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A Study of the Seasonal Composition and Abundance of Phytoplankton and Autotrophic Picoplankton in a Brackish Water Lake in Portsmouth Virginia

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A STUDY OF THE SEASONAL COMPOSITION AND ABUNDANCE OF PHYTOPLANKTON AND AUTOTROPHIC PICOPLANKTON IN A BRACKISH WATER LAKE, IN PORTSMOUTH, VIRGINIA

by

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ABSTRACT

A STUDY OF THE SEASONAL COMPOSITION AND ABUNDANCE OF PHYTOPLANKTON AND AUTOTROPHIC PICOPLANKTON IN A BRACKISH WATER LAKE, IN PORTSMOUTH, VIRGINIA.

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The phytoplankton and autotrophic picoplankton populations of Hoffler Lake, a brackish-water lake in Portsmouth, Virginia, were monitored from May 1997 through May 1998. Analyses of the phytoplankton community using the Utermöhl method showed a dominance of Chlorophytes (61-88% of the total abundance) throughout the year, including a winter bloom of *Chlamydomonas snowii* (maximum concentration of 2.5 x 10^7 cells/L). Subdominants were Cyanobacteria (10-33% of the total abundance) whose composition included several species of *Anabaena, Lyngbya,* and a fall bloom of *Microcoleus sp.* Diatoms, dinoflagellates, and cryptophytes played a secondary role in the phytoplankton community of Hoffler Lake. Autotrophic picoplankton were analyzed using epifluorescent microscopy. The picoplankton were divided into 2 groups, solitary cells (*Synechococcus spp.*) and a colonial form (*Microcystis incerta*). Average picoplankton concentrations were 1.3 x 10^8 cells/L throughout the year. A peak in cell numbers occurred in the summer with a total concentration for both groups of 3.5 x 10^8 cells/L. Comparison of the phytoplankton community analyses with temperature and salinity data indicated phytoplankton responded more to changes in temperature than salinity, but salinity did influence the species composition in Hoffler Lake.

To Jack Holt and John Clark,
with whom the long walks and talks in the snowy hills of
Pennsylvania inspired me to ask "Why?" and "How?"

And to my parents,
Who never asked "Why?" or "How much?"

"Mother, mother ocean I have heard you call..."

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Thanks to Jerry Nickerson and Thomas Duvall of the Hoffler Creek Wildlife Refuge organization for introducing me to Hoffler Lake, providing its history, helping with monthly collections, and offering constant enthusiasm in my project.

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INTRODUCTION

Brackish Water Lake Studies

Traditionally, limnology has been defined as the study of freshwater lakes (Williams 1986). As recently as the 1980s, Wetzel (1983) limited the scope of limnology to the study of freshwater communities and how the physical, chemical, and biotic environments affected them. With these viewpoints generally accepted, the study of saline lake waters has been regarded as a regional activity, rather than a major component of aquatic research (Williams 1986) and is evidenced by a lack of current literature in this area (Garg and Bhatnagar 1996). The first exception to the isolation of saline lake studies came with the establishment of a research laboratory near Devil's Lake, North Dakota in 1909, where scientific saline lake studies originated in North America (Hammer 1986, Williams 1986). However, until U. Theodore Hammer published Saline Lake Ecosystems of the World in 1986, there had been no books on the topic. Since then the scientific significance and economic importance of saline lakes has come to be recognized (Cognetti 1994, Shcherbak and Rodkin 1994) and they now represent a unique component for limnological studies (Williams 1986).

The *Journal of Phycology* is the model journal used in this thesis.

According to Ambroz (1977) and Moss (1994), saline lakes can be divided into 2 categories: primary saline lakes, which are endorheically saline, and secondary saline lakes, which become brackish due to natural or anthropomorphic inputs of seawater. Seawater inputs into saline lakes can occur via tidal rivers or percolation through permeable soils between the lake and the coast (Moss 1994).

Phytoplankton investigations have traditionally been included in limnological lake studies due to their ability to indicate trophic status (Wetzel 1983, Garg and Bhatnagar 1996). Starobogatov and Khlebovich (1977) and Cox (1998) state that the quantity and type of phytoplankton are key indicators of water quality, especially in brackish water, because of the variability between systems. Reports from Shcherbak and Rodkin (1994) and Bales et al. (1993) showed that diatoms, chlorophytes, and cyanobacteria dominated the flora of saline lakes. Saline lake studies by Caljon (1987) and Garg and Bhatnagar (1996) found diatoms and chlorophytes dominated in brackish water. Laugaste and Ott (1993) concluded that chlorophytes and cyanobacteria play a significant role in brackish water, but the role of diatoms is lessened. The work done on the phytoplankton community at Hoffler Lake will add another dimension to this debate.

Study Area

Hoffler Lake is a 30 acre clear water lake within the 142 acre Hoffler Creek Wildlife Refuge in Portsmouth, Virginia, at latitude 36°53'56.25"N and longitude 76°24'23.88"W (Figure 1). Hoffler Lake, initially called Twin Pines Pit, was created as a borrow pit in the mid-1980s during construction of the Western Branch Freeway (Rt. 164). In May 1997, ownership of the lake and its surrounding land was transferred from the Virginia Department of Transportation to the City of Portsmouth. Currently, the lake is under the management of the Hoffler Creek Wildlife Foundation.

Hoffler Creek Wildlife Refuge is bordered to the north and east by a residential community that separates the refuge from the James River. To the south and west are woodlands, Hoffler Creek, and extensive wetlands, which experience tidal intrusion twice daily. Bathymetry conducted in the lake prior to the start of this study shows a maximum depth of 17 m slightly south of lake center, with no inlet or outlet waterways, and no connection to Hoffler Creek. Additionally, a berm separates the tidal wetland area from the lake.

Hoffler Lake, with salinity levels ranging from 0.0 to 5.0 ‰ in the top 9 m of water, can be defined as a brackish-fresh water (oligohaline) lake according to Remane (1971). Because salinity is a critical factor which can effect the ecology and physiology of flora and fauna (Remane

1971, Underwood et al. 1998), Hoffler Lake offers a unique environment in which to conduct biological studies.

With this in mind, the initial objectives of this study were:

1) to determine the seasonal composition and abundance of phytoplankton and abundance of autotrophic picoplankton in Hoffler Lake;
2) to monitor specific chemical and physical parameters; and
3) based on the phytoplankton composition and physical data, to determine the trophic status of the lake.

The biological, chemical, and physical information obtained in this study will provide an important reference for future investigations of this lake as eutrophication progresses.

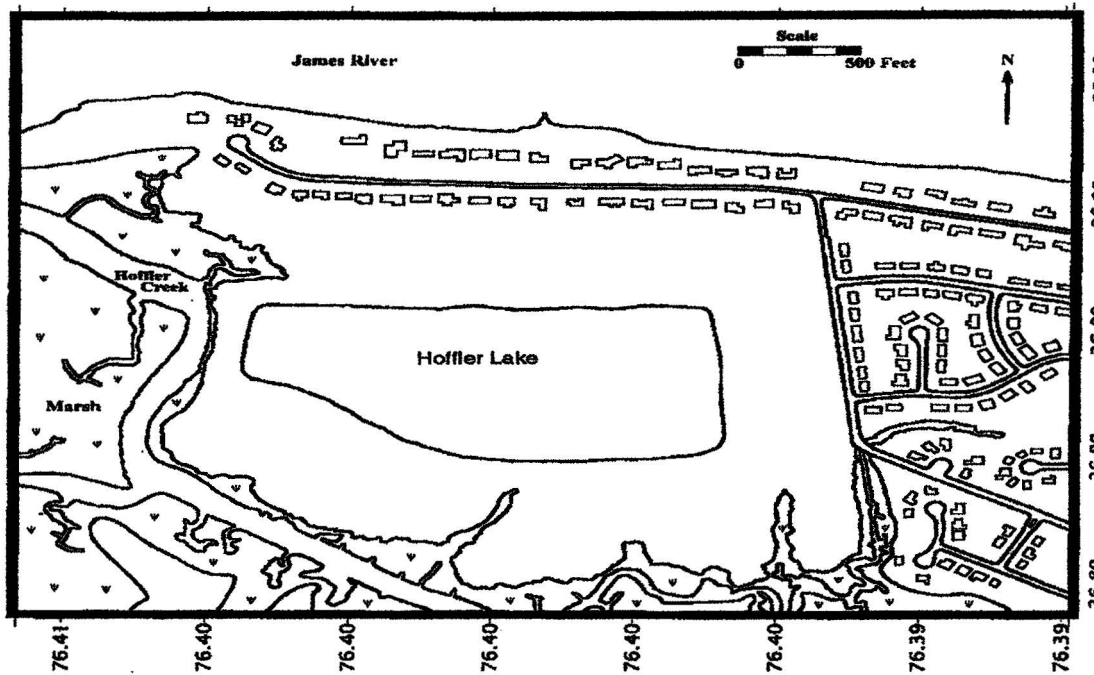

FIG. 1. Map of the Portsmouth, Virginia area showing Hoffler Lake and its surroundings.

METHODS

The initial examination of Hoffler Lake occurred in early May 1997. At this time, depth profiles were made by reading outputs of a Humminbird Fish Finder Model LCR 4000, which showed depth to bottom, across numerous transects of the lake. Based on the findings, 2 station locations were identified and the depth records were plotted to create a contour map of the lake (Figure 2). The 2 stations lie approximately in the center of the lake where the maximum depth for each site was 13 m.

Monthly water collections began late in May 1997 and continued through May 1998. Replicate water samples for phytoplankton (500 ml) and autotrophic picoplankton (125 ml) were taken from a boat at the surface and at 3 m with a Kemmerer water collection bottle.

