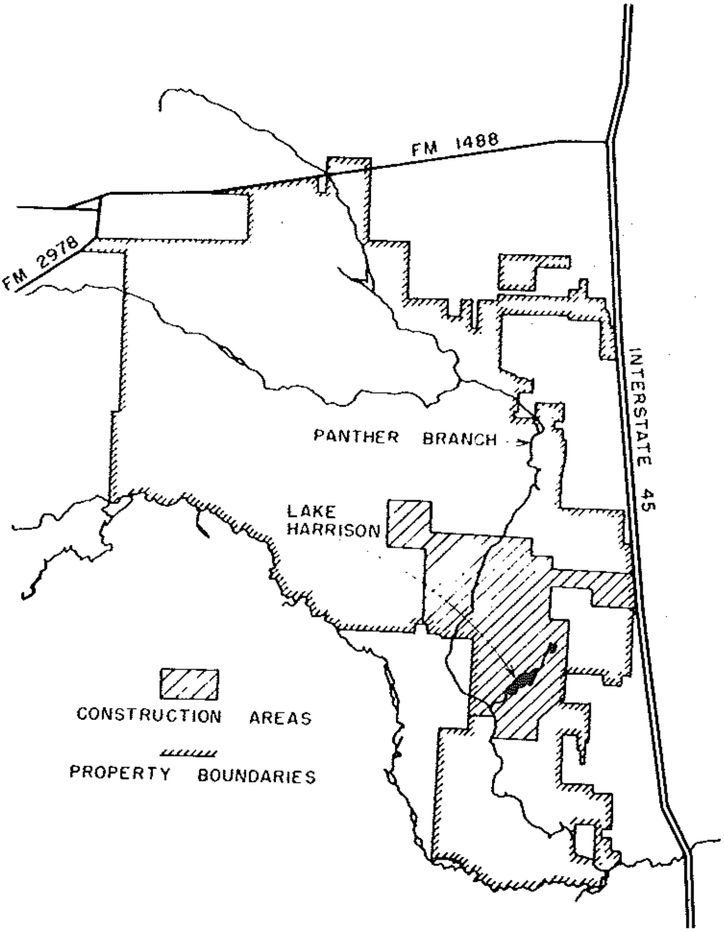
ccupy 2,760 ha, while 688 ha are designated for restricted industrial and commercial use. pproximately 30% of The Woodlands will remain as open space. To date, 10% of the atershed is under development (Fig. 1).

Lake Harrison is located in the southeastern portion of The Woodlands (Fig. 1) and was led during March 1974. This lake actually consists of two lakes separated by a decorative aterfall (Fig. 2). The upstream, smaller lake (Lake B) is maintained at a constant volume ensure continuous flow over the waterfall. During dry weather, no streamflow enters ke B and water level is maintained by recirculation of water from the lower lake (Lake , by piping in water from Panther Branch, or by inflow of tertiary treated sewage. Sewage w from The Woodlands community was not a major water source for the lake, but ojected sewage input is 6 mgd. During wet weather, Lake B is designed to receive storm- ter runoff from a 136-ha drainage area, which has experienced recreational and residential nstruction. Lake B has an average depth of 1.8 m, a surface area of 1.7 ha, and contains 669 m³ of water.



. The Woodlands construction activity in relation to Lake Harrison.

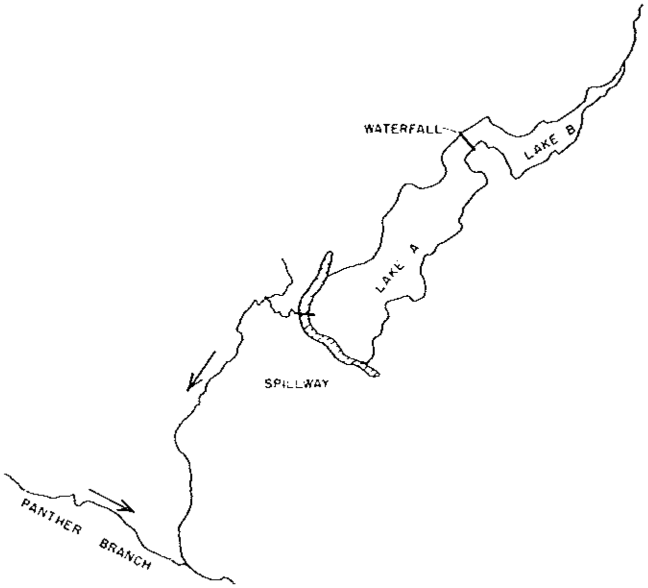


FIG. 2. Schematic of Lake Harrison.

