1993

Phytoplankton Relationships to Water Quality in Lake Drummond and Two Drainage Ditches

Christine G. Phillips
Old Dominion University

Harold G. Marshall
Old Dominion University, hmarshal@odu.edu

Original Publication Citation
Phillips, C. G., & Marshall, H. G. (1993). Phytoplankton relationships to water quality in Lake Drummond and two drainage ditches. *Castanea*, 58(1), 18-33. https://www.jstor.org/stable/4033794

CASTANEA 58(1): 18–33. MARCH 1993

Phytoplankton Relationships to Water Quality in Lake Drummond and Two Drainage Ditches in the Great Dismal Swamp, Virginia

CHRISTINE GREGORY PHILLIPS and HAROLD G. MARSHALL

Department of Biological Sciences, Old Dominion University, Norfolk, Virginia 23529-0266

ABSTRACT

A twelve-month phytoplankton study was conducted in Lake Drummond and Washington and Jericho Ditches from December 1988 to November 1989. Four dominant phytoplankton groups were identified at these sites. These were the Bacillariophyceae, Cyanophyceae, Cryptophyceae and an autotrophic picoplankton component. Over the past 20 years there has been a decrease in the mean pH levels of Lake Drummond and the replacement of one its former major components, the Chlorophyceae, by the Cyanophyceae. Based on water quality analysis results and species diversity indices, Lake Drummond is classified as in an early eutrophic stage of development.

INTRODUCTION

Lake Drummond is centrally located in the Virginia portion of The Great Dismal Swamp. Initial phytoplankton studies of Lake Drummond, conducted by Poore (1971) and Marshall and Poore (1972), indicated dominance and low diversity of diatoms and chlorophytes. Later studies by Poore and Marshall (1972) and Marshall (1976, 1979) characterized the phytoplankton populations and general water quality of Lake Drummond. These results identified Lake Drummond as a shallow (<2 m), acidic (mean pH 4.2–4.8), brown water, temperate lake, with a surface area of approximately 13 km^2 and a maximum diameter of 4.5 km. The phytoplankton typically expressed spring and fall maxima, dominated by the diatom *Asterionella formosa,* several *Melosira* spp. and various desmids. Due to the lake's shallow depth and prevailing wind patterns, stratification was rare, but turbidity was high and mean oxygen levels within the water column were generally above 6 mg/L. Since 1812 a feeder ditch has connected the lake to the Intercoastal Waterway, where Lake Drummond has served as a reservoir source of water to maintain navigable water levels within this canal.

Water drainage into Lake Drummond comes from surface and ground water sources, with surface flow enhanced by several drainage ditches, which include the Jericho and Washington Ditches. Differences in the phytoplankton composition of the Washington and Jericho Ditches were originally noted by Marshall (1979). The Jericho Ditch drains from the northern, peat enriched region of the

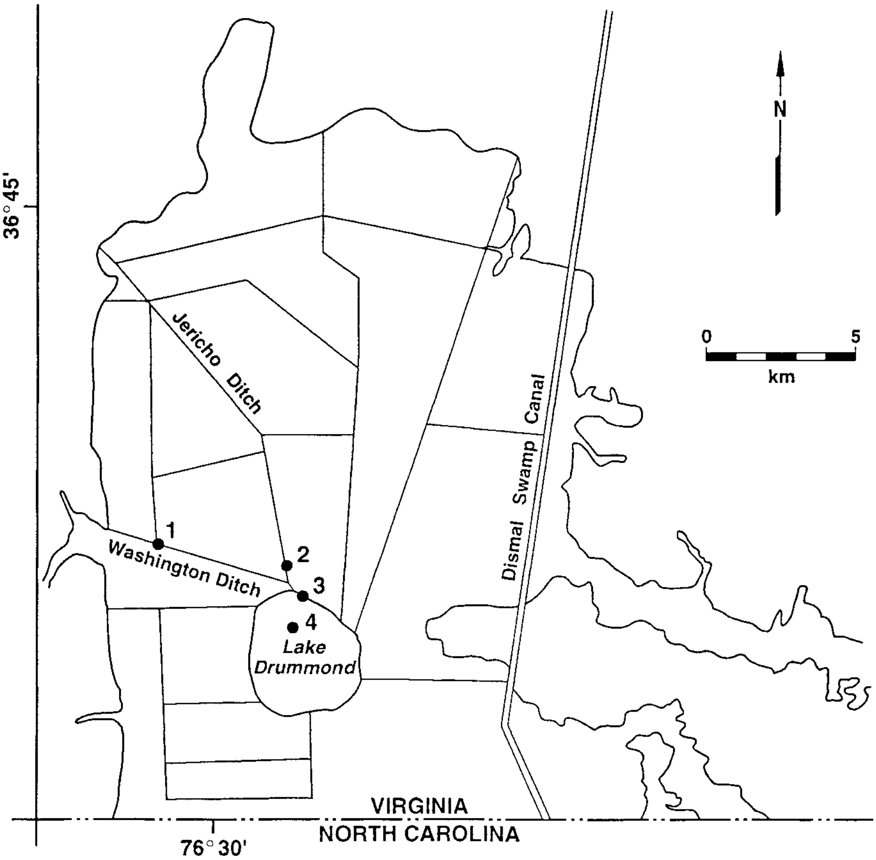

Figure 1. Station locations in the Dismal Swamp.

swamp and its water has darker coloration and greater acidity than waters of Washington Ditch. Washington Ditch drains from the west, from a higher elevation and less acidic region than the northern drainage area. The objectives of this study were to identify present phytoplankton associations and dominant species within Lake Drummond and the two drainage ditches in the Dismal Swamp, and to appraise the Lake's current water quality status.

METHODS

Surface water samples (500 ml) were collected monthly for phytoplankton analysis from stations (1, 2 and 4) in Lake Drummond, Jericho and Washington Ditches from December 1988 to November 1989 (Figure 1). A second station (3) in Lake Drummond was added from June to November 1989, for nutrient and chlorophyll analysis. The 500 ml phytoplankton samples were preserved with 4 ml of Lugol's solution and settled for 48 hours. This was followed by a two-step siphoning and settling procedure, with the final concentrate placed in a Zeiss settling chamber and analyzed with an inverted plankton microscope. To produce an 85% accuracy estimate, the samples were examined for phytoplankton using a random field and minimum count basis at 312× and 500× magnification (Venrick 1978). The entire chamber was also scanned at 125× for the larger and rarer forms. The final cell counts were calculated as cells per liter (cells/L).