Phytoplankton samples were preserved with 5 ml of Lugol's acidified iodine solution in the field. In the laboratory the samples were settled, siphoned, and secondarily preserved with 5 ml of 10% buffered formalin. The samples were examined under a Zeiss Opton inverted light microscope following a modified Utermöhl method (Marshall 1984). All phytoplankton taxa were identified to the lowest possible taxonomic rank during analysis at 2 different magnifications. At least 10 random fields (minimum count of 200 cells) were analyzed at 312x. Then the entire sample was read at 100x to identify larger, less abundant species. This

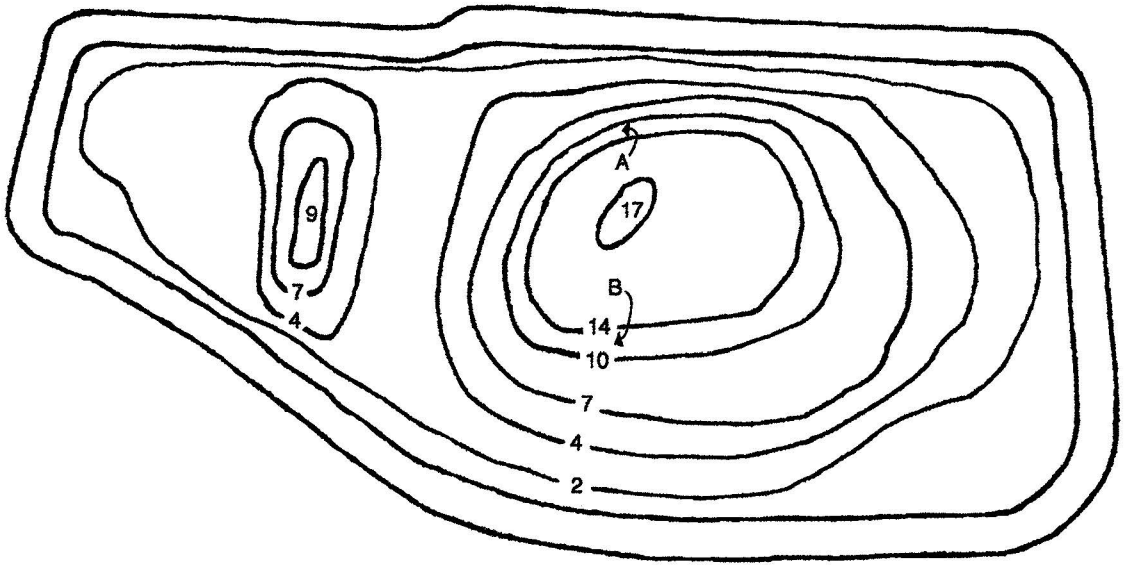

FIG. 2. Map indicating Hoffler Lake depth contours in meters. Located north and south of the deepest portion are Station A and Station B, respectively.

procedure has a precision estimate of 85% (Venrick 1978). Cell counts were converted from raw numbers to biovolume using the following equation (Kovala and Larrance 1966):

$$\frac{\text{Total \# of cells counted}}{\text{\# fields counted}} \times K \times \frac{1}{1\ [\text{sample}]} \times \frac{1}{\text{volume collected}}$$

where K is a constant that stands for the number of fields that comprise the surface area of the counting chamber. According to Hillebrand et al. (1999), the Kovala and Larrance equation is the most accurate to use for both freshwater and marine pelagic microalgae.

Picoplankton samples were preserved with 2 ml of gluteraldehyde in the field. Within 5 days of collection the samples were analyzed using epifluorescent microscopy at 1000x. Aliquots (2 – 4 ml) of the sample were passed through a blackened 0.2 µm Nucleopore filter backed with a 0.45 µm Nucleopore filter using a standard Millipore apparatus with a maximum pressure of 10 cm of Hg. After filtering the sample, the blackened filter was placed on a glass microscope slide and covered with immersion oil. A cover slip, plus immersion oil, was added before viewing. Slides were viewed on a Zeiss Axioskop epifluorescence microscope with a green filter set (Zeiss G546, FT580, LP590). Analysis of the samples included counts in 10 random fields of solitary cells (e.g. *Synechococcus spp.*) and clustered cells within a gelatinous matrix (e.g. *Microcystis incerta*).

Taxonomic identifications for phytoplankton and picoplankton were made using Cupp (1934), Cox (1998), Desikachavy (1959), Dodge (1982),

Marshall (1986), Patrick and Reimer (1966), Patrick and Reimer (1975), Popovsky and Pfiester (1990), Prescott (1951), Tiffany and Britton (1952), Whitford and Schumacher (1969), and others.

Chemical and physical parameters ascertained on a monthly basis at each station included pH, water temperature, salinity, and secchi depth. Water samples were also analyzed in the field on a quarterly basis (May, August, November, 1997 and February, May, 1998) for orthophosphate, ammonia-nitrogen, and nitrite-nitrogen concentrations using a titration method Hach Kit. Quarterly vertical profiles of the entire water column were conducted to measure pH, temperature, salinity, dissolved oxygen, specific conductance, and turbidity using a YSI Environmental Monitoring System Model 610-DM.

Initial statistical analyses for species abundance, composition, biomass, and biovolume were performed on PhytoSAS, with additional testing performed using SAS (SAS Institute, Inc. 1989).

RESULTS

Lake Characteristics

Hoffler Lake is bordered by a deciduous forest, Hoffler Creek, and extensive wetlands, which experience daily tidal intrusion. The lake has no inlet or outlet waterways and no connection to Hoffler Creek. Additionally, a berm separates the tidal wetland area from the lake. The lake has a relatively steep embankment covered with low vegetation on the east and west faces. The north and south sides of the lake are banked with a forested tree line. The lake is exposed to the prevailing wind patterns that may initiate seasonal mixing of surface waters.

Bathymetric measurements were taken at the lake prior to the start of this study. The measurements show one depression with a maximum depth of 17 m located slightly southwest of the lake center (Figure 2). A second depression, located at the south end of the lake, has a maximum depth of 9 m. The 2 depressions are separated by a 4 m deep berm. The lake stations sampled in this study were located east and west of the deepest central portion (Figure 2).

Hoffler Lake, with salinity levels ranging from 0.0 to 5.0 ‰ in the top 9 m of water, is defined as brackish-fresh (oligohaline) by Remane (1971). The salinity profile (Figure 3) created from the quarterly sampling information indicates that the salinity levels (0.0 – 5.0 ‰) fall within the oligohaline range in the top 9 m of water. The deepest 3 m of

water, however, have salinity levels that range from 3.8 to 9.0 ‰, which according to Remane (1971), can be classified as brackish (mesohaline). No seasonal changes in salinity were observed during the one year study. The method for this seawater input into Hoffler Lake is not known; however a likely explanation suggested by Hall (1999) may be saltwater percolation through permeable soils between the lake and the Hampton Roads estuary, as has been documented in other secondary saline lakes by Moss (1994).

In addition to the salinity profile, the quarterly values were collected for temperature (Figure 4) and dissolved oxygen (Figure 5). The temperature profile (Figure 4) shows that the lake was well mixed in late fall and winter. The November temperature range was 10.6 – 12.4°C from the surface to 12 m. The February temperature range was 7.58 - 9.56°C from the surface to 12 m. The lake waters were stratified from the spring throughout the summer. The May temperature range was 8.6 – 23.0°C from surface to 12 m and the August temperature difference was 9.9 – 28.3°C from surface to 12 m.

The dissolved oxygen profile (Figure 5) indicated that throughout the year waters in Hoffler Lake were only anoxic in depths greater than 9 m. The top 9 m of water consistently had dissolved oxygen concentrations between 5.3 – 9.6 mg/ml. The waters below 9 m had dissolved oxygen concentrations in the range of 0.8 – 2.9 mg/ml throughout the year.

Physical data collected monthly is given in Table 1 to show ranges, monthly averages, and seasonal averages of temperature, pH, salinity, and secchi depths. Table 2 shows quarterly data collected for the entire water column, with sampling at 3 m increments. Quarterly measurements of nitrite-nitrogen and ammonia-nitrogen were all at or below the detection limits (0.05 mg/ml and 0.02 mg/ml, respectively) of the Hach testing system used.

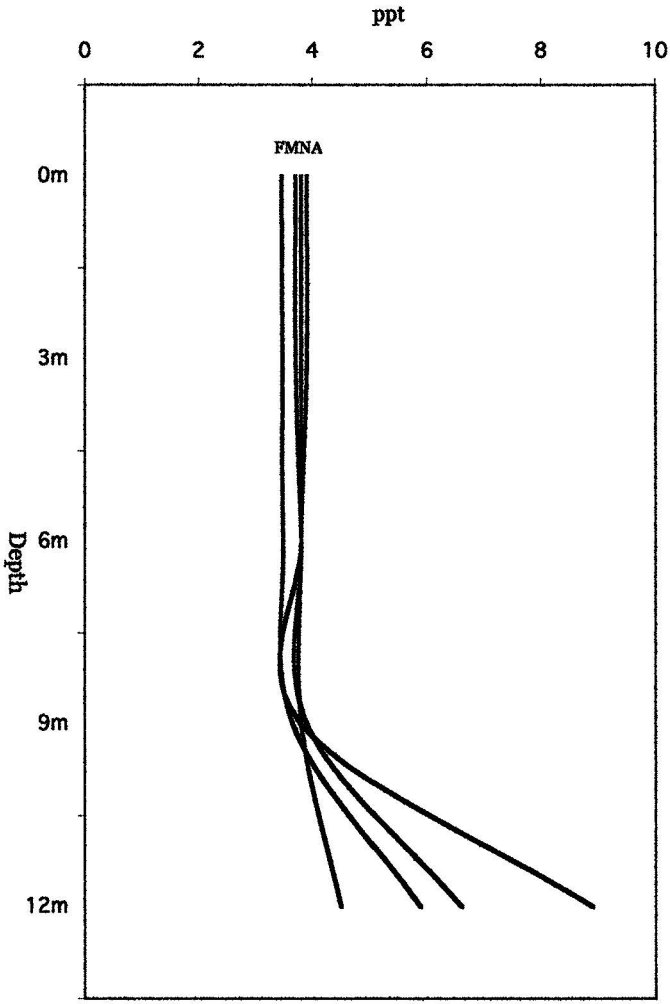

Figure 3. The salinity profile for Hoffler Lake. Measurements are given in ppt (‰). Lines for each sampling point are denoted by the month in which the sampling occurred: May (M), August (A), November (N), and February (F).

