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**Temporal variation and spatial heterogeneity of phytoplankton
abundance within a water supply impoundment**

Principe, Michael Anthony, Ph.D.

City University of New York, 1991

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TEMPORAL VARIATION AND SPATIAL HETEROGENEITY OF PHYTOPLANKTON
ABUNDANCE WITHIN A WATER SUPPLY IMPOUNDMENT

by

MICHAEL A. PRINCIPE

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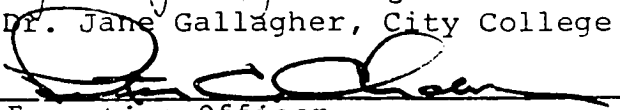
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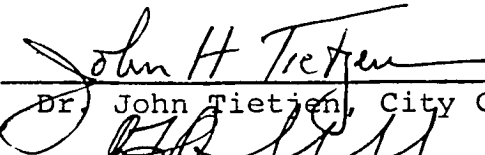
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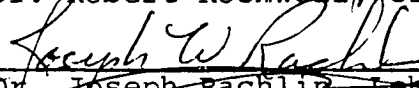
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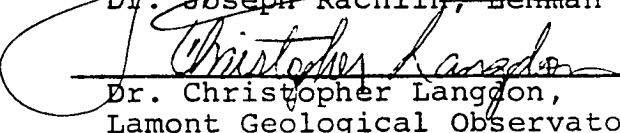
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Abstract

TEMPORAL VARIATION AND SPATIAL HETEROGENEITY OF PHYTOPLANKTON
ABUNDANCE WITHIN A WATER SUPPLY IMPOUNDMENT

by

Michael A. Principe

Advisor: Professor Jane Gallagher

The spatial heterogeneity and temporal variability of phytoplankton biomass and floristic composition was analyzed in Croton Reservoir, New York from 1984-1988 using a stepwise regression model of seven variables. The reservoir exhibited a longitudinal gradient of algal biomass, physical factors, and chemical factors from headwater to dam during the entire study period. Hydraulic residence time and reservoir volume levels played an important role in influencing the abundance and the composition of the phytoplankton, as well as affecting the extent of the physical and chemical longitudinal gradients. Although the reservoir's bathymetry and water flow superficially resembled a general model for reservoirs, analysis of the flow regimes showed that the impoundment did not have the pronounced riverine zone and clearly defined transitional zone predicted by the model. Findings suggested that, with the exception of the growing season (July-October) period, reservoir flow through rates were generally too rapid to

allow for the accumulation of algal biomass. The reservoir functioned as a rapidly flushed nutrient-rich system which occasionally exhibited longitudinal algal biomass gradients due to the combined sequential effect of increased growing season residence time coupled with intense fall precipitation. The impoundment exhibited the same classic pattern of phytoplankton succession as that observed in northern temperate mesotrophic-eutrophic lakes. However, this pattern of succession did not vary spatially within the reservoir. Nutrient availability never appeared to limit algal abundance, although the relative proportions of nutrients measured corresponded well with the spatial and temporal patterns of floristic composition observed within the impoundment, and were consistent with those described by current nutrient ratio-phytoplankton competition theory. It was observed that growing season cell losses and reduced biomass may have been attributable to grazing, light-limitation, and cell sedimentation. Grazing losses appeared to be more pronounced in the reservoir's lower zone, whereas nonalgal light-limitation, and sedimentation were more pronounced in the reservoir's upper zone. This investigation utilized one of the most complete long-term data sets available for a reservoir ecosystem and its findings will be used to formulate improved water quality management strategies.

PREFACE

There are a multitude of environmental factors controlling both phytoplankton abundance and floristic composition in freshwater ecosystems that can vary spatially and temporally. Such factors, as described by Reynolds (1984), may include: nutrient concentrations, day length, total irradiance, water column light availability, temperature, flow regime, the abundance of herbivorous animals, the inhibitory and stimulatory effect of trace metals, and phytoplankton antibiosis. Sommer (1990) has indicated that resources potentially limiting phytoplankton abundance include light, inorganic carbon, those mineral nutrients which become scarce during the vegetative period (usually phosphorus (P), nitrogen (N), for diatoms- silica (Si), and perhaps trace metals), and for some species vitamins. He noted that such factors as temperature, and toxicity, although considered important, are generally not considered "consumable" resources. Much research over the last 20 years within the field of phytoplankton ecology has centered on nutrients and their importance in governing both the abundance and the seasonal floristic shifts of freshwater phytoplankton populations. The competition research of Tilman (1982) and Kilham et al. (1986), and the biomass yield limitation work of Dillon and Rigler (1974), and Vollenweider (1975) have played an important role in the

formulation of phytoplankton nutrient utilization theory. The nutrient limitation models used in both experimental and observational ecological studies fall into two classes: those based on "chemostat" studies concerning saturation curves with an asymptotic approach to maximal uptake or reproductive rates with usually one nutrient being considered limiting, or those derived from log-log regressions of total biomass vs. total nutrient concentrations (yield limitation) (Sommer 1990). Models of the first type have been used extensively in the evaluation of phytoplankton competition based on nutrient limitation. Species-specific nutrient ratios (Si:P, N:P) derived from these models have been useful in the study of both seasonal and long-term changes in phytoplankton floristic composition. Sommer (1990) summarized the available information of taxonomic trends in nutrient competition with respect to diatoms, green algae, and cyanobacteria. He noted that several diatoms dominate at high Si:P ratios (they are superior P competitors), whereas cyanobacteria dominate at low N:P ratios (they are superior N competitors). Green algae, being the poorest N competitors, dominate at low Si:P, but high N:P ratios. All of these patterns are affected by temperature. It has also been suggested that the relative proportions or concentrations of the nutrients supplied to the phytoplankton, as expressed by these ratios, could be a strong selective force in both shaping

phytoplankton communities, as well as affecting levels of biomass yield per unit of limiting nutrient (Hecky and Kilham 1988).

The second class of model, that of yield limitation, has been useful in the prediction of algal biomass levels based upon nutrient loading levels. The yield limitation model developed by Dillon and Rigler (1974) used data from "phosphorus-limited" North American lakes to predict summer surface chlorophyll a concentrations based upon spring total phosphorus concentrations. Vollenweider (1975) developed a nutrient loading model which was based upon a lake's morphometry and flushing rate. He predicted that lakes that flush rapidly could receive more phosphorus and continue to maintain a given trophic level, whereas lakes that flush more slowly were most likely to change their trophic state upon receiving additional nutrient loading. The Vollenweider model has been used extensively to evaluate both lake and reservoir trophic status with respect to water quality management strategies.

The two classes of nutrient limitation models described above could be useful in the evaluation of phytoplankton dynamics since their combined output provides information pertinent to both species composition, and algal abundance. Sommer et al. (1986) have utilized Tilman's (1982) resource competition theory, i.e., the first class of nutrient-limitation models described above, in their

development of the "Plankton Ecology Group" (PEG) Model. This model was constructed based upon the succession in Lake Constance, and it was intended to provide a framework for interpretation of seasonal plankton succession in all lakes. The model assumes certain boundary conditions: a nutrient-rich lake in which nutrients are depleted in sequence P, Si, N from early spring to early fall. The model predicts the following seasonal sequence: Cryptophyceae and diatoms predominant during the spring at high Si:P ratios with cold water temperatures. Green algae become dominant after Si and P become depleted and N levels remain high. Once N levels become depleted and water temperature increases, cyanobacteria predominate. Finally, increased mixing and the decreased water temperatures of the fall give rise to nutrient replenishment and filamentous algal forms, including the diatoms.

There remains a question as to whether the temporal sequences contained within the PEG-Model are applicable to reservoirs. Reservoirs, due to their unique hydrologic nature, provide an additional opportunity to study and evaluate the sequential resource utilization statements contained within the PEG-model. In addition, comparative studies between lakes and reservoirs in general, can be useful with respect to developing a greater understanding of the structure and function of freshwater ecosystems. Since the late 1970's, many researchers have investigated the

complexities associated with the functional processes governing numerous reservoir ecosystems (Hyne 1978; Gloss et al. 1980, Kennedy et al. 1982, Thornton et al. 1981, Thornton et al. 1982, Kimmel and Groeger 1984, Soballe and Kimmel 1987). In general, reservoirs appear to be somewhat more productive than lakes in terms of phytoplankton abundance (Hutchinson 1973; Kimmel and Groeger 1984). This may be attributable to reservoirs having higher drainage area-to-lake surface area ratios and their receiving higher sediment, organic matter, and nutrient loads than do most lakes (Thornton et al. 1981; Benson 1982). Reservoir nutrient dynamics are primarily governed by morphometry inflow-outflow regimes, and discharge depth. This is in contrast to lakes in which nutrient cycling is controlled by vertical mixing induced by wind action, and internal nutrient cycling (Baxter 1977; Kennedy 1984; Pickett and Harvey 1988). Reservoirs also receive greater areal water loads, and experience shorter hydraulic residence times than lakes. In addition, it has been demonstrated that residence time is often empirically related to lake and reservoir water quality (Rechkow and Chapra 1983). Soballe and Kimmel (1987) categorized rapidly flushed lakes and impoundments as "transitional systems" with residence times within the 2-75 day range. Lakes and reservoirs with residence times greater than 120 days were termed "lacustrine systems."

Numerous studies have noted that reservoirs tend to

occupy an intermediate position between rivers and lakes, and are often described as "river-lake hybrids" (Lind 1971; Henderson et al. 1973; Ryder et al. 1974; Margalef 1975; Ryder 1978; Goldman and Kimmel 1978; Thornton et al. 1981; Jenkins 1982; Benson 1982). As a result, impounded rivers often exhibit longitudinal productivity and algal biomass gradients. Thornton et al. (1981) developed a conceptual model of reservoirs which described the spatial heterogeneity of the physical, chemical, and biological conditions found within impoundments, and proposed that reservoirs consist of three longitudinal zones, i.e., riverine, transitional, and lacustrine. The riverine zone is narrow, has a channelized basin, high flow, high turbidity, low light availability, light limited primary production, and is more eutrophic in character. The transitional zone is a broader deeper basin with reduced flow, less turbidity, a reduced nutrient supply, and exhibits mesotrophic characteristics. The lacustrine zone is broad and deep, has little flow, nutrient limited primary production, greater light penetration, and is more oligotrophic in character.

Kimmel and Groeger (1984) note that reservoirs possess both horizontal and vertical gradients of environmental factors that control algal biomass. Longitudinal changes in basin morphology and flow velocity result in differences in suspended particle concentrations, nutrient levels, mixing depth, and thereby, in variations in light and nutrient

availability for phytoplankton in various parts of the reservoir. In addition, Kimmel et. al (1990) suggest that because a transition from a riverine to a lacustrine environment occurs within the reservoir basin, reservoirs characteristically exhibit a striking degree of spatial heterogeneity in phytoplankton abundance. Tilman et. al (1982) suggest that significant advances in our understanding of phytoplankton ecology can be achieved if scientists utilize a synthesis of approaches to address the ecological processes occurring at varying scales within the aquatic environment. The reservoir ecosystem presents a unique opportunity to investigate phytoplankton ecology within an environment which exhibits highly variable physical, chemical, and biological regimes. In addition, reservoirs have a distinct advantage over natural systems in that they can be manipulated to test hypotheses that may be important in influencing phytoplankton populations.

Croton Reservoir, the study site in this investigation, is the final receiving reservoir of the Croton River. The reservoir is owned and operated by the City of New York (the City), and supplies the City with approximately 10 - 15 % of its annual drinking water supply needs. Water diverted from this reservoir for drinking water purposes has historically been of good quality, having low turbidity and being microbiologically superior as determined by coliform bacteria analyses. As such, chlorination has been the only

treatment process necessary to render the water potable prior to entry to the New York City distribution system. However, because of the increase in residential development in the Croton Watershed over the last 30 years and its attendant negative water quality impacts, and the recent implementation of the more stringent standards of the Safe Drinking Water Act Amendments of 1986, the City has decided to construct a filtration facility before the end of this decade. Nevertheless, maintenance of superior water quality will continue to play an important role in the management of the Croton Supply, regardless of the implementation of filtration technology. As such, the key water quality management objective for the City in the years to come, is to halt or reverse the process of eutrophication, i.e., increased algal abundance, within the numerous Croton Watershed impoundments which are currently experiencing its degrading effects. Successful management of the eutrophication process as it occurs within Croton Reservoir is contingent upon a thorough understanding of the temporal variation and spatial heterogeneity of phytoplankton abundance within the impoundment.

Preliminary analysis of a four-year (1984-1987) limnological investigation at four sites within Croton Reservoir suggested that an algal biomass gradient may have been present along the length of the impoundment. This four year investigation was extended by an additional year of

data collection (1988), in which the frequency and intensity of sampling was increased in order to address questions that the preliminary data analysis noted as being important. The purpose of this study was: first, to determine if Croton Reservoir conformed to the parameters of the zonation model described by Thornton et al. (1981); and second, to ascertain how the variation among abiotic and biotic factors may have accounted for the heterogeneity in phytoplankton biomass and floristic composition along gradients of time and space in the reservoir ecosystem. In addition, the study was designed to address the following hypotheses:

- (1) Croton Reservoir is a spatially homogeneous system with respect to phytoplankton abundance and floristic composition.
- (2) Spatial variations in phytoplankton biomass do not occur seasonally within Croton Reservoir.
- (3) The factors governing phytoplankton abundance are the same spatially and temporally along the entire longitudinal axis of Croton Reservoir.
- (4) Hydraulic residence time does not play a significant role in influencing phytoplankton abundance and floristic composition within the reservoir.
- (5) Differences among sampling stations for single epilimnetic samples are due to true differences in biomass over time, and differences in phytoplankton abundance with depth are not significant.
- (6) The relation of phytoplankton biomass and composition with abiotic and biotic factors in different seasons does not change when shorter time scales are examined.
- (7) Abiotic factors alone can account for the variation in phytoplankton biomass.

This is one of the few investigations of a limnetic system that has a sufficient database to thoroughly explore the nature of temporal and spatial interactions of variables that may influence phytoplankton abundance and composition. This investigation will help to further clarify the distinction between the patterns of phytoplankton abundance observed within both low flow, "steady-state", nutrient-limited lacustrine environments, and within hydrodynamic, nonequilibrium, nutrient enriched reservoirs. The findings from this study will not only provide an additional contribution to the body of research concerning the ecological processes occurring in reservoirs, but will also aid in the development of effective water quality management practices for the Croton-Muscoot Reservoir complex. It is important to note that many of the analyses done in this study were directed at uncovering possible cause and effect relationships. However, since this study was entirely observational, causal assumptions were made cautiously.

In order to promote clarity and facilitate publication, the dissertation has been divided into four papers (Chapters 1-4) each of which has been written in manuscript format. Chapter 1 describes longitudinal zonation, water budget dynamics, hydraulic residence time in Croton Reservoir, and reservoir management issues. The format of Chapters 2-4 were based on the use of data from the years 1984-1987 as background for the detailed analysis undertaken in 1988.

Chapter 2 describes the spatial and temporal patterns present within the reservoir with respect to key physical and chemical variables. Chapter 3 deals with the distribution of biomass in the reservoir in relation to the physical and chemical factors presented in Chapters 1 and 2. Chapter 4 concerns the floristic composition and patterns of succession of the phytoplankton within Croton Reservoir. Chapter 5 summarizes Chapters 1-4, and discusses a synthesis of the research findings in conjunction with Croton Reservoir water quality management strategies, as well as future research needs.

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CHAPTER 1

Longitudinal zonation, water budget dynamics, and
hydraulic residence time within Croton Reservoir, New York

ABSTRACT

The hydrology and physiography of Croton Reservoir (southeastern New York State) were studied from 1984 to 1988 to determine the reservoir's morphometry, longitudinal zonation characteristics, water budget, and hydraulic residence time. With the exception of the drought year of 1985, and the recharge year of 1986, 58-77% of the reservoir's total annual output was discharge over the reservoir spillway; only 19-37% of the reservoir's total output could be attributed to aqueduct diversions. Hydraulic residence time calculations indicated that Croton Reservoir was a rapidly flushed transitional system with a mean residence time and a mean flushing rate of 0.17 years and 6.2 volume changes per year respectively. With the exception of the drought year of 1985, summer (July-October) residence times were generally greater than annual residence times by a factor of 2.1. Annual residence time values did not significantly differ during the five year study period, but summer residence times did differ. Results of the study suggest that it may be more biologically meaningful to use summer residence time determinations, or residence times of shorter time scales than those of annual duration when performing ecological and water quality assessments of rapidly flushed systems such as Croton Reservoir. In addition, although the Croton Reservoir's bathymetry and water flow superficially resembled a general model for

reservoirs, analysis of the flow regimes showed that the Croton Reservoir did not have the pronounced riverine zone and clearly defined transitional zone predicted by the model.

INTRODUCTION

Comparative studies between lakes and reservoirs can be useful with respect to developing a greater understanding of the structure and function of reservoir ecosystems. Since the late 1970's, many researchers have investigated the complexities associated with the functional processes governing numerous reservoir ecosystems (Hyne 1978; Gloss et al. 1980, Kennedy et al. 1982, Thornton et al. 1981, Thornton et al. 1982, Kimmel and Groeger 1984, Soballe and Kimmel 1987). In general, reservoirs appear to be somewhat more productive than lakes in terms of phytoplankton abundance (Hutchinson 1973; Kimmel and Groeger 1984). This may be attributable to reservoirs having higher drainage area-to-lake surface area ratios and their receiving higher sediment, organic matter, and nutrient loads than do most lakes (Thornton et al. 1981; Benson 1982). Reservoir nutrient dynamics are primarily governed by morphometry inflow-outflow regimes, and discharge depth. This is in contrast to lakes in which nutrient cycling is controlled by

vertical mixing induced by wind action, and internal nutrient cycling (Baxter 1977; Kennedy 1984; Pickett and Harvey 1988). Reservoirs also receive greater areal water loads, and experience shorter hydraulic residence times than lakes. Numerous studies have noted that reservoirs tend to occupy an intermediate position between rivers and lakes, and are often described as "river-lake hybrids" (Lind 1971; Henderson et al. 1973; Ryder et al. 1974; Margalef 1975; Ryder 1978; Goldman and Kimmel 1978; Thornton et al. 1981; Jenkins 1982; Benson 1982). As a result, impounded rivers often exhibit longitudinal productivity and algal biomass gradients. Thornton et al. (1981) developed a conceptual model of reservoirs which described the spatial heterogeneity of the physical, chemical, and biological conditions found within impoundments, and proposed that reservoirs consist of three longitudinal zones, i.e., riverine, transitional, and lacustrine. The riverine zone is narrow, has a channelized basin, high flow, high turbidity, low light availability, light limited primary production, and is more eutrophic in character. The transitional zone is a broader deeper basin with reduced flow, less turbidity, a reduced nutrient supply, and exhibits mesotrophic characteristics. The lacustrine zone is broad and deep, has little flow, nutrient limited primary production, greater light penetration, and is more oligotrophic in character.

Another contrasting factor between lakes and reservoirs

is hydraulic residence time. Residence time is most commonly assessed on an annual time scale in limnological studies. Reservoirs generally have significantly lower hydraulic residence times than lakes, and residence time is often empirically related to lake or reservoir water quality (Reckhow and Chapra 1983). Reckhow (1988) investigated trophic state relationships among eighty lakes and reservoirs located within southeastern United States. For the seventy lakes he used in his analysis of phosphorus dynamics, he noted median, mean, minimum, and maximum residence times of 0.177, 0.393, 0.015, and 3.20 years respectively. Soballe and Kimmel (1987) categorized rapidly flushed lakes and impoundments as "transitional systems" with residence times within the 2-75 day range. Lakes and reservoirs with residence times greater than 120 days were termed "lacustrine systems." Marzolf (1984) compared the morphometric features of some glacial lakes in Michigan with some Kansas river reservoirs. He noted that the lakes had a mean residence time of 1622 days (range: 328-5694), whereas the reservoirs had a mean residence time of 427 days (range: 62-1095).

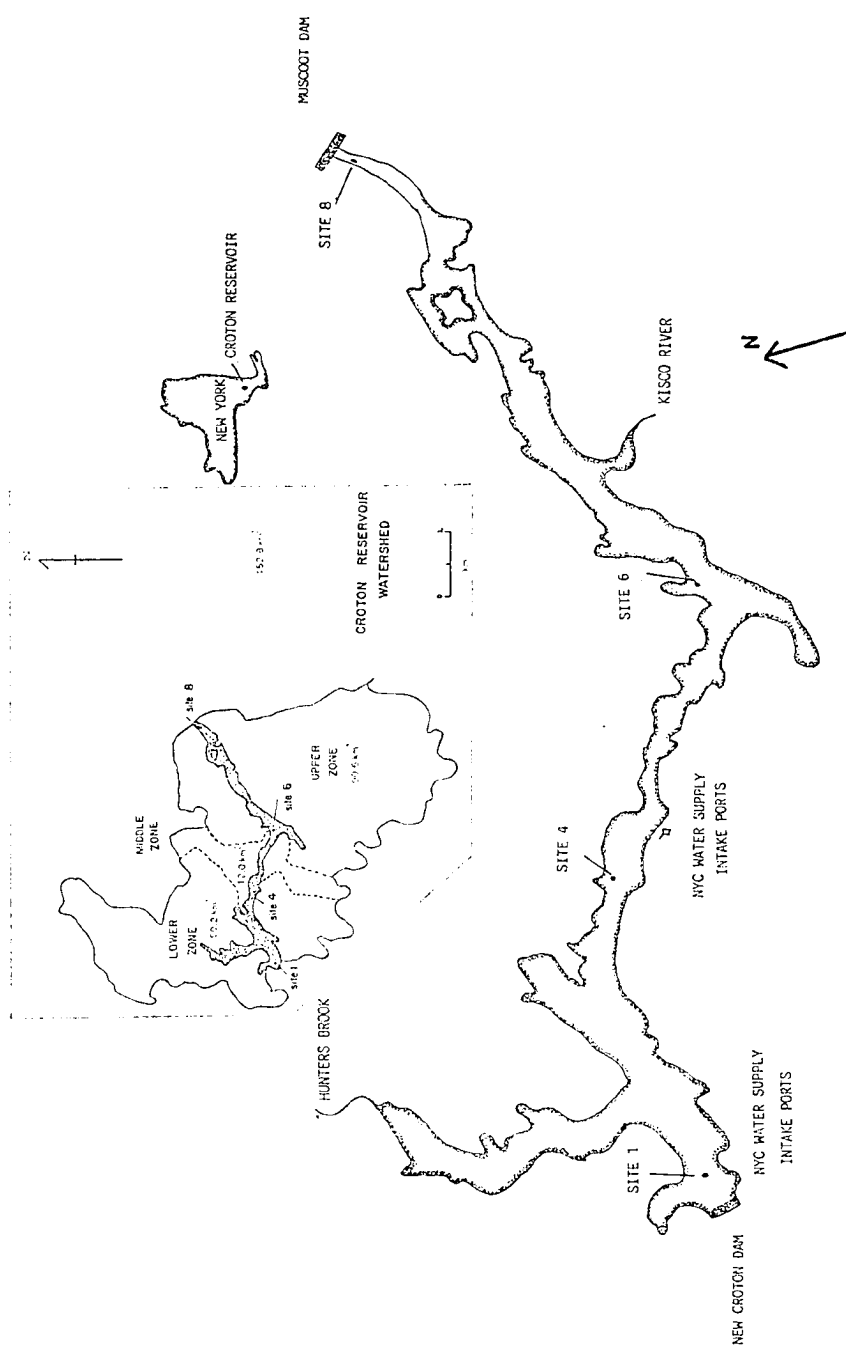
The purpose of this study was to: first, investigate the existence of longitudinal zonation within Croton Reservoir as described by the conceptual model proposed by Thornton et al. (1981); second, develop a water budget for Croton Reservoir over a group of highly variable hydrologic

years thus allowing for an assessment of the impacts of water supply uses upon the reservoir's hydrology; and third, investigate the relationship between Croton Reservoir's annual and summer hydraulic residence time (for the purpose of this study, summer will be defined as the period from July through October, since this is the period of most pronounced thermal stratification and phytoplankton accumulation in Croton Reservoir) and determine whether an assessment of residence time on shorter time scales was more meaningful biologically when studying the spatial and temporal variability of algal biomass within a rapidly flushed impoundment. The findings from this study were directly applicable to the management of Croton Reservoir as a drinking water supply, and provided a foundation for future investigations into the spatial heterogeneity and temporal variability of the physical, chemical, and biological factors operating within the impoundment.

STUDY AREA

Croton Reservoir (Figure 1-1) is the final receiving reservoir of the Croton River. The impoundment is located in southeastern New York ($41^{\circ} 13' 39''$ N, $73^{\circ} 51' 27''$ W), and lies 59.6 meters above mean sea level. The reservoir is

Figure 1-1. Map of Croton Reservoir and its immediate watershed area. Sample site locations, New York City's (NYC) water supply intake locations and zonal watershed boundaries are illustrated.



CROTON RESERVOIR

Scale 1 cm = 465 m

owned and operated by the City of New York, and supplies the City with approximately 10-15 % of its annual drinking water supply needs. Figure 1-2 depicts Croton Reservoir within the configuration of the New York City Water Supply System. The reservoir was formed after the Croton River, a tributary to the Hudson River, was impounded first in 1842 and then was latter expanded to its current size (surface area 9.13 km^2) with the construction of the New Croton Dam in 1905. The Croton Watershed covers a total area of 971.25 km^2 . The Croton Reservoir basin (drainage area 152.80 km^2) is one of the nine sub-basins which comprise the entire Croton River basin (Figure 1-3). There are twelve major impoundments within the Croton Watershed; the East, West, and Middle Branches of the Croton River are impounded, as well as the Muscoot, Titicus and Cross Rivers. The releases from all these impoundments flow into the Muscoot Reservoir where they are finally released to the Croton Reservoir by way of the Muscoot Gatehouse and spillway. Figure 1-4 depicts a schematic cross section of Croton Reservoir along its longitudinal axis. Water can be released downstream to the Croton River through a release structure at the dam or over the spillway when reservoir's capacity is exceeded. Diversion to the Croton Aqueduct (New York City's water supply) can be regulated through a number of intake ports located both at the dam and at the Croton Reservoir Gatehouse.

Figure 1-2. The New York City water supply system.