Field samples were collected for nutrient analysis and vacuum-filtered with Whatman glass fiber filters (GF/F), acidified with 6N H_2SO_4, and stored at 4°C, until they were processed. Nitrate-nitrite, silica and ammonia concentrations were measured with an autoanalyzer (Orion Scientific Instruments Corp. Model AC 200). An automated cadmium reduction method was used for nitrate-nitrite (absorbance 550 nm). Silica was determined using an automated molybdate oxalic acid (abs. 660 nm) and ammonia with automated alkaline phenol (abs. 630 nm). Detection limits for these nutrients are: nitrate-nitrite 0.0025 mg/L, silica 0.0234 mg/L, and ammonia 0.0056 mg/L. Orthophosphate and total dissolved phosphate were determined colorimetrically on a spectrophotometer (Perkin-Elmer, Model 552 uv/vis), using 2-reagent ascorbic acid, abs. 880 n, EPA 1979). An autoclave was used for the digestion process for measuring total dissolved phosphate (APHA 1985). Total dissolved nitrogen was determined colorimetrically with a spectrophotometer (Perkin-Elmer, Model 552 uv/vis), using persulfate oxidation (abs. 550 nm) (D'Elia et al. 1977); the detection limit was 0.05 mg/L. Dissolved organic carbon levels were determined on a Horiba non-dispersive infrared analyzer (NDIR, Horiba, Model PIR-2000), using wet oxidation with infrared analysis (Menzel and Vaccaro 1964). The detection limit for organic carbon was 0.5 mg/L. The pH was measured with a Corning pH Meter, Model 245.

One ml of 1% magnesium carbonate solution was added to water samples collected for chlorophyll analysis to reduce chlorophyll degradation. Samples were then placed on ice and transported to the laboratory. Approximately 400 ml of sample water were concentrated using a vacuum filter with Whatman glass fiber filters (GF/C) and frozen until processed (APHA 1985). Following an extraction procedure for chlorophyll *a*, *b*, *c*, carotene and phaeophytin *a*, the supernate was analyzed with a spectrophotometer (Perkin-Elmer, Model 552) at various wavelengths (APHA 1985). Final concentrations are reported in milligrams per cubic meter (mg/m^3).

Phytoplankton composition data from all sites were analyzed with reduction techniques (Williams and Stephenson 1973) to identify the species that most characterized the populations from each ditch and the lake. A cluster analysis of the reduced data set was performed using station, data and taxa distance coefficients (Williams and Stephenson 1973). These distance coefficients produced standardized Euclidean distance dendrograms using a flexible beta ($\beta = -0.25$) clustering algorithm. The dendrograms grouped phytoplankton taxa by temporal (monthly) distribution and by site. A discriminant analysis of variance and multivariate analysis of variance (MANOVA) were then applied to the seasonal and site taxonomic groups that produced these dendrograms to determine if there were species that could be associated with the separation within these groups.

Table 1. Monthly environmental parameters from December 1988 to November 1989

	Lake Drummond		Washington Ditch		Jericho Ditch		Rainfall
Date	pH	Temp °C	pH	Temp °C	pH	Temp °C	(cm)
Dec 20	5.10	4.0	5.10	2.0	3.51	2.5	2.41
Jan 20	3.92	9.0	5.22	7.0	3.18	7.0	10.08
Feb 27	4.02	4.5	5.26	4.0	3.15	6.0	16.13
Mar 19	3.23	13.5	5.20	11.0	3.15	12.0	27.40
Apr 23	3.88	11.0	4.59	14.0	3.04	14.5	17.07
May 18	3.77	16.0	5.42	17.0	2.97	16.0	17.91
Jun 28	3.62	30.0	5.58	28.0	3.06	24.5	19.99
Jul 26	3.50	34.0	5.06	25.0	2.99	23.5	17.40
Aug 23	3.92	25.0	5.29	27.0	3.13	24.5	30.33
Sep 27	3.52	16.3	5.22	15.0	3.27	18.5	16.38
Oct 29	3.63	19.0	5.45	15.0	3.18	15.5	9.52
Nov 16	3.55	18.5	5.47	17.0	3.27	16.0	12.45

RESULTS AND DISCUSSION

Physical and Environmental Parameters

Surface water temperatures in Lake Drummond ranged from 4.0 to 34.0°C; 2.0 to 28.0°C in the Washington Ditch; and 2.5 to 24.5°C in the Jericho Ditch (Table 1). The mean pH values for Lake Drummond, Washington Ditch and Jericho Ditch were 3.8, 5.2 and 3.1, respectively. A decrease in mean pH concentrations was noted between Poore's (1971) study (mean pH 4.30) and the present study (mean pH 3.80). During our study period, rainfall totaled 197.07 cm and exceeded the 30-year monthly means for Dismal Swamp. A general increase in pigment and nutrient concentrations was observed from summer into fall (Table 2). Higher concentrations were noted in fall months for phosphates (0.13 mg/L), nitrate-nitrite (0.18 mg/L), silica (4.36 mg/L) and total organic carbon (98.10 mg/L). Concentrations of orthophosphates remained at, or below 0.03 mg/L throughout the study, in contrast to high summer levels for ammonia (0.39 mg/L) and total dissolved nitrogen (2.68 mg/L). Lake Drummond's mean total phosphorous level was 0.04 mg/L and mean total nitrogen concentrations 1.64 mg/L. Wetzel (1983) gave a mesotrophic range for total phosphorus as 0.011 to 0.095 mg/L, with an overlapping range of 0.016 to 0.386 mg/L for eutrophic lakes, and the eutrophic levels for total nitrogen as >0.361 mg/L. The mean chlorophyll *a* level was 4.92 mg/m^3, with the mesotrophic range identified as 4.9 to 49.5 mg/m^3. Although secchi depths were not taken in this study, Poore (1971) gave a Secchi disk depth range of 0.08–0.64 m for the lake. Wetzel (1983) characterizes eutrophic lakes as having a Secchi disk depth of <7.0 m. Total nitrogen to total phosphorus ratios in Lake Drummond ranged from 30:1 to 138:1, with a mean ratio of 66:1. Weiss and Kuenzler (1976) state ratios greater than 10–12:1 are indicative of phosphorus-limiting conditions. Total pigment concentrations (Table 2) remained relatively low and constant in summer, decreasing into the early fall, and finally rising rapidly in late fall. The chlorophyll *a* concentrations,

Table 2. Results of nutrient analysis (mg/L) in Lake Drummond from June 1989 through November 1989, with chlorophylls and phaeophytin in mg/m³

Date	NH_3	NO^2/NO_3	OPO_4	SiO_2	TDN	TOC	TPO_4	Chl *a*	Chl *b*	Chl *c*	Pha *a*
Jun 28	0.16	0.09	—	1.83	2.68	70.26	0.02	4.08	1.14	3.54	0.00
Jul 25	0.29	0.08	0.01	2.26	2.42	66.08	0.02	4.07	0.26	2.08	0.23
Aug 23	0.39	0.09	0.02	2.65	1.06	66.55	0.03	4.32	0.55	1.86	1.50
Sep 27	0.33	0.05	0.03	4.36	1.43	51.70	0.04	1.00	0.54	0.32	0.00
Oct 29	0.21	0.18	0.02	4.01	1.06	69.68	0.02	0.76	0.00	0.00	0.02
Nov 16	0.13	0.18	0.02	3.83	1.20	98.10	0.13	15.32	1.49	1.80	15.30
Mean	0.25	0.11	0.02	3.15	1.64	70.39	0.04	4.92	0.66	1.60	2.84

corrected for phaeophytin *a*, ranged from 0.76 mg/m³ in October to 15.32 mg/m³ in November. According to Wetzel's (1983) trophic classification of lakes and reservoirs, which utilizes nutrient and chlorophyll concentrations and Secchi disk depths, Lake Drummond is in an early eutrophic stage, with phytoplankton growth phosphate limited during summer and fall.