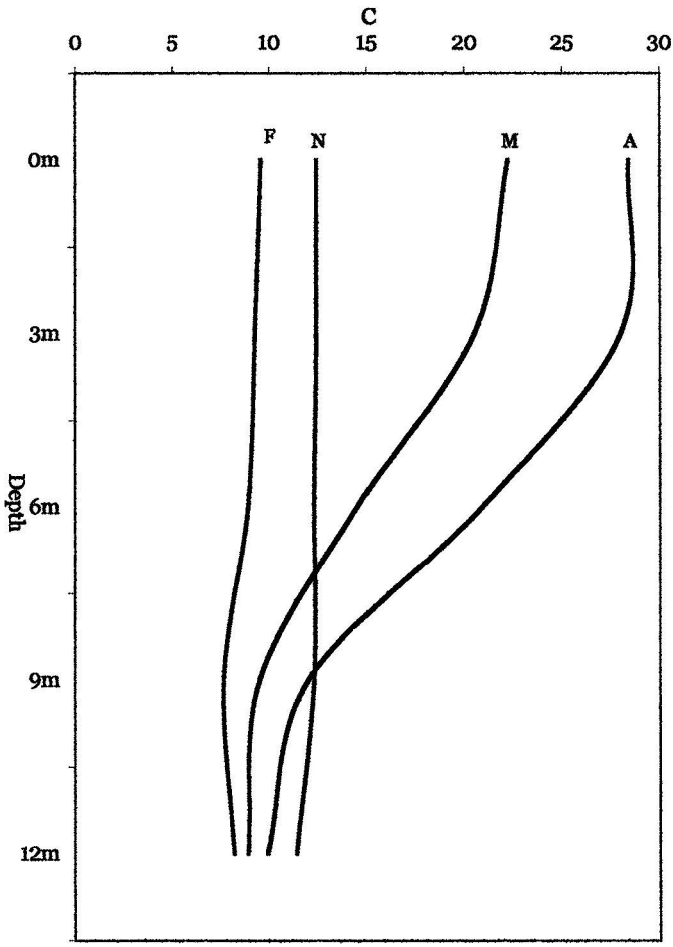

Figure 4. The temperature profile of Hoffler Lake. Measurements are given in °C. Lines for each sampling point are denoted by the month in which the sampling occurred: May (M), August (A), November (N), and February (F).

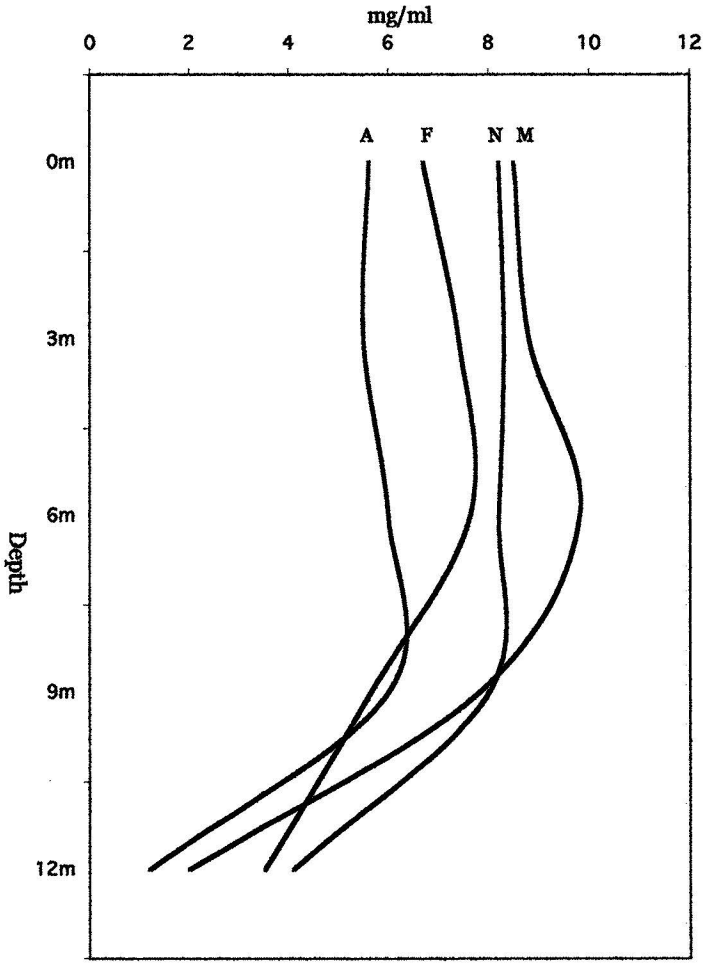

Figure 5. The dissolved oxygen profile of Hoffler Lake. Measurements are in mg/ml. Lines for each sampling point are denoted by the month in which the sampling occurred: May (M), August (A), November (N), and February (F).

Table 1. Monthly physical data for Hoffler Lake by season. Ranges, means, and averages are given for temperature, pH, salinity, and secchi depths for the top 3 m of the water column.

	Temperature		pH		Salinity		Secchi Depth	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Summer								
June	22-22	22	8.3-9	8.78	3.75-4.9	4.16	2.7-3	2.85
July	25-25	25	7.8-8.36	8.17	3.8-4.2	4	2.5-3	2.75
August	28-28.4	28.18	8-8.3	8.18	3.9-3.9	3.9	1.6-1.7	1.65
Average		25.06		8.38		4.02		2.42
Fall								
September	23-24	23.75	7.29-7.49	7.39	4-5	4.5	1.4-1.6	1.5
October	17.5-18	17.89	6.52-7.6	7.1	3-3.7	3.48	1-1.2	1.1
November	12.3-12.4	12.38	7.1-7.2	7.13	3.8-3.8	3.8	1.3-1.3	1.3
Average		18.01		7.21		3.93		1.3
Winter								
December	8-9.5	8.63	6.43-7.01	6.71	2-3	2.38	2-2	2
January	8-9	8.5	7.17-8.24	7.61	0-3	1.75	1.2-1.3	1.25
February	9.16-9.56	9.4	7.97-8.14	8.04	3.46-3.47	3.46	0.85-1.25	1.05
Average		8.84		7.45		2.53		1.43
Spring								
March	10.5-12	11.13	7.4-8.22	7.8	2-4.5	3.25	1.5-1.5	1.5
April	16-16.5	16.25	7.01-7.86	7.51	0-3.5	1.88	1.8-2	1.9
May	20-23	21.31	8-8.3	8.14	3.7-3.7	3.7	2.7-3	2.83
Average		16.23		7.82		2.94		2.08

Table 2. Quarterly profile data for Hoffler Lake. The values given are averages for Stations A and B.

	0m	3m	6m	9m	12m
Spring (29 V 97)					
Temperature (°C)	21.4	20.8	16.1	9.8	8.9
pH	8.2	8.3	8.1	7.9	6.4
Dissolved Oxygen (mg/mL)	8.7	9.1	10.1	10.9	2.9
Salinity (‰)	3.7	3.7	3.7	3.8	8.6
Summer (21 VIII 97)					
Temperature (°C)	28.4	28.0	20.9	12.0	9.9
pH	8.1	8.3	8.1	7.8	6.6
Dissolved Oxygen (mg/mL)	5.6	5.5	6.0	6.0	1.2
Salinity (‰)	3.9	3.9	3.8	3.8	8.9
Fall (17 XI 97)					
Temperature (°C)	12.4	12.4	12.3	12.3	11.4
pH	7.2	7.1	7.1	7.1	7.4
Dissolved Oxygen (mg/mL)	8.2	8.3	8.2	8.0	4.1
Salinity (‰)	3.8	3.8	3.8	3.8	4.5
Winter (26 II 98)					
Temperature (°C)	9.6	9.3	8.9	7.6	8.2
pH	8.1	8.1	8.0	7.9	7.3
Dissolved Oxygen (mg/mL)	6.7	7.4	7.1	7.9	3.5
Salinity (‰)	3.5	3.5	3.5	3.7	5.9
Spring (21 V 98)					
Temperature (°C)	23.0	20.1	12.9	9.2	8.9
pH	8.0	8.1	8.1	7.7	7.1
Dissolved Oxygen (mg/mL)	8.1	8.4	9.5	4.6	0.9
Salinity (‰)	3.7	3.7	3.8	4.0	4.5

Seasonal Patterns in the Phytoplankton Population

All phytoplankton and picoplankton analyses were conducted on data representing averages between stations A and B. Using a paired t-test it was determined there were no significant differences between the phytoplankton or the picoplankton populations at Station A and Station B. Additional statistical analyses indicated there were no significant differences between the surface or 3 m deep waters at Stations A and B in regards to the temperature and salinity data. Temperature and salinity were used to define how the phytoplankton community responded to changes in these parameters. Table 3 shows $t_{calculated}$ and $t_{critical}$ values for statistical tests performed on the Hoffler Lake data. Critical values are as reported in Zar (1996) at the $t_{0.05(2),12}$ level for a 95% confidence interval.