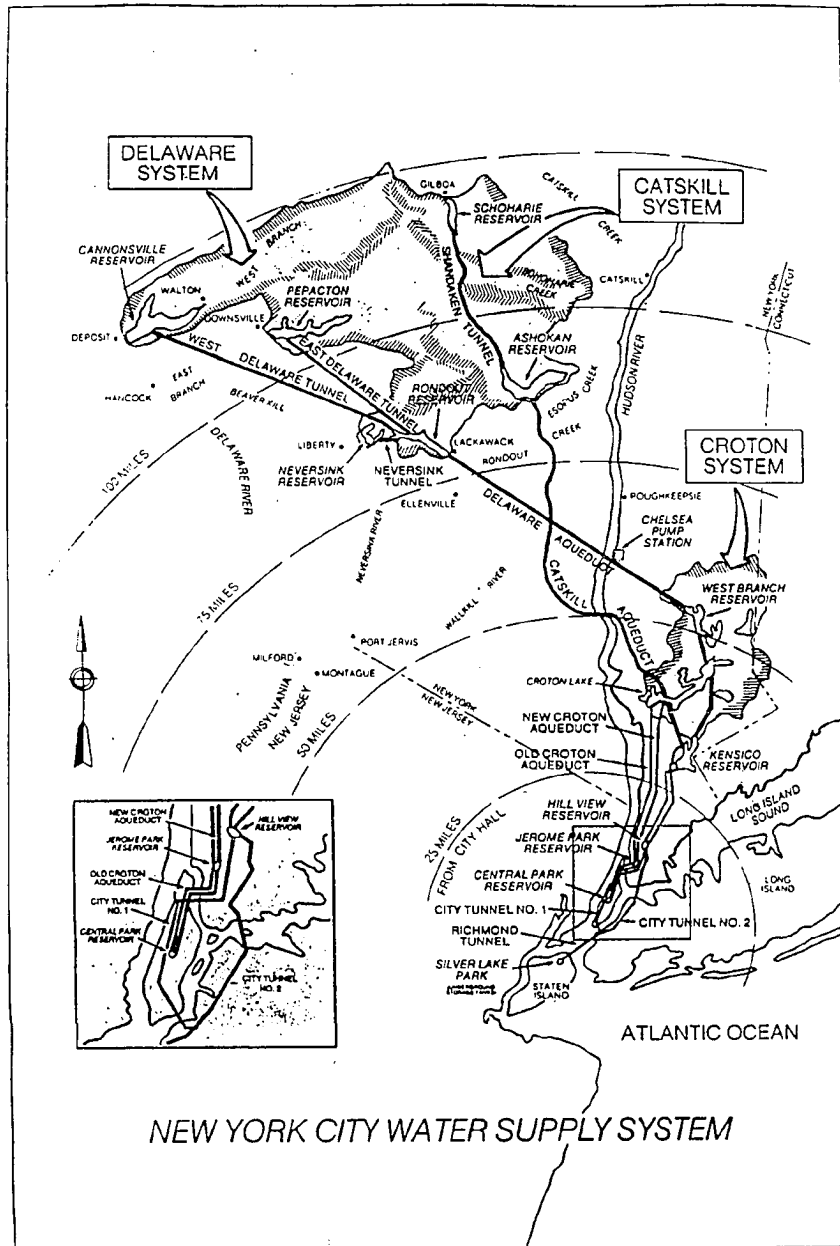
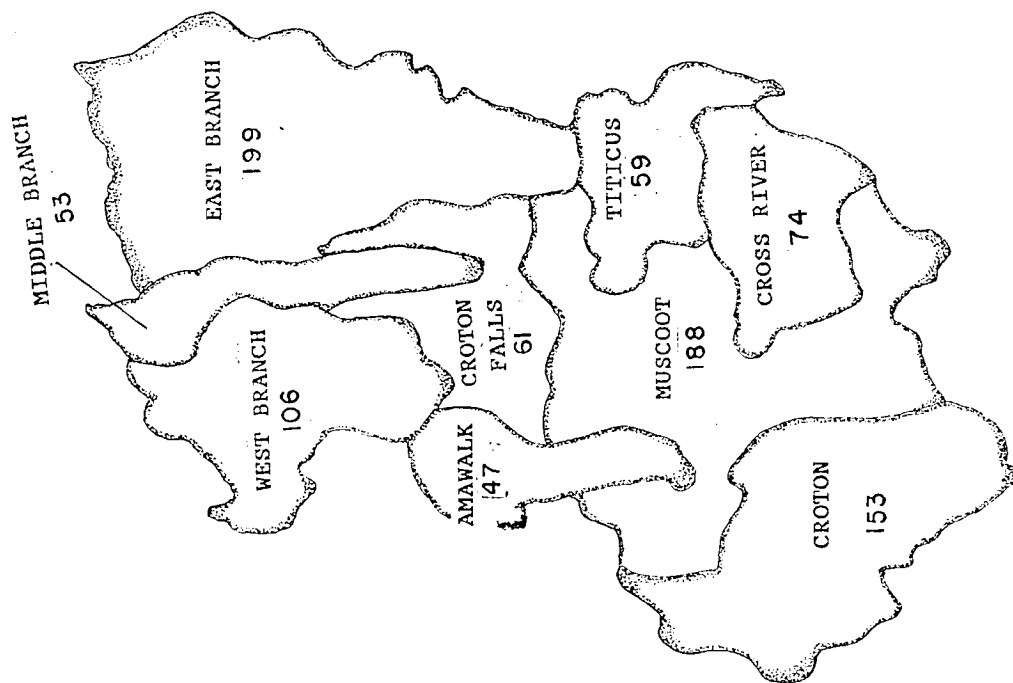


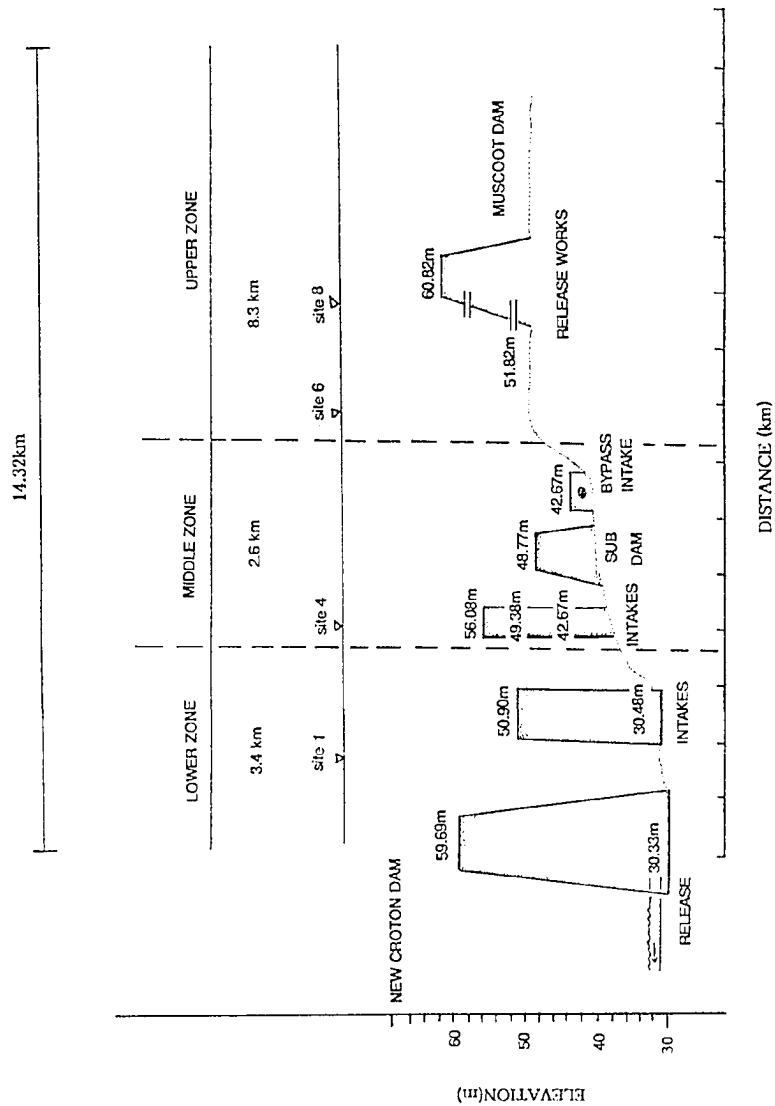
Figure 1-3. Sub-basin map of the Croton River Watershed.



CROTON WATERSHED
AREAS OF SUBDIVISIONS
 in square kilometers

Figure 1-4. Longitudinal cross section of Croton Reservoir. Mean elevation above sealevel (MSL) in meters, is noted for spillway crests of the Croton and Muscoot Dams, the Croton and Muscoot releaseworks, and the water supply intake ports. Sample site locations 1, 4, 6, and 8, reservoir zone demarcations, and reservoir zone length in kilometers are illustrated.

CROTON RESERVOIR
SCHEMATIC CROSS SECTION



Much of the reservoir's basin is underlain by metamorphic and igneous rock overlain by unconsolidated deposits of Pleistocene and Recent age. Formations present in the area consist of Fordham gneiss, Manhattan schist, Inwood marble, and the Cortlandt igneous complex. Soils in the area are mostly well drained alfisols derived from glacial till and are described as highly erodible. Most of the immediate watershed of Croton Reservoir is forested with slopes greater than 20% (SCS 1978).

Land use areas within the Croton Reservoir basin are broken down as follows: forested-10,697 hectares (70%), agriculture-1528 hectares (10%), and urban-3056 hectares (20%). As of 1980, approximately 200,000 people were estimated as living within the Croton Watershed. Most of the land use is termed "low density residential," particularly in the effective drainage area of the Croton Reservoir. Approximately 50,000 people are served by sewage treatment plants which discharge to Croton River tributaries. Upwards of 70,000 people use on-site subsurface disposal systems (Westchester Co. 1978).

Basin Morphometry and Reservoir Zonation

Morphometric parameters for Croton Reservoir are listed in Table 1. The reservoir has a surface area of 9.13×10^6 m², a volume of 90.77×10^6 m³, and a mean and maximum depth of 9.9 and 36.6 m, respectively. The effective drainage area

Table 1-1. Morphometric parameters for Croton Reservoir calculated for the entire reservoir and for each longitudinal zone: upper (U), middle (M), and lower (L), at full pool elevation.

Morphometric Parameter	Zone			
	Total	Lower	Middle	Upper
Drainage Area (A_d)* (10^6m^2)	152.80	50.20	12.00	90.60
Surface Area (A_o) (10^6m^2)	9.13	3.75	1.29	4.09
% Total A_o	100.00	41.00	14.30	44.80
$A_d:A_o$	16.70	13.40	9.20	22.10
Volume (V) (10^6m^3)	90.77	56.77	10.71	23.29
% Total V	100.00	62.50	11.80	25.70
Max. Depth (m)	36.60	36.60	30.50	15.30
Mean Depth (m)	9.90	15.20	8.30	5.70
Relative Depth (Z_r) (%)	1.07	1.67	2.38	0.67
Center of Gravity (m) (Z_g)	8.00	11.80	7.20	4.40
Epilimnetic Volume (10^6m^3) (depth < 7 m)	40.85	18.17	5.36	16.54

*Total drainage area of the Croton Watershed is $971.30 \times 10^6\text{m}^2$. Drainage area listed under the total column in this Table is for the Croton Reservoir sub-basin of the Croton Watershed.

of the impoundment is $152.80 \times 10^6 \text{ m}^2$, although the reservoir ultimately receives drainage from the entire Croton Watershed which has a total drainage area of $971.30 \times 10^6 \text{ m}^2$. The effective $A_d:A_o$ ratio for the reservoir is 16.70, whereas the Croton Watershed $A_d:A_o$ ratio for the reservoir is 106.40. Croton Reservoir has a dendritic shoreline development index of 4.9 which is typical of a flooded river valley caused by either natural or artificial damming (Hutchinson 1957).

The long (14.32 km), narrow basin of the reservoir progressively increases in depth from Muscoot Dam (10 m) to the Croton Dam (36.6 m) (Figure 1-4). Demarcation of the upper, middle, and lower longitudinal zones, is depicted in Figure 1-4, and each zone is morphometrically described in Table 1-1. Selection of the boundaries for each zone was based primarily upon drainage patterns, basin morphometry, and the potential for vertical mixing. The upper zone is long (8.3 km), narrow, and shallow (mean depth of 5.7 m and maximum depth of 15.3 m). It has the largest drainage area ($90.60 \times 10^6 \text{ m}^2$) and surface area ($4.09 \times 10^6 \text{ m}^2$) of the three zones. With the exception of the Hunter Brook, which is tributary to the lower zone, the upper zone receives all major tributary inputs to the reservoir. This is reflected in the upper zone's high $A_d:A_o$ ratio (22.10). The upper zone also has a low relative depth (0.67 %), and shallow center of gravity (4.4 m), which suggests that the potential for

vertical mixing is greater within this zone than in the middle or lower zones. The upper zone is separated from the middle zone by a constriction in the basin which occurs 8.3 km downstream of the Muscoot Dam. At this point, the reservoir is less than 185 m in width. The middle zone is the shortest in length (2.6 km), has the smallest surface area ($1.29 \times 10^6 \text{ m}^2$), drainage area ($12.00 \times 10^6 \text{ m}^2$), and volume ($10.71 \times 10^6 \text{ m}^3$) of the three zones. For most of its length, the middle zone remains as narrow as the upper zone, broadening to 0.50 km just prior to the lower zone boundary. However, the middle zone progressively deepens to a maximum depth of 30.6 m (mean depth of 8.30 m). The combination of wind protection from the steep slopes on both of its sides, minimal drainage input, and a relative depth value of 2.38%, suggests that the middle zone is less likely to experience the same degree of vertical mixing as the upper zone. The lower zone begins 11 km downstream from the Muscoot Dam. At this point the reservoir widens to 1.1 km and gradually reaches a maximum depth of 36.6 m. The lower zone comprises 62.5 % of the reservoir's total volume, and 41 % of the reservoir's total surface area. It has a smaller surface and drainage area than the upper zone and the greatest mean depth, and center of gravity of all zones.

METHODS

The hydrology of the Croton Reservoir Basin was studied for the five year period beginning January 1984 and ending December 1988. Daily data pertinent to precipitation at the study site, Muscoot and Croton Reservoir elevations, Croton Aqueduct diversions, and Croton Reservoir water volume fluctuations were obtained from the New York City Department of Environmental Protection (NYC-DEP), Bureau of Water Supply's Sources Division Office in Valhalla, N.Y. Water releases below the Croton Reservoir dam are regulated by the New York State Department of Environmental Conservation. During non-drought periods, these releases are fixed at $0.021 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ from July 1 to March 31, and $0.230 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ from April 1 to June 30. During drought periods no releases are made. Water releases from the Muscoot Reservoir Gatehouse are usually fixed at $0.378 \times 10^6 \text{ m}^3 \text{ d}^{-1}$, although this release may vary during drought conditions; total Muscoot releases are usually within the 0.0265 to $0.378 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ range (Muursepp, pers. comm.).

A bathymetric map of the Croton Reservoir, constructed by the International Map Co. (1980), was used to calculate morphometric parameters for the reservoir. The surface area of the reservoir (A_0) was derived from the bathymetric map by means of grid enumeration analysis (Olson 1960) following the procedure outlined by Wetzel and Likens (1979). Total

volume was then determined from the area beneath a hypsographic curve constructed from the area-depth (A_z) data. The reservoir was divided into three distinct zones, lower (L), middle (M), and upper (U), based upon the morphometry, drainage basin topography, and flow regime associated with each zone. The derivation of morphometric parameters for the entire reservoir and each longitudinal zone follow the notation and definitions of Hutchinson (1957).

Annual outflow from Croton Reservoir was calculated from available NYC-DEP hydrologic data, which consisted of measured values for Croton Reservoir spillage (calculated from reservoir elevation data; see below), releases, aqueduct diversions, and estimates of evaporation losses from the reservoir's surface (NOAA, USGS 1984-1988). These calculated outflow determinations were then checked for accuracy by comparing them to the estimated outflows values derived from Croton Reservoir inflow data using the water balance equation listed below:

$$\text{Inflow} \pm \text{Change in Storage} = \text{Outflow} \quad (1)$$

where inflow was defined as the sum of net atmospheric input (m^3), net runoff (m^3), and Muscoot Reservoir spillage (calculated from reservoir elevation data; see below) and releases to Croton Reservoir (m^3); and where the annual change in reservoir storage was determined by the difference between the reservoir volumes (in m^3) measured on January

1st and December 31th of each year.

A major component of the annual inflow to Croton Reservoir was the discharge over the Muscoot Reservoir spillway. Similarly, a major contributor to the annual Croton Reservoir outflow was the discharge over the Croton Reservoir spillway to the Croton River. Flows over both the Croton and Muscoot Reservoir spillways were calculated from the standard broadcrested weir equation:

$$D = c(L)(H)^{3/2} \quad (2)$$

where D is discharge in cubic feet per second, c is the height coefficient, L is the length of the weir in feet, and H is the height of the discharge over the weir in feet (measured by NYC-DEP) . This formula is generally used for a broadcrested weir with a 1.22 meter width. The "c" coefficient used in all discharge calculations was 2.64. This coefficient has been determined by New York City engineering staff to be the best estimator of discharge over the Croton and Muscoot Reservoir spillways under varying hydrologic conditions. All values produced by equation 2 were subsequently converted to cubic meters per day.

Runoff and precipitation inputs were calculated following a procedure outlined by Reckhow and Chapra (1983). Net runoff plus net precipitation input to the reservoir was calculated from the following equation:

$$Q = (A_d \times r) + (A_s \times Pr) \quad (3)$$

where Q is the total annual inflow volume (m^3), A_d is the

watershed area (m^2), r is the total annual unit runoff (m) excluding groundwater, A_s is the lake surface area (m^2), and P_r is the mean annual net precipitation (m). Total annual unit runoff and mean annual evaporation data were obtained from the NOAA and USGS 1984-1988 climatological and water resource data records for the Hudson Valley Region.

The total annual inflow volume from precipitation and runoff was computed for the entire Croton Reservoir Basin, and for each individual zone on an annual basis. Total water input to the reservoir was determined by the addition of the Muscoot release, total discharge over the Muscoot spillway, and the total annual inflow to the reservoir from precipitation and runoff. As previously mentioned, the total water output was determined by the addition of the Croton release, total discharge over the Croton spillway, the total diversion to the Croton Aqueduct, and reservoir surface evaporation losses. Ground water inflows and ground water outflows were not included in the water balance because of the total unavailability of data, and the difficulty in accurately determining these gains or losses through field measurements. Winter (1981) pointed out that the interaction of lakes and ground water is the most elusive hydrologic factor of all with respect to water balance studies of lakes. He noted that because ground water flow near lakes has been poorly understood, discussion of it in most lake water budgets is limited. In fact, in most cases ground

water is calculated as the budget residual or error. Accordingly, an output/input (O/I) ratio was developed to assess the accuracy of the Croton Reservoir annual water budget calculations, and to account for water balance discrepancies which may have been attributable to influences of ground water, and/or analytical error.

Data reduction of NYC-DEP weekly values over the 1984-1988 period for reservoir volume, Croton and Muscoot Reservoir spillway discharges, and the Croton Aqueduct Diversion were performed as follows: monthly means were computed from weekly values of reservoir volume, spills, and the diversion. These monthly values were then used to compute annual mean values for each of the variables.

Hydraulic residence time (T_w) was calculated after Reckhow and Chapra (1983) as follows:

$$T_w = \frac{\text{lake volume } (m^3)}{\text{annual output } (m^3 \text{ yr}^{-1})} \quad (4)$$

Residence times were calculated on an annual basis, a yearly summer seasonal basis (July through October) and on a monthly basis for the entire reservoir and for each individual longitudinal zone. Reservoir volumes and outputs were adjusted appropriately for differing time scales, i.e., monthly means of weekly values for reservoir volume and outflow were used to calculate monthly residence time; summer residence time was calculated by averaging the monthly reservoir volumes measured during July-October and

dividing that average by the total water outflow from the reservoir during that period; annual residence time was calculated by averaging the monthly reservoir volumes measured during January-December, and dividing that average by the total annual water outflow from the reservoir. All residence times are expressed in years. Flushing rate is defined as $1/T_w$ (Vollenweider 1975) and is expressed as the number of times the reservoir replaces its volume per year.

All statistical analyses were performed using the Statistical Analysis System (SAS Institute Inc., Version 6.03, 1988). Residence time values and monthly precipitation values were normally distributed when transformed to natural logarithms. Analysis of variance with the Tukey-Kramer multiple comparison method was used to test for significant differences (at $p < 0.05$ and $p < 0.10$) between hydraulic residence times which occurred within the reservoir during the five year study period.

RESULTS

Precipitation and Reservoir Volume

The climate of the Croton Watershed is generally a modified continental type characterized by mild winters, relatively cool summer temperatures, an abundance of precipitation well distributed throughout the year, and a mean annual temperature of 11°C. Table 1-2 lists the mean

monthly precipitation measured at Croton Reservoir for the period 1984-1988. Precipitation appears to be fairly well distributed throughout the year, with somewhat higher amounts occurring during the summer months and the month of November. Figure 1-5 depicts total monthly precipitation occurring during the five year study period. Annual precipitation recorded in the watershed during the 1984-1988 period ranged between 82.4 cm to 135.8 cm (Table 1-3). Long-term annual precipitation totals for this area range between 115 cm-130 cm with minimum and maximum values of 63.5 cm and 170 cm respectively (Westchester Co. 1978). These data indicate that both 1984 and 1985 were anomalous precipitation years. The two greatest monthly precipitation totals recorded over the five year period occurred in May (26.95 cm) and July (24.92 cm) of 1984 (Figure 1-5). The 1985 annual precipitation total of 82.4 cm, was the lowest annual total recorded during the study period, and 1985 was classified as a drought year by the New York City Bureau of Water Supply. Precipitation totals for 1986, 1987, and 1988 were normal to slightly below normal.

Reservoir volume fluctuations measured from January 1984 to December 1988 and illustrated in Figure 1-6. Summer to fall drawdown most noticeably occurred in 1984 and 1985. Drawdown was most pronounced during the fall of 1985, when the reservoir dropped 3.44 m below crest elevation on

Table 1-2. Mean monthly precipitation measured at Croton Reservoir for the period 1984 - 1988.

Month	Mean Precip. (centimeters)	Min.	Max.
January	4.97	2.29	8.26
February	8.81	6.25	11.02
March	5.60	1.27	10.72
April	9.46	0.58	18.46
May	10.73	1.55	26.95
June	7.09	1.19	9.55
July	14.86	6.25	24.92
August	9.94	3.28	16.33
September	8.02	2.51	13.66
October	7.28	3.73	12.98
November	13.27	7.04	21.59
December	5.39	3.28	10.01

Figure 1-5. Monthly precipitation (cm) recorded at Croton Reservoir from 1984 to 1988.

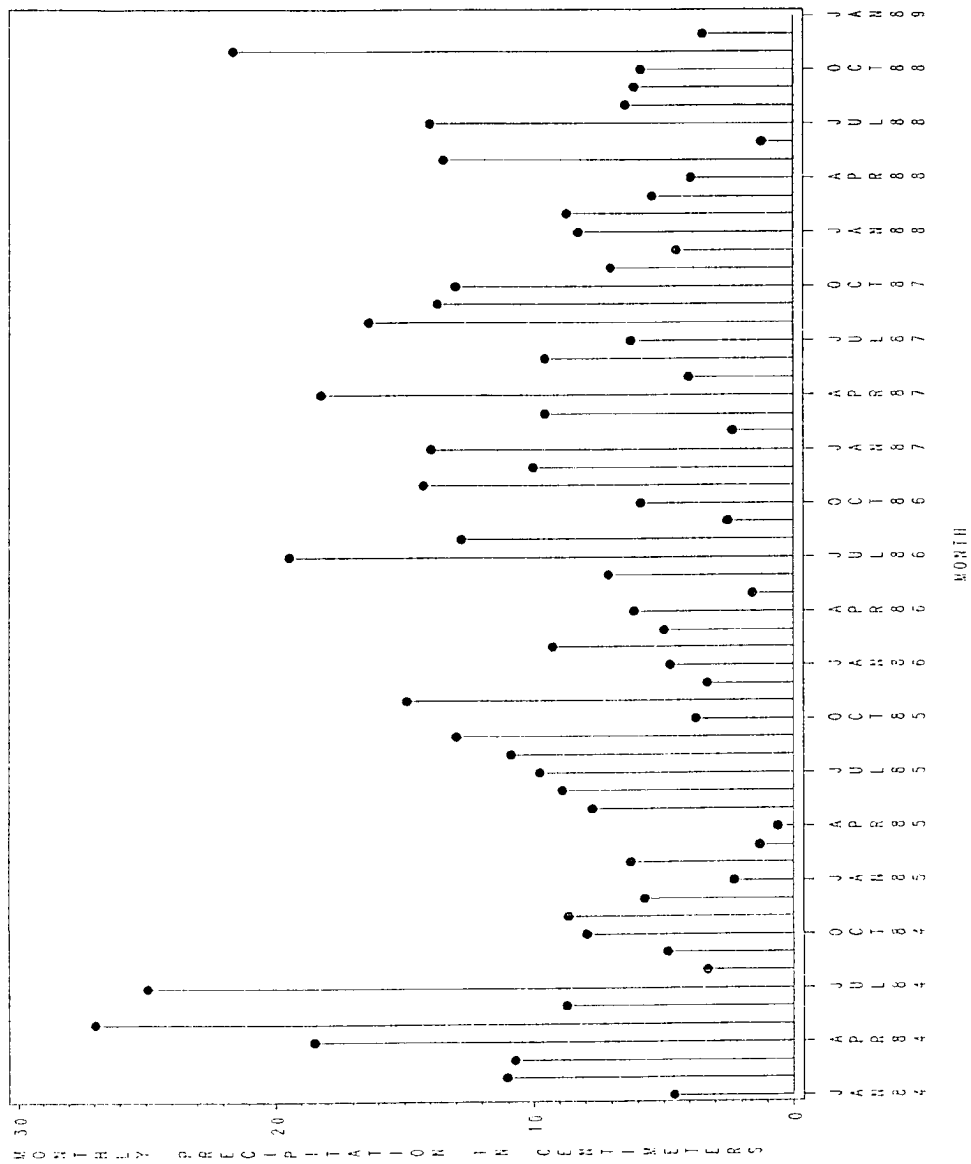
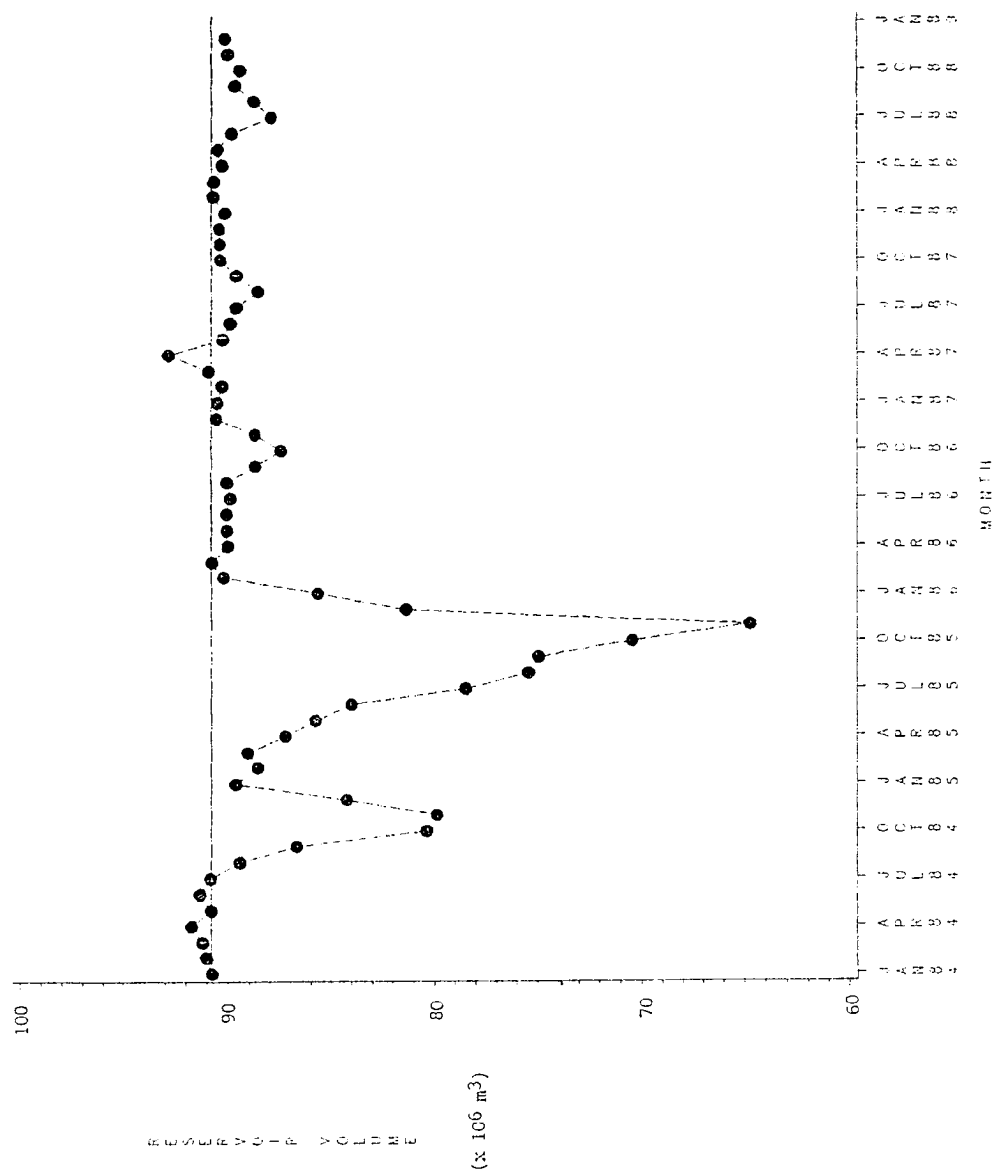


Table 1-3. Net A_o precipitation and net runoff for Croton Reservoir from 1984 to 1988 calculated* for the entire reservoir and for each longitudinal zone: upper (U), middle (M), and lower (L).

Year	Annual Precip. (cm)	Net Runoff + A_o Net Precipitation ($10^6 m^3$)			
		Zone			
		Total	Lower	Middle	Upper
1984	135.8	100.03	33.30	8.19	58.54
1985	82.4	54.94	17.76	5.27	31.91
1986	98.6	78.40	25.93	6.28	46.20
1987	118.3	83.04	27.57	6.75	48.72
1988	98.4	68.07	22.57	5.50	40.02

* Calculation of net A_o precipitation and runoff amounts for each drainage area were performed according to a procedure outlined by Reckhow and Chapra (1983). See text for details.