Lake Drummond: Phytoplankton Composition and Distribution

A total of 52 taxa were classified from Lake Drummond during the study (Phillips 1990). These included species from the Bacillariophyceae (19), Dinophyceae (1), Cyanophyceae (or cyanobacteria) (12), Euglenophyceae (4), Chlorophyceae (16), Cryptophyceae (1) and Chrysophyceae (1). In addition, a picoplankton category, defined here as autotrophic cells <2 μm in cell size was included. The seasonal phytoplankton distribution, excluding the picoplankton, displayed growth peaks in winter, spring, summer and fall (Figure 2). Highest cell concentrations were associated with winter (December, January) and the following fall (November) and were dominated by diatoms and chlorophytes. The winter bloom subsided in February and was followed by a second and more modest development in March, decreasing in late spring. The summer months were accompanied by another growth period (June, July), before declining in early fall. This was followed by a rapid development of cells in late November. The November bloom coincided with highest concentrations of chlorophyll *a*, phaeophytin *a*, nitrate-nitrite, total phosphate and total organic carbon. This later development may be a response to upwelling action in the lake due to intense storm activity and drainage which occurred in November 1990.

The bacillariophyceans had numerous seasonal pulses, with a low of 7.2×10^4 cells/L in August and a December high of 6.6×10^6 cells/L. The dominant species was *Asterionella formosa*. Species of *Tabellaria, Fragilaria* and *Eunotia* were also common. *Asterionella ralfssi* var. *americana*, a common diatom in acid waters, was not observed. Poore (1971) noted in his phytoplankton study of Lake Drummond that *A. formosa* was the most abundant species with concentrations reaching 1.4×10^7 cells/L. Marshall (1976) later noted in a seventeen-month study of Lake Drummond that *A. formosa* was the dominant species, with *M. granulata, F. crotonensis, Suririella* sp. and *Navicula* sp. also common. Charles

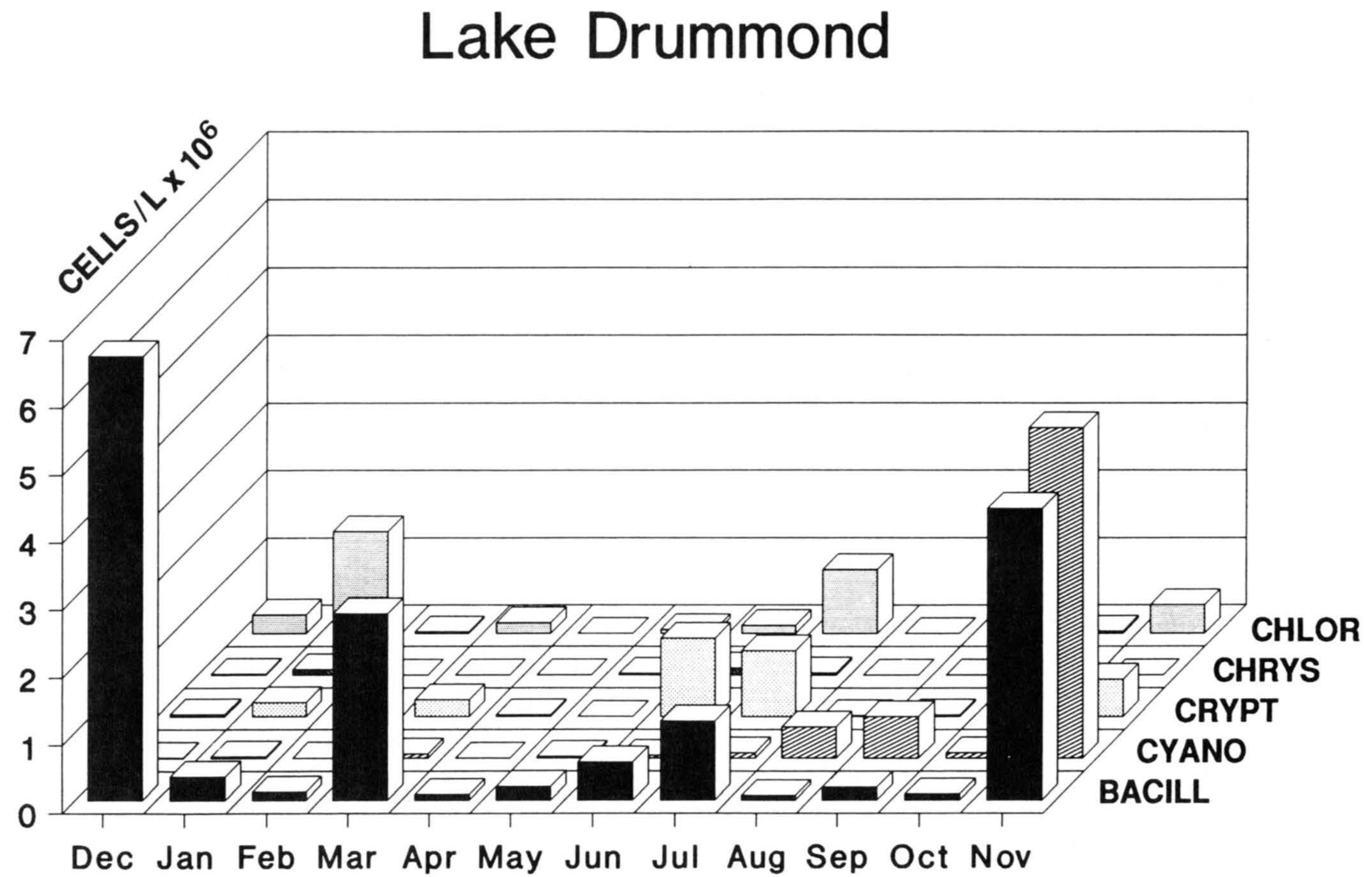

Figure 2. Concentrations of major phytoplankton categories in Lake Drummond from December 1988 through November 1989. Chlorophyceans (chlor), chrysophyceans (chrys), cryptomonads (crypt), cyanobacteria (cyano) and bacillariophyceans (bacill).

(1985) classified *A. formosa* and *F. crotonensis* as acidophilic, in contrast to Dixit et al. (1988) who consider the higher abundances of these species not dependent on a specific pH.