The phytoplankton analysis on Hoffler Lake indicated several seasonal patterns, as well as trends within each major taxonomic group. In all, 123 phytoplankton species were identified to at least the genus level in Hoffler Lake from surface and 3 m whole water samples. There were 11 grouping categories (i.e. centric diatoms < 20 μ) that were used for phytoplankton that could not be further identified using light microscopy. The phytoplankton were broken down into 6 major categories. There were 31 chlorophytes, 25 cyanobacteria, 47 diatoms, 21 dinoflagellates, 6 euglenophytes, and 5 taxa grouped into an "other" category (Table 4). Of the 123 taxa identified, 47% were typical freshwater species and 29%

Table 3. Results of paired t-test analysis for phytoplankton communities at Hoffler Lake. Since $T_{calculated}$ is less than $T_{critical}$ the Ho is not rejected indicating there are no significant differences between phytoplankton communities at Stations A and B in Hoffler Lake.

Null Hypothesis: Phytoplankton communities will be the same between Stations A and B in Hoffler Lake at a 95% confidence interval ($t_{0.05(2),12}$).
Ho: $\mu_a = \mu_b$ Ha: $\mu_a \neq \mu_b$

MAJOR PHYTOPLANKTON CATEGORY	$T_{calculated}$	$T_{critical}$	POWER
Chlorophytes – Surface	0.182	2.179	97.70%
Chlorophytes – 3m	1.699	2.179	68.45%
Cryptophytes – Surface	0.841	2.179	90.99%
Cryptophytes – 3m	1.779	2.179	65.55%
Cyanobacteria – Surface	0.898	2.179	89.97%
Cyanobacteria – 3m	0.020	2.179	98.46%
Diatoms – Surface	1.689	2.179	68.79%
Diatoms – 3m	0.763	2.179	92.22%
Dinoflagellates – Surface	0.370	2.179	96.49%
Dinoflagellates – 3m	0.817	2.179	91.31%
MAJOR PICOPLANKTON CATEGORY	$T_{calculated}$	$T_{critical}$	POWER
Microcystis incerta – Surface	0.669	2.179	93.50%
Microcystis incerta – 3m	1.769	2.179	66.30%
Synechococcus sp. – Surface	0.669	2.179	93.50%
Synechococcus sp. – 3m	1.688	2.179	68.29%

Table 4. Phytoplankton at Hoffler Lake by major taxonomic group. Within each group more descript taxa are denoted as being typical of marine (M) or fresh (F) waters. Taxa without a designation were not identified to a level wherein the typical location could be determined.

CHLOROPHYTES

F *Actinastrum hantzschii* Lagerheim
F *Actinastrum hantzschii v. fluvilatile* Schroeder
F *Ankistrodesmus falcatus* Beijerinck
F *Ankistrodesmus falcatus v. mirabilis* West
F *Arthrodesmus validus v. incrassatus* Scott & Gronbald
F *Chlamydomonas snowii* Printz
Chlamydomonas sp.
Chlorella sp.
Chlorophycean unidentified
F *Closterium dianae* Ehrenberg
F Closterium parvulum Naegeli
F *Cosmarium ornatum* Ralfs
F *Cosmarium subreniforme* Nordstedt
F *Cosmarium tenue* Archer
F *Crucigenia quadrata* Morren
F *Crucigenia tetrapedia* (Kirchner) West & West
F desmid unidentified
F *Dictyosphaerium pulchellum* Wood
F *Hyalotheca dissiliens v. tatrica* Raciborski
Micractinium sp.
F *Oedogonium sp.*
F *Oocystis sp.*
F *Scenedesmus bijuga* (Turpin) Lagerheim
F *Scenedesmus quadricauda* (Turpin) Brebisson
F *Schroederia setigera* (Schroeder) Lemmermann
F *Selenastrum minutum* Naegeli
F *Selenastrum westii* Smith
F *Starastrum americanum* (West & West) Smith
F *Stigeoclonium glomeratum* (Hazen) Collins
F *Ulothrix sp.*
F *Zygnema sp.*

CYANOBACTERIA

F *Anabaena sp.*
F *Anabaena wisconsinense* Prescott
F *Aphanizomenon flos-aqua* Ralfs

Table 4. Continued.

CYANOBACTERIA
Aphanocapsa sp.
Aphanothece sp.
blue-green spheres > 3.0μ
blue-green trichome
F *Chroococcus limneticus* Lammerman
Chroococcus sp.
F *Chroococcus varius* Braun
F *Cylindrosperum doryphorum* Bruhl & Briswas
M *Dactylococcopsis raphidioides* Hansging
Lyngbya sp.
F *Merismopedia elegans* Braun
F *Merismopedia punctata* Meyen
F *Merismopedia tenuissima* Lammerman
Microcoleus sp.
F *Microcystis aeruginosa* Kuetzing
F *Microcystis incerta* Lammerman
Nostoc sp.
Oscillatoria sp.
F *Spirulina laxa* Smith
F *Spirulina major* Kuetzing
Spirulina sp.
Synechococcus sp.
DIATOMS
Amphora sp.
F *Asterionella formosa* Hassell
F *Aulacoseira granulata* (Ehrenberg) Ralfs
M *Biddulphia aruita* (Lyngbye) Brebisson
centric diatom < 20μ
centric diatom > 20μ
M *Ceratulina pelagica* (Cleve) Hendey
M *Chaetoceros affinis* Lauder
M *Chaetoceros neogracile* van Laningham
M *Chaetoceros sp.*
M *Chaetoceros subtilis* Cleve
F *Cocconeis fluvatiles* Wallace
Cocconeis sp.
M *Coscinodiscus sp.*
M *Cyclotella caspia* Grunow
M *Cyclotella striata* (Kuetzing) Grunow

Table 4. Continued.

DIATOMS

M *Cylindrotheca closterium* (Ehrenberg) Reimann & Lewin
F *Cymbella affinis* Kuetzing
Diploneis sp.
M *Eucampia zodiacus* Ehrenberg
F *Eunotia praerupta* Ehrenberg
Fragilaria sp.
F *Gomphonema sp.*
M *Gyrosigma fasciola* (Ehrenberg) Griffith & Henfrey
Gyrosigma sp.
M *Leptocylindrus danicus* Cleve
M *Leptocylindrus minimus* Gran
M *Meridion circulare* (Grenville) Agardh
F *Navicula cuspidata* (Ehrenberg) Cleve
Navicula sp.
M *Nitzschia pungens* Grunow
M *Nitzschia seriata* Cleve
Nitzschia sp.
pennate diatom < 20μ
pennate diatom > 20μ
Pinnularia sp.
M *Pleurosigma angulatum* (Quekett) Smith
M *Pleurosigma salinarum* Grun
M *Rhaphoneis amphiceros* Ehrenberg
M *Rhizosolenia imbricata* Brightwell
M *Rhizosolenia setigera* Brightwell
M *Skeletonema costatum* (Grenville) Cleve
F *Skeletonema potamos* Ehrenberg
Staroneis sp.
Suriella sp.
Synedra sp.
M *Thalassionema nitzschioides* (Grunow) Grunow & Hustedt

DINOFLAGELLATES

M *Ceratium furca* (Ehrenberg) Claparede & Lachman
F *Ceratium hirundinella* (Miller) Dujardin
dinoflagellate cyst
dinoflagellate unidentified
M *Dinophysis punctata* Jorgensen
M *Diplopsalis lenticula* Bergh
M *Gymnodinium danicans* Campbell

Table 4. Continued.

DINOFLAGELLATES

F *Gymnodinium impatins* Skuja
F *Gymnodinium mitratum* Schiller
Gymnodinium sp.
M *Gymnodinium splendens* Lebour
F *Gymnodinium uberrium* Kofoid & Swezy
M *Heterocapsa rotundata* (Lohmann) Hanson
F *Peridinium cinctum* (Muller) Ehrenberg
F *Peridinium inconspicuum* (Playfair) Lefevre
F *Peridinium lomnickii v. splendida* Woloszynska
F *Peridinium sp.*
M *Prorocentrum micans* Ehrenberg
M *Prorocentrum minimum* (Pavillard) Schiller
M *Prorocentrum sp.*
M *Scrippsiella trochoidea* Loeblich III

EUGLENOPHYTES

F *Euglena acus* Ehrenberg
F *Euglena polymorpha* Dangeard
M *Eutreptia lanowii* Steuer
F *Phacus sp.*
F *Trachelomonas acanthostoma* (Stokes) Deflandre
F *Trachelomonas volvocina* Ehrenberg

OTHERS

Cryptomonas sp.
M *Dictyocha fibula* Ehrenberg
green cells 5 - 10mm
greens cells 3 - 5 mm
F *Pyramimonas torta* Conrad & Kufferath

were typical marine species. Marine species identified were primarily diatoms and dinoflagellates, while freshwater species were mostly chlorophytes and cyanobacteria.

Chlorophytes were the dominant phytoplankton group in both surface and 3 m deep waters, with a total concentration of 3.5×10^8 cells/L for the year (Figure 6). Cyanobacteria (cells > 3.0 μ) were the subdominant group with a total yearly concentration of approximately 1.0×10^8 cells/L. Diatoms, dinoflagellates, cryptophytes, and prasinophytes had secondary roles in the phytoplankton community. The picoplankton species, *Microcystis incerta* and *Synechococcus spp.*, were present year round and had maximum concentrations between 2.0×10^8 and 3.0×10^8 cells/L (Figure 7). Although the salinity (0.0 - 5.0 ‰) is described as oligohaline, it was not uncommon for every sample to contain genera typically regarded as marine forms, as well as those regarded as freshwater species.