Figure 1-6. Reservoir volumes in cubic meters measured during the 1984 - 1988 study period. A reference line has been drawn at the reservoir's crest elevation.



November 12. Reservoir volume recorded on that date was $64.50 \times 10^6 \text{ m}^3$ (71% of crest volume). From 1986 through 1988 reservoir volumes were generally maintained near crest capacity year round with slight drops in volume usually occurring in late summer and early fall.

Water Budget and Hydraulic Residence Time

Table 1-4 lists the water budget by year for Croton Reservoir from 1984 to 1988. Tables 1-5 and 1-6 depict hydrologic features of the reservoir for the same period. With the exception of the drought year of 1985, and the recharge year of 1986, 58-77% of the reservoir's total output was discharge over the Croton spillway. Only 19-37% of the reservoir output could be attributed to the Croton Aqueduct diversion or "draft." The greatest amount of water ($876 \times 10^6 \text{ m}^3$) was output from the reservoir in 1984, which was also the year of highest precipitation, and shortest annual residence time (Table 1-6). The least amount of water ($362 \times 10^6 \text{ m}^3$) was output from the system during the drought year of 1985, accordingly, annual hydraulic residence time during this year was the longest of the five year study period. Table 1-4 illustrates that at least 80% or more of the total annual water input to the reservoir was from the combined discharge of the Muscoot spillway and release. Discharge over the Muscoot spillway alone accounted for 50-70% of the reservoir's total annual water input.

Table 1-4. Water budget for Croton Reservoir from 1984 to 1988 expressed in 10^6 m^3 and as percentages of total water output and input.

Year	Output (% of total output)					Input (% of total input)				
	Croton Total	Croton Spill	Croton Draft	Croton Release	Surface Evaporation	Total	Muscoot Spill	Muscoot Release	Runoff + Precipitation	
1984	883	624 (71)	219 (25)	33 (3)	7.1 (1)	863	625 (72)	138 (16)	100 (12)	
1985	369	0 (0)	362 (98)	0 (0)	6.6 (2)	381	217 (57)	110 (29)	55 (14)	
1986	424	189 (45)	202 (48)	26 (6)	6.9 (1)	459	285 (62)	96 (21)	78 (17)	
1987	593	448 (77)	112 (19)	26 (3)	7.2 (1)	572	351 (61)	138 (24)	83 (15)	
1988	479	271 (58)	175 (37)	26 (4)	6.6 (1)	463	257 (56)	138 (30)	68 (14)	

Table 1-5. Croton Reservoir hydrologic data for the period 1984 - 1988. ¹USGS; ²NYCDEP; ³NOAA .

Measure	Year				
	1984	1985	1986	1987	1988
Annual Runoff ¹ (m/yr)	0.62	0.35	0.50	0.52	0.43
Land Input (10 ⁶ m ³)	94.73	53.48	76.40	79.46	65.70
Gross Precipitation ² (m/yr)	1.36	0.82	0.98	1.18	0.98
Evaporation ³ (m/yr)	0.78	0.73	0.76	0.79	0.72
Net Precipitation (m/yr)	0.58	0.09	0.22	0.39	0.26
Net Atmosph. Input (10 ⁶ m ³)	5.30	0.45	2.00	3.58	2.37
Muscoot Spillage ² (10 ⁶ m ³)	625.00	217.00	285.00	351.00	257.00
Muscoot Release ² (10 ⁶ m ³)	138.00	110.00	96.00	138.00	138.00
Total Input (I) (10 ⁶ m ³)	863.03	380.93	459.40	572.04	463.07
Change in Storage ² (10 ⁶ m ³)	-6.56	-8.26	4.91	-0.08	0.02
Est. Output (E) (10 ⁶ m ³)	869.59	389.19	454.49	572.12	463.06
Calc. Output (O) ² (10 ⁶ m ³)	883.10	368.60	423.90	593.20	478.60
(E) - (O)	-13.51	20.59	30.59	-21.16	-15.54
(I) - (O)	-20.07	12.33	35.50	-21.16	-15.53
Percent Error (%) (I - O / O) x 100	2.30	3.30	8.40	3.60	3.20

Table 1-6. Hydrologic features of Croton Reservoir from 1984 to 1988.

Year	Annual Precip. (cm)	Mean Volume (10^6m^3)	Output (10^6m^3)	Input (10^6m^3)	O/I*	T_w^{**} (y)	Flush Rate (y^{-1})
1984	135.8	88.15	883	863	1.04	.10	9.9
1985	82.4	80.77	369	381	.92	.22	4.5
1986	98.6	89.30	424	459	.92	.21	4.7
1987	118.3	90.26	593	572	1.04	.15	6.5
1988	98.4	89.80	479	463	1.03	.19	5.3
5 Year Mean	106.7	87.66	550	550	1.00	.17	6.2

* O/I: Output:Input ratio- see text for explanation.

** T_w : Hydraulic residence time = $\frac{\text{lake volume (m}^3\text{)}}{\text{annual output (m}^3 \text{ y}^{-1}\text{)}}$

Precipitation and runoff from the reservoir's immediate drainage basin accounts for 12-17% of the total annual water input to the impoundment. Table 1-3 lists the net A_0 precipitation and net runoff contribution to the reservoir for the entire reservoir and for each longitudinal zone. As expected, the greatest runoff years were coincident with the years of greatest precipitation. The upper zone contributed the greatest amount of runoff, followed by the lower zone and the middle zone respectively. The output: input (O/I) ratio listed in Table 1-6 indicates the amount of water input not accounted for in the water output determinations, or vice versa. Theoretically, the O/I ratio should be equal to 1 if the water budget is balanced. For the five year study period, O/I values ranged from 0.92 to 1.04 with a mean of 0.99. The lowest O/I values were measured during the two most hydrologically variable years of the 1984-1988 period, those years being 1985 and 1986. Table 1-5 illustrates that approximately 2.3%-8.4% (mean of 4.2%) of the total annual water input was not accounted for in the calculated water budget output over the five year study period. Table 1-5 also demonstrates that *estimated* water output and *calculated* water output compare favorably, i.e., approximately 1.5%-7.2% (mean of 4.2%) of the *calculated* water output was not accounted for in the *estimated* water output over the five year study period. Output losses or gains, may be attributed to unaccounted for ground water

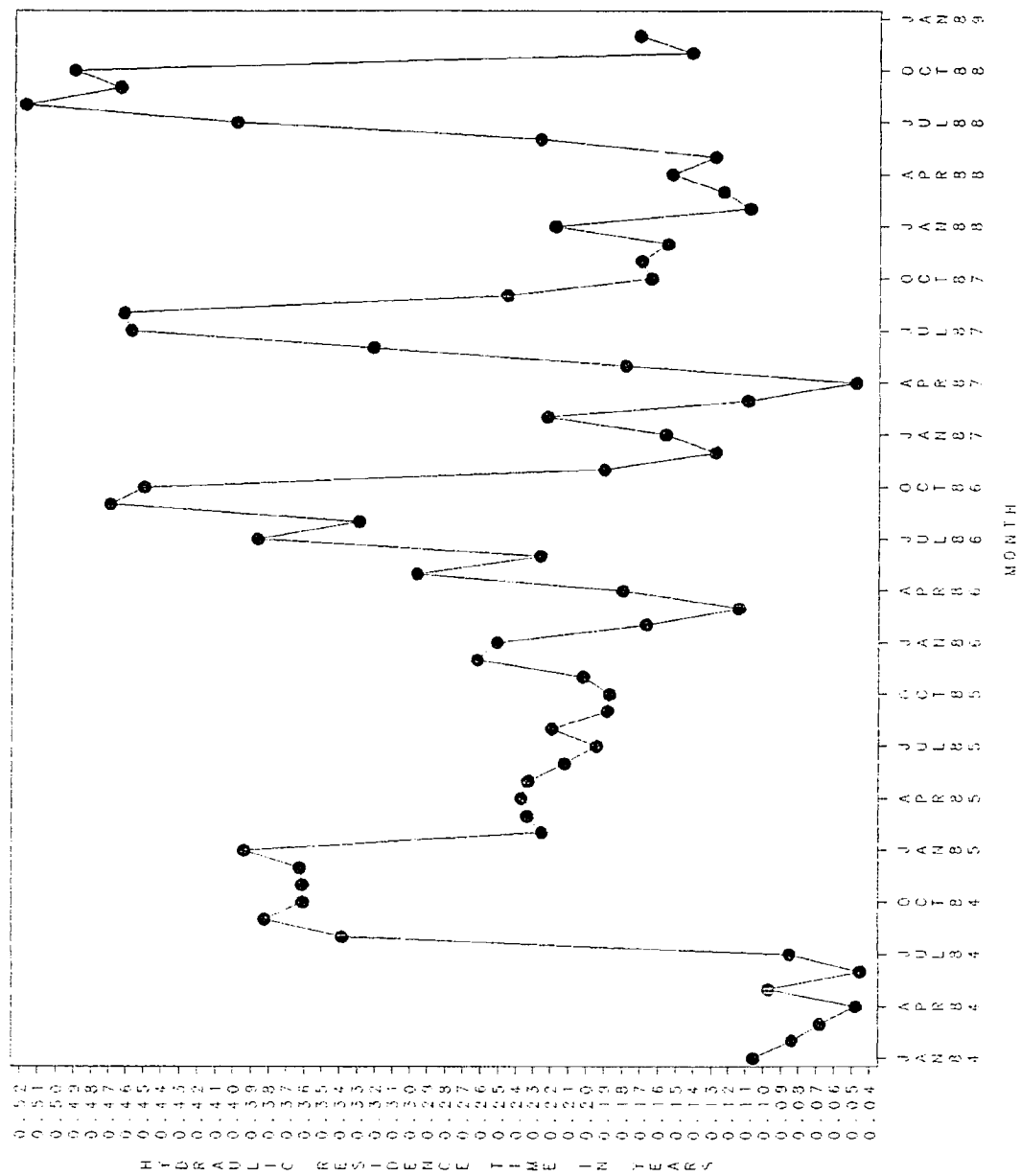
inflow or seepage losses, and/or errors in measurements, assumptions, or calculations.

Annual hydraulic residence time measured for each of the five years during the study period ranged between 0.10-0.22 years with a five year mean of 0.17 years. Residence time was longest in 1985 and shortest in 1984 (Table 1-6). These data suggest that the entire Croton Reservoir is a rapidly flushed "transitional" system (Soballe and Kimmel 1987). The reservoir completely flushes between 4.5 to 10 times a year (mean flushing rate of 6.2). Table 1-7 lists both annual and summer residence times for the entire reservoir and each of the longitudinal zones for the 1984 to 1988 period. In comparing annual residence time calculations to summer season residence time calculations it can be seen that with the exception of 1985, summer residence times are generally greater than annual residence times by a factor of 2.1. When viewing the zonal residence times it can be seen that most of the water resides longer in the lower zone than in the upper and middle zones throughout the annual and summer season periods. The middle zone displays the shortest residence times of the three zones. Figure 1-7 depicts monthly residence times measured for Croton Reservoir from January 1984 through December 1988. The correlation between monthly residence time and monthly precipitation analyzed on an annual basis was significant, but weak ($r=-0.32$, $p<0.01$). However, monthly residence time and monthly

Table 1-7. Hydraulic residence times (T_w) for Croton Reservoir for the years 1984 through 1988, calculated for the entire reservoir and each longitudinal zone on both an annual and on a summer basis. Summer is defined as the 120 day period beginning July 1 and ending October 31.

Year	Mean Volume (10 ⁶ m ³)	Output (10 ⁶ m ³)	Zone Residence Time (yr)			
			<i>T_w</i>	<i>Lower</i>	<i>Middle</i>	<i>Upper</i>
<i>Annual</i>						
1984	88.15	883	0.10	0.06	0.01	0.03
1985	80.77	369	0.22	0.14	0.03	0.06
1986	89.30	424	0.21	0.13	0.03	0.05
1987	90.26	593	0.15	0.10	0.02	0.04
1988	89.80	479	0.19	0.12	0.02	0.05
<i>Summer</i>						
1984	86.78	148	0.20	0.12	0.02	0.05
1985	74.80	127	0.20	0.12	0.02	0.05
1986	88.98	74	0.40	0.25	0.05	0.10
1987	89.49	108	0.28	0.17	0.03	0.07
1988	88.90	64	0.46	0.29	0.05	0.12

Figure 1-7. Monthly hydraulic residence times (measured in years) observed during the 1984-1988 study period.



precipitation were not correlated during the summer season. No significant difference between each of the study years was detected when a yearly comparison of monthly residence times on an annual basis was undertaken for the 1984-1988 period ($n=60$, $F=1.58$, $p<0.19$). However, a significant difference between the study years was detected when a yearly comparison of the monthly residence times measured during the summer was performed ($n=20$, $F=2.98$, $p<0.05$). A comparison of the yearly growing season monthly residence time means revealed that 1988 had a longer residence time than 1985 at the $p<0.10$ significance level. No significant differences between any of the other yearly summer season monthly residence times means were detected at the $p<0.10$ significance level. Spatially, monthly residence times, when analyzed on both an annual and a summer season basis, were significantly different among each of the longitudinal zones ($p<0.05$). The lower zone exhibited a residence time greater than the upper zone, which in turn, exhibited a residence time greater than the middle zone.

DISCUSSION

Croton Reservoir does not entirely conform to the conceptual reservoir model proposed by Thornton et al. (1981). The most significant deviation from the model was the lack of a clearly defined transitional zone along Croton Reservoir's longitudinal axis. The impoundment's configuration is similar to the model in that it receives a large percentage (80%) of its total hydraulic input from a single tributary located a considerable distance (14 km) from the dam. However, in the case of Croton Reservoir, this input must first flow through the Muscoot releaseworks, or over the Muscoot spillway before discharging into the impoundment. The relatively high flow, elevated suspended solids and organic matter input, and advective nutrient supply normally characteristic of a large, unencumbered tributary input, are most likely abated or mediated by the flow regulation associated with the Muscoot releaseworks. As a result, one would expect the upper zone of the Croton Reservoir to exhibit less pronounced riverine characteristics than the model's prediction.

In theory, the upper, middle, and lower zones depicted for Croton Reservoir, should correspond to the model's riverine, transitional, and lacustrine zones respectively. Although, from both the hydraulic and morphometric perspectives, the upper zone does represent the riverine

zone and the lower zone does represent the lacustrine zone, the middle zone does not completely conform to the model parameters which define the transitional zone. In particular, the reservoir's middle zone is narrower and has a much shorter residence time than the conceptual transitional zone. However, the middle zone does exhibit the transitional characteristics of being less prone to vertical mixing than the riverine zone because of its greater relative depth (Table 1-1), and of having a location downstream of the Muscoot Dam, intermediate between the upper and lower zones. It is often difficult to clearly define the extent and spatial variability of the transitional zone within reservoir ecosystems. Kennedy (1984) pointed out that although the model provides a useful classification of distinct water quality conditions within reservoirs, the zonal boundaries are often difficult to delineate. Thus, these longitudinal patterns should be viewed as a continuum. It is likely that the transitional zone may move upstream or downstream, on a seasonal basis.

With the exception of the drought year of 1985, and the recharge year of 1986, the Croton Aqueduct diversion (draft) was less of a contributor to the reservoir's total annual water output (19-37%) than discharge over the Croton spillway (58-77%). In addition, residence time was negatively correlated with precipitation on an annual basis, suggesting that the reservoir had some response, e.g.

spillage, to precipitation events when studied annually. However, precipitation was not correlated with residence during the summer season, thus indicating that the Croton draft was an important determinant of total water output and residence time during that period. Although the Croton draft only accounts for 19-37% of the reservoir's total annual water output, it does account for 50-85% of the total summer water output. In non-drought years, water output generally, accounts for 13-18% of the total annual water output (Table 6). During the drought year of 1985, summer water output accounted for 34% of the total annual water output. These data suggest that it is important to view water budget information seasonally as opposed to annually. Precipitation and discharge over the spillway appear to be the most important factors contributing to the reservoir's water budget on an annual basis. However, during the summer season, which is a much more important period biologically, particularly in terms of the accumulation of phytoplankton biomass, the Croton draft, in most cases, was the single output component involved in water budget and residence time calculations.

Since residence time is directly related to water output, it is also important to study residence time from a seasonal as well as from an annual perspective. Summer residence time may play a significant role in determining algal abundance. It is generally agreed that increased water

residence time leads to higher levels of phytoplankton biomass in lakes and reservoirs that are not nutrient limited (Fogg 1965, Dickman 1969, Gloss et al. 1980, Kimmel and Groeger 1984, Pridmore and McBride 1984, Soballe and Thelkeld 1985, Kimmel et al., 1990). In most cases, algal abundance in lakes and reservoirs tends to be lower in systems with short residence times (Soballe and Kimmel 1987, Taylor 1971, Morris and Lewis 1988). Residence time can also play a role in determining the floristic composition of the phytoplankton assemblage within a water body. Rechkow (1988) noted in his study of eighty southeastern U.S. lakes and reservoirs that lakes dominated by cyanobacteria were generally flushed more slowly. Croton Reservoir behaved as a rapidly flushed "transitional system" during the 1984-1988 study period based upon a review of annual residence times. However, the two 1986 and 1988 summer season residence times would characterize Croton Reservoir as a "lacustrine system," with a residence time greater than 120 days (0.33 years) (Soballe and Kimmel 1987). In general, Croton Reservoir summer residence times were greater than annual residence times by a factor of 2.1. In addition, the calculated hydraulic residence time for the reservoir during the summer period were most likely shorter than the actual residence time of the water within the reservoir's photic zone due to the effects of thermal stratification, hypolimnetic releases, and density flows (Wood 1981, Kimmel

and Groeger 1984). The use of summer season residence times, or residence times of smaller time scales than that of annual duration may be more appropriate for ecological assessments of rapidly flushed systems such as Croton Reservoir. For example, 1985 exhibited the longest annual residence time, but also exhibited one of the shortest summer residence times of the five year study period (Table 1-6 and 1-7). Thus, it may be misleading or ineffectual to assess hydraulic residence time effects upon a reservoir's ecological structure and function based solely on annual residence time values. This may even be more inappropriate for rapidly flushed impoundments which experience drawdown and reduced water output during the summer months. Within the Croton Reservoir, the draft is the major determinant of residence time during the summer. The combination of drawdown, or decreased reservoir volume, and increased diversions to the Croton Aqueduct both act to decrease summer residence time. In contrast, if the reservoir is maintained at crest elevation during the summer season, and the aqueduct diversion is decreased, hydraulic residence time will increase. This situation may lead to increases in algal biomass, thus further substantiating decreased diversions to the aqueduct because of poorer water quality. From a water quality management standpoint, it may be beneficial to optimize reservoir volume levels and aqueduct diversions to achieve a summer residence time which stays

below the threshold level beyond which phytoplankton abundance elevates drastically.

For cross sectional analysis of lakes and reservoirs, annual residence time calculations are useful in that they allow for comparisons among lakes and reservoirs that exhibit different physical, chemical, and biological characteristics. However, analysis of residence time on shorter time scales, i.e., seasonal, is essential to time series or systematic longitudinal studies, and could prove to be useful in the management of water quality within rapidly flushed impoundments such as Croton Reservoir.

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CHAPTER 2

The Physical and Chemical Characteristics of Croton Reservoir, New York

ABSTRACT

The spatial and temporal variability of physical and chemical factors was studied in Croton Reservoir, New York, initially from 1984-1987, and more intensively during 1988. The reservoir exhibited a longitudinal gradient for a number of key physical and chemical variables during both study periods. This gradient was consistent with those described by current reservoir zonation models which depict high flow or rapidly flushed impoundments with a large, less pronounced riverine zone and a limited transitional zone. The upper zone of the reservoir exhibited a greater frequency of mixing, higher nutrient concentrations, and lower transparency and light penetration measurements than the reservoir's lower zone. Seasonally, the upper zone had higher total phosphorus (TP) concentrations in the fall, while the lower zone exhibited higher TP concentrations in the spring and greater Secchi disc transparency in the fall. Dissolved inorganic nitrogen (DIN):TP ratios were highest in the spring, and lowest in the summer when DIN became depleted. TP, free carbon dioxide, and reactive silica were always present above detection levels. Overall, the spatial and temporal physical and chemical patterns observed during 1984-1987 were confirmed in 1988, however gradients detected during the 1988 sampling period were more pronounced than those encountered during 1984-1987, particularly for TP, and

Secchi disc measurements. The longer 1988 summer hydraulic residence time and the heavier than normal November 1988 precipitation were most likely responsible for these pronounced gradients. Results from the multiple depth epilimnetic sampling, performed biweekly in 1988, suggested that there were no significant differences with depth for TP, DIN, $\text{NO}_2+\text{NO}_3\text{-N}$, $\text{NH}_3\text{-N}$, total nitrogen, alkalinity, and dissolved oxygen for depths above nine meters. A comparison of the 1988 monthly to biweekly sampling frequencies revealed that monthly sampling intervals were inadequate for detecting seasonal patterns of physical and chemical factors when such patterns were being analyzed on an annual basis. In addition, it was also determined that the four sampling sites used in the study were the minimum number of stations necessary to adequately assess the spatial and temporal heterogeneity of the physical and chemical factors that occurred along the longitudinal axis of Croton Reservoir.

INTRODUCTION

Numerous studies have noted that reservoirs tend to occupy an intermediate position between rivers and lakes, and are often described as "river-lake hybrids" (Lind 1971; Henderson et al. 1973; Ryder et al. 1974; Margalef 1975; Ryder 1978; Goldman and Kimmel 1978; Thornton et al. 1981; Jenkins 1982; Benson 1982). As a result, impounded rivers often exhibit longitudinal gradients of both biotic and abiotic factors. Thornton et al. (1981) developed a conceptual model of reservoirs which described the spatial heterogeneity of the physical, chemical, and biological conditions found within impoundments, and proposed that reservoirs consist of three longitudinal zones, i.e., riverine, transitional, and lacustrine. The riverine zone is narrow, has a channelized basin, high flow, high turbidity, low light availability, light-limited primary production, and is more eutrophic in character. The transitional zone is a broader deeper basin with reduced flow, less turbidity, a reduced nutrient supply, and exhibits mesotrophic characteristics. The lacustrine zone is broad and deep, has little flow, nutrient limited primary production, greater light penetration, and is more oligotrophic in character.

Kennedy and Walker (1990) indicated that the boundaries between the riverine, transitional, and lacustrine zones are often difficult to delineate and

temporally unstable. They also noted that an advective flow regime in combination with a long, narrow basin morphology often results in the spatial variability of nutrient related processes and the establishment of gradients from headwater to dam. Broad-based assessments of the eutrophication process have revealed that nitrogen and phosphorus can alternate seasonally as the limiting nutrient and this can change spatially along the length of long morphometrically complex lakes where mixing is incomplete and the inflow concentrations differ greatly from the average lake concentrations (OECD 1982). Thornton et al. (1982) noted in their longitudinal study of DeGray Lake that mean epilimnetic total phosphorus concentrations for head water transects ranged from 30 to 40 $\mu\text{g P L}^{-1}$ during all sampling months, decreased approximately 10 $\mu\text{g P L}^{-1}$ by mid-reservoir, and then remained unchanged between the mid-reservoir locations and the dam. Pickett and Harvey (1988) observed in their study of Lake Moultrie, that annual average concentrations of total phosphorus, nitrate plus nitrite nitrogen, and dissolved orthophosphorus generally decreased with distance downstream. They also noted that in-lake nutrient concentrations reflected inflow variations (low flow from May through October) and nutrient loading rates. Increases in total nutrient levels occurred in the winter and early spring, and were associated with high streamflows and surface runoff. In summer and fall, total

nutrient levels were lower concurrent with decreasing streamflow. Elser and Kimmel (1985) studied the availability of nutrients for phytoplankton production within a multiple-impoundment series. They noted that late in the growing season, alkaline phosphatase activity (APA) increased downstream within each reservoir, reflecting uptake-to-downlake decreases in phosphorus availability. Brown et al. (1986) found that concentrations of all forms of phosphorus generally declined in the two downstream sampling stations of Cannonsville Reservoir following thermal stratification during spring. Increases in phosphorus concentrations followed the onset of isothermal conditions in early autumn at these two downstream stations. Upstream stations consistently exhibited higher phosphorus concentrations than downstream stations. They found that the reservoir developed a spatial gradient in total phosphorus concentration during the summer months. The highest phosphorus concentrations observed occurred within the upper reaches of the reservoir. Phosphorus concentrations decreased along the longitudinal gradient toward the dam. As observed with phosphorus, dissolved inorganic nitrogen levels generally decreased through the spring and summer period at all stations, and then increased in autumn. There was no evidence of a dissolved inorganic nitrogen gradient through the reservoir.

The hydrodynamics involved in the settling process of the suspended materials in reservoirs or lakes often results

in the production of longitudinal gradients in turbidity and available light (Brown 1984; Groeger and Kimmel 1984).

Kimmel and Lind (1972) noted significant spatial variability in light penetration within the water column of a southern U.S. eutrophic reservoir. They found that light penetration was limited throughout the reservoir by turbidity. Silt from turbidity inflow, suspended particulate matter, and large phytoplankton standing crops restricted trophogenic zone thickness. The photic depth was consistently greater at the downstream dam sampling location than in the tributary arms, which were similar. Thornton et al. (1982) observed that mean epilimnetic turbidity levels in DeGray Lake were lowest during July, and exhibited longitudinal changes from the inflow sampling sites to the dam. The variance in turbidity was greatest at the upstream sites on all sampling dates, and lowest near the dam. Pickett and Harvey (1988) noted that Secchi transparencies increased progressively toward the dam of Lake Marion. However, a high degree of variability occurred in Lake Marion's upper reaches. Low transparencies existed in the sediment-laden river, while fairly high transparencies, subsequent to increases in sedimentation, were found in the adjacent floodplain. Highest transparencies recorded were in the downstream third of the lake.

The purpose of this study was to investigate the existence of a longitudinal gradient of key physical and

chemical variables from headwater to dam within Croton Reservoir, and to determine whether the reservoir conformed to the conceptual reservoir longitudinal zonation models proposed by Thornton et al. (1981), and Kimmel and Groeger (1984). Preliminary patterns of spatial heterogeneity and temporal variability of the abiotic factors present within the reservoir were first studied from 1984 to 1987, and further evaluated during 1988. The findings from this study were directly applicable to the management of Croton Reservoir as a drinking water supply, and provided a foundation for the future study of the spatial and temporal patterns of phytoplankton abundance and floristic composition which typically occur within the impoundment.

STUDY AREA

Croton Reservoir is the final receiving reservoir of the Croton River. The impoundment is located in southeastern New York State ($41^{\circ}13'39''$ N, $73^{\circ}51'27''$ W), and lies 59.6 meters above mean sea level. The reservoir has a surface area of $9.13 \times 10^6 \text{ m}^2$, a volume of $90.77 \times 10^6 \text{ m}^3$, and a mean and maximum depth of 9.9 and 36.6 m, respectively. The effective drainage area of the impoundment is $152.80 \times 10^6 \text{ m}^2$, although the reservoir ultimately receives drainage from the entire Croton watershed which has a total drainage area of $971.30 \times 10^6 \text{ m}^2$. The effective $A_d:A_o$ ratio for the

reservoir is 16.70, whereas the Croton Watershed $A_d:A_o$ ratio for the reservoir is 106.40. Croton Reservoir has a dendritic shoreline development index of 4.9 which is typical of a flooded river valley caused by either natural or artificial damming (Hutchinson 1957). The reservoir is owned and operated by the City of New York, and supplies the City with approximately 10-15% of its annual drinking water supply needs. A more detailed description of the study area is contained within Chapter 1.

METHODS AND MATERIALS

Water samples were collected and analyzed for key chemical and physical variables, and field surveys were performed monthly during the ice-free season (March-December) from 1984 through 1987 at four sites located along the longitudinal axis of Croton Reservoir from the headwaters to the dam. These four sites were chosen because they were thought to represent zones of differing flow regimes in the impoundment, i.e., riverine, transitional, and lacustrine. Sites 1, 4, 6, and 8 were located 0.23, 3.95, 6.50, and 12.00 kilometers from the dam respectively. The sampling design and analytical matrix of this study were based upon a eutrophication assessment program developed by the Organization for Economic Cooperation (OECD 1982). This program was designed to quantify the relationship between

nutrient load in waters and their trophic reaction.