The chlorophyceans exhibited bimodal distribution with winter and summer peaks of 1.5×10^6 and 9.4×10^5 cells/L, respectively, with *Microspora* spp., and *Staurastrum paradoxum* dominating the winter and *Microspora* sp., *Oocystis* sp. and *Closteriopsis longissima* abundant in the summer. A winter-summer bimodal pattern of development was also expressed by the chrysophyceans; however, their concentrations did not exceed 1.0×10^5 cells/L. A January pulse was composed entirely of *Ochromonas* sp., with a shift to *Mallomonas* sp. in June. Other common background chrysophyceans were *Synura* sp., *Dinobryon cylindricum* and *Chrysococcus tesselatus*. Chrysophyceans have been characterized as the most dominant component in acidified lakes by Willén (1969) and Lyden and Grahn (1985); however this dominance was not observed in Lake Drummond and may be a response to existing phosphate levels. In a report on Ontario Lakes, Nicholls et al. (1977) reported lakes with high total phosphorus concentrations (i.e., >0.04 mg/L) as poorly represented by chrysophyceans (contributing $<5\%$ to total phytoplankton). Seasonal concentrations of cryptomonads fluctuated throughout the year, with a summer pulse of 1.2×10^6 cells/L in June. This group was composed of several species which were placed into a broad taxonomic group. Poore's (1971) study identified two forms of cryptomonads peaking in concentrations during the late summer (May) at 2.0×10^5 cells/L, and Marshall (1976) identified one cryptophycean, *Cryptomonas ovata*. Cyanophycean (cyanobacteria) concentrations remained modest during the winter and spring months at less than 6.1×10^5 cells/L. A gradual increase in cell concentrations occurred during the late summer, decreasing in concentration in October and followed by a large pulse of 4.9×10^6 cells/L in November. The dominant species in this group was *Microcystis incerta*. Other frequent species were *Phormidium* sp., *Aphanothece* sp., and a group of unidentified trichomes. Poore's (1971) study identified one species of cyanophycean, *Spirulina nordstedtii*, whose concentrations did not exceed 8.0 cells/L. *Merismopedia elegans* was the only cyanophycean noted by Marshall (1976) in Lake Drummond.

Euglenophyceans were present, but in low concentrations and included species of *Euglena, Phacus* and *Trachelomonas*. Concentrations for this group did not exceed 1.4×10^3 cells/L. In addition, dinophyceans reached highest concentrations in December at 3.3×10^4 cells/L. Marshall (1976) reported several dinophyceans including *Protperidinium wisconsinense, P. westii* and *P. limbatum*; however, these were not noted in this study. Reports from Yan and Stokes (1978) and Hultberg and Andersson (1982) identified dinophyceans as having higher concentrations in acidic lakes; however, this study did not find dinophyceans to be significant contributors to the phytoplankton composition or concentrations.

Considering cellular abundance, the picoplankton concentrations in Lake Drummond represented nearly 83% of the total phytoplankton. A preliminary examination with epifluorescence microscopy indicated these picoplankton cells consisted primarily of autotrophic cyanobacteria, 0.5 to 1.5 μm in size. In lesser abundance within this group were isolated chlorophycean cells (e.g., *Chlorella* sp.). The picoplankton concentrations ranged from 3.5 × 10^6 cells/L in October to 6.3 × 10^7 cells/L in November (Figure 3). In general, there were slight changes in abundance from winter through summer in the lake, with modest increases in concentrations in late spring (May) and summer (August), before a major fall development (November).

Nygaard (1949) established a trophic state index for lakes based on species composition. These indices in relation to Lake Drummond (Phillips 1990) are as follows: 1) Myxophyceae index (Myxophyceae/Desmideae) for Lake Drummond was 3.0, with 0.1–3.0 as eutrophic; 2) chlorophycean index (Chlorococcales/Desmideae) was 3.0, with 0.2–9.0 as eutrophic; 3) bacillariophycean index (centric/pennate diatoms) was 0.58, with 0.00–1.75 as eutrophic; 4) euglenophycean index (Euglenophyceae/Myxophyceae + Chlorococcales) was 0.25, with 0.1–0.2 as eutrophic; and 5) the compound index (Myxophyceae + Chlorococcales + centric diatoms + Euglenophyceae/Desmideae) was 8.75, with 1.2–2.5 as eutrophic. Although additional species may subsequently be identified and influence the above indices, the general pattern presented by these relationships is the presence of a developing eutrophic flora in Lake Drummond.

Washington Ditch and Jericho Ditch

Jericho Ditch had the lowest mean pH (3.16) of the stations and the lowest species diversity. Twenty-nine species were recorded for Jericho Ditch compared to 43 for the Washington Ditch (Phillips 1990). Jericho Ditch also possessed several growth maxima that were more similar to those in Lake Drummond than in Washington Ditch (Figures 4–5). Comparisons of phytoplankton between the two ditches showed several differences. The highest picoplankton concentrations were associated with Washington Ditch with a late summer maximum of 6.8 × 10^7 cells/L (Figure 3); while the lowest levels were in Jericho Ditch, where concentrations did not exceed 1.4 × 10^7 cells/L. Washington Ditch had greater abundance of bacillariophyceans, but lower concentrations of chlorophytes than Jericho Ditch. The larger pennates that dominated the flora in Lake Drummond were generally few or absent in the ditches; these included *Asterionella formosa, Eunotia* sp. and *Fragilaria crotonensis.* The more common diatoms in these ditches were small (<20 μm) centrics and pennates.

The dominant algal categories in these ditches were chlorophytes and cryptomonads. The chlorophytes were dominated by *Microspora* sp., *Scenedesmus quadricauda* and *Staurastrum paradoxum* with a spring maximum of 6.4 × 10^4 cells/L in Jericho Ditch (Figure 5). The chrysophytes had peak concentrations in spring and summer in Washington Ditch, being dominated by *Ochromonas* sp.; while higher concentrations (2.7 × 10^5 cells/L) were found in Jericho Ditch during late fall. Other common chrysophytes included *Dinobryon cylindricum, Kephyrion ovale* and *Synura* sp. Both ditches had similar growth patterns for cryptomonads, with spring peaks at 2–3 × 10^4 cells/L. Euglenoids and dinoflagellates during spring and summer represented only minor components of the flora in both ditches, and these groups were most abundant in summer. In addition, one prasinophyte (*Pyraminonas* sp.) was noted for the Jericho Ditch.