An analysis of the phytoplankton community at Hoffler Lake by season indicated chlorophytes dominated in abundance year round. In the summer (June – August), several chlorophyte species (*Actinastrum hantzschii, A. hantzschii* var. *fluvilatile, Cosmarium subreniforme, Selenastrum minutum,* and *Zygnema sp.*) comprised 66% of the total phytoplankton population, with cell concentrations approximately 5.0×10^6 cells/L (Figure 8). The cyanobacteria were the subdominant group,

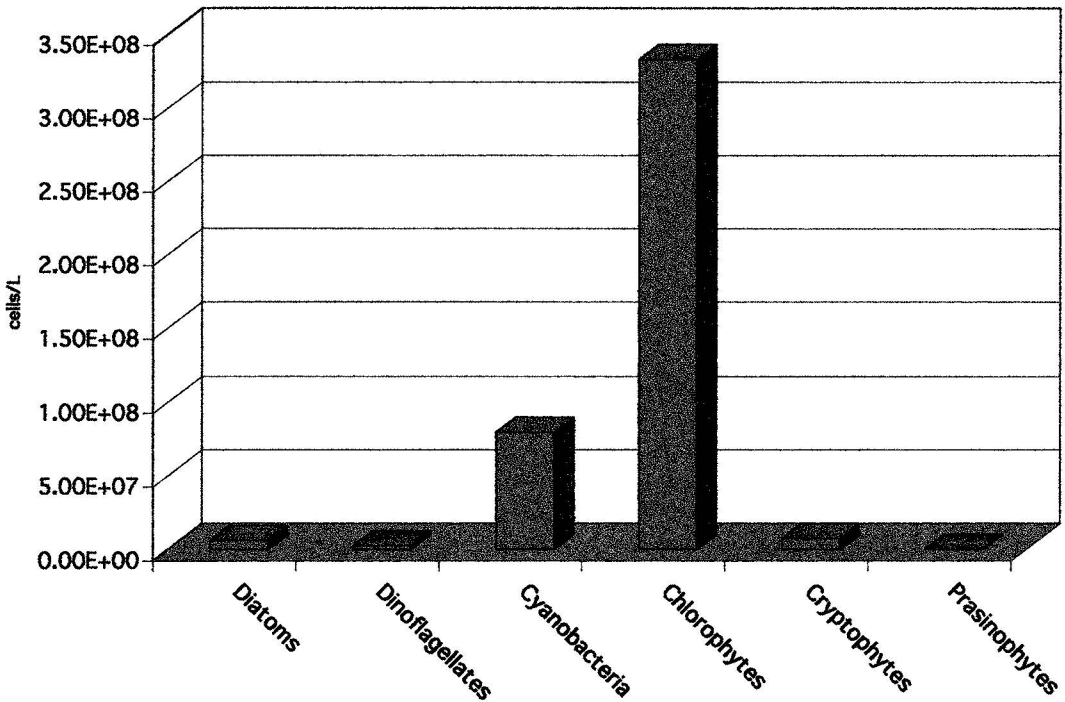

FIG. 6. Total annual phytoplankton concentrations at Hoffler Lake.

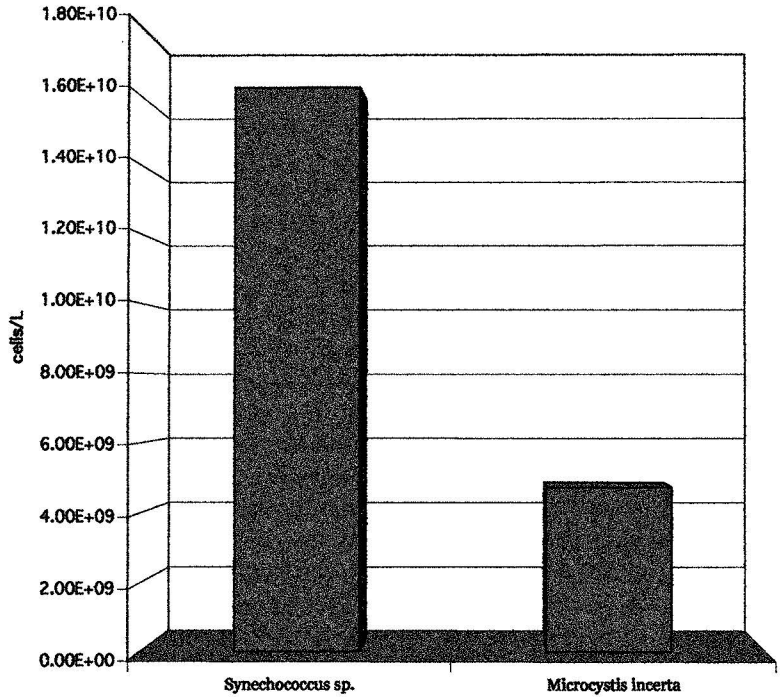

FIG. 7. Total annual picoplankton abundance at Hoffler Lake.

with cell concentrations representing 23% of the total phytoplankton population. Common cyanobacteria during this period were members of the genera *Anabaena* and *Lyngbya*. Cryptophytes, diatoms, and dinoflagellates made up the remaining 11% of the population.

In the fall (September – November), cyanobacteria populations increased to 33% of the total populations (Figure 9) with cell concentrations near 7.0×10^6 cells/L for surface and 3 m deep waters in Hoffler Lake. The major factor contributing to this increase was an October bloom of *Microcoleus sp.* Chlorophytes remained dominant (61% of total population) with cell concentrations ranging between 1.0×10^6 and 1.0×10^7 cells/L. Cryptophytes, diatoms, and dinoflagellates comprised the remaining 7% of the population. There was a small dinoflagellate bloom of *Peridinium inconspicuum* and *Gymnodinium uberrium* in November ($< 2.0 \times 10^5$ cells/L) and a diatom bloom in October ($< 3.0 \times 10^5$ cells/L) of small centric diatoms.

The winter (December – February) phytoplankton population in Hoffler Lake was dominated by chlorophytes (Figure 10). A bloom of *Chlamydomonas snowii* in December, with cell concentrations of 2.5×10^7 cells/L, caused the chlorophytes to comprise 88% of the total phytoplankton population. Cyanobacteria (*Anabaena spp.* and *Aphanizomenon flos-aqua)* were reduced to only 10% of the total population. Diatoms and cryptophytes comprised 1% each and there were no dinoflagellates in any of the winter samples. However, the winter was

the only time prasinophytes (represented by *Pyramimonas torta*) were present in the phytoplankton population even though their numbers were not large enough to greatly contribute to the population percentages.

The spring (March – May, average of 1997 and 1998 data) phytoplankton analysis (Figure 11) included a reduction in chlorophyte concentrations to 74% of the total cell concentration. This was facilitated by a sharp decline in the *Chlamydomonas snowii* bloom. There was an increase in the cyanobacteria cell concentration to 21% of the total population due to a bloom of *Microcystis aeruginosa*. An early spring bloom of *Peridinium inconspicuum* and a late spring bloom of *Heterocapsa rotundata* increased the dinoflagellate contribution to 2% of the total cell concentration. Cryptophytes and diatoms composed the remaining 3% of the population.

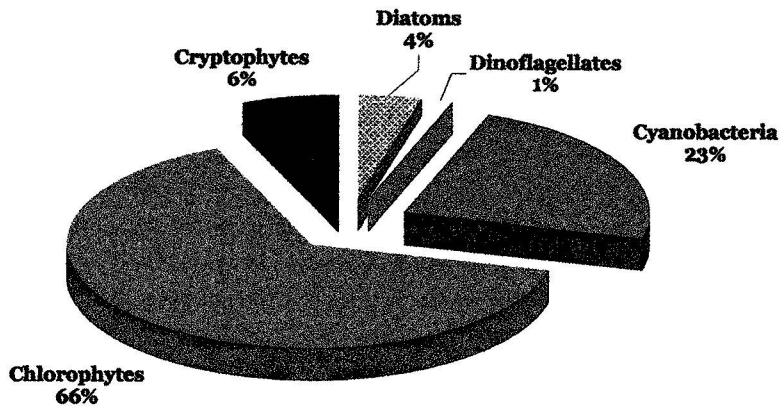

FIG. 8. Percent composition of each major phytoplankton category present during the summer months at Hoffler Lake.

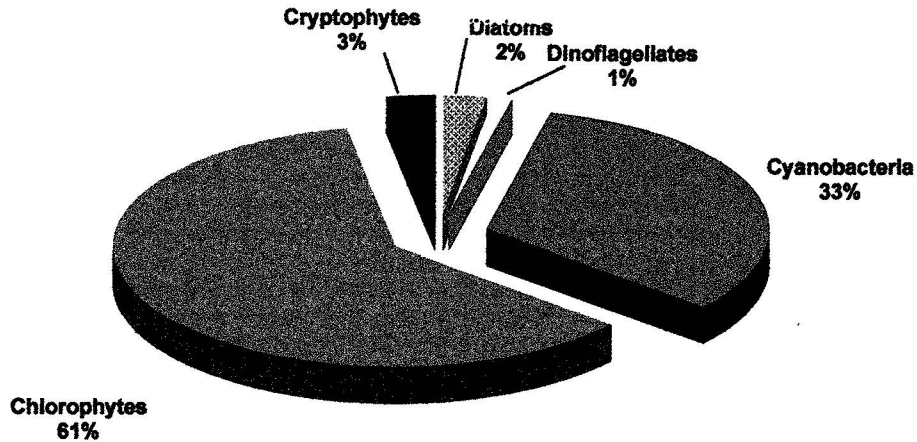

FIG. 9. Percent composition of each major phytoplankton category present during the fall months at Hoffler Lake.

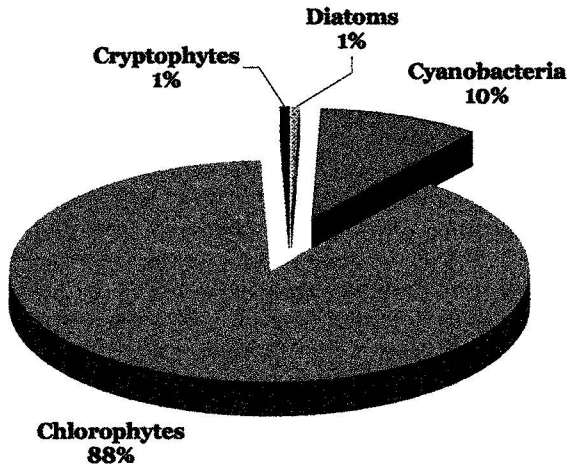

FIG. 10. Percent composition of each major phytoplankton category present during the winter months at Hoffler Lake.