Lake A is a variable volume lake for storm-water storage and noncontact recreation. During dry weather, ground water is pumped into the lake to compensate for water lost by evaporation. Lake A has a drainage area of 196 ha, which contains residential and recreational development. Lake A has an average depth of 2.4 m, a surface area of 5.1 ha, and a water volume of 111,013 m^3.

Collection and preservation of samples. When possible, surface water samples for chemical analyses were collected at monthly intervals. Samples were taken in precleaned, glass, dissolved oxygen bottles which were packed in ice for transport to the laboratory. In the laboratory, portions of each sample were filtered through 0.5 μm Millipore "cellotate" filters and preserved with mercuric chloride (40 mg 1^{-1}). Samples were refrigerated at 4 C until time of analysis. All analyses were completed within the time period recommended by the U.S. Environmental Protection Agency (1971).

Water samples for algal enumeration and nutrient limitation studies were collected at monthly intervals in precleaned, 3.7-liter glass bottles. Samples for phytoplankton identification were collected by making several horizontal tows with a #25 mesh plankton net. Preservatives were not added to these samples and each was processed immediately upon arrival at the laboratory.

Storm-water runoff was collected at various time intervals during eight separate storm events from the inflow and outflow of Lake Harrison. Methods for collecting water for chemical and nutrient limitation studies were similar to those described previously. Sampling commenced at the first indication of rainfall and continued until there was a decline and "leveling off" in discharge.

Analytical procedures. Analyses of NO_3-N, NO_2-N, NH_3-N, O-PO_4, and total-PO_4 were

onducted with a Technicon Autoanalyzer. Suspended solids were determined by the
iembrane filtration technique (Standard Methods 1971). Total organic carbon was measured
ith a Beckman carbon analyzer and turbidity of thoroughly mixed samples was determined
ith a Hach Turbidimeter. Temperature and pH were measured in the field by use of a
iercury thermometer and portable pH meter, respectively. Dissolved oxygen was meas-
red with a portable Beckman dissolved oxygen probe and meter.

Algal enumerations were conducted by the procedures outlined in Standard Methods
971). One liter of each water sample was concd to a final volume of 5 ml in a Sedgwick-
after column. A whipple disk and Sedgwick-Rafter counting cell were used to make algal
ounts.

Algal species were identified by microscopic examination of material from plankton tows
id from concd samples used for cell enumeration. Each sample was examined until no
lditional species were observed. A variety of taxonomic references (Gomont 1892; Huber-
estalozzi 1938–1961; Patrick and Reimer 1966; Prescott 1962; Smith 1950; Tiffany and
ritton 1952; West and West 1904–1912) were consulted for species identification.

Methods used in batch culture bioassays were similar to those described by Ward et al.
975). *Selenastrum capricornutum* was used as the test alga in all bioassays.

RESULTS AND DISCUSSION

iter quality. Investigations of the Lake Harrison system were confined primarily to the
aller, upstream lake (Lake B). Suspended solids and turbidity in Lake B were high
oughout most of the study period due to large concn of particulate materials transported
the lake by surface drainage from construction sites (Table 1). Water piped into Lake
rom Panther Branch also contained high concn of suspended solids. Consequently, light
ietration into the water column was reduced greatly and the euphotic zone was restricted
:he upper few centimeters of the lake.

The pH of Lake B was usually alkaline, but fluctuations into the acidic range were
erved (Table 1). Stabilization of pH at 8.3 (Sept. to Nov. 1975) was due primarily to
ow of alkaline, treated sewage effluent into the lake. The overall alkaline pH probably
ects impact of watershed alteration and manipulation of influent water on lake-water
lity, since small, undisturbed lakes in The Woodlands vicinity generally have acid or
r neutral pH values.

oncentrations of nitrogen and phosphorus varied considerably in Lake B (Table 1). In
y phases of development (Nov. 1973 to May 1974), waterfall construction was in
gress and the lake experienced extreme fluctuations in water volume. During this period,
ace runoff was the only source of water and nutrients for the lake. On completion of
spillway, the lake basin filled rapidly and extreme fluctuations in water level ceased.
eased concn of nitrogen (Aug. 1974 and Sept. 1975) resulted from surface drainage
1 heavily fertilized lawns and inflow of water from Panther Branch, which received
ation drainage from the golf course. Phosphorus concn were also higher during periods
igh nitrogen concn.