Cyanophycean concentrations in Washington Ditch resembled those from Lake Drummond and had only moderate abundance throughout the year. They

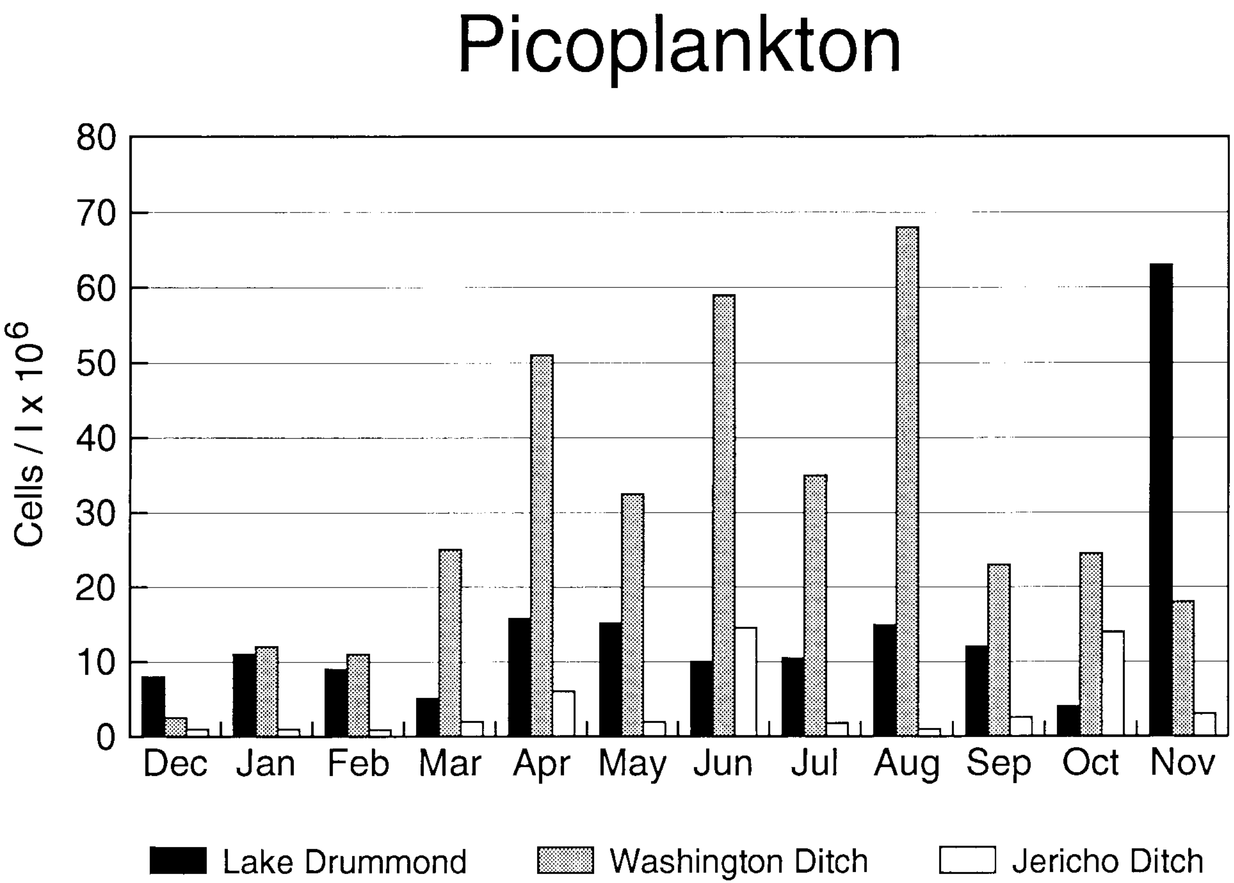

Figure 3. Autotrophic picoplankton concentrations in Lake Drummond, Washington Ditch and Jericho Ditch from December 1988 through November 1989.

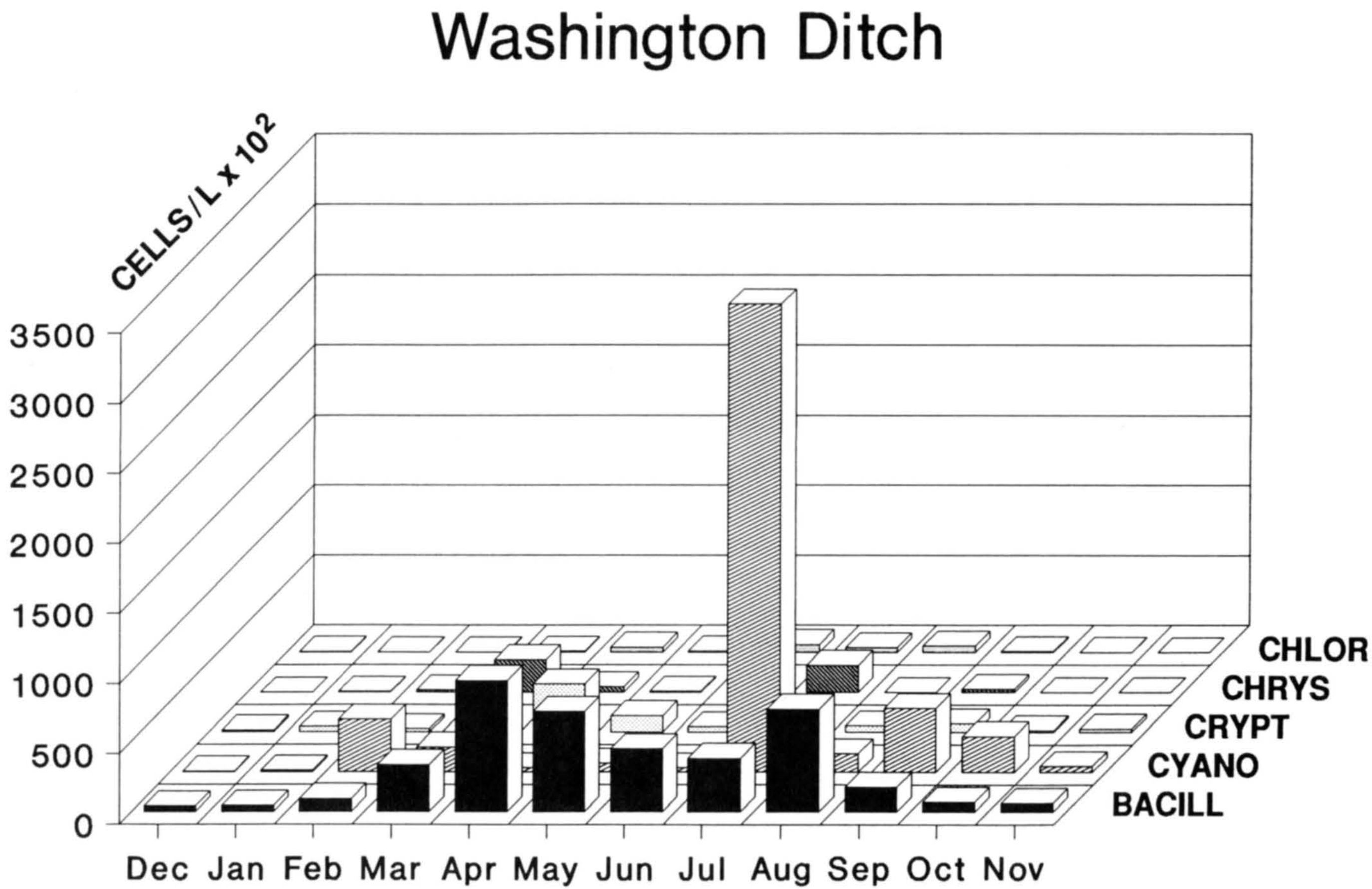

Figure 4. Concentrations of major phytoplankton categories in Washington Ditch from December 1988 through November 1989. Chlorophyceans (chlor), chrysophyceans (chrys), cryptomonads (crypt), cyanobacteria (cyano) and bacillariophyceans (bacill).