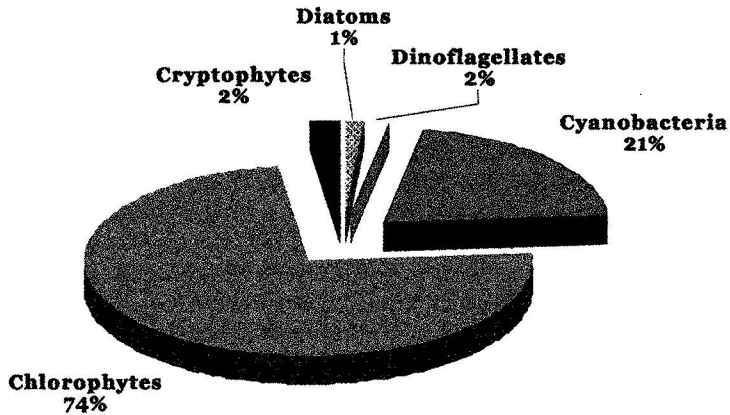

FIG. 11. Percent composition of each major phytoplankton category present during the spring months at Hoffler Lake.

Phytoplankton Characteristics by Major Group

Chlorophytes (30 taxa) had the greatest concentration of all phytoplankton categories throughout the year. The baseline concentrations for chlorophytes were approximately 2.0 x 10^6 cells/L (Figure 12) and were represented year round by *Actinastrum hantzschii, A. hantzschii* var. *fluvilatile, Cosmarium subreniforme,* and *Selenastrum minutum.* This concentration increased to 2.0 x 10^7 cells/L, when *Chlamydomonas snowii* bloomed in December. The bloom corresponded to the decrease in water temperature from the summer high of 28.2°C to 8.5°C, the winter low. The bloom persisted over a period when water temperature varied by 0.9°C (8.5°C – 9.4°C) in the top 3 m of the water column and salinity ranged from 1.75 to 3.5 ‰.

Cyanobacteria (26 taxa) were the subdominant group throughout the year with a baseline concentration of 1.0 x 10^6 cells/L (Figure 13). A bloom of *Microcoleus sp.* in October increased the concentration to 7.0 x 10^6 cells/L. This bloom corresponded with a decreased temperature (17.9°C) and a moderate salinity level (3.5 ‰). A second, smaller bloom (approximately 3.0 x 10^6 cells/L) of *Microcystis aeruginosa* late in spring accompanied increasing temperatures (21.3°C) and salinity (3.7 ‰) similar to the fall bloom.

Two of the remaining phytoplankton groups, diatoms (Figure 14) and dinoflagellates (Figure 15) had blooms prior to the onset or after the water temperature maximum (28.2°C) was reached in Hoffler Lake.

Neither group had a bloom that corresponded to the salinity maximum (4.5 ‰). The cryptophyte bloom in September (5.5 x 10^5 cells/L) corresponded with the salinity maximum and an elevated temperature (23.8°C) (Figure 16). Diatoms were represented by 47 taxa, dinoflagellates by 21 taxa, and the cryptophytes were by species within the *Cryptomonas* genus.

The picoplankton (Figure 17) showed a similar pattern of development to the phytoplankton. The colonial picoplankter, *Microcystis incerta*, reached peak concentrations (2.0 x 10^8 cells/L in June and 1.5 x 10^8 cells/L in April) prior to the onset of the water temperature maximum in August. This was in contrast to *Synechococcus spp.*, the single celled picoplankter identified in Hoffler Lake. *Synechococcus spp.* reached maximum cell concentrations in August at 2.5 x 10^8 cells/L when the water temperature was at its highest (28.2°C). In April, a second bloom of *Synechococcus spp.* occurred concurrently with the *Microcystis incerta* bloom. The average cell concentration for both groups during this bloom was 1.5 x 10^8 cells/L. Neither group had blooms that corresponded to the salinity maximum (4.5 ‰, in September). Picoplankton blooms occurred when the salinity levels were 1.9, 4.2, and 3.9 ‰, for April, June and August, respectively.

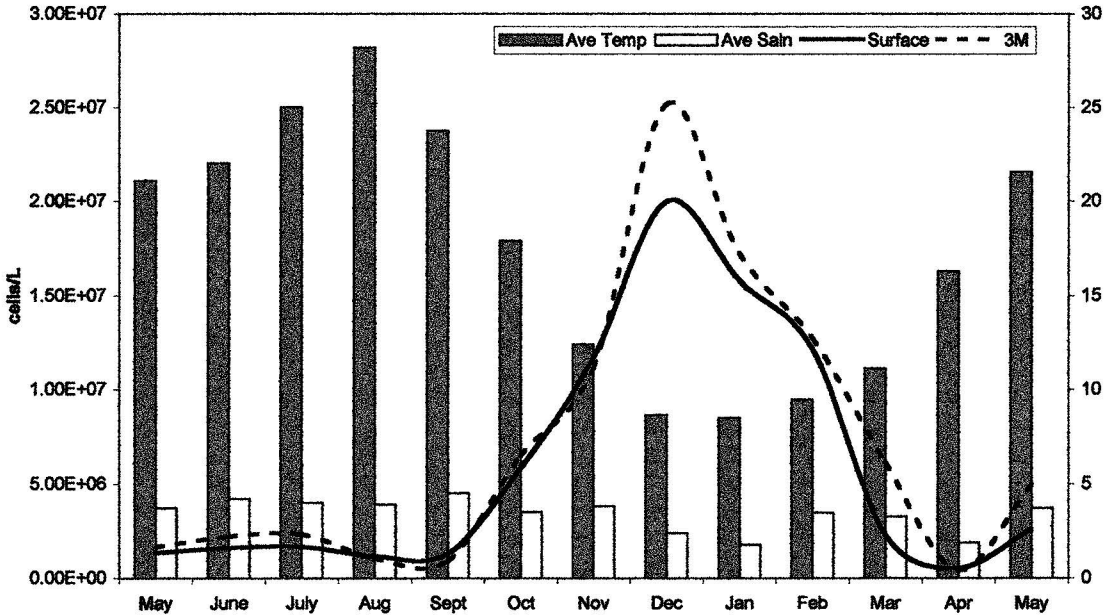

FIG. 12. Chlorophyte abundance with monthly salinity and temperature values for Hoffler Lake.

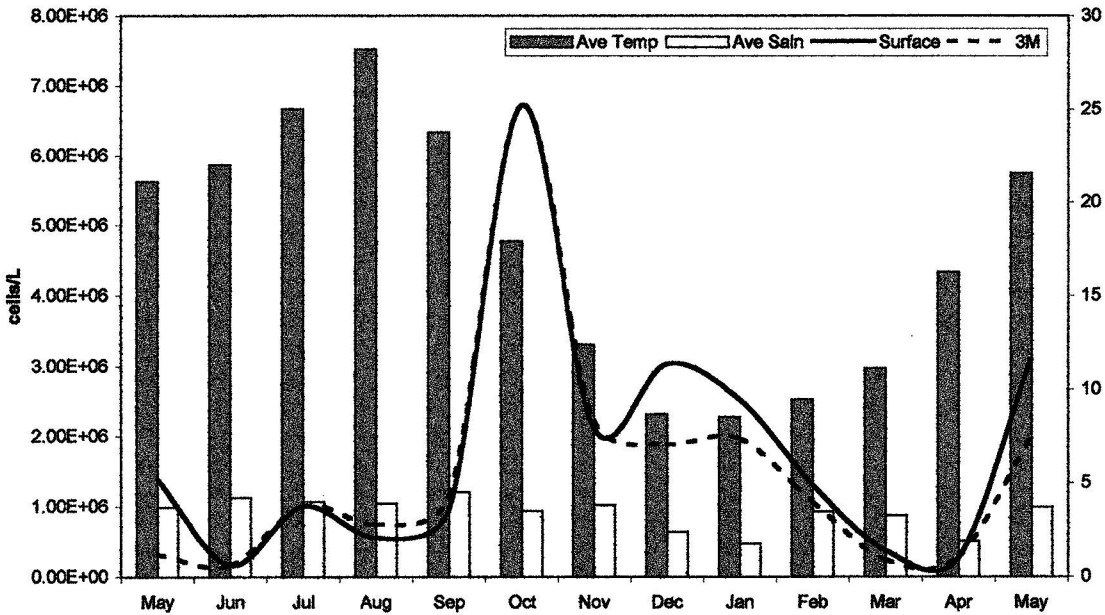

FIG. 13. Cyanobacteria abundance with monthly salinity and temperature values for Hoffler Lake.