In addition to the monthly surveys performed during 1984-1987 and continued in 1988, more intensive biweekly sampling was carried out in 1988. These biweekly surveys consisted of multiple depth sampling (1, 3, 5, 7, and 9 meter intervals) at each of the four sampling locations. Results obtained from the 1988 monthly and biweekly surveys allowed for both a further refinement and evaluation of the monthly testing performed during 1984-1987, and a confirmation of the spatial and temporal patterns observed during that same period. Table 2-1 lists the dates sampling was performed during the five year study period.

For each of the monthly surveys, epilimnetic water samples, as determined by prior *in situ* measurements of the thermocline and photic zone depths, were collected from each of the sites with a 2.2 liter acrylic Van Dorn sampler at each site and brought back to the laboratory for analysis. For each of the 1988 biweekly surveys, water samples were collected with a Van Dorn sampler at the multiple epilimnetic depths described above, and brought back to the laboratory for analysis as well. Vertical profiles of temperature, pH, and dissolved oxygen were measured *in situ* using a Hydrolab Surveyor II (Hydrolab Corp., Austin, Texas). Measurements of light penetration were made using a Kahlisco Model 268WA310 underwater irradiator. Transparency was measured using a 20 cm Secchi disc.

Table 2-1. Sampling dates, both monthly and biweekly, during the the five year study period.

<u>Monthly Surveys 1984-1988</u>					
Year	1984	1985	1986	1987	1988
Date	April 25	April 24	March 26	March 30	March 28
	May 24	May 20	April 21	April 23	April 25
	June 20	June 13	May 19	June 01	May 23
	July 19	July 09	June 16	June 23	June 28
	August 09	August 20	July 22	July 27	July 27
	September 11	September 19	August 18	August 15	August 25
	October 03	October 16	September 15	September 28	September 26
	October 31	November 13	October 21	October 27	October 17
	November 27		November 20	November 30	November 03
			December 10	December 21	December 07
<u>Biweekly Surveys</u>					
Year	1988				
Date	March 28				
	April 10				
	April 25				
	May 05				
	May 23				
	June 09				
	June 23				
	July 19				
	July 27				
	August 10				
	August 25				
	September 06				
	September 26				
	October 17				
	November 03				
	November 15				
	December 07				

Water for soluble reactive phosphorus (SRP) was filtered through Gelman type A\E glass fiber filters prior to analysis.

Total phosphorus (TP) concentrations were determined by the automated ascorbic acid-molybdate method (Standard Methods 1988, 1985, 1989). Total phosphorus aliquots were digested with persulfate prior to analysis. Soluble reactive phosphorus concentrations were determined by the ascorbic acid - molybdate methods using a Perkin-Elmer Lambda 3b dual beam spectrophotometer (Parsons et al. 1984). Nitrite plus nitrate nitrogen ($\text{NO}_2 + \text{NO}_3\text{-N}$) concentrations were determined by the automated cadmium reduction method (Standard Methods 1981, 1985, 1989). Ammonia nitrogen ($\text{NH}_3\text{-N}$) concentrations were determined by the automated alkaline phenol-hypochlorite method (Standard Methods 1981, 1985, 1989). Total nitrogen (TN) concentrations were determined using persulfate-sodium hydroxide oxidation for digestion to nitrate, followed by cadmium reduction (Valderrama 1981). Dissolved inorganic nitrogen (DIN) was determined by summing nitrite plus nitrate nitrogen and ammonia nitrogen. DIN:TP ratios were calculated on a weight by weight basis. Reactive silica concentrations were estimated by the molybdate-metol/oxalic acid method (Parsons et al. 1984). Alkalinity was determined by automated potentiometric titration utilizing two pH endpoints, 4.5 and 4.2 (Standard Methods 1981, 1985, 1989). Free carbon dioxide (CO_2) was determined

by calculation using pH and alkalinity measurements as per the method described by Cole (1979). Free carbon dioxide values were corrected for the ionic strength of the water (activity coefficient), and temperature. Turbidity of the water samples was measured with a Turner Model 40 nephelometer (Standard Methods 1981, 1985, 1989). Color was determined by the visual comparison method using platinum cobalt standards (Standard Methods 1981, 1985, 1989). Detection limits for the analyses listed above were as follows: total phosphorus 5.0 ug/L; soluble reactive phosphorus 1.0 ug/L; nitrite plus nitrate nitrogen 0.005 mg/L; ammonia nitrogen 0.005 mg/L; total nitrogen 0.005 mg/L; reactive silica 0.20 mg/L; alkalinity 1.0 mg CaCO₃/L; turbidity 1.0 nephelometric turbidity unit (ntu); and color 5 platinum-cobalt units. Concentrations measured at values below the minimum detection limit (MDL), were set to the MDL value to allow for statistical analysis.

All statistical analyses were performed using the Statistical Analysis System (SAS Institute Inc., Version 6.03, 1988). All variables subjected to parametric statistical analysis were examined for normal distributions. TP, SRP, NO₂+NO₃-N, NH₃-N, CO₂, DIN, DIN:TP, and TN were normally distributed when transformed to natural logarithms. Analysis of variance with the Tukey-Kramer multiple comparison method was used to test for significant differences ($p < 0.05$, unless noted otherwise) between spatial

and temporal physical-chemical patterns observed in the reservoir during the five year study period.

RESULTS

Spatial Patterns

Chemical Variables

Monthly Surveys

No significant differences for pH, alkalinity, CO₂, and dissolved oxygen were detected in site by site comparisons for the 1984-1987 and 1988 periods (Table 2-2).

With the exception of NH₃-N, which was present in significantly greater concentrations at Site 8 than at Sites 1 and 4, during the 1984-1987 period, no significant spatial differences were detected for the other measured nutrients during that same time period. However, during 1988, TP concentrations were greater at Site 8 than at Sites 1 and 4, whereas other nutrient variables did not exhibit spatial differences (Table 2-3). This pattern of higher TP concentrations within the upper zone of the reservoir was less pronounced, but nevertheless present during the 1984-1987 period.

The overall spatial pattern that emerged from the 1984-1987 monthly chemistry survey data was one of higher TP and NH₃-N concentrations in the upper zone of the reservoir. The

Table 2-2. Summarized results for pH, alkalinity, free CO₂, and dissolved oxygen single depth epilimnetic measurements as reported monthly for the 1984-1987 and 1988 time periods. Means, standard errors and sample size (n) are listed for each variable. Means with the same letter superscript, or means without superscript notations listed, are not significantly different (as determined by the Tukey-Kramer multiple comparisons test, p=0.05). All results are expressed as mg L⁻¹. Alkalinity was measured as mg of CaCO₃ L⁻¹. Free CO₂ has been corrected for temperature and the ionic strength of the water.

Site	pH (units)	Alkalinity	Free CO ₂	Dissolved Oxygen
<u>1984 - 1987</u>				
1	7.33 ± 0.70 (37)	51.9 ± 0.89 (36)	5.26 ± 1.31 (35)	9.97 ± .40 (35)
4	7.45 ± 0.42 (43)	52.3 ± 0.76 (42)	3.97 ± 0.76 (41)	8.52 ± .41 (40)
6	7.66 ± 0.05 (41)	53.9 ± 0.77 (39)	2.46 ± 0.52 (38)	9.21 ± .43 (39)
8	7.61 ± 0.03 (62)	54.8 ± 0.68 (60)	2.79 ± 0.39 (54)	9.04 ± .43 (58)
<u>1988</u>				
1	7.26 ± 0.43 (16)	57.3 ± 0.80 (15)	5.62 ± 1.44 (15)	9.73 ± 0.66 (16)
4	7.19 ± 0.16 (12)	57.4 ± 1.16 (12)	7.51 ± 1.90 (12)	9.38 ± 0.97 (12)
6	7.13 ± 0.32 (9)	59.2 ± 2.89 (10)	8.63 ± 3.76 (9)	10.01 ± 0.93 (9)
8	7.40 ± 0.11 (11)	58.0 ± 1.52 (11)	4.70 ± 1.25 (11)	8.97 ± 0.95 (11)

Table 2-3. Summarized results for total phosphorus (TP), nitrite plus nitrate nitrogen ($\text{NO}_2+\text{NO}_3\text{-N}$), ammonia nitrogen ($\text{NH}_3\text{-N}$), dissolved inorganic nitrogen (DIN), and reactive silica (Si) single depth epilimnetic measurements as reported monthly for the 1984-1987 and the 1988 time periods. Means, standard errors, and sample size (n) are listed for each variable. Means with the same letter superscript, or means without superscript notations listed, are not significantly different (as determined by the Tukey-Kramer multiple comparisons test, $p=0.05$). All results are expressed as mg L^{-1} with the exception of TP which is reported as ug L^{-1} .

Site	TP	$\text{NO}_2+\text{NO}_3\text{-N}$	$\text{NH}_3\text{-N}$	DIN	Si
<u>1984 - 1987</u>					
1	19.7 ± 2.3 (35)	0.12 ± 0.02 (36)	0.04 ± 0.01 (33) ^a	0.17 ± 0.03 (33)	3.46 ± 0.28 (35)
4	19.3 ± 2.4 (40)	0.15 ± 0.02 (41)	0.05 ± 0.01 (39) ^{ab}	0.20 ± 0.03 (39)	3.74 ± 0.24 (42)
6	24.7 ± 2.6 (39)	0.16 ± 0.04 (41)	0.07 ± 0.01 (39) ^{abc}	0.23 ± 0.04 (39)	3.57 ± 0.20 (39)
8	25.9 ± 1.8 (58)	0.16 ± 0.03 (60)	0.08 ± 0.01 (57) ^c	0.24 ± 0.03 (57)	3.84 ± 0.18 (59)
<u>1988</u>					
1	18.3 ± 1.4 (16) ^a	0.16 ± 0.05 (16)	0.05 ± 0.01 (16)	0.20 ± 0.06 (16)	2.99 ± 0.84 (4)
4	18.0 ± 1.8 (12) ^{ab}	0.13 ± 0.03 (12)	0.03 ± 0.01 (12)	0.16 ± 0.03 (12)	3.07 ± 0.71 (4)
6	22.6 ± 1.7 (10) ^{abc}	0.11 ± 0.03 (10)	0.03 ± 0.01 (10)	0.14 ± 0.03 (10)	3.10 ± 1.00 (3)
8	31.5 ± 2.6 (11) ^c	0.11 ± 0.03 (11)	0.04 ± 0.01 (11)	0.15 ± 0.04 (11)	2.62 ± 0.83 (3)

pattern of higher TP concentrations in the upper zone became more pronounced in the 1988. Epilimnetic pH, alkalinity, CO₂, dissolved oxygen, silica, NO₂+NO₃-N, and DIN did not display significant spatial differences during the 1984-1987, and 1988 monthly survey periods.

Biweekly Surveys

As with the monthly surveys of 1984-1987 and 1988, no significant differences between sampling sites were detected for pH, alkalinity, and concentrations of CO₂, and dissolved oxygen during the 1988 biweekly survey period (Table 2-4). Significant differences between sites existed for TP, NH₃-N, DIN, and TN concentrations (Table 2-5). All of these nutrients were generally detected at higher concentrations within the upper zone of the reservoir, i.e., Sites 6 and 8. No spatial differences were detected for SRP and NO₂+NO₃-N.

Table 2-4. Summarized results for pH, alkalinity, free CO₂, and dissolved oxygen, multiple depth epilimnetic measurements as reported biweekly for 1988 from March to December. Means, standard errors, and sample size (n) are listed for each variable. Means with the same letter superscript, or means without superscript notations listed, are not significantly different (as determined by the Tukey-Kramer multiple comparisons test, p=0.05). All results expressed as mg L⁻¹. Alkalinity was measured as mg of CaCO₃ L⁻¹. Free CO₂ has been corrected for temperature and the ionic strength of the water.

Site	pH (units)	Alkalinity	Free CO ₂	Dissolved Oxygen
<i>1988 Biweekly Surveys, Multiple Depths</i>				
1	7.33 ± 0.06 (68)	56.6 ± 0.43 (64)	5.58 ± 0.76 (64)	10.43 ± 0.32 (68)
4	7.24 ± 0.05 (68)	56.7 ± 0.48 (68)	6.74 ± 0.68 (64)	9.69 ± 0.34 (68)
6	7.22 ± 0.09 (49)	58.6 ± 0.48 (45)	6.97 ± 1.12 (44)	9.29 ± 0.46 (48)
8	7.34 ± 0.04 (68)	57.3 ± 0.54 (64)	5.67 ± 0.55 (63)	9.84 ± 0.30 (67)

Table 2-5. Summarized results for total phosphorus (TP), soluble reactive phosphorus (SRP), nitrite\ nitrate nitrogen ($\text{NO}_2+\text{NO}_3\text{-N}$), ammonia nitrogen ($\text{NH}_3\text{-N}$), dissolved inorganic nitrogen (DIN), and total nitrogen (TN) as reported biweekly for 1988 from March to December. All variables were measured at multiple depths within the epilimnion. Means, standard errors, and sample size (n) are listed for each variable. Means with the same letter superscript, or means without superscript notations listed, are not significantly different (as determined by the Tukey-Kramer multiple comparisons test, $p=0.05$).

Site	TP (ug L ⁻¹)	SRP (ug L ⁻¹)	NO ₂ +NO ₃ -N (mg L ⁻¹)
1988 Biweekly Surveys			
1	18.4 ± 0.60 (68) ^a	2.8 ± 0.35 (68)	0.12 ± 0.02 (64)
4	19.7 ± 0.63 (68) ^{ab}	2.9 ± 0.32 (68)	0.12 ± 0.01 (64)
6	20.7 ± 0.68 (49) ^b	2.9 ± 0.29 (49)	0.07 ± 0.01 (49)
8	28.6 ± 0.75 (68) ^c	3.4 ± 0.38 (68)	0.13 ± 0.01 (64)
NH ₃ -N DIN TN			
	(mg L ⁻¹)	(mg L ⁻¹)	(mg L ⁻¹)
1	0.03 ± 0.003 (64) ^a	0.15 ± 0.02 (64) ^a	0.43 ± 0.02 (60) ^a
4	0.03 ± 0.002 (64) ^a	0.15 ± 0.02 (64) ^{ab}	0.45 ± 0.02 (63) ^a
6	0.04 ± 0.003 (49) ^a	0.11 ± 0.01 (49) ^{abc}	0.39 ± 0.01 (44) ^a
8	0.05 ± 0.003 (63) ^b	0.18 ± 0.01 (63) ^c	0.54 ± 0.01 (64) ^b

Depth Analysis

Table 2-6 lists summarized chemistry results, listed by depth for all sites combined as measured biweekly during 1988. Figures 2-3 and 2-4 illustrate seasonal variations for $\text{NO}_2+\text{NO}_3\text{-N}$, DIN, DO, and CO_2 , with depth as measured biweekly during 1988. TP, $\text{NH}_3\text{-N}$, TN, and alkalinity did not display any significant spatial differences with depth on both an annual and seasonal basis. However, concentrations of dissolved oxygen, $\text{NO}_2+\text{NO}_3\text{-N}$, and DIN measured at 9 meters were found to be significantly different than the concentrations measured at some of the more shallow depths. After further analysis of each site individually, it was found that the $\text{NH}_3\text{-N}$, $\text{NO}_2+\text{NO}_3\text{-N}$, and DIN concentrations that were significantly higher at the 9 meter sampling depth were restricted to the shallower sites, i.e., Sites 6 and 8. These higher concentrations at the shallower sites that contributed to higher DIN values present in the combined site analysis described above. In addition, dissolved oxygen concentrations were found to be significantly lower at the 9 meter depth. Furthermore, seasonal analysis of these data revealed that differences in concentration with depth for $\text{NO}_2+\text{NO}_3\text{-N}$, DIN, and dissolved oxygen only occurred during the summer months (Figures 2-1 and 2-2). However, free CO_2 concentrations generally increased with depth during both the spring and summer months (Figure 2-2).

Table 2-6. Summarized results, listed by depth, for total phosphorus (TP), nitrate+nitrite nitrogen ($\text{NO}_2+\text{NO}_3\text{-N}$), ammonia nitrogen ($\text{NH}_3\text{-N}$), total nitrogen (TN), dissolved inorganic nitrogen (DIN), alkalinity, dissolved oxygen (DO), and free carbon dioxide (CO_2) as reported biweekly from March to December 1988 for sites 1, 4, 6, and 8 combined. Means, standard errors, and sample size (n) are listed for each variable. Means with the same letter superscript, or means without superscript notations listed, are not significantly different (as determined by the Tukey-Kramer multiple comparison test, $p=0.05$).

Depth (m)	TP ($\mu\text{g L}^{-1}$)	$\text{NO}_2+\text{NO}_3\text{-N}$ (mg L^{-1})	$\text{NH}_3\text{-N}$ (mg L^{-1})	TN (mg L^{-1})
1	21.34 ± 0.90 (63)	0.05 ± 0.01 (60) ^a	0.03 ± 0.01 (60)	0.42 ± 0.03 (58)
3	21.14 ± 0.89 (64)	0.06 ± 0.01 (61) ^{ab}	0.03 ± 0.01 (61)	0.43 ± 0.02 (57)
5	20.42 ± 0.79 (63)	0.07 ± 0.02 (60) ^{ab}	0.03 ± 0.01 (60)	0.44 ± 0.03 (58)
7	20.76 ± 0.81 (63)	0.08 ± 0.01 (60) ^{ab}	0.03 ± 0.01 (59)	0.43 ± 0.03 (58)
9	21.03 ± 0.94 (63)	0.14 ± 0.02 (59) ^b	0.04 ± 0.02 (58)	0.45 ± 0.04 (57)
	DIN (mg L^{-1})	Alkalinity ($\text{mg CaCO}_3 \text{ L}^{-1}$)	DO (mg L^{-1})	CO_2 (mg L^{-1})
1	0.10 ± 0.01 (60) ^a	57.1 ± 0.47 (59)	9.91 ± 0.24 (63) ^a	2.19 ± 1.18 (59) ^a
3	0.11 ± 0.01 (61) ^a	56.9 ± 0.51 (60)	10.21 ± 0.26 (64) ^a	2.91 ± 1.17 (60) ^{ab}
5	0.12 ± 0.01 (60) ^{ab}	57.3 ± 0.49 (59)	9.89 ± 0.38 (63) ^a	4.29 ± 1.12 (59) ^{bc}
7	0.14 ± 0.01 (59) ^{ab}	57.3 ± 0.51 (59)	9.38 ± 0.48 (61) ^{ab}	6.98 ± 1.11 (57) ^{cd}
9	0.18 ± 0.01 (58) ^b	57.3 ± 0.53 (59)	7.99 ± 0.57 (63) ^b	10.13 ± 1.11 (59) ^d

Figure 2-1. Mean seasonal concentrations by depth as measured biweekly from March to December 1988 for: (a) nitrite plus nitrate nitrogen (mg L^{-1}), and (b) dissolved inorganic nitrogen (mg L^{-1}). Significant within season differences with depth (by Tukey-Kramer multiple comparison test $p=0.05$) noted with arabic letters (depths with the same letters are significantly different).

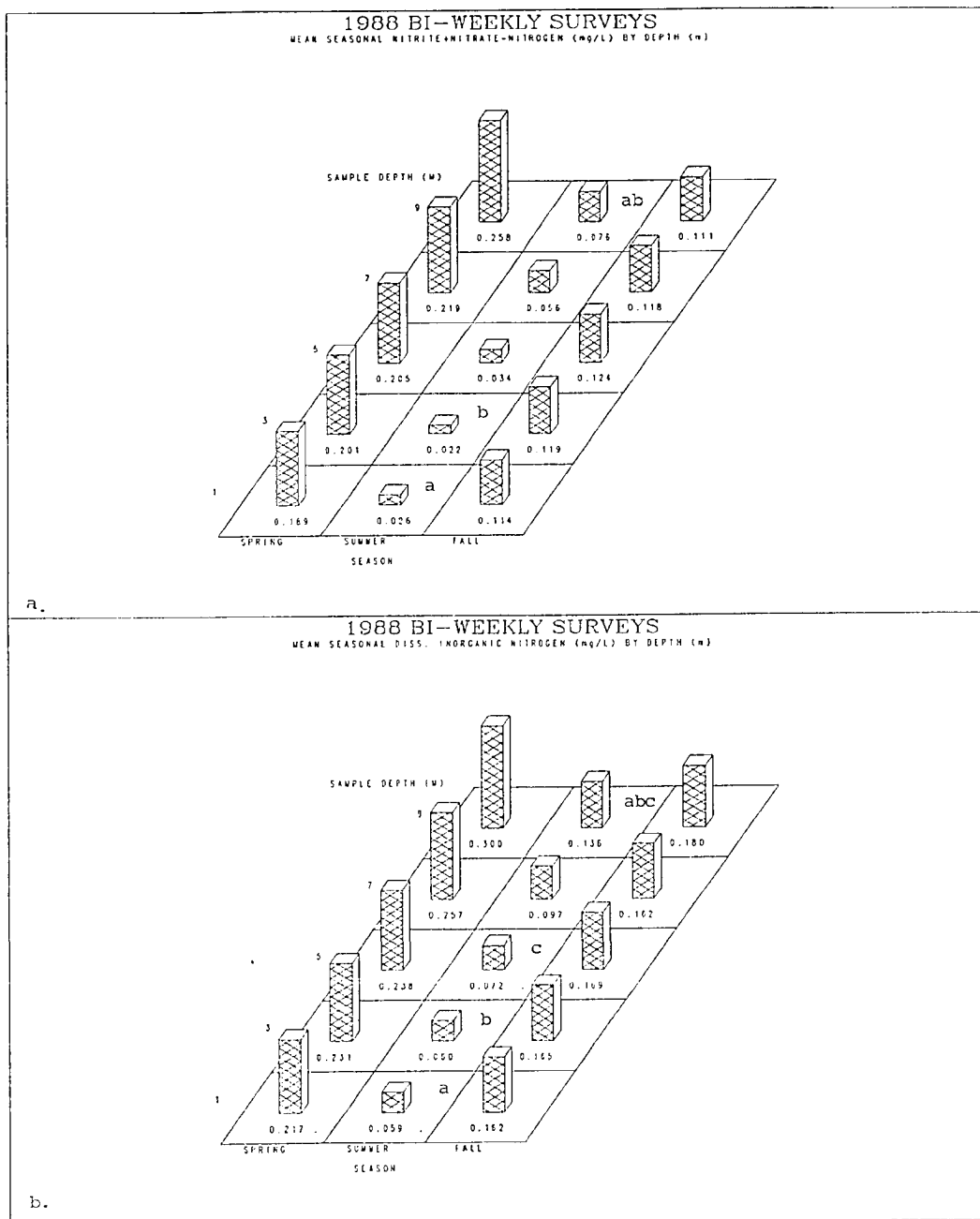
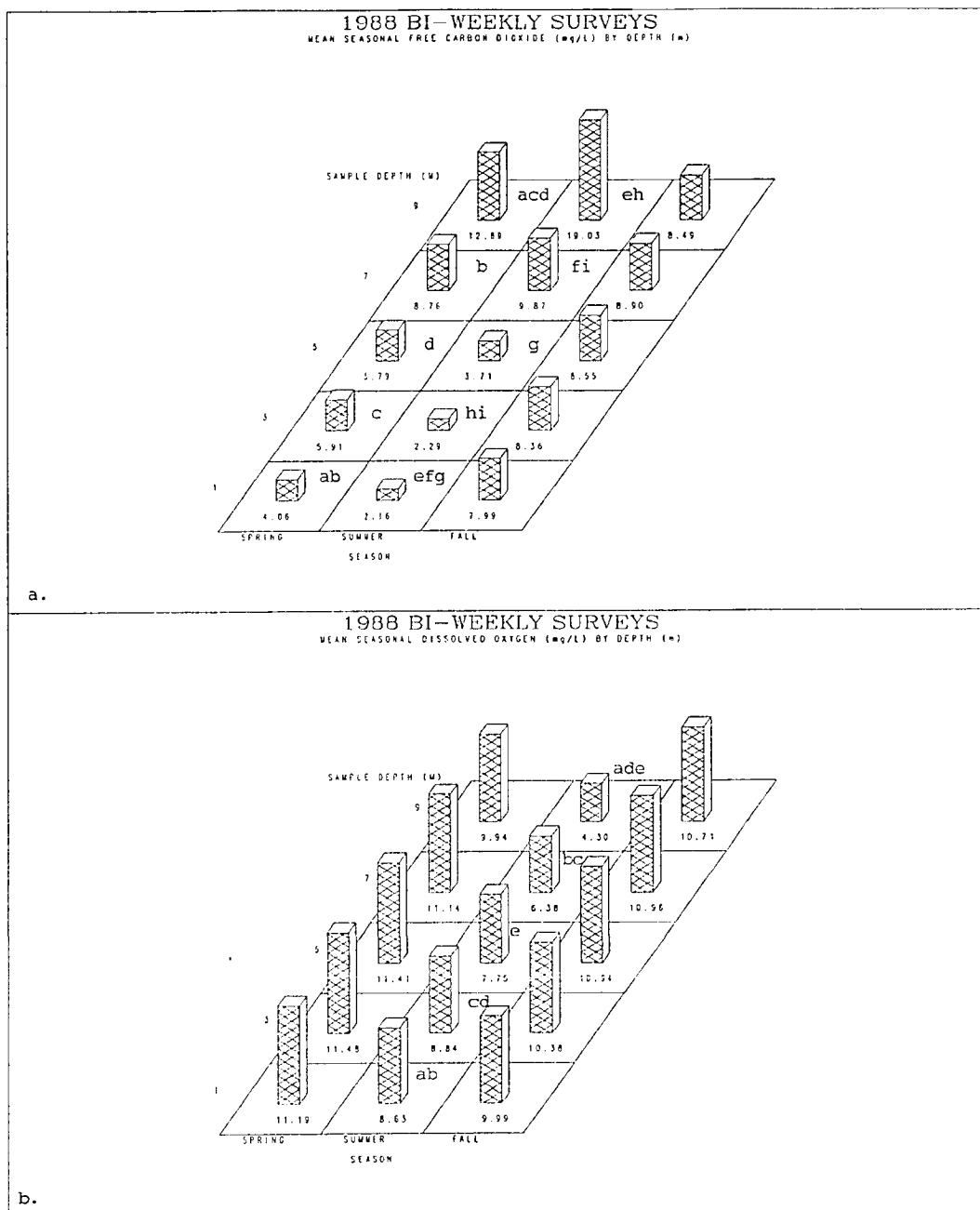


Figure 2-2. Mean seasonal concentrations by depth as measured biweekly from March to December 1988 for: (a) free carbon dioxide (mg L^{-1}), and (b) dissolved oxygen (mg L^{-1}). Significant within season differences with depth (by Tukey-Kramer multiple comparison test $p=0.05$) noted with arabic letters (depths with the same letters are significantly different).



Physical Variables

Monthly Surveys

Table 2-7 lists the summarized results for turbidity, color, Secchi disc, and compensation depth as reported monthly for the 1984-1987, and 1988 time periods. Measurements of all four physical variables were noted as being significantly different in site by site comparisons during both time periods. The upper zone of the reservoir exhibited higher turbidity and color levels, and lower Secchi disc and compensation depth measurements than the lower zone of the impoundment. This pattern was observed during the 1984-1987 period, and further confirmed in 1988.

Biweekly Surveys

Table 2-8 lists summarized results for turbidity, color, Secchi disc, and compensation depth as reported biweekly for 1988 from March to December. Measurements of all physical variables were noted as being significantly different in site by site comparisons during 1988. Trends evident in both the 1984-1987, and 1988 monthly surveys described above, were confirmed in the 1988 biweekly surveys. Turbidity and color values were higher, and Secchi disc and compensation depth measurements were generally lower in the upper zone of the reservoir.

Table 2-7. Summarized results for turbidity, color, Secchi disc, and compensation depth (1% light level) as reported monthly for the 1984 - 1987 and the 1988 time periods. Means, standard errors, and sample size (n) are noted for each variable. Means with the same letter superscript are not significantly different (as determined by the Tukey-Kramer multiple comparisons test $p=0.05$).