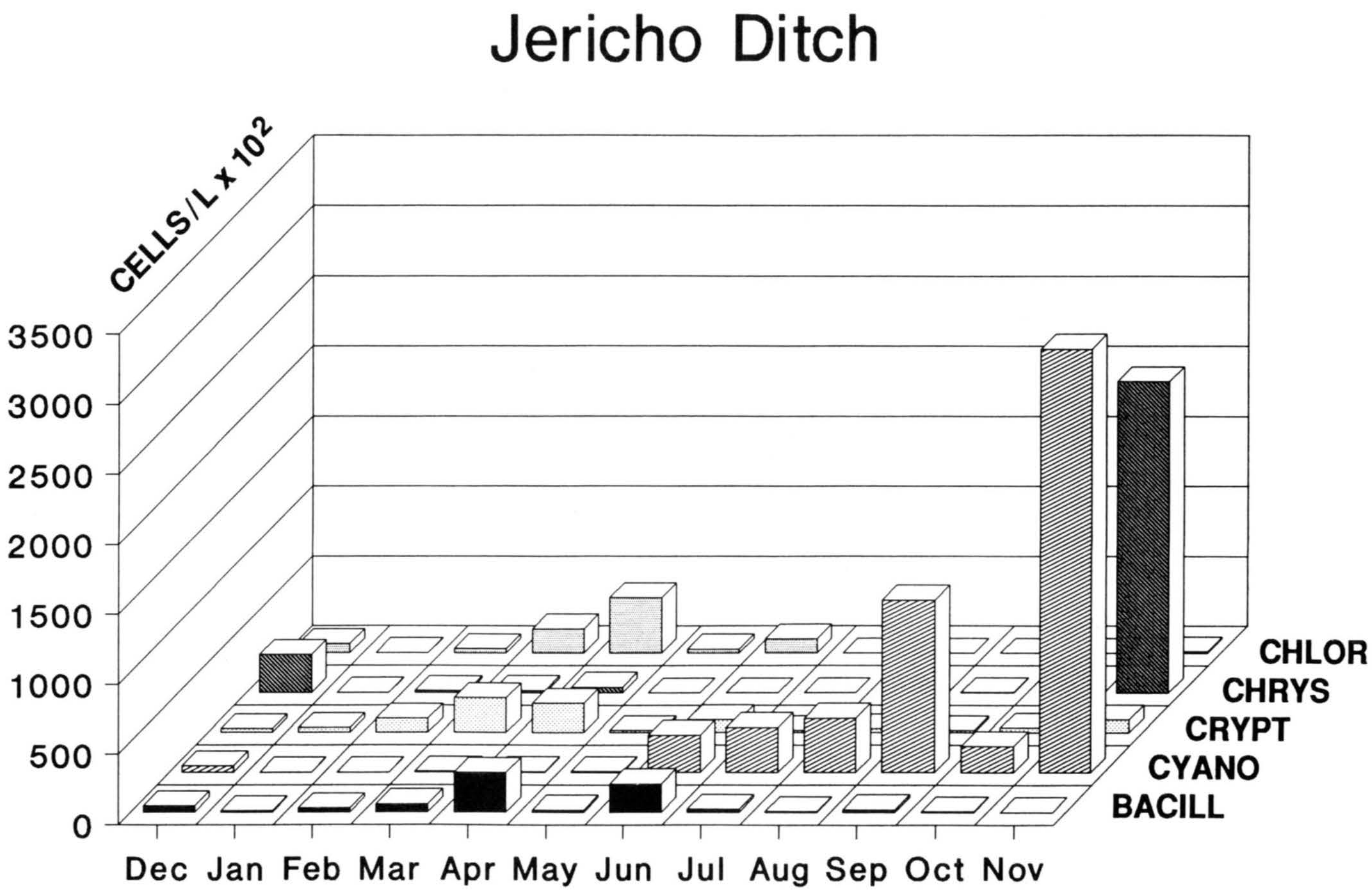

Figure 5. Concentrations of major phytoplankton categories in Jericho Ditch from December 1988 through November 1989. Chlorophyceans (chlor), chrysophyceans (chrys), cryptomonads (crypt), cyanobacteria (cyano) and bacillariophyceans (bacill).

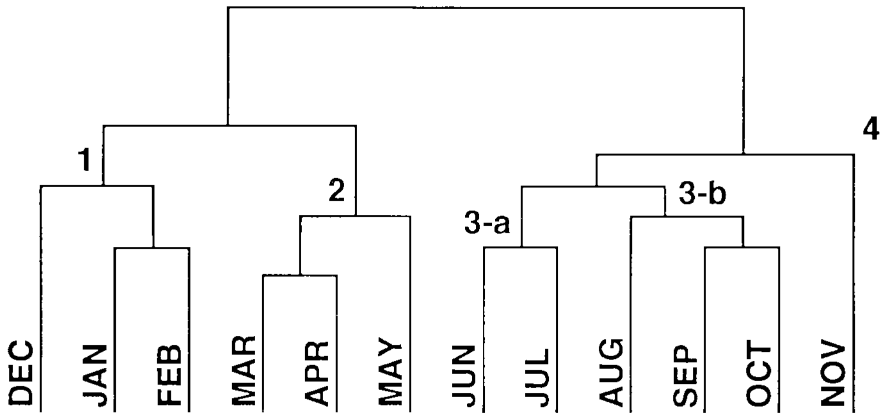

Figure 6. Standardized distance dendrogram noting degree of similarity for seasonal phytoplankton assemblages in Washington Ditch, Jericho Ditch and Lake Drummond (1 = winter, 2 = spring, 3a = summer, 3b = early fall and 4 = late fall).

peaked at 3.3 × 10^5 cells/L in July and were characterized by *Merismopedia* spp., *Microcystis* spp. and unidentified trichomes. In Jericho Ditch, cyanophycean concentrations were lower than Washington Ditch, with a November peak of 3.0 × 10^5 cells/L. The most common species in Jericho Ditch was *Synechococcus lineare*. Komarek (1976) reclassified *Rhabdoderma lineare* to *Synechococcus lineare* and suggested it may be frequently missed in the samples due to its small size (1–15 μm). Kwiatkowski and Roff (1976) reported high numbers of this species in five northern Ontario acidic lakes, with a pH range of 4.05 to 7.15. Willén (1969) also noted this species in Lake Assjön, Sweden (pH 7.20). Two other previously unrecorded cyanophyceans were identified in Jericho Ditch and Lake Drummond, but not noted in Washington Ditch were *Aphanothece* sp. and *Phormidium* sp. Neither of these species, or *Synechococcus lineare*, have been previously identified in Lake Drummond.