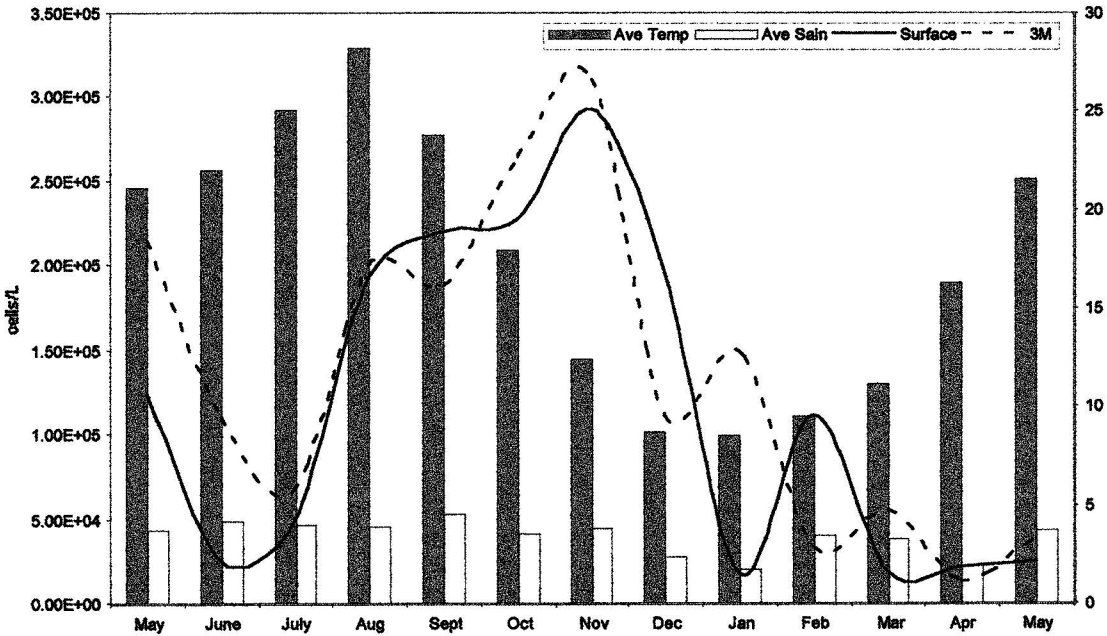

FIG. 14. Diatom abundance with monthly salinity and temperature values for Hoffler Lake.

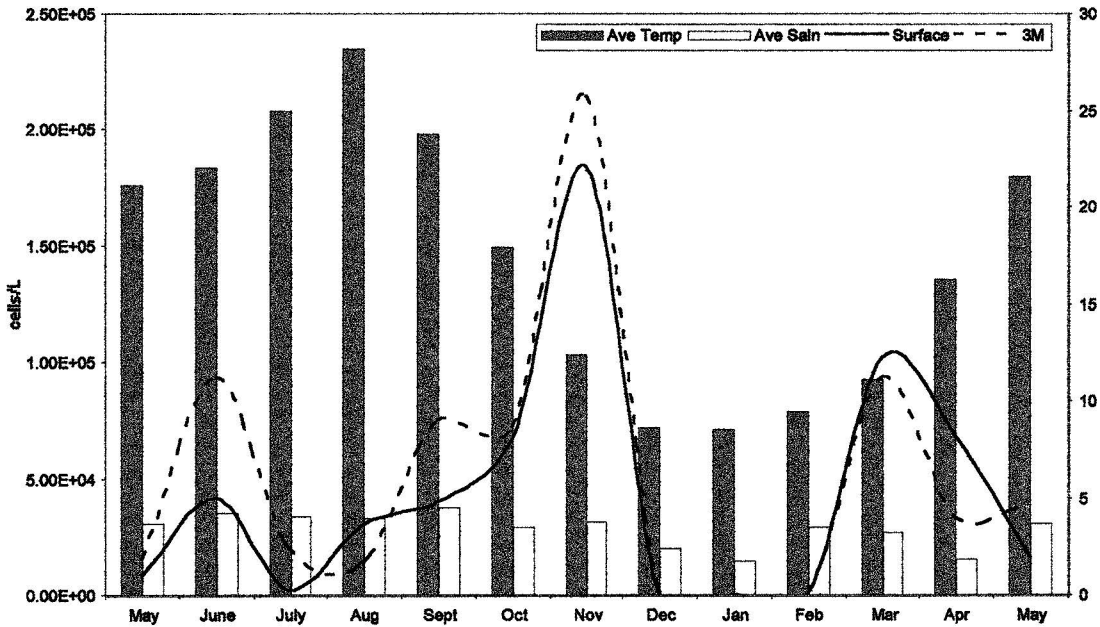

FIG. 15. Dinoflagellate abundance with monthly salinity and temperature values for Hoffler Lake.

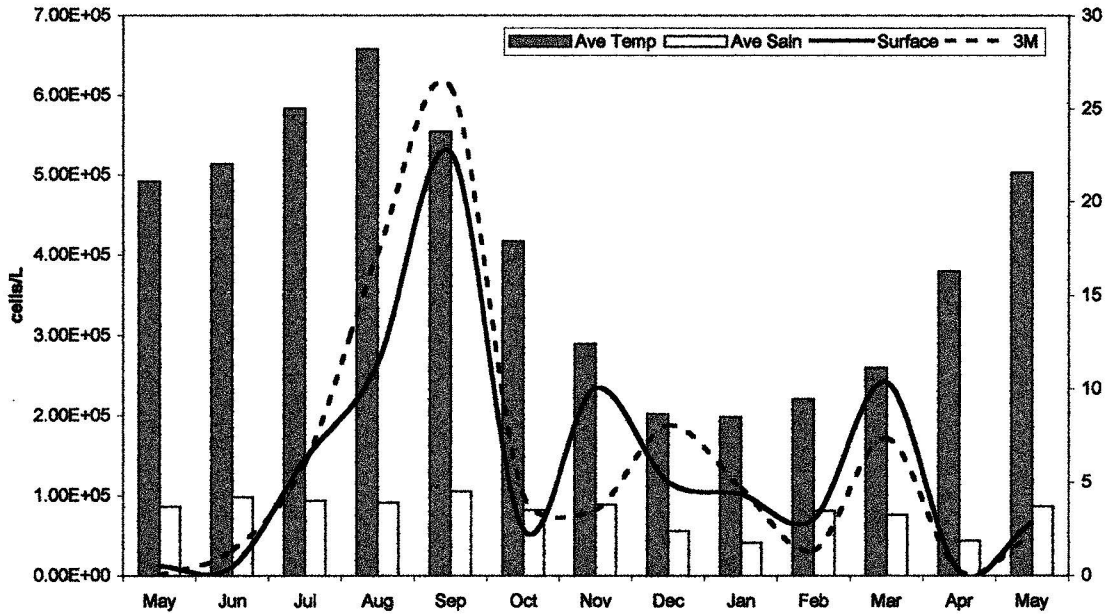

FIG. 16. Cryptophyte abundance with monthly salinity and temperature values for Hoffler Lake.

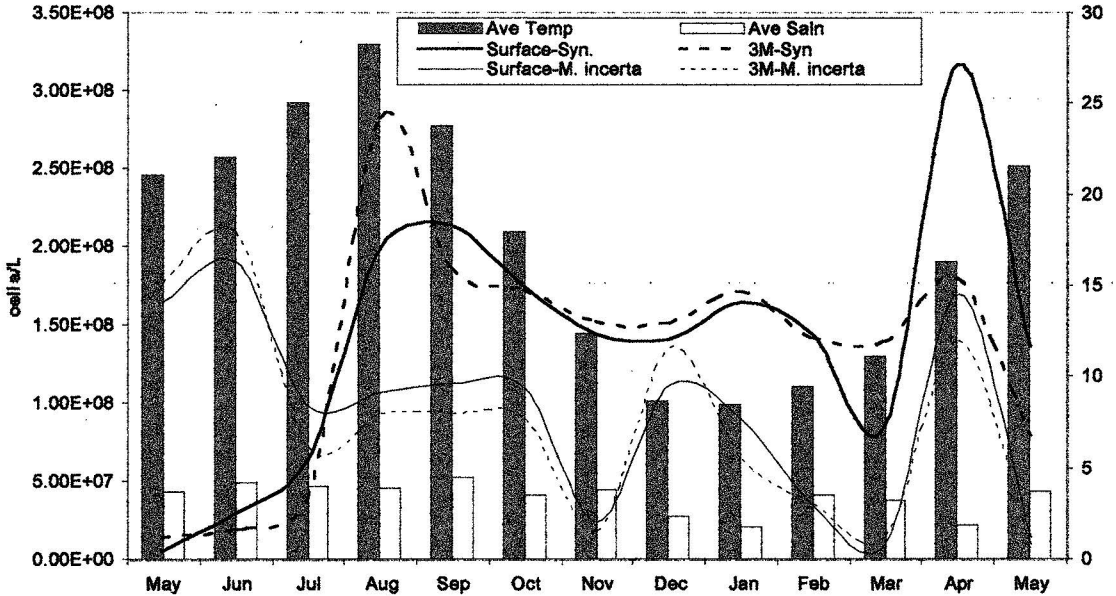

FIG. 17. Abundance of colonial, *Microcystis incerta*, and single celled, *Synechococcus spp.*, picoplankters with monthly salinity and temperature values for Hoffler Lake.

DISCUSSION

The establishment of a research laboratory near Devil's Lake, North Dakota in 1909 initiated saline lake studies in North America (Hammer 1986, Williams 1986). However, since then saline lake studies have been generally neglected by the limnological community and have been considered more of a local interest rather than a major component in this field of study (Williams 1986). The few published scientific reports on saline lakes have provided valuable limnological theories and are worthy of consideration by aquatic ecologists (Laugaste and Ott 1993, Moss 1994), especially considering the biological and chemical diversity saline lakes offer (Hammer 1978). Hoffler Lake has provided another setting in which to study a brackish water environment.

Hoffler Lake has salinity levels that range from 0.0 to 5.0 ‰ in the top 9 m of water and 3.8 to 9.0 ‰ in bottom waters. These values place its classification, according to Remane (1971), between brackish-fresh water (oligohaline) and brackish water (mesohaline). No changes in salinity observed during the study fit into a seasonal pattern. A likely explanation for the brackishness of Hoffler Lake, according to Hall (1999), may be daily tidal flux and saltwater percolation through permeable soils lying between the lake and the Hampton Roads estuary. A similar mechanism has also been suggested by Moss (1994) in his study of secondarily saline lakes in the Norfolk Broadland, England.

According to Moss (1994) and Cognetti (1994) diversity in brackish water lakes should be lower than that of marine and freshwater environments, particularly if the salinity levels greatly fluctuate and are below 15 ‰. However, lakes with these attributes have the potential to develop much greater diversities if a steady state concentration in salinity is reached. If Hoffler Lake is tidally influenced a steady state condition will probably not be met and the dominance of the phytoplankton community by smaller, more adaptable species of chlorophytes and cyanobacteria will continue, even as the lake goes through the eutrophication process.