orm-water runoff was a significant source of dissolved and particulate solids for Lake
ible 2). Concentrations of suspended solids were higher in surface runoff water than
w flow water (no surface drainage). Additional studies indicated that approx. 80% of
v suspended solids remained in the lake system. Turbidity increased with surface
ff due to the influx of solids into the lake. Average concen of NH_3-N, NO_3-N, and
cially PO_4-P were also higher in storm-water runoff than in low flow water.

TABLE 1. *Water quality of Lake B during months between November 1973 and November 1975* [a]

Month	Suspended Solids	Turbidity (JTU)	pH	Temp. (C)	NH_3-N	NO_3-N	NO_2-N	PO_4-P
Nov.	650	—[b]	8.5	16.0	0.13	0.06	0.04	0.22
Dec.	507	—	7.8	15.9	0.08	0.06	0.04	0.08
an.	400	—	7.4	19.5	0.21	0.10	0.02	0.01
Feb.	406	135	7.9	18.7	0.11	0.09	0.02	0.05
Mar.	704	381	7.9	23.2	0.07	0.09	0.01	0.07
un.	642	380	8.0	31.0	0.09	0.11	0.01	0.05
ul.	—	—	7.8	28.0	0.10	0.10	0.02	0.01
Aug.	1068	440	7.5	29.0	0.05	0.29	0.04	0.10
Sept.	1050	500	6.4	25.0	0.07	0.27	0.01	0.06
Oct.	1140	560	8.0	24.0	0.02	0.11	0.01	0.05
an.	313	25	7.8	13.0	0.08	0.11	0.01	0.01
Feb.	131	78	6.1	10.4	0.06	0.03	0.01	0.01
Jul.	10	38	7.9	27.4	0.02	0.03	0.01	0.09
Aug.	14	27	8.1	28.3	0.05	0.03	0.03	0.03
Sept.	1250	690	8.3	24.0	0.14	0.39	0.21	0.05
Oct.	1278	580	8.3	19.5	0.09	0.21	0.04	0.04
Nov.	78	42	8.3	22.5	0.09	0.02	0.04	0.02

[a] All parameters in mg l^{-1}, except pH, turbidity, and temp.

[b] —, Data not available.

TABLE 2. *Comparison of average and maximum water quality parameters for low flow and stormwater runoff in Lake B*[a]

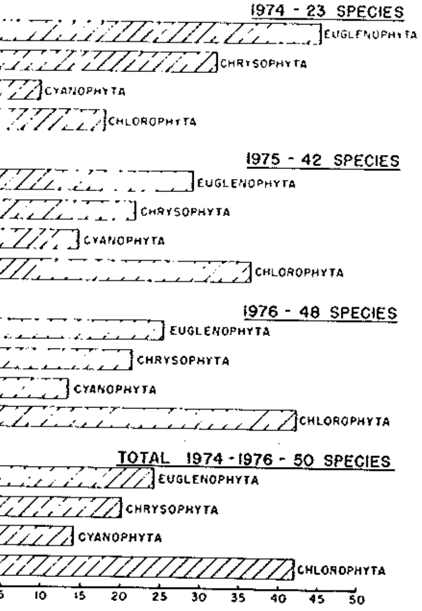
	Low Flow		Stormwater Runoff	
	Ave.	Max.	Ave.	Max.
Suspended solids	603	1278	1273	2660
Turbidity (JTU)	298	690	375	900
NH_4-N	0.09	0.21	0.11	0.15
NO_3-N	0.12	0.39	0.15	2.1
NO_2-N	0.03	0.21	0.01	0.05
PO_4-P	0.06	0.22	0.11	0.36

[a] All parameters in mg l^{-1}, except turbidity.

Algal composition, standing crops, and biomass. Fifty species of algae, representing 35 genera, were identified from Lake B. Over a 3-yr period, there was a 54% increase in number of total algal species, with an 80% increase in species of Chlorophyta. The largest percentage of total species was initially euglenoids, but dominance was assumed later by chlorophycean algae (Fig. 3). Chrysophycean and blue-green algae never dominated species composition.