Phytoplankton Spatial and Temporal Relationships

Fifty-two taxa were incorporated into standardized distance dendrograms (Figure 6). The cluster analysis by season produced seasonal taxonomic groups. These were: group 1, winter (December, January, February); group 2, spring (March, April, May); group 3-a, early summer (June, July); group 3-b, late summer–mid fall (August, September, October); and group 4, late fall (November). The discriminant analysis produced 95% confidence ellipses for each seasonal group in relation to taxa. Taxa listed in the discriminant axes are statistically significant (α = 0.01) and represent those species contributing most to the differentiation of seasonal groups.

The cluster analysis (Figure 7) which evaluated taxa in relation to site, produced two site groups. These were: 1. Washington Ditch and Jericho Ditch; and 2. Lake Drummond. This cluster analysis indicated taxa in Washington Ditch and Jericho Ditch to be more similar to each other in composition and abundance

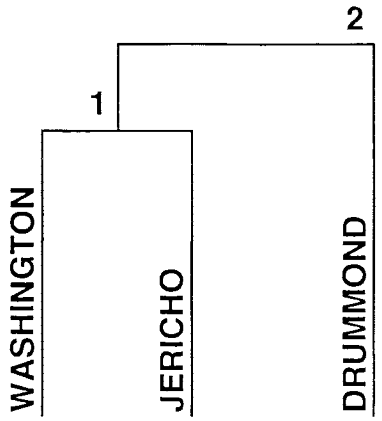

Figure 7. Standardized distance dendrogram noting degree of similarity for phytoplankton assemblages during the 12 month period at all station sites.

than to taxa in Lake Drummond. However, discriminant analysis/MANOVA conducted on the species at these sites did not yield any distinct patterns for the individual taxa. There was considerable overlap in composition at these sites and there was not enough separation of these into site groups regarding their annual assemblages. In contrast, when these statistical procedures were applied to the phytoplankton taxa associated with seasons, several taxa were identified with the seasonal patterns (Figure 8). The first two discriminant functions accounted for 80.9% of the variance (DF-1 = 59.8%, DF-2 = 21.1%). The seasonal groups were distinguished by four taxonomic assemblages. In addition, the discriminant analysis grouped the phytoplankton into cold (winter-spring) and warm (summer-fall) water phytoplankton assemblages.

Summer and fall taxa represented the most similar phytoplankton groups in regard to composition and abundance. These seasons were associated with warmer water temperatures and increasing concentrations of picoplankton, chlorophyceans (*Mougeotia* sp. and *Closteriopsis longissima*), cyanophyceans (*Microcystis incerta, Aphanothece* sp., *Phormidium* sp.) and the chrysophyte *Synura* sp. Phytoplankton assemblages associated with the cooler water temperatures of winter and spring included *Melosira distans*, with increasing concentrations of *Merismopedia glauca* in spring.

SUMMARY

The phytoplankton of Lake Drummond was characterized by bacillariophyceans, cryptophyceans and cyanophyceans (cyanobacteria). The diatom *Asterionella formosa* was a dominant species in the lake, attaining maximum concentrations in winter and fall. Studies by Poore (1971) and Marshall (1976) have noted similar major taxonomic components to those found in this study; however, since then there has been a shift in species dominance from chlorophycean to cyanobacteria and a decrease in the mean pH values. Shapiro (1984) has indicated

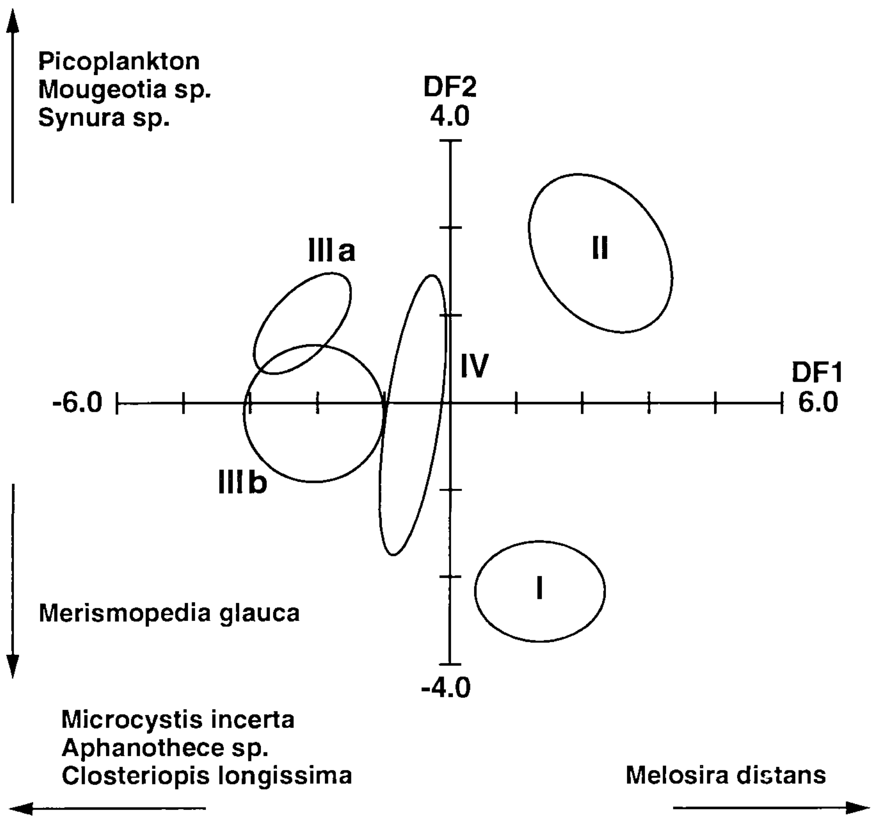

Figure 8. The 95% confidence ellipses for discriminant analysis of seasonal phytoplankton associations (I = winter, II = spring, IIIa = summer, IIIb = early fall and IV = late fall). Arrows indicate directions of increased abundance.

the addition of nutrients to lakes will generally increase the concentrations of cyanobacteria and that this often results as a population shift from chlorophyte dominant species to cyanobacteria. Shapiro reported by adding CO_2, or HCl, plus nutrients, to an acidic lake, that it produced a return shift from cyanobacteria to the chlorophytes. Shapiro (1984) has also noted shifts between chlorophytes and cyanobacteria populations related to changes in pH due to lake circulation. King (1970) reported cyanobacteria will become more dominant when productivity increases and the demand for CO_2 increases, due to the cyanobacteria being more efficient in utilizing low concentrations of CO_2 in comparison to the chlorophytes. Lake Drummond may be following similar patterns associated with the shift to increased cyanobacteria abundance, where these major population changes are accompanying increased nutrient entry and a lowering of pH in the lake.