The continued dominance of the phytoplankton community by smaller algae is supported by the work of Claustre (1994), Riegman et al. (1993), and Heiskanen and Keck (1996). These researchers found cyanobacteria and smaller phytoflagellates that could outcompete larger phytoplankton for nutrients, dominated saline systems with low, regenerated nutrients. Heiskanen and Keck (1996) go on to state that the success of large colonial and chain-forming diatoms, which were not found in Hoffler Lake in a significant abundance, are dependent on high nutrient concentrations and shallow water with sufficient vertical mixing. Spring through summer stratification and year round low nutrient levels were common in Hoffler Lake as nitrate-nitrogen and ammonia-nitrogen concentrations were consistently at or below the detection limit of the testing system used.

The results of the plankton analysis at Hoffler Lake show several patterns comparable with other saline lakes. This phytoplankton analysis closely corresponds to the work done by Laugaste and Ott (1993) at Lake Yaskhan in Estonia. Similar to Lake Yaskhan, chlorophytes and cyanobacteria formed the dominant phytoplankton groups in Hoffler Lake throughout the year (Figure 6). Laugaste and Ott (1993) also noted a spring/summer bloom of *Microcystis spp.*, as was seen in Hoffler Lake, with a spring bloom of *M. aeruginosa* and a summer bloom of *M. incerta.*

Diatom biomass was also low in Lake Yaskhan (5 g/m^3 at the summer peak, as compared to 6 g/m^3 during the fall peak in Hoffler Lake). Laugaste and Ott (1993) state at the lower brackish limit (below 5 ‰), the critical salinity level is not met for many organisms, particularly diatoms, and the water becomes characterized by very scanty phytoplankton populations. This conclusion is also supported by Jeppesen et al. (1994) who state that even though the fresh to brackish water threshold is placed at 5 ‰, significant shifts in species occur between 0.5 and 2 ‰. While diatoms were not prevalent in Hoffler Lake no major species shifts were detected with changes in salinity.

Shcherbak and Rodkin (1994) reported in Sakskoye Lake, Ukraine, the phytoplankton population was dominated by diatoms (from the genera *Thalassiosira, Chaetoceros, Cyclotella, Navicula,* and *Nitzschia*) and chlorophytes (from the genera *Dunaliella, Oocystis, Scenedesmus,* and *Chlamydomonas*). Several species from within these genera were reported

in Hoffler Lake (Table 4). However, the phytoplankton in Hoffler Lake was dominated by chlorophytes, particularly by the genus *Chlamydomonas*, and there were only isolated occurrences of the diatom taxa listed above.

Shcherbak and Rodkin (1994) report many taxa identified in Sakskoye Lake were freshwater species that had adapted to higher salinity levels through osmoregulation. Caljon (1987) and Raven (1999) state this is often the physiological process that occurs with marine algal species introduced into a less saline environment. With both typical freshwater and marine species of phytoplankton identified in Hoffler Lake (Table 4) this may be the case here as well. Transitions between populations with marine and freshwater affinities are often found when the salinity is between 5 and 6 ‰ (Starobogatov and Khlebovish 1977, Snoeijs 1995). However, the success of marine species in deep (stratified), brackish environments is often poor because salinity becomes the limiting factor for growth, reproduction, colonization, and adaptation (Cognetti 1994, Raven 1999, Blinn 1993, Rijstenbil 1991). This same condition was demonstrated in Hoffler Lake by the absence of dominant marine phytoplankton species. Jackson et al. (1987) state that freshwater species observed in saline environments often persist but do not actively grow at salinity levels between 1 and 8 ‰. Lack of growth was not the case in Hoffler Lake as evidenced by blooms of several freshwater species. *Chlamydomonas snowii* bloomed when the salinity ranged from 1.75 to 3.5

‰, and *Peridinium inconspicuum* and *Gymnodinium uberrium* reached peak cell concentrations when the salinity was 3.8 ‰.

Bales et al. (1993) showed that diatoms and cyanobacteria dominated the flora of the saline lake, Hickling Broad in England. While an abundant diatom population was not identified in Hoffler Lake, the lake was similar to Hickling Broad in the dominance of colonial cyanobacteria. Where *Aphanothece sp.* comprised an excess of 70% of the phytoplankton abundance in Hickling Broad, particularly in the summer, a similar taxon, *Microcystis incerta,* played a significant role in phytoplankton abundance in Hoffler Lake.

There were several similarities seen in the phytoplankton composition between Hoffler Lake and the Warri/Forcados estuary of Nigeria, as presented by Idiem'Opute (1990). Idiem'Opute (1990) showed in the Warri/Forcados estuary typical freshwater species were represented by taxa in the Chlorophyta, Bacillariophyta, and Cyanobacteria. In Hoffler Lake, 27 of the 30 chlorophyte taxa and 13 of the 26 cyanobacteria taxa are freshwater species (Table 4). However, unlike the Warri/Forcados estuary, Hoffler Lake only had 7 freshwater diatom taxa. There were 24 typical marine taxa noted from the 47 diatom taxa identified in Hoffler Lake (Table 4). Idiem'Opute (1990) states the true marine species identified in the Warri/Forcados were diatoms and dinoflagellates. The same condition is generally true in Hoffler Lake. The marine taxa identified (37 total) were predominantly diatoms or

dinoflagellates, with the exception of *Dactylococcopsis raphidioides* (cyanobacteria) and *Dictyocha fibula* (silicoflagellate).

Underwood et al. (1998) state that earlier field studies have shown salinity and temperature are the important environmental factors influencing species abundance. However, work done in the Colne, England, demonstrated that salinity is not as important as once thought in influencing changes in species composition (Underwood et al. 1998). The work at Hoffler Lake supports this conclusion. Hoffler Lake had both freshwater and marine species present regardless of the salinity levels. Even when the average salinity was 1.75 ‰ marine species such as *Cyclotella caspia, Prorocentrum minimum,* and *Skeletonema costatum* were common. Phytoplankton blooms existed over a range of salinities. For example, *Chlamydomonas snowii,* a freshwater chlorophyte, bloomed (maximum concentration of 2.0×10^7 cells/L) throughout the winter over a salinity range of 1.75 to 3.5 ‰. During this bloom, true marine species, such as *Cyclotella caspia, C. striata, Leptocylindrus danicus, Prorocentrum sp., P. minimum,* and *Skeletonema costatum,* were common.

This initial study of phytoplankton at Hoffler Lake indicates that the upper strata of the lake is an oligohaline, oligotrophic environment with a lens of higher salinity present in its deepest depression. The lake is well mixed during the fall and winter months and begins to stratify in the spring. Despite the prevailing wind patterns that can affect the lake, the lake remains stratified throughout the summer. During the stratified

period several blooms of smaller algal taxa were noted, including *Cryptomonas sp.*, *M. aeruginosa*, and *M. incerta*. When the water began to mix in the fall, blooms of larger phytoplankton occurred. These blooms began with *Microcoleus sp.* in October and continued as a winter long bloom of *Chlamydomonas snowii*. Domination of the phytoplankton community by taxa from the chlorophyte and cyanobacteria groups indicates that a fluctuation in salinity may be the limiting factor for growth and sustainability of larger plankton species.

SUMMARY

1. Hoffler Lake is a 30 acre clear water lake with 2 major depressions (9 m and 17 m) separated by a berm (4 m) and surrounded by deciduous forest and wetlands.
2. Hoffler Lake is characterized by brackish surface waters with a salinity range of 0 - 5 ‰ (oligohaline) and a bottom lens of higher salinity waters with a range of 3.8 - 9.0 ‰ (mesohaline).
3. The yearly average water temperature in the top 3 m was 15.7°C and ranged from 8.5 - 28.2°C. The yearly average pH in the top 3 m of water was 7.12 with an average secchi depth of 1.7 m.
4. There were 123 phytoplankton taxa identified in Hoffler Lake. Of these 123 taxa there were 31 chlorophytes, 25 cyanobacteria, 47 diatoms, 21 dinoflagellates, 6 euglenophytes, and 5 were grouped into an "other" category.
5. Of the 123 taxa identified 47% were typical freshwater species and 29% were marine species. The marine species identified were primarily diatoms and dinoflagellates, while freshwater species were mostly chlorophytes and cyanobacteria.
6. Chlorophytes were the most abundant phytoplankton group found in Hoffler Lake, comprising 61 – 88% of the total abundance. The dominant species were *Actinastrum hantzschii*, *A. hantzschii* var. *fluvilatile*, *Cosmarium subreniforme*, *Selenastrum minutum*, and

Zygnema sp. A bloom of *Chlamydomonas snowii* occurred during the winter months and reached a maximum cell concentration of 2.0 x 10^7 cells/L.

7. Larger cyanobacteria (cells > 3 μ) made up 10 – 33% of the total phytoplankton abundance with species such as *Anabaena sp., Anabaena wisconsinense, Microcoleus sp.* and *Microcystis aeruginosa* predominating.
8. Diatoms, dinoflagellates, cryptophytes, and prasinophytes played a secondary role in the Hoffler Lake phytoplankton population.
9. Seasonal patterns included a summer bloom of *Cryptomonas sp.* during the temperature maximum, fall blooms of *Microcoleus sp., Peridinium inconspicuum,* and *Gymnodinium uberrium* during lake turn over, a winter bloom of *Chlamydomonas snowii* at the temperature minimum, and spring blooms of *Peridinium inconspicuum* and *Microcystis aeruginosa.* However, chlorophytes remained the most abundant group throughout the year, despite blooms by algae in other major taxonomic groups.
10. Autotrophic picoplankton, both *Synechococcus spp.* and *Microcystis incerta,* were abundant in Hoffler Lake with a yearly average abundance of 1.3 x 10^8 cells/L.

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