Site	Turbidity (NTU)	Color (units)	Secchi Disc (m)	Comp. (m)
<u>1984 - 1987</u>				
1	1.44 ± 0.14 (36) ^{ab}	17 ± 0.96 (36) ^a	2.86 ± 0.10 (37) ^a	5.73 ± 0.20 (37) ^a
4	1.42 ± 0.08 (42) ^a	19 ± 0.72 (42) ^{ab}	2.50 ± 0.09 (40) ^{ab}	5.28 ± 0.15 (36) ^a
6	1.72 ± 0.18 (39) ^{ab}	21 ± 1.10 (39) ^b	2.23 ± 0.08 (36) ^{bc}	not measured
8	1.89 ± 0.07 (60) ^b	27 ± 1.42 (60) ^c	1.94 ± 0.07 (37) ^c	4.30 ± 0.20 (20) ^b
<u>1988</u>				
1	1.36 ± 0.11 (14) ^a	20 ± 1.37 (16) ^a	2.95 ± 0.17 (10) ^a	5.66 ± 0.38 (8) ^a
4	1.60 ± 0.11 (11) ^{ab}	20 ± 1.37 (12) ^a	2.65 ± 0.20 (10) ^{ab}	5.36 ± 0.20 (9) ^a
6	1.80 ± 0.20 (9) ^{ab}	23 ± 1.79 (10) ^{ab}	2.30 ± 0.12 (9) ^{bc}	not measured
8	2.07 ± 0.08 (9) ^b	28 ± 2.41 (11) ^b	1.80 ± 0.08 (10) ^c	3.51 ± 0.26 (9) ^b

Table 2-8. Summarized results for turbidity, color, Secchi disc, and compensation depth (1% light level) as reported biweekly for 1988 from March to December. Turbidity and color were measured at multiple depths within the epilimnion. Means, standard errors, and sample size (n) are listed for each variable. Means with the same letter superscript are not significantly different (as determined by the Tukey-Kramer multiple comparisons test, $p=0.05$).

Site	Turbidity (NTU)	Color (units)	Secchi Disc (m)	Comp. Depth (m)
<i>1988 Biweekly Surveys</i>				
1	1.36 ± 0.06 (68) ^a	19 ± 0.48 (68) ^a	2.94 ± 0.13 (18) ^a	5.66 ± 0.38 (8) ^a
4	1.57 ± 0.07 (67) ^a	19 ± 0.62 (68) ^a	2.57 ± 0.14 (18) ^{ab}	5.36 ± 0.20 (9) ^a
6	1.45 ± 0.03 (49) ^a	21 ± 0.93 (49) ^a	2.33 ± 0.08 (15) ^{bc}	not measured
8	2.01 ± 0.06 (67) ^b	27 ± 0.99 (68) ^b	1.90 ± 0.07 (18) ^c	3.51 ± 0.26 (9) ^b

Temporal Patterns

Yearly Patterns

Figures 2-3 and 2-4 illustrate yearly means as measured monthly from 1984 through 1988 for TP, DIN, DIN:TP ratios, Secchi disc, reactive silica, and free CO₂. No significant difference between variables for years 1984-1988 were detected for TP, DIN:TP, and Secchi disc (Figure 2-3). However, significant differences between years did emerge for DIN, reactive silica, and CO₂ (Figure 2-4). DIN concentrations were greater in 1986 than in 1984. Reactive silica concentrations were greater in 1986 than in both 1988 and 1985, and were also greater in 1984 than in 1985. Free CO₂ concentrations were greater in 1988 than in all other years.

Figures 2-5, 2-6, and 2-7 illustrate yearly spatial patterns observed during the five year study period. Spatial differences among the years were noted for TP, DIN:TP, reactive silica, and Secchi disc transparency. TP concentrations were significantly greater within the upper zone of the reservoir during 1988; this pattern was not observed during any of the other years (Figure 2-5).

Figure 2-3. Mean yearly: (a) total phosphorus (TP) concentrations ($\mu\text{g L}^{-1}$); (b) dissolved inorganic nitrogen (DIN) to TP ratios; and (c) Secchi disc depth (m) measurements as measured monthly from 1984 to 1988. Significant differences between years (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (years with same letter are significantly different).

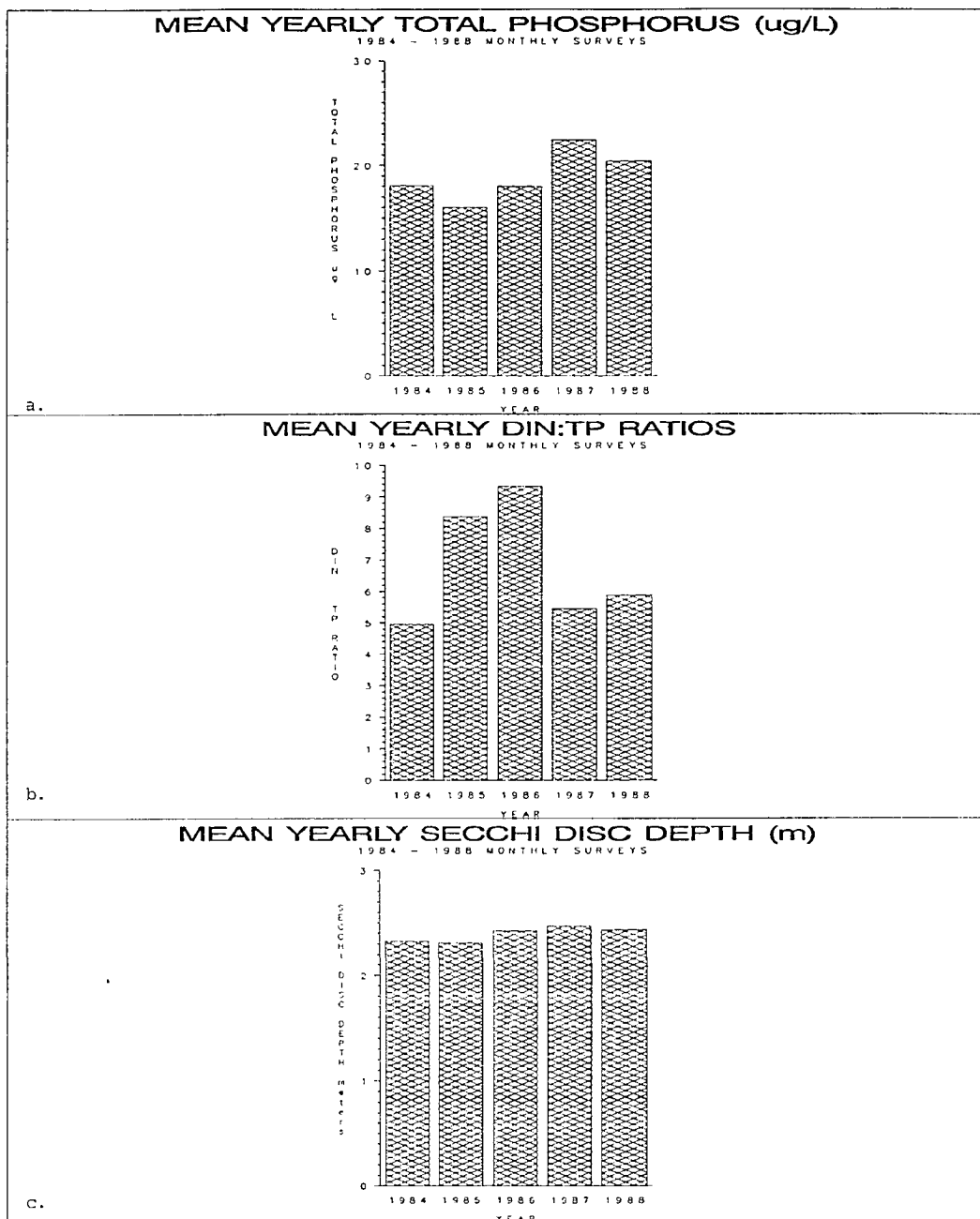


Figure 2-4. Mean yearly: (a) dissolved inorganic nitrogen (mg L^{-1}) ;(b) free carbon dioxide (mg L^{-1}); and (c) total reactive silica (mg L^{-1}) as measured monthly from 1984 to 1988. Significant differences between years (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (years with same letter are significantly different).

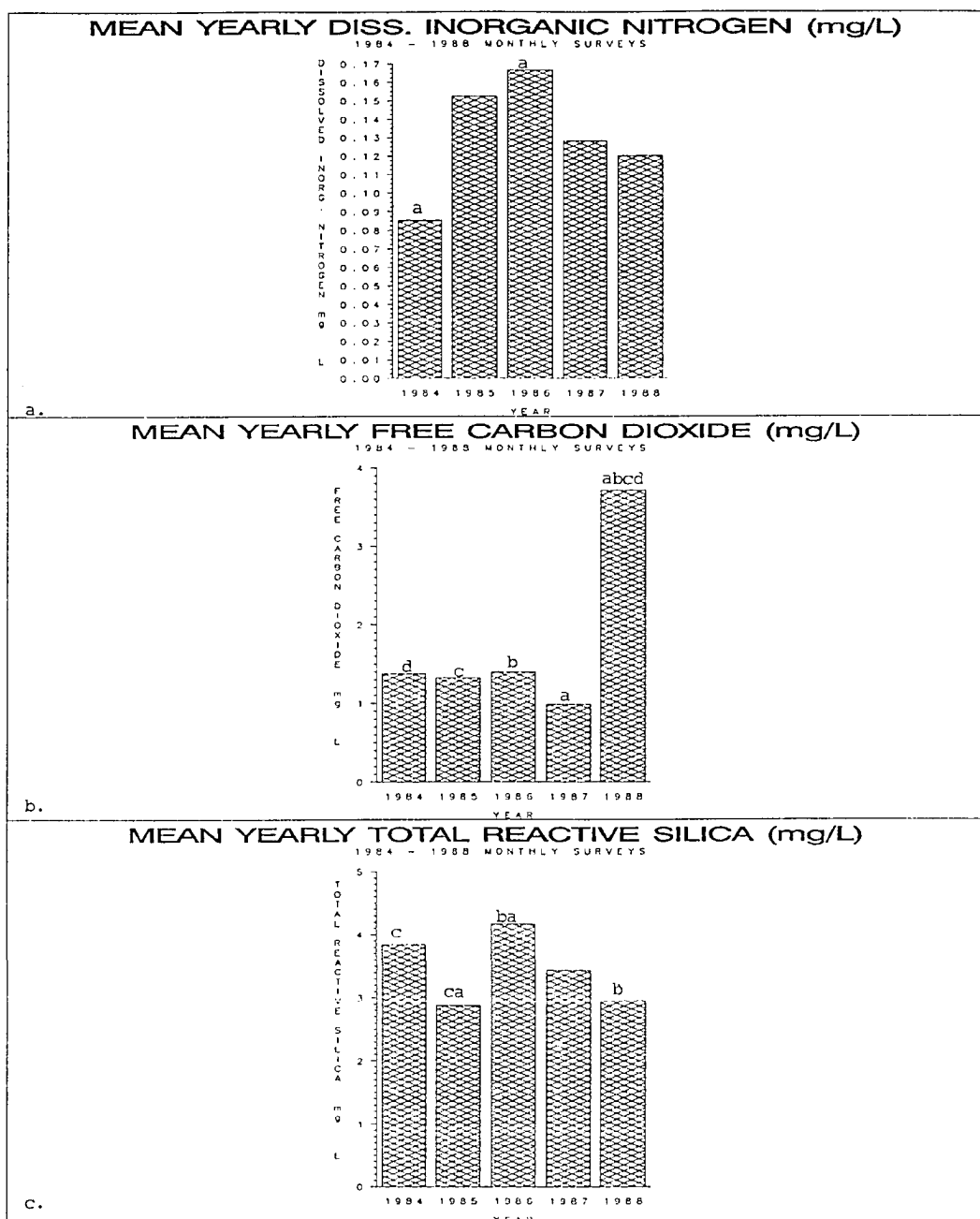
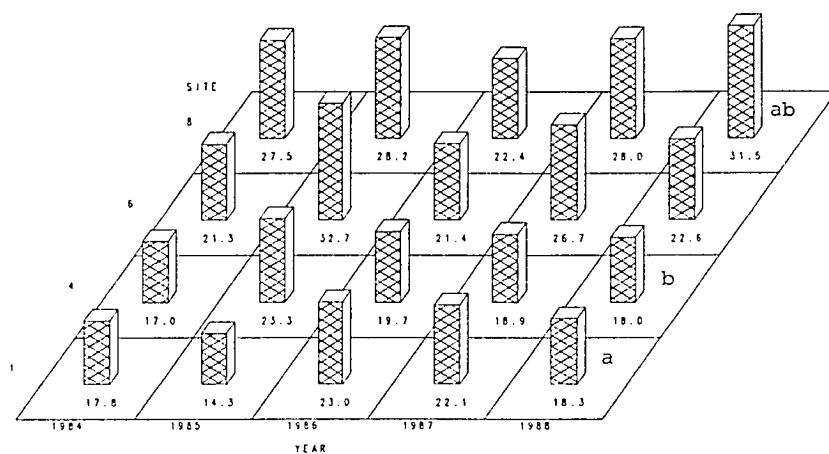
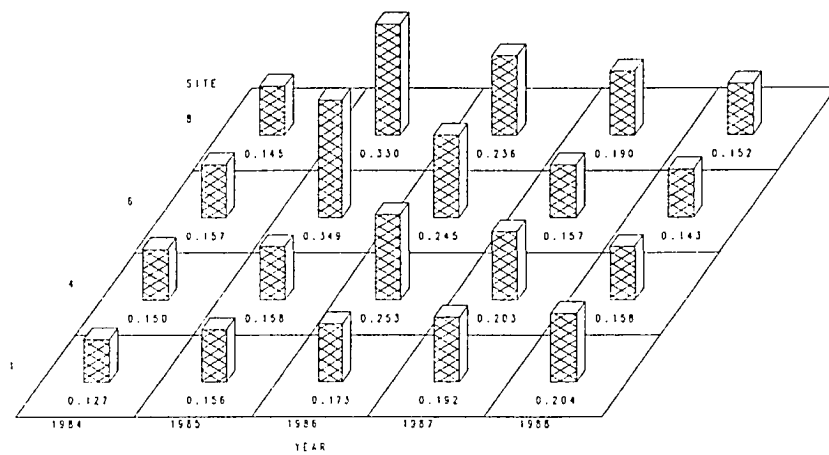


Figure 2-5. Mean yearly spatial total phosphorus and dissolved inorganic nitrogen concentrations as measured monthly from 1984 to 1988. Significant within year differences between sites (Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (sites with the same letters are significantly different). Significant differences between years at specific sites (rows) are noted to the right of the chart. (a) mean yearly total phosphorus ($\mu\text{g L}^{-1}$), 1984-1988; (b) mean yearly dissolved inorganic nitrogen (mg L^{-1}), 1984-1988.

MEAN YEARLY TOTAL PHOSPHORUS ($\mu\text{g/L}$) 1984 – 1988

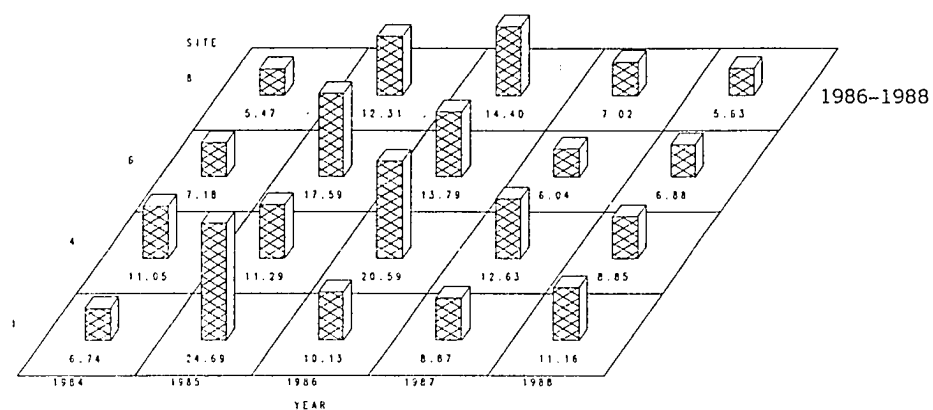
a.

MEAN YEARLY DISSOLVED INORGANIC NITROGEN (mg/L) 1984 – 1988

b.

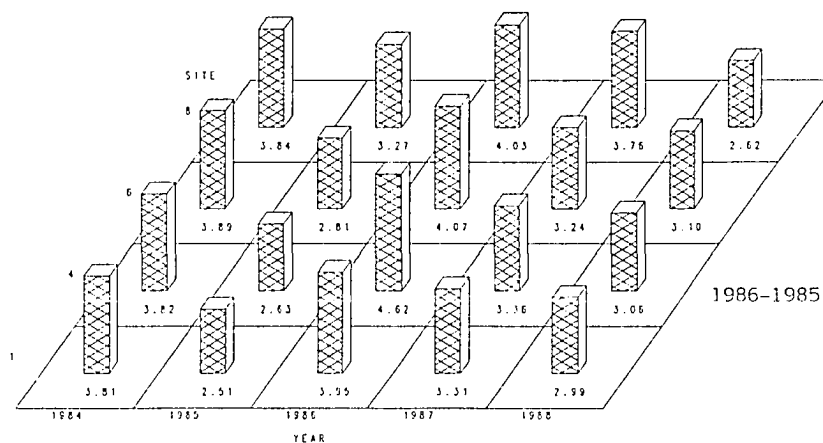
Figure 2-6. Mean yearly spatial dissolved inorganic nitrogen (DIN): total phosphorus (TP) ratios and total reactive silica concentrations as measured monthly from 1984 to 1988. Significant within year differences between sites (Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (sites with the same letters are significantly different). Significant differences between years at specific sites (rows) are noted to the right of the chart. (a) mean yearly DIN:TP ratios, 1984-1988; (b) mean yearly total reactive silica (mg L^{-1}), 1984-1988.

MEAN YEARLY DIN:TP RATIO 1984 - 1988



a.

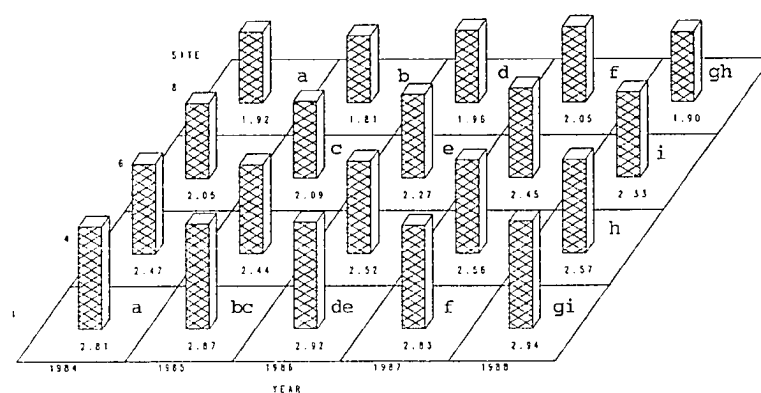
MEAN YEARLY TOTAL REACTIVE SILICA (mg/L) 1984 - 1988



b.

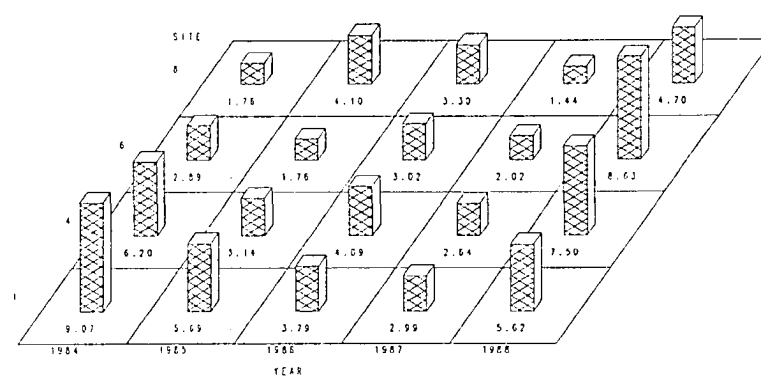
Figure 2-7. Mean yearly spatial Secchi disc measurements and free carbon dioxide concentrations as measured monthly from 1984 to 1988. Significant within year differences between sites (Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (sites with the same letters are significantly different). Significant differences between years at specific sites (rows) are noted to the right of the chart. (a) mean yearly Secchi disc depths (m), 1984-1988; (b) mean yearly free carbon dioxide (mg L^{-1}), 1984-1988.

MEAN YEARLY SECCHI DISC (M) 1984 - 1988



a.

MEAN YEARLY FREE CARBON DIOXIDE (mg/L) 1984 - 1988



b.

DIN:TP measurements and reactive silica concentrations displayed within site differences during 1986 as opposed to other years (Figure 2-6). Secchi disc transparency measurements were generally greater within the lower zone of the reservoir throughout the entire five year study period. However, evidence of a longitudinal gradient for Secchi disc transparency was most apparent in 1988 with differences between lower zone and upper zone sites being highly significant as Figure 2-7 illustrates ($F=10.72$, $p<0.0001$, $n=40$; Site 1>Sites 6 and 8, and Site 4>8 at $\alpha=0.05$).

Monthly Patterns

Figures 2-8 through 2-16 depict temporal patterns for physical and chemical variables measured monthly from 1984-1988 for Sites 1, 4, 6, and 8. The general patterns that emerge from each figure are listed below.

Upper zone TP concentrations were generally greater than lower zone concentrations with all sites showing an early depletion of TP in the summer months, although, this pattern was not as evident in 1988 (Figure 2-8). All sites exhibited a DIN peak in the spring and a depletion of DIN in the summer (Figure 2-9). With the exception of 1988, DIN:TP ratios decreased during late summer to early fall at all sites (Figure 2-10). Reactive silica and free carbon dioxide concentrations generally peaked in the spring, became depressed in the summer and subsequently increased in the

Figure 2-8. Mean epilimnetic total phosphorus concentrations ($\mu\text{g L}^{-1}$) as measured monthly from 1984-1987 and biweekly during 1988 for: (a) Site 1, (b) Site 4, (c) Site 6, and (d) Site 8. Note the different scales on the vertical axes; a reference line has been drawn at total phosphorus = $20 \mu\text{g L}^{-1}$ to facilitate site comparisons.

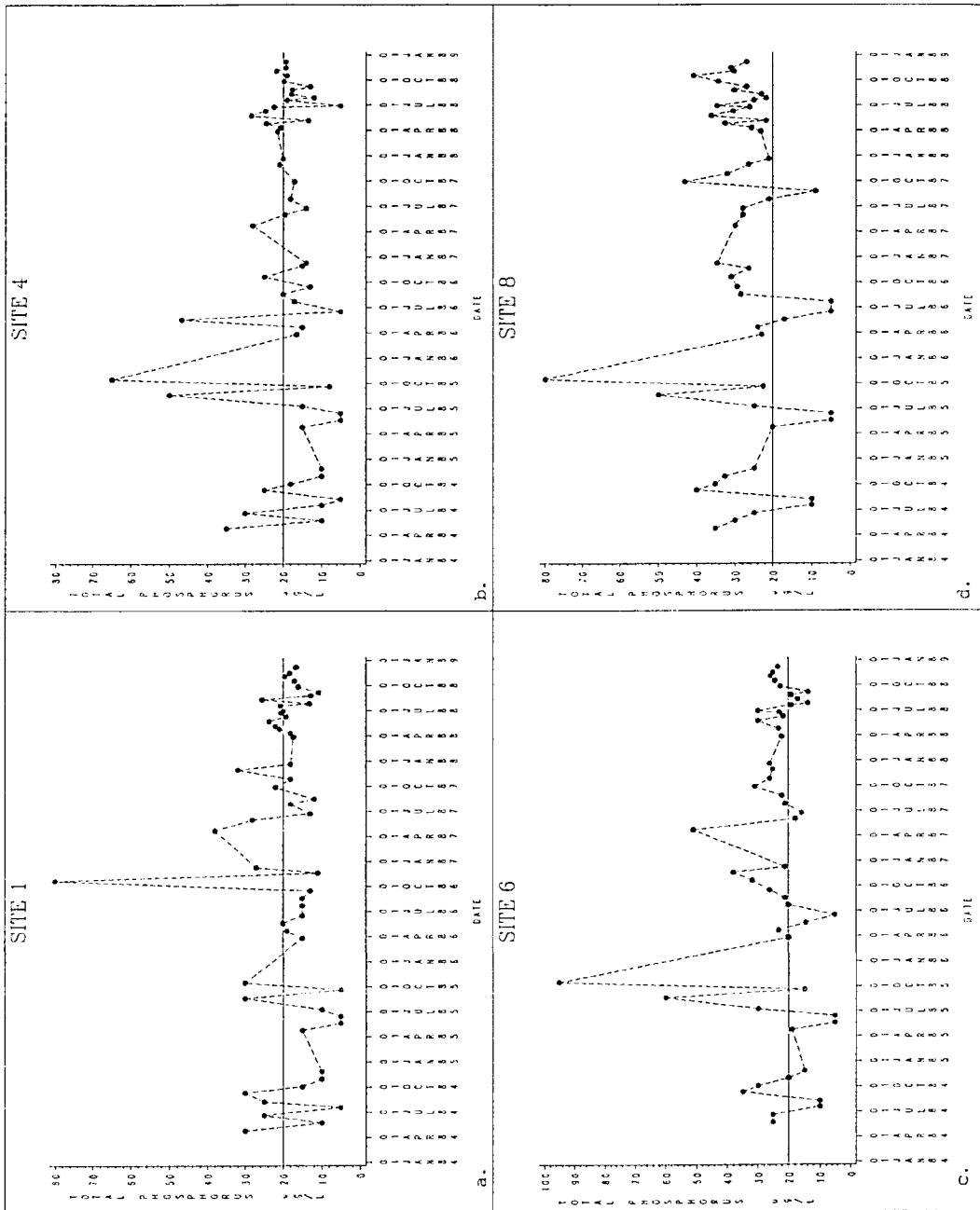


Figure 2-9. Mean epilimnetic dissolved inorganic nitrogen (mg L^{-1}) as measured monthly from 1984-1987 and biweekly during 1988 for: (a) Site 1, (b) Site 4, (c) Site 6, and (d) Site 8. Note the different scales on the vertical axes.