Algal cell numbers fluctuated drastically over a 2-yr period (Fig. 4). Initially, euglenoids dominated algal standing crop, while diatoms and blue-green algae alternated as codominants. Relative numbers of euglenoids eventually decreased and dominance was assumed alternately by diatoms or blue-green algae. Chlorophycean algae were minor components of standing crops, even though the chlorophyta was the most diverse of the algal groups.

Since algal species differ in size, cell numbers do not always reflect actual biomass.



3. Percent species composition, by division, or Lake B over a 3-yr period.

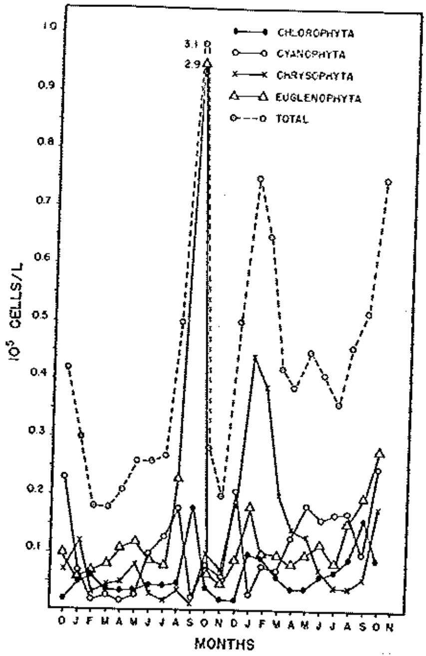
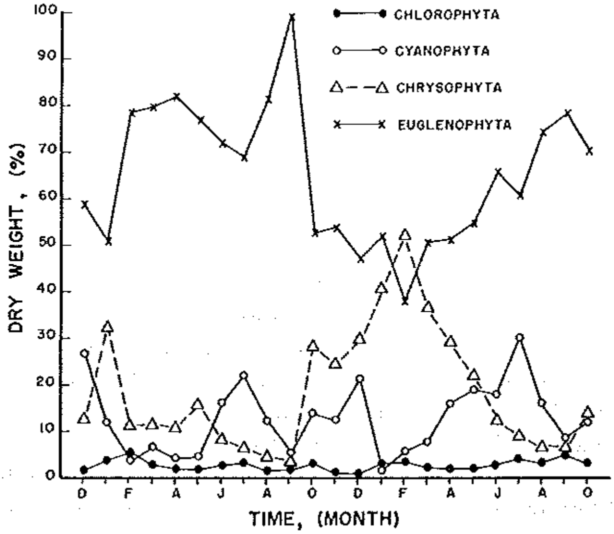


FIG. 4. Monthly standing crops, by division, in Lake B (Dec. 1973 to Nov. 1975).

refore, total cell numbers were converted to dry weight and cell volume estimates by of tables available in the literature (Bellinger 1974; Nalewajko 1966; Wetzel 1975) and ulations performed in our laboratory. Fig. 5 presents estimates of algal biomass by sion on the basis of percent of total dry weight. Euglenoids dominated algal biomass, ept on one occasion (Feb. 1975) when diatoms were dominant. Crysophycean algae e major codominants during winter months, while cyanophycean algae were major ominants in summer months. Chlorophycean algae were minor contributors to algal ls in the lake.

emporal changes in algal populations were noted, but regression analysis (Table 3) cated that measured physiochemical parameters were not responsible for total changes gal numbers. Other factors or interactions of various factors probably exerted more ct on changes in algal numbers. Also, composition and standing crop of algae were enced significantly by recirculation of water into the lake and by use of Panther Branch r to maintain constant lake volume.

gal populations in Lake B were relatively low when compared to other aquatic eco- ems. For example, cell numbers exceeding 10^4 cells ml^{-1} have been reported for Lake nigan (Schelske and Stoermer 1972) and highly nutrified water in southeastern Texas on et al. 1976). Algal cell numbers and biomass in Lake B were well below the 10^6 l^{-1} (Kramer et al. 1972) or 8 mg l^{-1} (Morton et al. 1972) values reported as being cient to classify algal growth as a water bloom. Algal cell volume (0.62 mm^{-3} l^{-1}) in B was also well below the bloom proportions (10 mm^{-3}) reported by Kramer et al.). Average total algal biomass in Lake B was 38.88 μg l^{-1}, while average suspended



IG. 5. Percent dry weight of algae, by division, in Lake B (Dec. 1973 to Oct. 1975).