The major taxonomic flora identified in Washington Ditch were bacillariophyceans, cyanophyceans and cryptophyceans, whereas, in the more acidic

Jericho Ditch the dominant algae were cyanophyceans, chrysophyceans and chlorophyceans. The most dominant species in Jericho Ditch was *Synechococcus lineare,* exhibiting peak concentrations in fall. Taxa in the Washington Ditch and Jericho Ditch were more similar to each other than to those in Lake Drummond. In both ditches, the winter was associated with the diatom *M. distans* while spring had increasing concentrations of picoplankton, *Mougeotia* sp. and *Synura* sp. The summer and fall months were related to increasing concentrations of cyanophyceans and chlorophyceans. The prominence of a picoplankton component reported here, was not investigated in earlier studies, and consists mainly of autotrophic cyanobacteria <2 μm in size.

Results of the nutrient and chlorophyll analyses indicated a general rise in values from summer to fall for total dissolved nitrogen, nitrate-nitrite, total phosphate, silica and total organic carbon. Late summer (August) and fall (September, October) nutrient levels were associated with mostly declining lake phytoplankton concentrations, with the exception of cyanophyceans. Maximum concentrations for the picoplankton and cyanophyceans were in November. The lake's eutrophic status was rated by several indices that were based on nutrient and chlorophyll concentrations, and species composition. Based on these indices, Lake Drummond was considered in an early eutrophic stage.

ACKNOWLEDGMENTS

We thank Cheryl Hess, John Siebel and Raymond Alden III for their assistance with the statistical analyses, Steve Sokolowski, Suzanne Doughten and the Applied Marine Research Laboratory water quality staff for nutrient analyses. Special thanks is given to Jim Phillips for assistance with the sample collections.

LITERATURE CITED

American Public Health Association. 1985. Standard methods for examination of water and wastewater. 16th edition. Washington, D.C. 1,268 p.

Charles, D.F. 1985. Relationships between surface sediment diatom assemblages and lake water characteristics in Adirondack lakes. Ecology 66:994–1011.

D'Elia, C.F., P.A. Steudler, and N. Corwin. 1977. Determination of total nitrogen in aqueous samples using persulfate digestion. Limnol. Oceanogr. 22:760–764.

Dixit, A.S., S.S. Dixit, and R.D. Evans. 1988. The relationship between sedimentary diatom assemblages and lake water pH in 35 Quebec lakes. Canad. J. Paleolimnol. 1:23–38.

Environmental Protection Agency. 1979. Method for chemical analysis of water and wastes. EPA-600/4-79-020/. U.S. Environmental Protection Agency, Cincinnati, Ohio. p. 365.3-1–365.3-4.

Hultberg, H. and I.B. Andersson. 1982. Liming of acidified lakes: induced long-term changes. Water, Air and Soil Pollution 18:311–331.

King, D.L. 1970. The role of carbon in eutrophication. J. Water Pollution Contr. Fed. 42:2035–2051.

Komarek, J. 1976. Taxonomic review of genera *Synechocystis* Sauv. 1982, *Synechococcus* Näg 1949, and *Cyanothece* gen. nov. (Cyanophyceae). Arch. Protistenk. 118:119–179.

Kwiatkowski, R.E. and J.C. Roff. 1976. Effects of acidity on the phytoplankton and primary productivity of selected northern Ontario lakes. Canad. J. Bot. 54:2546–2561.

Lyden, A. and O. Grahn. 1985. Phytoplankton species composition, biomass and production in Lake Gårdsjön—an acidified clearwater lake in Sweden. Ecol. Bull. 37: 195–202.

Marshall, H.G. 1976. The phytoplankton of Lake Drummond, Dismal Swamp, Virginia. Castanea 41:1–9.

Marshall, H.G. 1979. Lake Drummond: with a discussion regarding its phytoplankton composition. p. 169–182. *In:* Kirk, P.W. (ed.). The Great Dismal Swamp. University of Virginia Press, Charlottesville.

Marshall, H.G. and W.H. Poore, Jr. 1972. Phytoplankton composition at Lake Drummond in the Dismal Swamp, Virginia, Summer 1970. Castanea 37:59–67.

Menzel, D.W. and R.F. Vaccaro. 1964. The measurement of dissolved organic and particulate carbon in seawater. Limnol. and Oceanogr. 10:138–142.

Nicholls, K.H., E.C. Carney, and G.W. Robinson. 1977. Phytoplankton of an inshore area of Georgian Bay, Lake Huron, prior to reduction in phosphorus loading. J. Great Lakes Res. 3:79–92.

Nygaard, G. 1949. Hydrobiological studies on some ponds and lakes. Part II: The quotient hypothesis and some new or little known phytoplankton organisms. Kgl. Danske. Vidensk. Selsk. Biol. Skrifter. 7:221–293.

Phillips, C.G. 1990. Phytoplankton in Lake Drummond and two drainage ditches in the Great Dismal Swamp, Virginia. Masters thesis. Old Dominion University, Norfolk, Virginia. 92 p.

Poore, W.H., Jr. 1971. Phytoplankton composition at Lake Drummond in the Dismal Swamp, Virginia. Masters thesis, Old Dominion University, Norfolk, Virginia. 83 p.

Poore, W.H., Jr. and H.G. Marshall. 1972. Lake Drummond of the Dismal Swamp: I. Phytoplankton composition. Virginia J. Sci. 23:72–76.

Shapiro, J. 1984. Blue-green dominance in lakes: the role and management significance of pH and CO_2. Int. Revue ges. Hydrobiol. 69:765–780.

Venrick, E.L. 1978. How many cells to count. p. 167–180. *In:* Sourina, A. (ed). Phytoplankton manual. UNESCO, Paris.

Weiss, C.M. and E.J. Kuenzler. 1976. The trophic state of North Carolina lakes. Report no. 78. Water Resources Institute of the University of North Carolina, Chapel Hill. 224 p.

Wetzel, R.G. 1983. Limnology. Saunders College Publishing Co., Philadelphia, Pennsylvania. 767 p.

Willén, T. 1969. Phytoplankton from Swedish lakes II. Lake Assjön 1961–1962. Oikos 20:67–77.

Williams, W.T. and W. Stephenson. 1973. The analysis of three-dimensional data (sites × species × times) in marine ecology. J. Exp. Mar. Biol. Ecol. 11:207–227.

Yan, N.D. and P. Stokes. 1978. Phytoplankton of an acidic lake, and its responses to experimental alterations of pH. Environ. Conser. 5:93–100.

Received May 5, 1992; Accepted October 26, 1992.