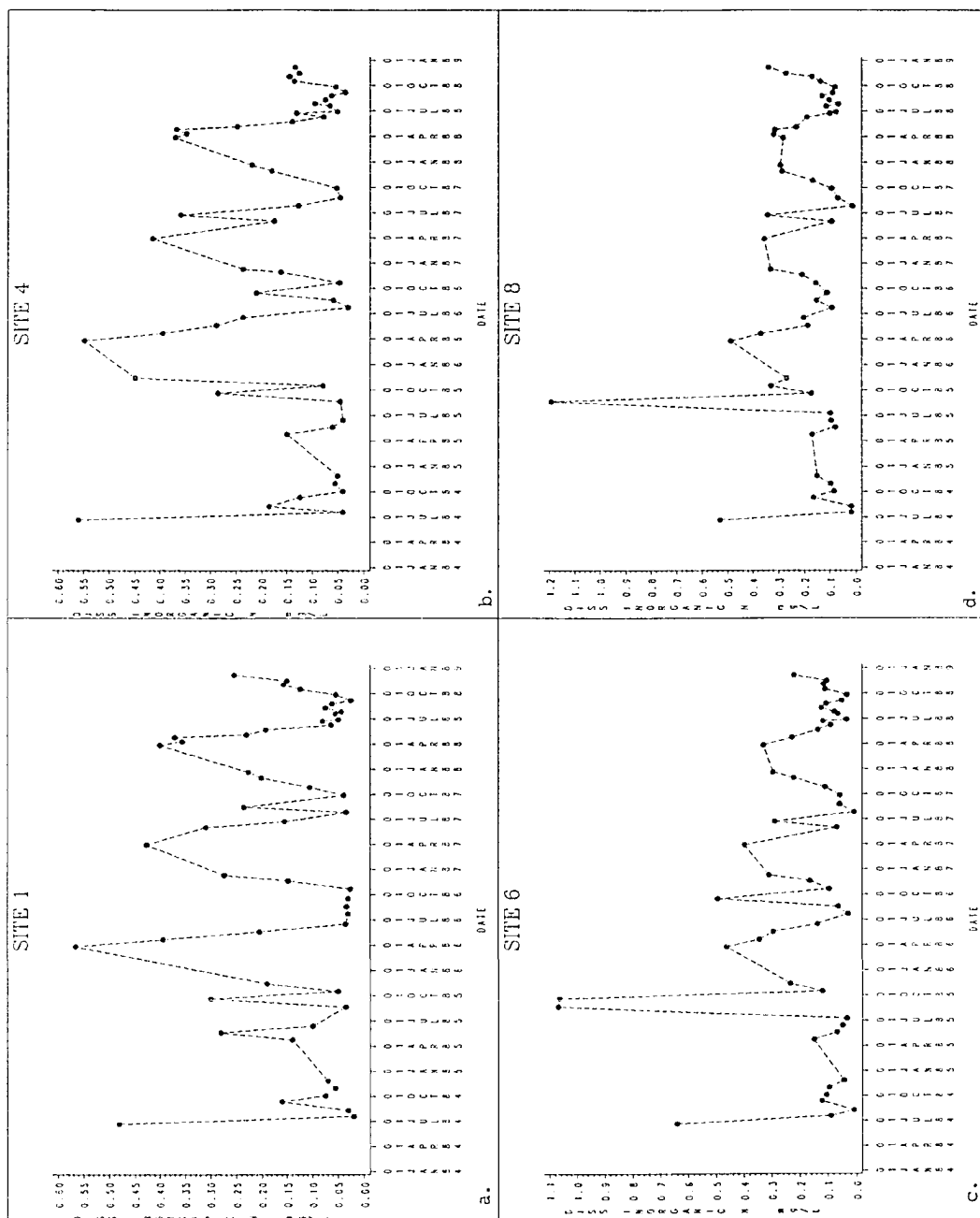
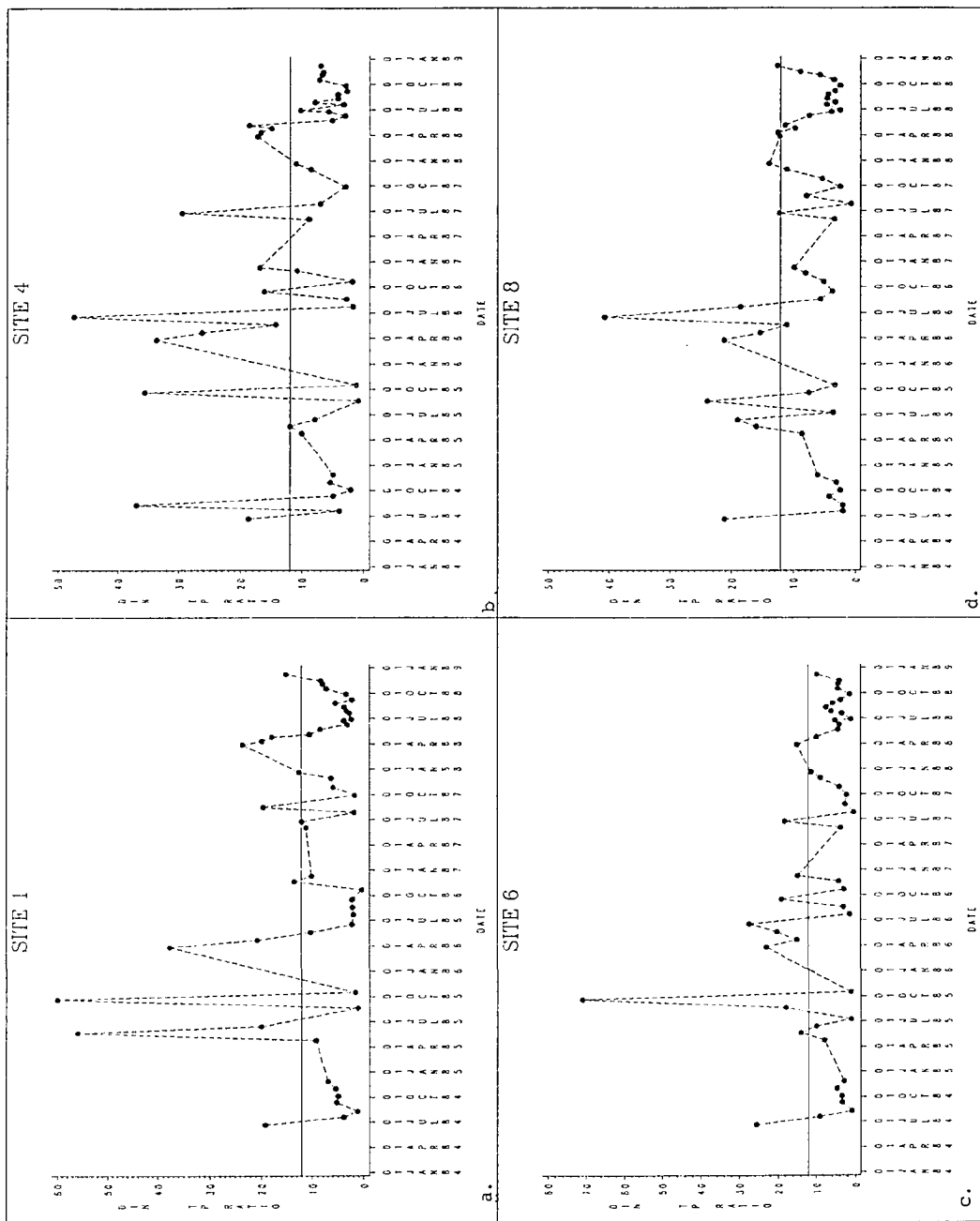


Figure 2-10. Mean epilimnetic dissolved inorganic nitrogen (DIN) to total phosphorus (TP) ratios as measured monthly from 1984-1987 and biweekly during 1988 for: (a) Site 1, (b) Site 4, (c) Site 6, and (d) Site 8. Note the different scales on the vertical axes; a reference line has been drawn at DIN:TP=12 to facilitate site comparisons.



fall; this pattern was observed for all sites (Figures 2-11 and 2-12). Upper zone Sites 6 and 8, displayed lower Secchi disc and compensation depth readings than lower zone Sites 1 and 4, with periods of greater transparency generally occurring later in the year (Figures 2-13 and 2-14). Similar temporal patterns of epilimnetic temperature were observed for all sites, with peak temperatures occurring in August of each year (Figure 2-15). Figure 2-16 illustrates thermocline depth with time for Sites 1, 4, 6, and 8 from 1984 to 1988. Isothermal conditions occurred most frequently at the shallow upper zone Sites 6 and 8. Isothermal conditions were noted on 60% of all sampling dates for Site 8, as opposed to 12% of all sampling dates for Site 1.

Seasonal Patterns

Figures 2-17 through 2-22 illustrate seasonal spatial patterns observed during the 1984-1987 monthly survey period, the 1988 monthly survey period, and the 1988 biweekly survey period for TP, DIN, DIN:TP ratios, carbon dioxide, reactive silica, and Secchi disc transparency. The 1984-1987 monthly surveys revealed a trend, with no statistical significance, of greater TP concentrations within the upper zone of the reservoir, during the fall months (Figure 2-17). This pattern was also observed in the 1988 monthly and biweekly survey data. In addition, the 1988 biweekly surveys revealed that TP concentrations in the

Figure 2-11. Mean epilimnetic total reactive silica (mg L^{-1}) as measured monthly from 1984-1988 for: (a) Site 1, (b) Site 4, (c) Site 6, and (d) Site 8. Note the different scales on the vertical axes.

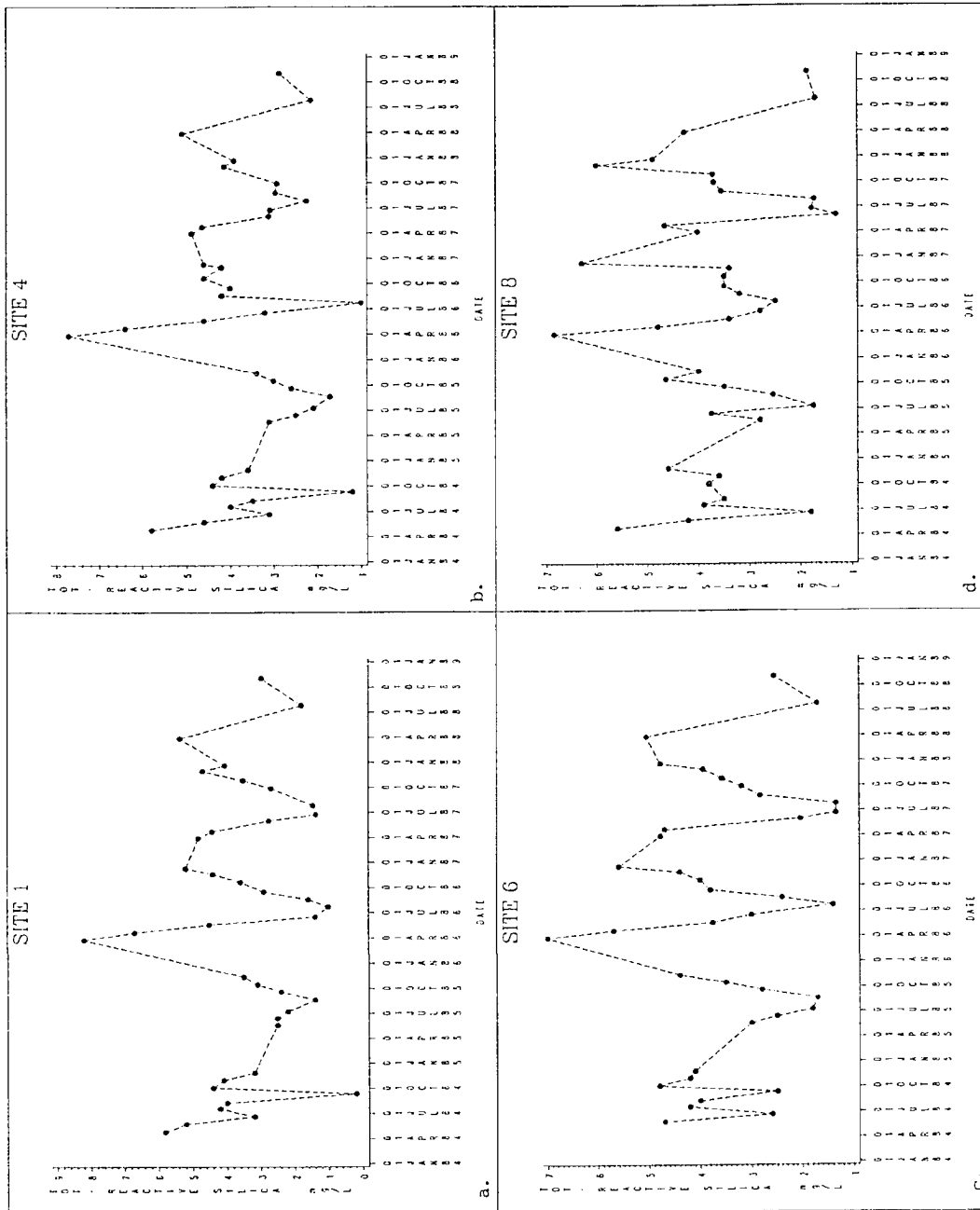


Figure 2-12. Mean epilimnetic dissolved free carbon dioxide (mg L^{-1}) as measured monthly from 1984-1987 and biweekly during 1988 for: (a) Site 1, (b) Site 4, (c) Site 6, and (d) Site 8. Note the different scales on the vertical axes.

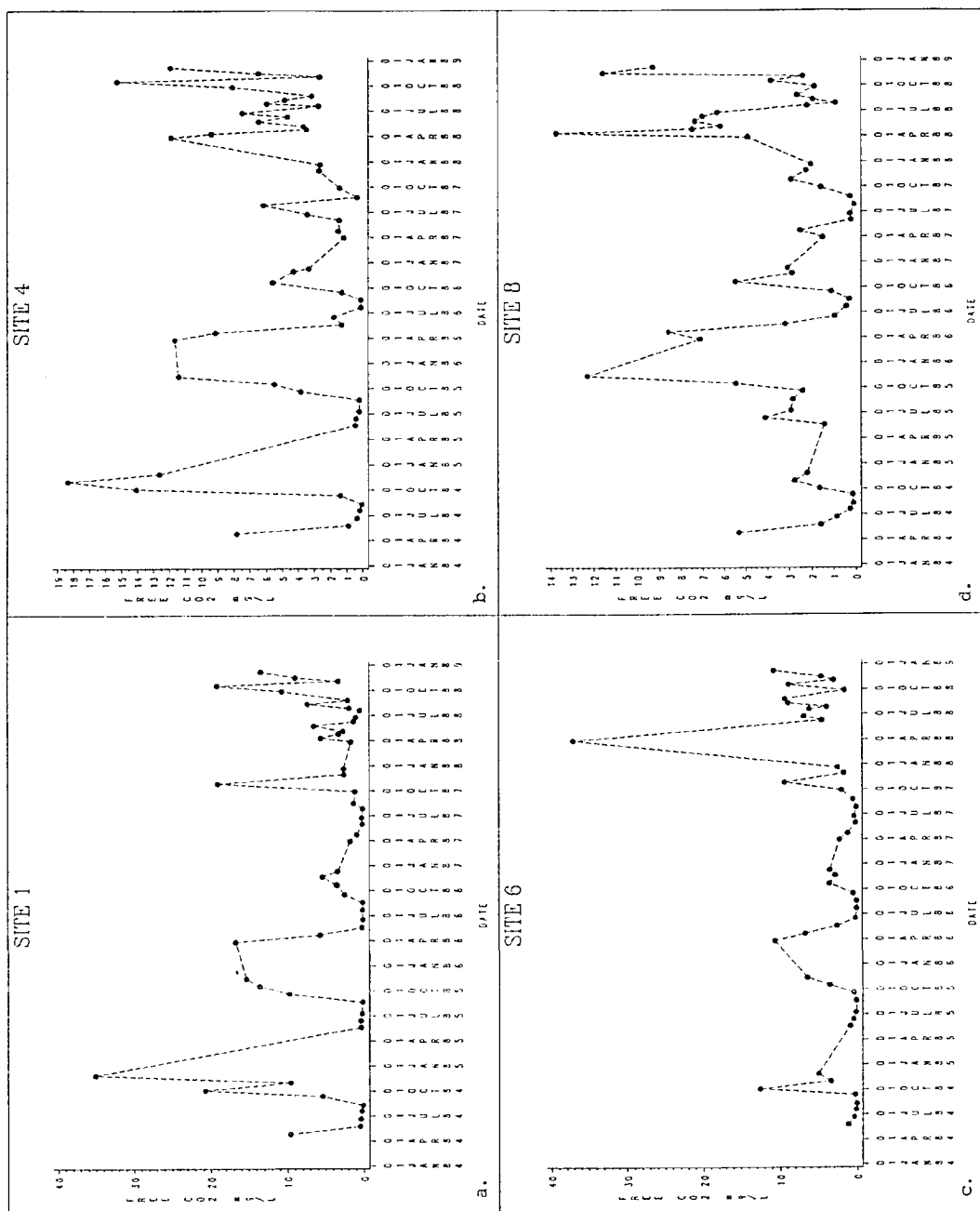


Figure 2-13. Mean Secchi disc depth (in meters) as measured monthly from 1984-1987 and biweekly during 1988 for: (a) Site 1, (b) Site 4, (c) Site 6, and (d) Site 8. A reference line has been drawn at Secchi disc depth =2 m. to facilitate site comparisons.

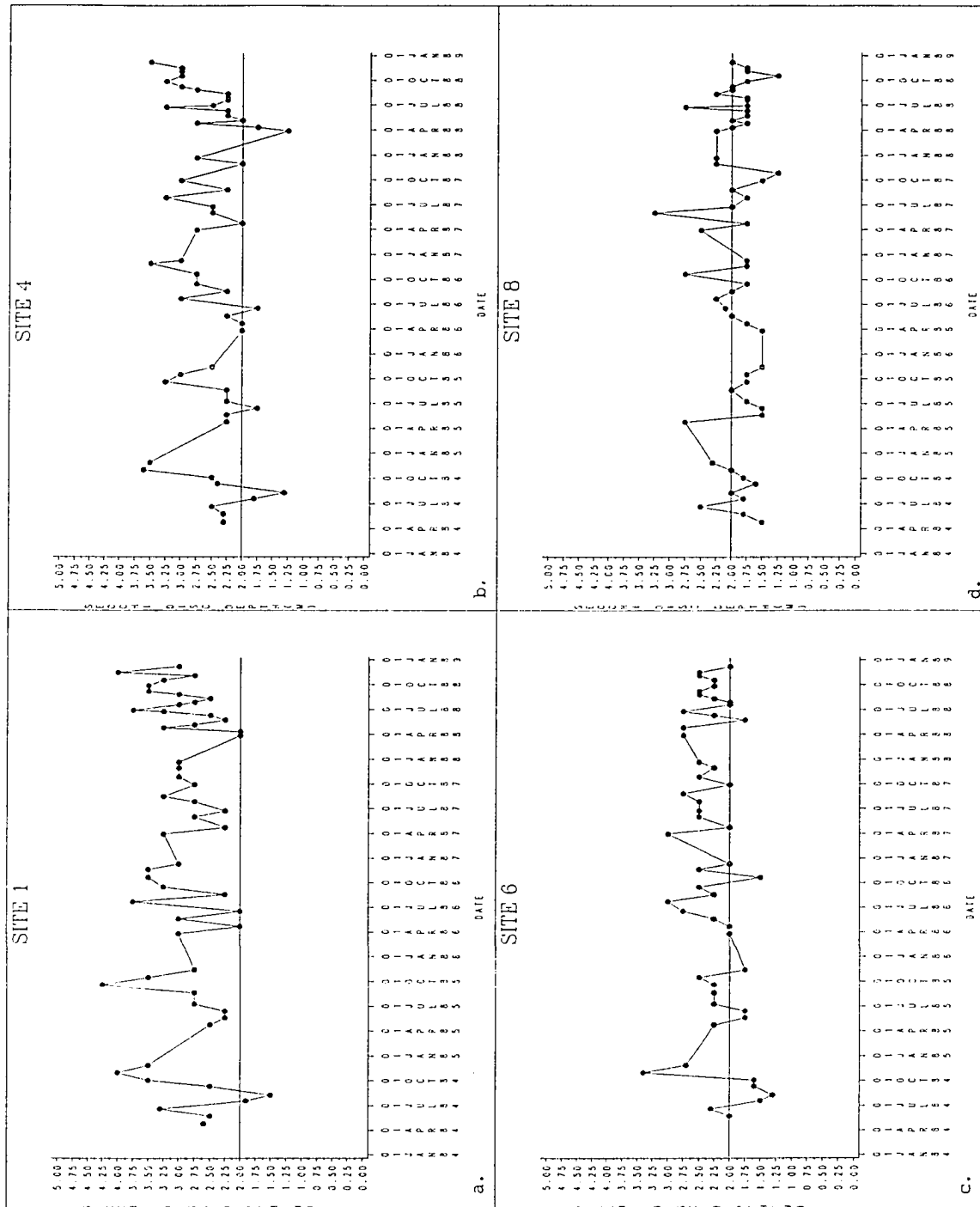


Figure 2-14. Mean compensation depth (in meters) as measured monthly from 1984-1988 for: (a) Site 1, (b) Site 4, and (c) Site 8. A reference line has been drawn at compensation depth =5 m. to facilitate site comparisons.

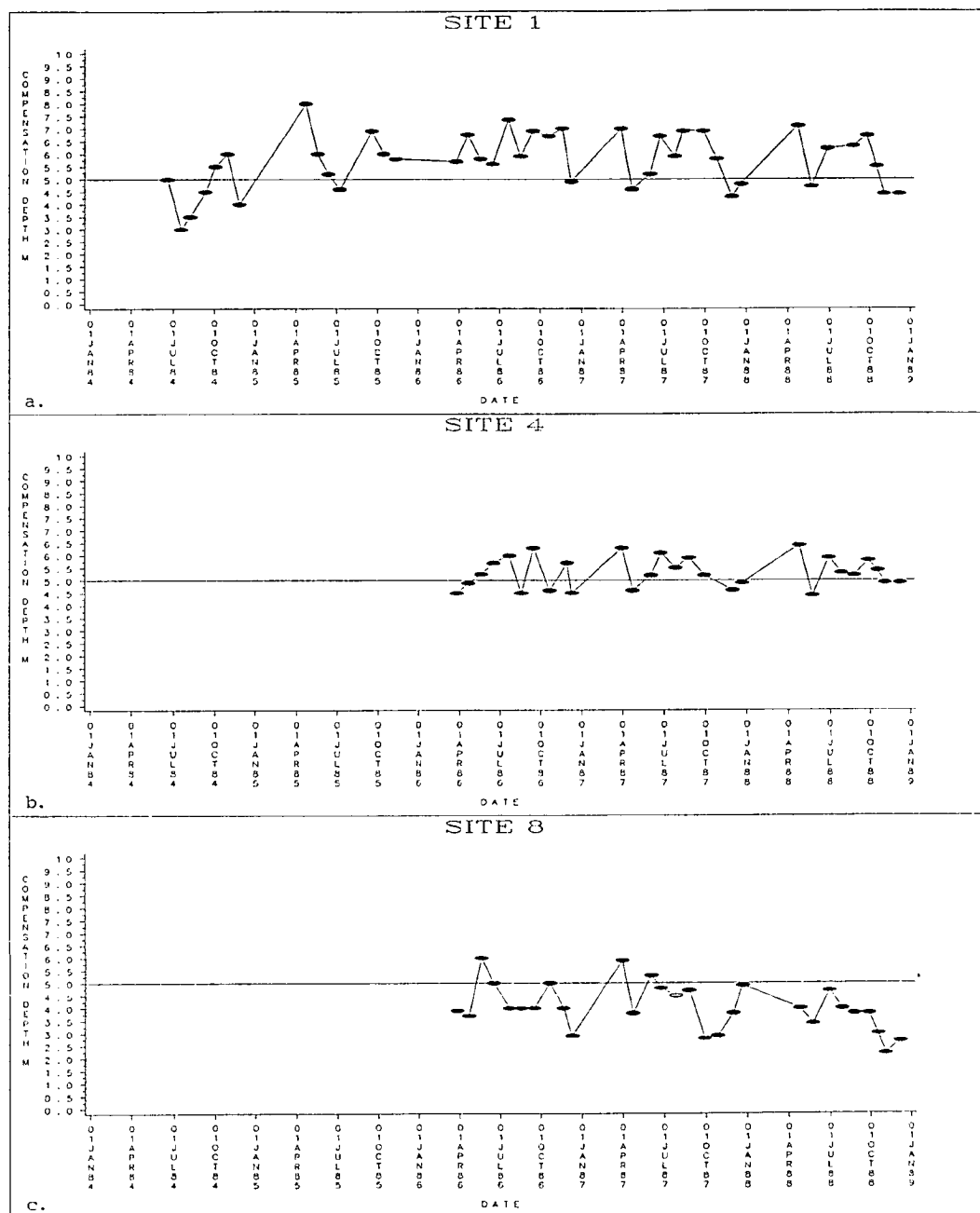


Figure 2-15. Mean epilimnetic temperature ($^{\circ}\text{C}$) as measured monthly from 1984-1987 and biweekly during 1988 for: (a) Site 1, (b) Site 4, (c) Site 6, and (d) Site 8.

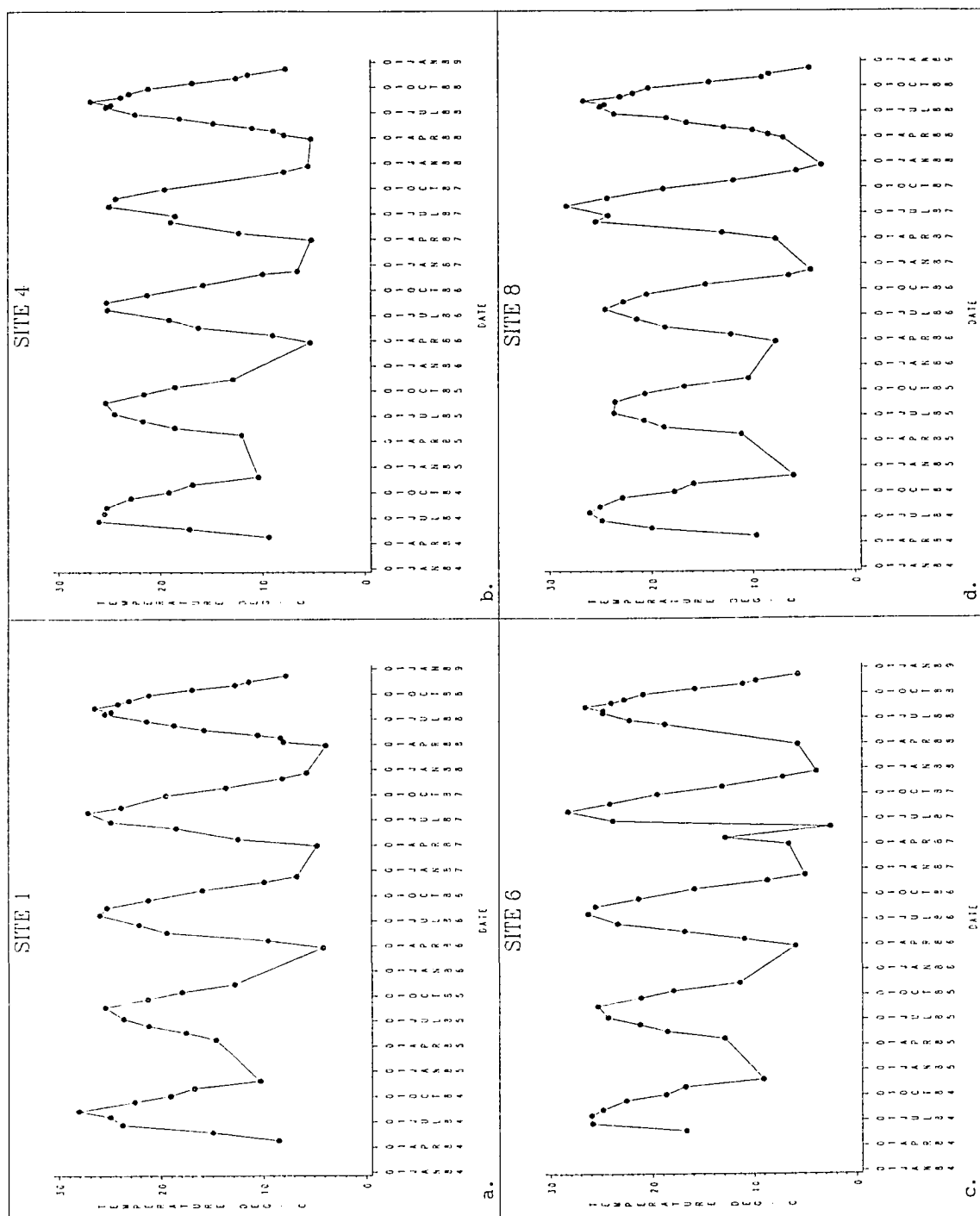
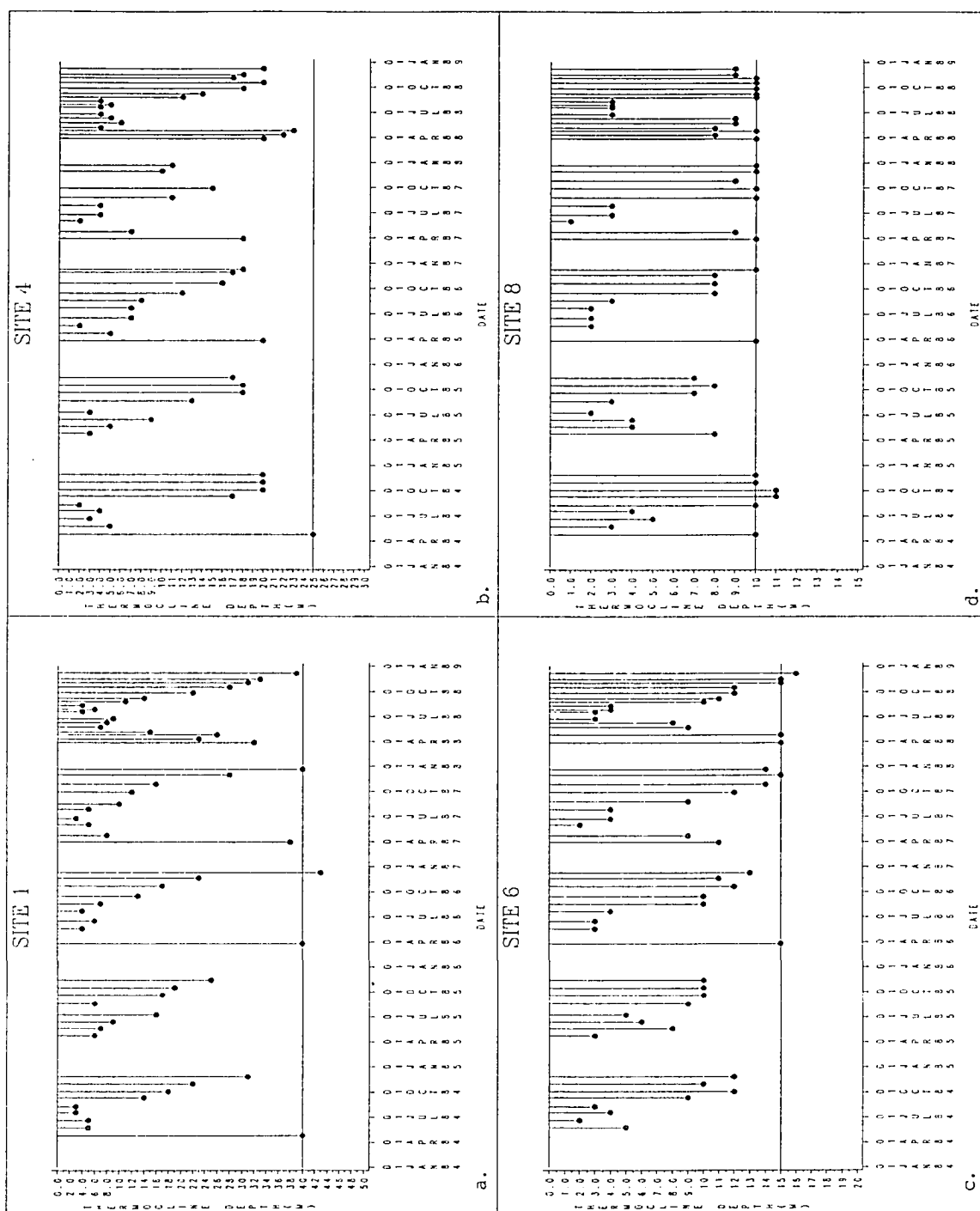


Figure 2-16. Thermocline depth (meters) as measured monthly from 1984-1987 and biweekly during 1988 for: (a) Site 1, (b) Site 4, (c) Site 6, and (d) Site 8. A reference line has been draw at the maximum depth of each site when the reservoir is at full pool elevation.



upper zone of the reservoir were significantly greater than TP concentrations in the lower zone of the reservoir during spring, summer, and fall. Overall, the upper zone sites had higher TP concentrations in the fall, while the lower zone sites exhibited higher TP concentrations in the spring. TP concentrations generally were lowest during the summer months, particularly within the reservoir's lower zone. This pattern is also illustrated in Figure 2-8.