ABLE 3. *Regression analyses with physiochemical parameters and algal numbers in Lake B*

hysiochemical arameters	Chlorophyta	Algal Division		Euglenophyta
		Cyanophyta	Chrysophyta	
O_3-N	0.341[a]	0.009	0.056	0.501
uspended Solids	0.159	0.031	0.007	0.014
O_4-P	0.102	0.127	0.057	0.029
H_3-N	0.057	0.031	0.038	0.025
H	0.033	0.103	0.003	0.001
issolved Oxygen	0.005	0.112	0.106	0.003
emperature	0.000	0.002	0.606	0.012
Multiple R^2	0.696	0.415	0.872	0.585

Based on monthly averages.

ABLE 4. *Comparison of algal biomass and carbon content contributed by each algal division.*[a]

lgal Division	Weight Range (μg l^{-1})	Average Weight (μg l^{-1})	Average Carbon Content (μg l^{-1})
Chlorophyta	0.24– 2.16	0.74	0.37
Cyanophyta	0.52– 6.50	2.80	1.40
Chrysophyta	0.42– 18.48	4.62	2.31
Euglenophyta	6.5 –377.00	30.63	15.32
Total	11.6 –380.10	38.88	19.44

All parameters in θg l^{-1}.

olids was 603 mg l^{-1} (Table 4). Thus, algae were a minor part of the particulate material n Lake B and suspended solids were definitely not of algal origin.

gal carbon. According to Vollenweider (1969), algae are composed of 40 to 60% carbon weight. On the basis of a 50% carbon content, total dry weight values per month were nverted to carbon estimates (Table 4). These conversions indicated that algae contributed tle to organic loads of Lake B, since the average concn of total organic carbon was 16.85 g l^{-1}. The average rate of change in algal carbon, based on gains and losses in algal omass at 30-day intervals, was 0.14 mg C m^{-2} day $^{-1}$. Even though this figure is not a ily rate of carbon production, it can be used to make general comparisons between algal rbon in Lake B and other aquatic ecosystems. For example, Rodhe (1969) reported algal oduction values of 7 to 25 g C m^{-2} yr $^{-1}$ for oligotrophic lakes, 75 to 250 g C m^{-2} yr for naturally eutrophic lakes, and 350 to 700 g C m^{-2} yr $^{-1}$ for culturally eutrophic lakes. ven though these data are subject to interpretation, they provide a general picture of imary productivity in lakes with various trophic classifications. More specifically, Wetzel 975) reported annual productivity values (g C m^{-2} yr $^{-1}$) of 36 for Castle Lake, Calif. ligotrophic), 160 for Clear Lake, Calif. (mesotrophic), and 369 for Lake Wintergreen, ich. (eutrophic). Lake B probably had productivity rates resembling those of oligotrophic aters. Even considering loss of algal cells by grazing or sedimentation, it is unlikely that ake B had productivity rates approaching those of mesotrophic or eutrophic lakes.

utrient evaluations. Miller et al. (1976) stated that 1 μg P l^{-1} yields 0.43 mg dry weight algae, while 1 μg total soluble inorganic nitrogen per liter (TSIN; NH_3-N + NO_3-N + O_2-N) yields 0.038 mg dry weight of algae. These values were used to calculate theoretical gal yields from measured concn of TSIN and PO_4-P in Lake B (Table 5). These data dicate that theoretical yields were substantially higher than observed algal biomass, thus, ake B could theoretically support more algal biomass, provided that some factor other an nitrogen or phosphorus was not limiting for algal growth. Ratios of nitrogen and

ABLE 5. *Theoretical yields*[a] *of algae and N:P ratios based on nitrogen and phosphorus concn of Lake B*