DIN concentrations for all sites were generally highest in the spring and lowest in the summer (Figure 2-18). Spatial differences, usually being most pronounced in the fall, were noted in both the 1984-1987 monthly survey data, and the 1988 biweekly survey data. The reservoir's upper zone exhibited higher DIN concentrations in the fall during the 1984-1987 monthly survey period, and in the spring, summer, and fall during the 1988 biweekly survey period.

DIN:TP ratios were observed as being highest in the spring and lowest in either summer or fall for all sites (Figure 2-19). Significant spatial differences were only noted during the 1988 biweekly surveys, in which the reservoir's lower zone exhibited higher DIN:TP ratios than the reservoir's upper zone during the spring and fall.

Free carbon dioxide concentrations measured at each site during the 1984-1987, and 1988 monthly surveys, as well as the 1988 biweekly surveys, were generally highest in the

Figure 2-17. Seasonal spatial patterns of mean seasonal epilimnetic total phosphorus concentrations ($\mu\text{g L}^{-1}$) observed during: (a) the 1984-1987 monthly survey period, (b) the 1988 monthly survey period, and (c) the 1988 biweekly survey period. Significant differences between sites (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (sites with the same letters are significantly different). Significant differences between seasons at specific sites (rows) are noted to the right of the chart.

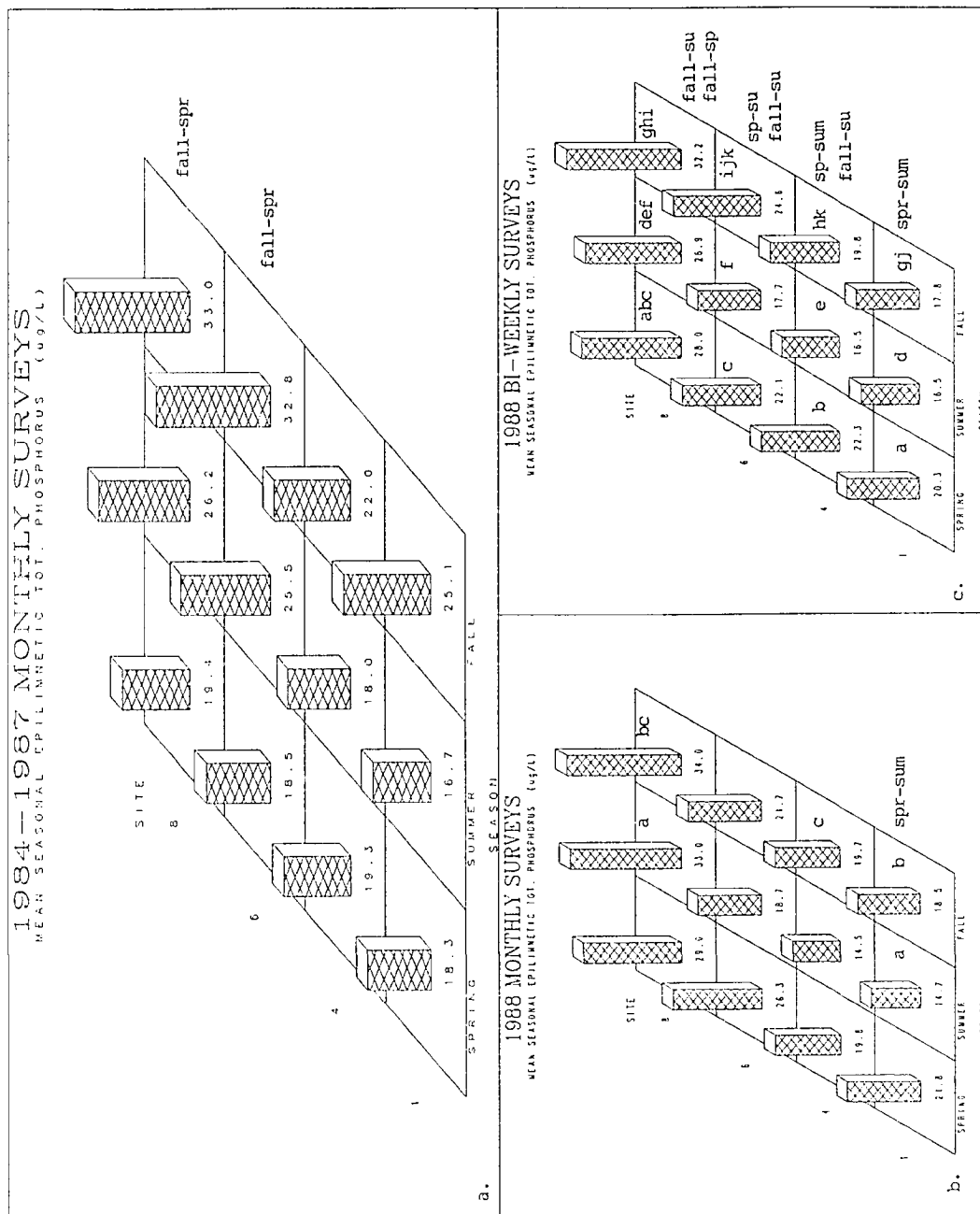
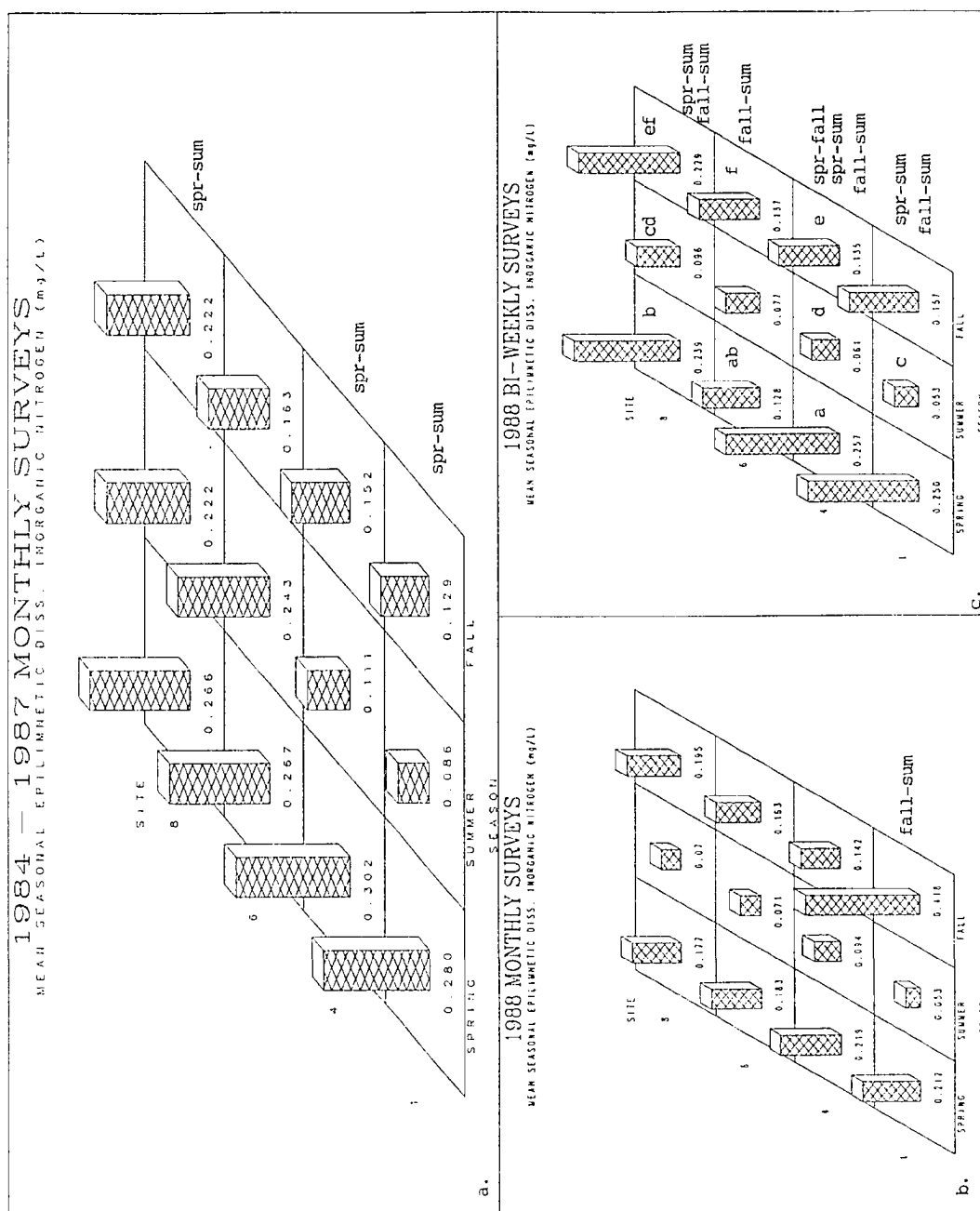


Figure 2-18. Seasonal spatial patterns of mean seasonal epilimnetic dissolved inorganic nitrogen concentrations (mg L^{-1}) observed during: (a) the 1984-1987 monthly survey period, (b) the 1988 monthly survey period, and (c) the 1988 biweekly survey period. Significant differences between sites (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (sites with the same letters are significantly different). Significant differences between seasons at specific sites (rows) are noted to the right of the chart.



fall and lowest in the summer (Figure 2-20). Significant spatial differences were noted during the fall of the 1984-1987 monthly surveys, where Site 1 exhibited greater free carbon dioxide concentrations than Site 8, and during the spring of the 1988 biweekly surveys, where Sites 4 and 8 exhibited greater free carbon dioxide concentrations than Site 1.

Reactive silica concentrations were measured monthly from 1984-1987, and seasonally during 1988. During 1984-1987, all sites generally exhibited fall and spring silica peaks with a summer silica depression (Figure 2-21). Spring and fall silica concentrations were greater than summer concentrations in 1988 as well ($n=14$, $F=136$, $p<0.0001$, and $\alpha=0.05$).

Secchi disc transparency measurements recorded during the 1984-1987 monthly surveys were greater in the lower zone as opposed to the upper zone of the reservoir during all seasons, with the highest values for Sites 1 and 4 usually being observed in the fall and the lowest values for these sites being observed in the spring (Figure 2-22). A similar pattern of greater Secchi disc measurements within the reservoir's lower zone was noted for both the 1988 monthly and biweekly survey data. However, within site seasonal variability was limited during 1988, with only Site 4 exhibiting seasonal differences, i.e., fall values being greater than spring values, during the biweekly surveys.

Figure 2-19. Seasonal spatial patterns of mean seasonal epilimnetic dissolved inorganic nitrogen (DIN):total phosphorus (TP) ratios observed during: (a) the 1984-1987 monthly survey period, (b) the 1988 monthly survey period, and (c) the 1988 biweekly survey period. Significant differences between sites (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (sites with the same letters are significantly different). Significant differences between seasons at specific sites (rows) are noted to the right of the chart.

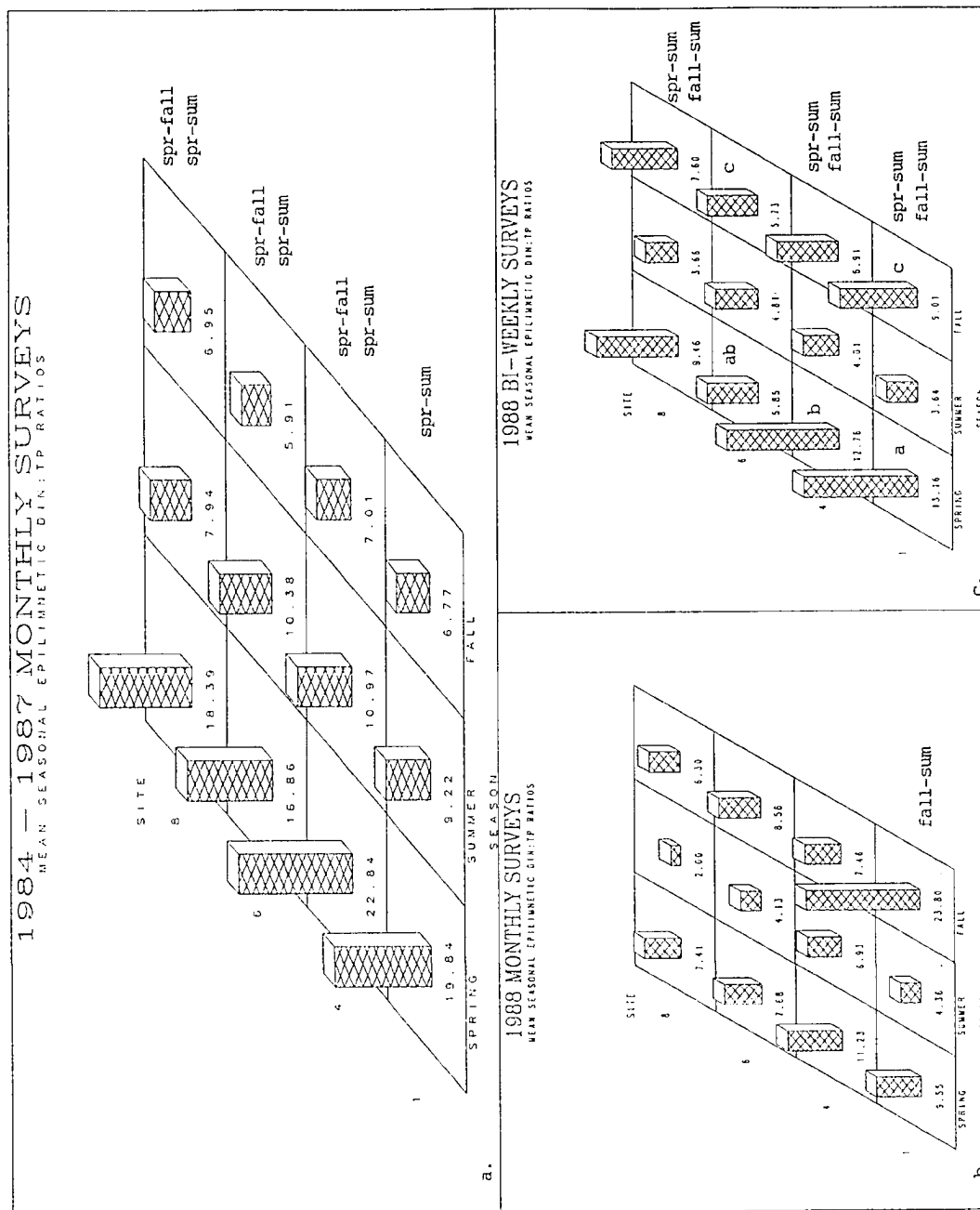


Figure 2-20. Seasonal spatial patterns of mean seasonal epilimnetic free carbon dioxide concentrations (mg L^{-1}) observed during: (a) the 1984-1987 monthly survey period, (b) the 1988 monthly survey period, and (c) the 1988 biweekly survey period. Significant differences between sites (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (sites with the same letters are significantly different). Significant differences between seasons at specific sites (rows) are noted to the right of the chart.

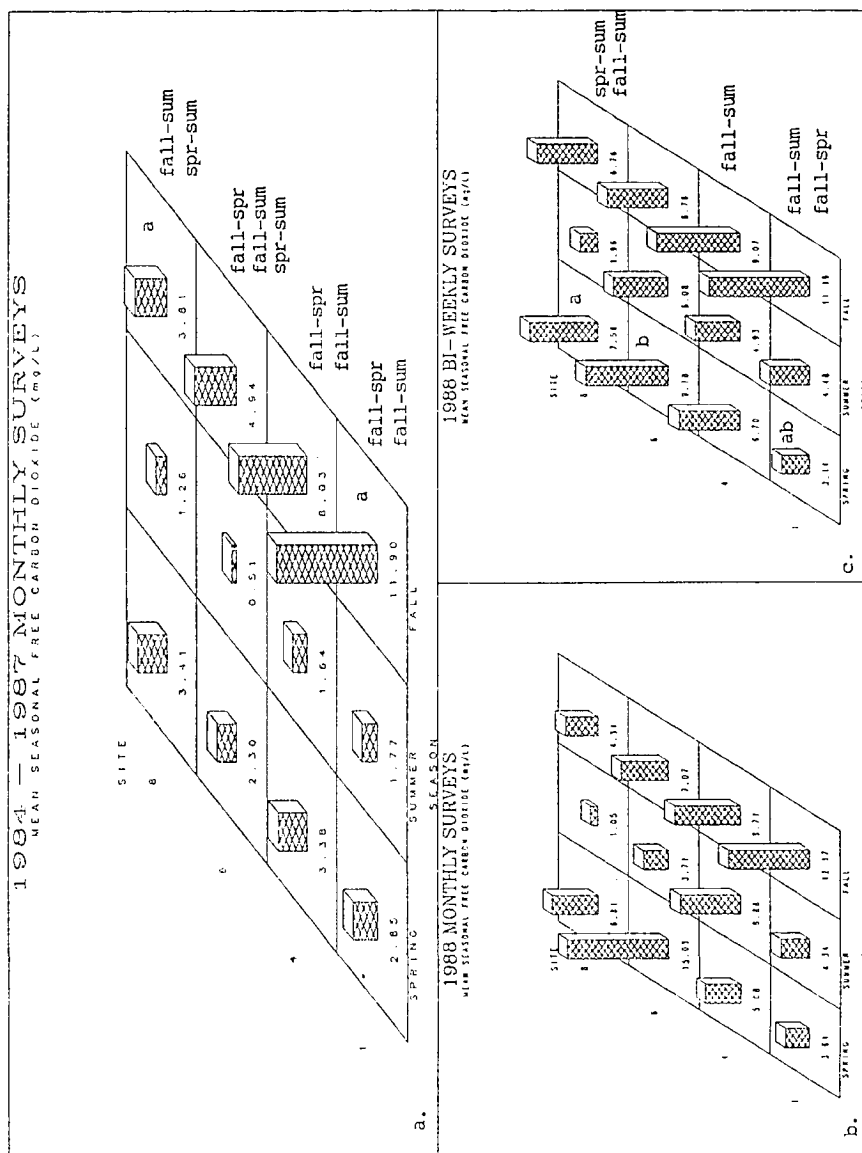


Figure 2-21. Seasonal spatial patterns of mean seasonal epilimnetic total reactive silica concentrations (mg L^{-1}) observed during the 1984-1987 monthly survey period. Significant differences between sites (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (sites with the same letters are significantly different). Significant differences between seasons at specific sites (rows) are noted to the right of the chart.

1984 - 1987 MONTHLY SURVEYS

MEAN SEASONAL TOTAL REACTIVE SILICA (mg/L)

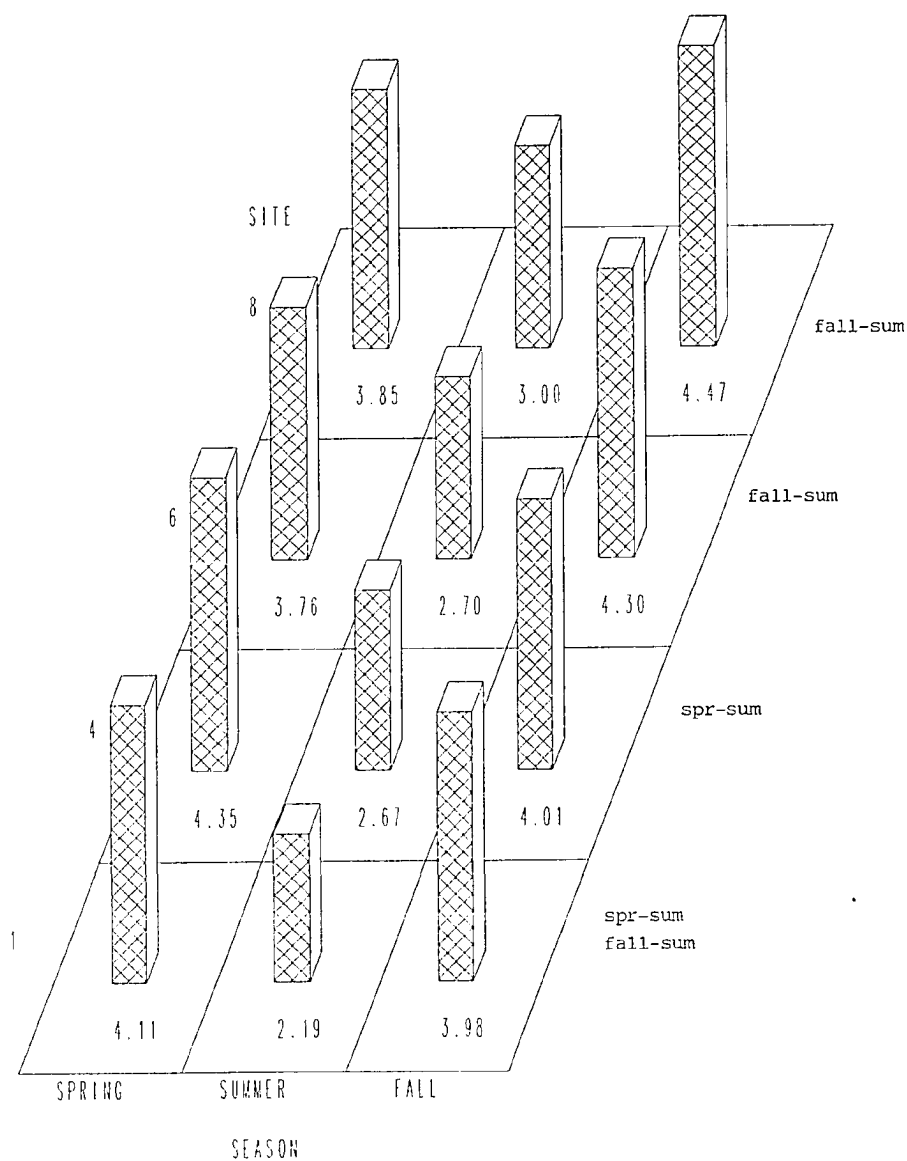
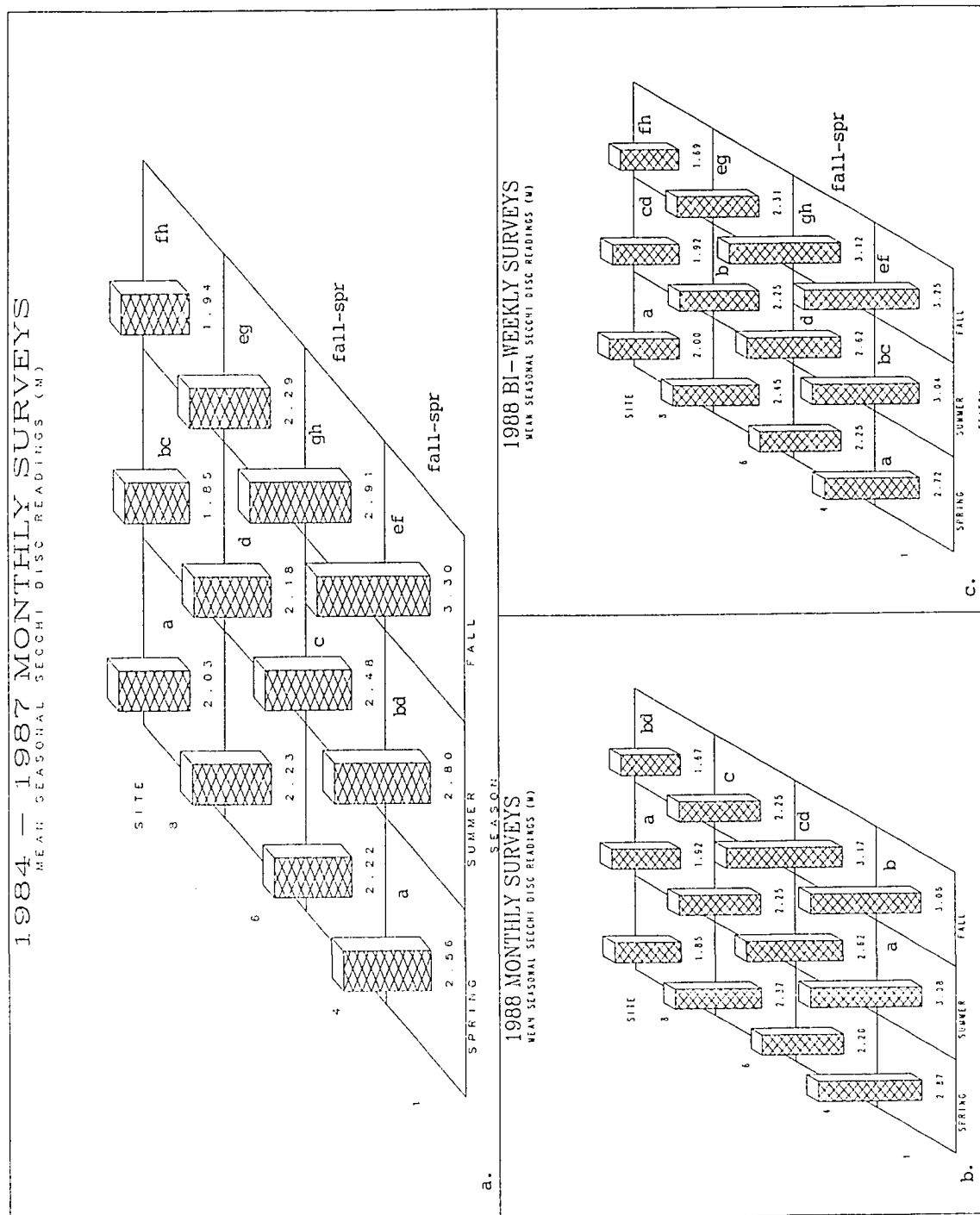


Figure 2-22. Seasonal spatial patterns of mean seasonal Secchi disc readings (meters) observed during: (a) the 1984-1987 monthly survey period, (b) the 1988 monthly survey period, and (c) the 1988 biweekly survey period. Significant differences between sites (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (sites with the same letters are significantly different). Significant differences between seasons at specific sites (rows) are noted to the right of the chart.