onth	TSIN[b] (mg l^{-1})	PO_4-P (mg l^{-1})	N:P	TSIN Yield (mg l^{-1})	PO_4-P Yield (mg l^{-1})	Recorded Algal Weight (μ g l^{-1})
c.	0.18	0.08	2.3:1	6.8	34.4	0.022
n.	0.33	0.01	33:1	12.5	4 3	0.015
b.	0.22	0.05	4.4:1	8.4	21.5	0.012
ar.	0.17	0.07	2.4:1	6.5	30.1	0.013
n.	0.21	0.05	4.2:1	8.0	21.5	0.016
.	0.22	0.01	22:1	8.4	4.3	0.015
g.	0.18	0.10	1.8:1	6.8	43.0	0.036
pt.	0.35	0.06	5.8:1	13.3	25.8	0.380
t.	0.14	0.05	2.8:1	5.3	21.5	0.014
n.	0.20	0.01	20:1	7.6	4.3	0.044
b.	0.10	0.01	10:1	3.8	4.3	0.031
.	0.06	0.09	1:1.5	2.3	38.7	0.017
g.	0.11	0.03	3.7:1	4.2	12.9	0.028
pt.	0.74	0.05	14.8:1	28.1	21.5	0.033
t.	0.34	0.04	8.5:1	12.9	17.2	0.052

heoretical yields based on conversion factors of Miller et al. (1976)

SIN: Total soluble inorganic nitrogen (NH_3-N + NO_3-N + NO_2-N) osphorus may be used to estimate which of these nutrients is potentially limiting for oduction of algal biomass. Miller et al. (1976) and Chiaudani and Vighi (1974) reported timum N:P ratios of 11.3 and 10, respectively, for growth of *Selenastrum capricornutum*. ratio of 15:1 was reported as optimum for algal growth by Fitzgerald (1972), while llenweider (1969) reported a range of 10 to 15 as optimum. On the basis of a 10:1 ratio, osphorus is a potential limiting nutrient for algal growth during some months, while trogen is potentially limiting in other months (Table 5). However, algal biomass in Lake never exceeded theoretical yields; thus these nutrients were probably not the primary iting factor in the lake.

Bioassays indicated that low flow water from Lake B could support a biomass of *S. pricornutum* which exceeded recorded algal biomass. A filtered and autoclaved sample oduced 27 mg l^{-1} dry weight of *S. capricornutum*, while a portion of the same sample toclaved before filtration supported a yield of 50 mg l^{-1}. Autoclaving of lake water emed to solubilize nutrients which could be utilized for growth by the test alga. Bioassays ith autoclaved, filter-sterilized water probably provided low estimate of growth-supporting pabilities of Lake B water. Yields of *S. capricornutum* were also increased by removal turbidity (suspended solids) from Lake B water by use of various size filters. A 97% duction in turbidity resulted in a 94% increase in algal yield, while a 56% turbidity duction increased algal yield by 84%. Nutrient spikes also indicated that phosphorus lditions stimulated algal growth in the majority of Lake B water samples. However, trogen was, on occasion, the limiting nutrient for algal growth in low flow water and was ways the limiting nutrient in surface runoff collected during storm events. Correlations etween theoretical yields, observed biomass, cell volume, and bioassay yields are not ossible since water samples for chemical analyses and algal bioassays were not collected multaneously. The stimulation of algal growth by nitrogen and phosphorus spikes does dicate that other nutrients were present in quantities sufficient to support added growth the test alga. Thus, nitrogen and phosphorus were primary limiting nutrients, but were t necessarily the limiting growth factors in Lake B.

ake comparison and conclusions. Lake B parameters were compared to those of lakes ith various trophic levels (Wetzel 1975). Total organic carbon and phosphorus concn in ake B resemble those of eutrophic lakes, while total nitrogen falls within the range of igo-mesotrphic lakes. However, phytoplankton biomass and algal carbon indicate that ake B was ultra-oligotrophic. Nutrient supplies seemed sufficient to support algal standing ops and biomass in excess of those actually observed in Lake B.

The high initial turbidity of Lake B probably limited algal diversity to those species hysiologically or morphologically adapted for existence at low light intensities. Reductions turbidity seemed to allow a more diverse assemblage of algae, composed primarily of lorophycean species, to develop in the lake. However, even with reduced turbidity, algal iomass was dominated by euglenoids and chrysophytes or blue-green algae. Growth of een algae may have been limited by the high pH, high turbidity, or a combination of ese factors. The relatively low algal biomass indicates that some factor, possibly turbidity, as limiting algal growth. However, dense floating mats of *Spirogyra* sp. and *Oedogonium* . developed in the littoral of Lake B. Reduced turbidity would probably be accompanied y comparatively higher yields of algae in Lake B, and, at this time, algal growth would robably be limited by nitrogen and phosphorus concn in the lake. Future reductions in ke turbidity might necessitate some management strategy, such as regulation of detention ne or use of well water to dilute nutrients entering the lake via treated sewage effluent Panther Branch water.

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