DISCUSSION

Croton Reservoir exhibited a longitudinal gradient from headwaters to the dam for a number of key physical and chemical variables during both the 1984-1987, and the 1988 study periods. This gradient was consistent with those described by current reservoir zonation models which depict high flow or rapidly flushed impoundments with a large, less pronounced "riverine" zone and a limited "transitional" zone (Thornton et al. 1981, Kimmel and Groeger 1984). However, Croton Reservoir failed to conform to the parameters of the "idealized" 3-zone model. Overall, the spatial and temporal physical and chemical patterns observed during 1984-1987 were confirmed in the 1988 "test year," although some of the patterns that occurred in 1988 were unique to that year. In general, the upper zone of the reservoir exhibited higher nutrient concentrations, higher values for color and turbidity, and lower transparency and light penetration measurements than the reservoir's lower zone. Seasonally, the upper zone of the reservoir exhibited higher TP concentrations in the fall, while the lower zone exhibited higher TP concentrations in the spring. The elevated TP concentration present in the upper zone of Croton Reservoir during the fall months may be attributable to the massive late summer die-off and decomposition of the dense stands of *Myriophyllum spicatum* that thrive throughout much of Muscote

Reservoir, and portions of the upper zone of Croton Reservoir. Decomposition of this macrophyte can lead to the release of significant amounts of phosphorus to the water column (Landers 1982, Smith and Adams 1986). In addition, as noted in Chapter 1, Croton Reservoir receives approximately 80% of its water input from Muscoot Reservoir. Muscoot Reservoir receives approximately 5000 kg yr^{-1} of TP from sewage treatment plant (STP) discharges within its basin (Stepczuk 1990). The combined phosphorus load generated by the macrophyte die-off and the STP's during the low flow, long residence time condition which normally exists in the fall, may explain these higher fall TP concentrations within the upper zone of Croton Reservoir. This TP gradient intensified in Fall 1988, when heavier than normal November precipitation (21.59 cm) enhanced the flushing action of Muscoot Reservoir and increased the allochthonous load of sediments and nutrients into Croton Reservoir. During this period TP was highly correlated with turbidity ($r=0.95$ $p<0.0001$) and suspended solids ($r=0.90$ $p<0.0001$), suggesting that a large component of the TP was particulate. DIN concentrations for all sites were highest in the spring and lowest in the summer, with the reservoir's upper zone generally exhibiting higher concentrations in the fall. DIN and TP were positively correlated within the upper zone of the reservoir during spring, summer, and fall ($r=0.26$, $p<0.01$), however this relationship was found to be stronger

during the fall months ($r=0.55$, $p<0.03$). All sites exhibited a somewhat weaker relationship during the spring, summer, and fall ($r=0.19$, $p<0.02$). DIN:TP ratios were highest in the spring during periods of elevated DIN levels, and lowest in the summer when DIN became depleted. Greatest Secchi disc transparency was observed in the fall within the reservoir's lower zone. Mixing of the entire water column occurred more frequently within the upper zone of the reservoir as opposed to the lower zone, i.e., Site 1 was isothermal on 12% of all sampling dates, whereas Site 8 was isothermal on 60% of all sampling dates.

Hydraulic Residence Time Effects

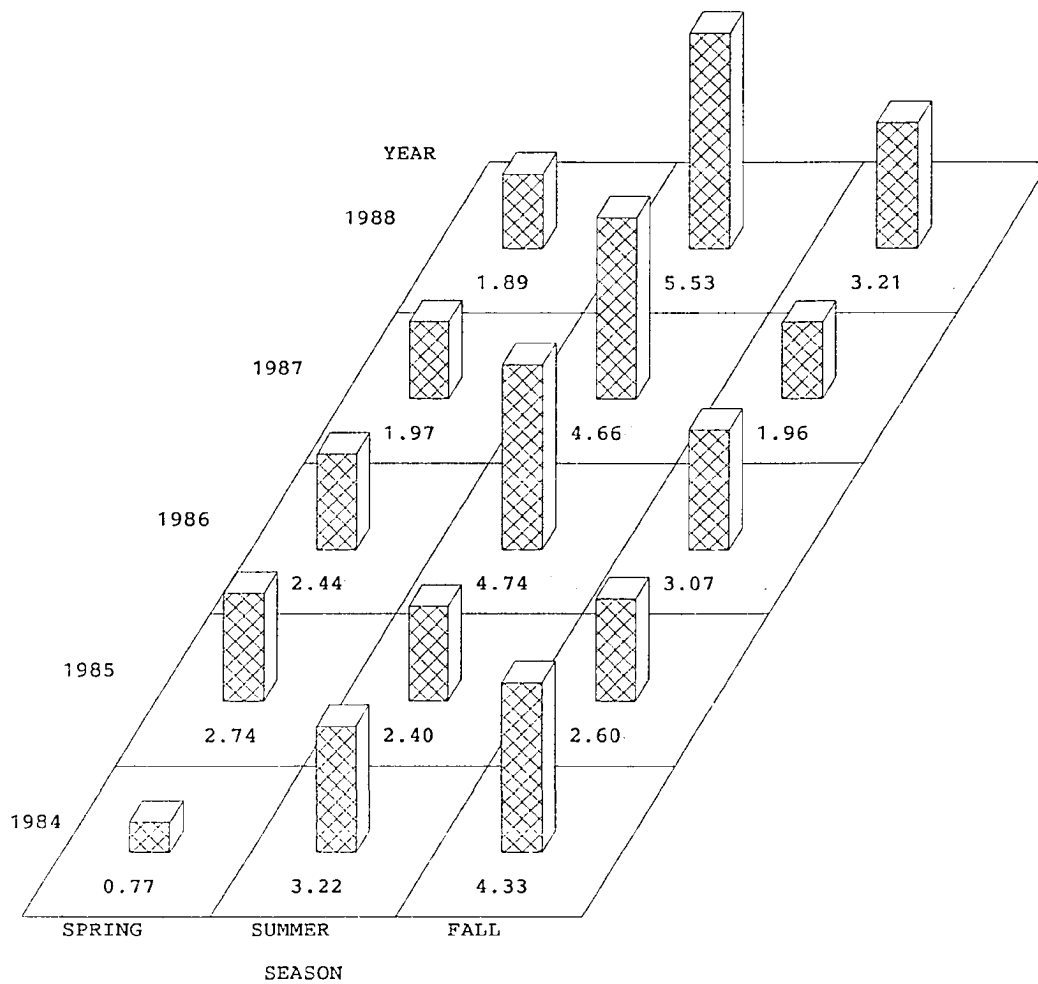
Although, the patterns described above were evident during the 1984-1987 sampling period, and further confirmed during 1988, the longitudinal gradients of abiotic factors detected within the impoundment during the 1988 sampling period were more pronounced than those noted during 1984-1987. This was particularly true for TP concentrations and Secchi disc transparency measurements. Kennedy and Walker (1990) noted that maximum gradients would tend to develop in reservoirs with long residence times, high sedimentation rates (high TP retention), and advectively dominated flow regimes. Minimum gradients would tend to develop in reservoirs with short residence times, low sedimentation rates, and dispersive flow regimes. They also indicated that

reservoirs tend to have shorter hydraulic residence times, which may require reservoir nutrient budgets to be based on seasonal as opposed to annual time scales. Figure 2-23 illustrates seasonal hydraulic residence times by year for Croton Reservoir. Residence time was longest in the summer, and shortest in the spring ($F=33.69$, $p<0.0001$, $n=190$; *summer>fall>spring at alpha=0.05*). An analysis of summer residence times revealed that 1986, 1987, and 1988 had significantly greater residence times than 1984 and 1985, and that 1988 exhibited the longest summer residence time of all years. This longer residence time in 1988 may have contributed, most likely through the process of increased sedimentation rates, to the pronounced TP and Secchi disc longitudinal gradient present within the impoundment during that year.

A number of other significant residence time-abiotic factor relationships were noted during the five year survey period. Light penetration measurements were found to be positively correlated with summer hydraulic residence time within the upper zone of the reservoir (compensation depth: $r=0.89$, $p<0.03$). Lower zone Sites 1 and 4 exhibited a similar relationship for all months that surveys were performed (Secchi disc: $r=0.24$, $p<0.02$; compensation depth: $r=0.30$, $p<0.03$). These results suggest that increased residence time may play a role in increasing both zonal sedimentation rates and photic zone depths, particularly in

Figure 2-23. Seasonal hydraulic residence times measured in months during the 1984-1988 study period.

1984 – 1988 SEASONAL HYDRAULIC RESIDENCE TIMES (MONTHS)



the reservoir's upper zone. It was also noted that DIN concentrations were negatively correlated with hydraulic residence time values (or positively correlated with flushing rate) in the upper zone of the reservoir for all survey months ($r=-0.48$, $p<0.0001$). This relationship was even more pronounced during the fall months ($r=-0.79$, $p<0.0008$). These results are expected since epilimnetic DIN would most likely become depleted during the low flow period of late summer stratification. Allochthonous input of DIN is often limited during periods of decreased flushing, and most water column DIN would be exhausted by abundant phytoplankton populations. Such conditions are ideal for the development of cyanobacteria populations, particularly when TP concentrations remain above 10 ug L^{-1} (Reckhow 1988, Morris and Lewis 1988).

Yearly Patterns

In addition to the unique spatial patterns observed in 1988 for TP and Secchi disc transparency, some significant differences between years were also observed for DIN, reactive silica, and CO_2 concentrations. Both DIN and silica concentrations were significantly greater in 1986 than in other years. Both of these variables had higher than normal spring peak concentrations during 1986. These peaks were most likely attributable to the increased runoff generated

during the reservoir's recovery from the preceding year's drought condition. The reservoir's volume increased from 71% in November of 1985 to 100% in March of 1986. Silica also has a higher than normal spring peak concentration in 1984. Similarly, this peak was most likely the result of the increased runoff contributed to the reservoir from the abnormally high levels of precipitation which occurred during March, April, and May of that year. Free carbon dioxide concentrations were greater in 1988 than in all other years. Upon further analysis it was noted that alkalinity values were significantly higher in 1988 than in all years but 1985 ($F=18.42$, $p<0.0001$, $n=216$, and $\alpha=0.05$), and pH values were significantly lower in 1988 than in all years but 1984 ($F=5.11$, $p<0.0006$, $n=220$, and $\alpha=0.05$). In addition, alkalinity values were found to be greatest in the fall and lowest in the spring ($F=22.87$, $p<0.0001$, $n=216$, and $\alpha=0.05$). The combination of low pH and high alkalinity values would account for the higher free carbon dioxide concentrations observed during 1988. The underlying process responsible for the low pH and high alkalinity values observed in 1988 is unclear, and warrants further investigation.

Depth Effects

Results obtained from the analysis of the multiple depth sampling data collected during the biweekly surveys of 1988 revealed that, with the exception of free carbon dioxide, no significant differences with depth within the epilimnion of Croton Reservoir, were noted for TP, $\text{NH}_3\text{-N}$, $\text{NO}_2\text{+NO}_3\text{-N}$, TN, DIN, alkalinity, and dissolved oxygen for depths above 9 meters. Concentrations of dissolved oxygen, $\text{NO}_2\text{+NO}_3\text{-N}$, and DIN measured at 9 meters were found to be significantly different than concentration measured at some of the shallower depths. These differences were only apparent during the summer months at Sites 6 and 8. These higher concentrations measured at the 9 meter depths of the shallower sites were most likely attributable to the upwelling of the nutrient rich hypolimnia and associated sediments present at each of these sites.

It was also noted that dissolved oxygen concentrations were significantly lower at the 9 meter depth during the summer months. This was most likely the result of the effects of summer thermal stratification and the gradual depletion of oxygen concentrations below the thermocline.

Free CO_2 concentrations did significantly differ with depth, with concentrations generally increasing with depth during both the spring and summer months. This was expected, since CO_2 concentrations are a function of pH, temperature,

and alkalinity, some of which vary with depth.

Based upon the analysis of the patterns of concentration with depth described above it was concluded that, with the exception of CO₂, physical-chemical measurements made at depths less than 9 meters would be representative of epilimnetic concentrations. Differences among sites for single epilimnetic samples were assumed to be due to true epilimnetic differences in chemical concentrations over time, and that differences in chemical concentrations with depth were not significant. Therefore, all analyses of epilimnetic chemical concentrations were adjusted accordingly; only sample depths less than 9 meters were used in statistical analyses concerning epilimnetic physical-chemical constituents measured during 1984-1987, and 1988.

Sampling Frequency

With the exception of NH₃-N and DIN concentrations, analyses performed at the monthly intervals seemed to adequately describe the physical and chemical spatial patterns occurring within the epilimnion of Croton Reservoir. Overall, the spatial patterns observed in the 1988 biweekly data, were also apparent in the 1988 monthly data. In most cases, the biweekly sampling tended to

highlight the trends already apparent in the monthly data, primarily through increased sample size. However, as mentioned above, monthly sampling during 1988 failed to uncover spatial patterns concerning TP, $\text{NH}_3\text{-N}$, and DIN concentrations that were detected by the biweekly sampling. This is what one might expect to find since certain transitory nitrogen species have consistently demonstrated greater seasonal variability than other physical and chemical variables throughout the five year study period. In addition, although seasonal trends were noted upon the analysis of the 1984-1987 monthly survey data, i.e., all four years grouped together, seasonal differences were not adequately described by the 1988 monthly survey data alone. Temporal patterns for CO_2 concentrations, TP concentrations, Secchi disc transparency, DIN:TP ratios, and DIN concentrations detected within the 1988 biweekly survey data, were not revealed upon analysis of the 1988 monthly survey data. These results suggest that sampling performed at monthly intervals may not be adequate when it comes to detection of seasonal patterns of physical and chemical factors on an annual basis. Biweekly sampling could possibly be utilized during transitional periods such as April - May and October-November, with sampling at monthly intervals being used at all other times. Future sampling efforts should take these observations into account, and make the appropriate design modifications .

Significant differences detected between the four sites for key physical and chemical variables for both the 1984-1987 and the 1988 survey periods indicated that the information collected from the four sample sites was necessary to adequately describe the longitudinal gradient of abiotic factors within Croton Reservoir. Therefore, future water quality sampling surveys of Croton Reservoir should include at least these four sample locations if the spatial and temporal heterogeneity of abiotic factors is to be adequately assessed.

CONCLUSION

Croton Reservoir exhibited a longitudinal gradient from headwaters to dam for a number of key physical and chemical variables during both the 1984-1987, and the 1988 study periods. This gradient was consistent with those described by current reservoir zonation models which depict high flow or rapidly flushed impoundments with a large, less pronounced riverine zone and a limited transitional zone. However, the reservoir failed to conform to the "idealized" parameters of the 3-zone model. With the exception of DIN concentrations, nutrient concentrations were always measured above detection levels. The upper zone of the reservoir exhibited higher nutrient concentrations, higher values for color and turbidity, lower transparency and light

penetration measurements, and experienced greater mixing than the reservoir's lower zone.

Seasonally, the upper zone had higher TP concentrations in the fall, while the lower zone exhibited higher TP concentrations in the spring. DIN concentrations for all sites were highest in the spring and lowest in the summer, with the reservoir's upper zone generally exhibiting higher concentrations in the fall. DIN:TP ratios were highest in the spring, during periods of elevated DIN levels, and lowest in the summer when DIN became depleted (at or below the limit of detection) . Although TP concentrations varied, TP was always present above detection levels, and never appeared to be limiting. The same was true for reactive silica, and free carbon dioxide concentrations.

Greatest Secchi disc transparency was observed in the fall within the reservoir's lower zone. Mixing of the entire water column occurred most frequently within the upper zone of the reservoir.

Overall, the spatial and temporal physical and chemical patterns observed during 1984-1987 were confirmed in 1988, although some of the patterns that occurred in 1988 were unique to that year.

The longitudinal gradients of abiotic factors detected within the impoundment during the 1988 sampling period were more pronounced than those noted during 1984-1987. This was particularly true for TP concentrations and Secchi disc

transparency measurements. The longer hydraulic residence time which occurred during the summer of 1988, i.e., the longest residence time of all summers during the five year study period, and the heavier than normal November precipitation, most likely contributed to these pronounced gradients.

The multiple epilimnetic depth sampling which was performed biweekly during 1988 revealed that there were no significant differences with depth for TP, $\text{NO}_2 + \text{NO}_3\text{-N}$, $\text{NH}_3\text{-N}$, TN, DIN, alkalinity, and dissolved oxygen for depths above 9 meters. Differences among sites for single epilimnetic samples were assumed to be due to true epilimnetic differences in chemical concentrations over time, and that differences in chemical concentrations with depth were not significant.

A comparison of the 1988 monthly to biweekly sampling frequencies revealed that monthly intervals may not have been adequate for the detection and accurate description of seasonal patterns of physical and chemical factors on an annual basis. It was also determined that the four sample sites utilized in this study were the minimum number of sample stations necessary to adequately assess the spatial and temporal heterogeneity of abiotic factors which occurred along the longitudinal axis of Croton Reservoir.

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CHAPTER 3

**Distribution of Algal Biomass Within Croton
Reservoir, New York**

ABSTRACT

The spatial heterogeneity and temporal variability of algal biomass was studied in Croton Reservoir, New York, initially from 1984-1987, and more intensively during 1988. The reservoir exhibited a longitudinal gradient of algal biomass from headwater to dam during both the 1984-1987, and the 1988 study periods. The spatial and temporal algal biomass patterns observed during 1984-1987 were confirmed in 1988, although some of the patterns that occurred in 1988 were unique to that year. Algal abundance was generally greatest within the upper zone of the reservoir during the fall months, although during 1988 both a summer and a pronounced fall algal biomass gradient was observed. The impoundment only conformed to the general biomass zonation model proposed for reservoirs during the summer-fall period of increased hydraulic residence time. Results from multiple depth epilimnetic sampling which was performed biweekly in 1988 suggested that there were no significant differences with depth for chlorophyll a at depths above nine meters. A comparison of the 1988 monthly to biweekly sampling frequencies revealed that monthly sampling intervals were inadequate for detecting seasonal patterns of algal biomass when such patterns were being analyzed on an annual basis. The patterns of correlation between algal biomass and abiotic and biotic factors varied both spatially and

temporally within the impoundment during both the 1984-1987 and 1988 study periods. Multiple regression analysis demonstrated that both silica and total nitrogen (TN) concentrations were important in explaining the variability in annual chlorophyll a concentrations, with TN being more important during the growing season (July-October). Algal light attenuation effects were most pronounced in the lower zone of the reservoir during both the growing season and the fall periods. Total phosphorus (TP) concentrations were most important in explaining the variability in algal abundance at all sites during the fall of 1988. Zooplankton biomass, explained the greatest amount of variability in epilimnetic chlorophyll a concentrations within the reservoir's lower zone, thus suggesting that phytoplankton losses by grazing may have been most important within the reservoir's lower zone. Hydraulic residence time and reservoir volume may have played an important role in determining both the abundance and the composition of the phytoplankton within the impoundment during the five year study period. The impoundment essentially behaved as a rapidly flushed nutrient-rich system which occasionally exhibited longitudinal algal biomass gradients due to the combined sequential effect of increased residence time during the growing season coupled with intense fall precipitation and reservoir destratification.

INTRODUCTION

Numerous studies have noted that reservoirs tend to occupy an intermediate position between rivers and lakes, and are often described as "river-lake hybrids" (Lind 1971; Henderson et al. 1973; Ryder et al. 1974; Margalef 1975; Ryder 1978; Goldman and Kimmel 1978; Thornton et al. 1981; Jenkins 1982; Benson 1982). As a result, impounded rivers often exhibit longitudinal gradients of both biotic and abiotic factors. Thornton et al. (1981) developed a conceptual model of reservoirs which described the spatial heterogeneity of the physical, chemical, and biological conditions found within impoundments, and proposed that reservoirs consist of three longitudinal zones, i.e., riverine, transitional, and lacustrine. The riverine zone is narrow, has a channelized basin, high flow, high turbidity, low light availability, light limited primary production, and is more eutrophic in character. The transitional zone is a broader deeper basin with reduced flow, less turbidity, a reduced nutrient supply, and exhibits mesotrophic characteristics. The lacustrine zone is broad and deep, has little flow, nutrient limited primary production, greater light penetration, and is more oligotrophic in character.

Kennedy and Walker (1990) indicated that the boundaries between the riverine, transitional, and lacustrine zones are often difficult to delineate and

temporally unstable. They also noted that an advective flow regime in combination with a long, narrow basin morphology often results in the spatial variability of nutrient related processes and the establishment of gradients from headwater to dam.

Longitudinal Algal Biomass Gradients

Thornton et al. (1982) discovered that DeGray Lake, Arkansas, exhibited marked longitudinal and vertical algal biomass variations on two of three seasonal sampling dates. Spatial variability of chlorophyll was measured via 15 transects located along the longitudinal axis of the reservoir. They found that epilimnetic chlorophyll a concentrations, while decreasing in a downstream direction in July and October, were lower and similar for all transects during the January sampling. Differences among transects were most pronounced in the upper region of the reservoir nearest the tributary inflows. Differences among transects from mid-reservoir to dam, when they existed, were minimal.

Pickett and Harvey (1988) assessed the spatial and temporal variability of chlorophyll a in Moultrie and Marion Lakes (the Santee-Cooper Lakes) of South Carolina. They found that chlorophyll concentrations were at a minimum during the winter, due to low temperature, low levels of

incident light, and increased turbidity. During the growing season, chlorophyll levels increased through the spring and summer, with an ultimate peak in September. Spatially, chlorophyll levels were homogeneous in Lake Moultrie, and heterogeneous in Lake Marion. Lake Marion's chlorophyll concentrations increased with distance downstream, reaching peak values at mid-pool. They concluded that differences in reservoir morphometry and hydrology explain the occurrence of pronounced longitudinal gradients in Lake Marion and the lack of longitudinal gradients in Lake Moultrie. As in similar reservoirs, the long, dendritic nature of Lake Marion, accompanied by high sedimentation rates and an advective regime, is conducive to the establishment of chemical and biological gradients.

Brown et al. (1986) noted consistently higher concentrations of phytoplankton in the two tributary arms to Cannonsville Reservoir, in Delaware County, N.Y. A clear gradient in chlorophyll a concentration was observed in the West Branch arm of the reservoir during the 1980 summer sampling period. A similar, but less severe gradient was noted in the other tributary arm (Trout Creek) of the reservoir. During 1980, mean summer chlorophyll a concentrations ranged from 69 ug/L in the upper West Branch arm of the reservoir to 20 ug/L near the dam outlet. Over the 2.5 year sampling period, the authors noted that although the pattern of phytoplankton species succession did

not appear to vary spatially, levels of phytoplankton biomass were quite variable through the reservoir and from year to year.

Temporal Variability of Algal Biomass

Most north temperate lakes experience an annual bimodal distribution of phytoplankton biomass. The seasonal pattern usually consists of a spring peak followed by a summer depression with the subsequent development of a less pronounced autumn peak, followed by low biomass levels throughout the winter (Hutchinson 1967). Marshall and Peters (1989) critically evaluated this seasonal cycle generality by analyzing a chlorophyll a time series from 56 north-temperate lakes and reservoirs. Their results confirmed the findings of others (Knowlton et al. 1984; Walmsley 1984; Walker 1985) which indicated that there exists a strong positive relationship between the mean chlorophyll a concentration and temporal (seasonal), variance, and that this relationship implies that temporal variation is greater in eutrophic lakes than in oligotrophic lakes. Sommer (1986) noted that eutrophic lakes developed well-differentiated spring and fall blooms in phytoplankton biomass, whereas oligotrophic lakes exhibited reduced spring blooms with occasional fall blooms. Lund (1978) observed that weekly plots of algal biomass from Blelham Tarn (1945-

1980) indicated that, as nutrient loading increased, spring and particularly fall blooms became more consistent and pronounced. During this 35 year period the trophic status of the tarn changed from mesotrophic to eutrophic. Marshall and Peters (1989) noted that these findings suggest that differences in floristic composition occur along a trophic gradient for longitudinal as well as cross-sectional data.

The purpose of this study was to investigate the existence of a longitudinal gradient of algal biomass from headwater to dam within Croton Reservoir, and to determine whether the reservoir conformed to the conceptual reservoir longitudinal zonation models proposed by Thornton et al. (1981), and Kimmel and Groeger (1984). Preliminary patterns of spatial heterogeneity and temporal variability of the phytoplankton abundance present within the reservoir were first studied from 1984 to 1987, and further evaluated during 1988. Zooplankton biomass information was gathered monthly during 1986 and 1987, and biweekly during 1988 to assess the impact of grazing upon algal biomass levels within different reservoir zones. Additional information concerning the hydrology and physiography of Croton Reservoirs and the spatial and temporal variability of the physical and chemical processes occurring within the impoundment were also evaluated during these time periods (Chapter 1 and Chapter 2). These data were reviewed in conjunction with the spatial and temporal algal biomass

information in an effort to discover possible cause and effect relationships. However, since this study was based entirely on observational data, causal assumptions were made cautiously.

The findings from this study were directly applicable to the management of Croton Reservoir as a drinking water supply, and provided a foundation for future research regarding the water quality impacts associated with the spatial and temporal variability of phytoplankton abundance as it occurs within the impoundment.

STUDY AREA

Croton Reservoir is the final receiving reservoir of the Croton River. The impoundment is located in southeastern New York State ($41^{\circ} 13' 39''$ N, $73^{\circ} 51' 27''$ W), and lies 59.6 meters above mean sea level. The reservoir has a surface area of $9.13 \times 10^6 \text{ m}^2$, a volume of $90.77 \times 10^6 \text{ m}^3$, and a mean and maximum depth of 9.9 and 36.6 m, respectively. The effective drainage area of the impoundment is $152.80 \times 10^6 \text{ m}^2$, although the reservoir ultimately receives drainage from the entire Croton watershed which has a total drainage area of $971.30 \times 10^6 \text{ m}^2$. The effective $A_d:A_o$ ratio for the reservoir is 16.70, whereas the Croton Watershed $A_d:A_o$ ratio for the reservoir is 106.40. Croton Reservoir has a dendritic shoreline development index of 4.9 which is

typical of a flooded river valley caused by either natural or artificial damming (Hutchinson 1957). The reservoir is owned and operated by the City of New York, and supplies the City with approximately 10-15% of its annual drinking water supply needs. A more detailed description of the study area is contained within Chapter 1.

METHODS AND MATERIALS

Water samples were collected and analyzed for key chemical, physical, and biological variables, and field surveys were performed monthly during the ice-free season (March-December) from 1984 through 1987 at four sites located along the longitudinal axis of Croton Reservoir from the headwaters to the dam. These four sites were chosen because they were thought to represent zones of differing flow regimes in the impoundment, i.e., riverine, transitional, and lacustrine. Sites 1, 4, 6, and 8 were located 0.23, 3.95, 6.50, and 12.00 kilometers from the dam respectively. The sampling design and analytical matrix of this study were based upon a eutrophication assessment program developed by the Organization for Economic Cooperation (OECD 1982). This program was designed to quantify the relationship between nutrient load in waters and their trophic reaction.

In addition to the monthly surveys performed during 1984-1987 and continued in 1988, more intensive biweekly sampling was carried out in 1988. These biweekly surveys consisted of multiple depth sampling (1, 3, 5, 7, and 9 meter intervals) at each of the four sampling locations. Results obtained from the 1988 monthly and biweekly surveys allowed for both a further refinement and evaluation of the monthly testing performed during 1984-1987, and a confirmation of the spatial and temporal patterns observed during that same period. The dates sampling was performed during the five year study period are listed in Chapter 2.

For each of the monthly surveys, epilimnetic water samples, as determined by prior *in situ* measurements of the thermocline and photic zone depths, were collected from each of the sites with a 2.2 liter acrylic Van Dorn sampler at each site and brought back to the laboratory for analysis. For each of the 1988 biweekly surveys, water samples were collected with a Van Dorn sampler at the multiple epilimnetic depths described above, and brought back to the laboratory for analysis as well. Vertical profiles of temperature, pH, and dissolved oxygen were measured *in situ* using a Hydrolab Surveyor II (Hydrolab Corp., Austin, Texas). Physical and chemical analyses were performed as outlined in Chapter 2.

Chlorophyll *a* was determined spectrophotometrically by the trichromatic method after filtration through a 0.45 μm

membrane filter followed by acetone extraction without maceration or phaeophytin correction (Parsons et al. 1984, Jones and Lee 1982). This procedure, originally begun in 1984, was adhered to throughout the five year study period (1984-1988) to preserve database continuity, despite certain deficiencies mentioned below. The lack of employing cell maceration during the extraction procedure may have contributed to an underestimation of algal chlorophyll content, particularly with respect to the cyanobacteria.

Total phytoplankton counts were determined following a method described in Standard Methods (1955, 1965). This method, or some modification of it, has been used by the New York City Water Supply Laboratories, as well as many other water supply laboratories located in the United States, since the early 1900's. During the 1984-1988 study period, water samples collected from the reservoir were immediately transported to the laboratory where a subsample was concentrated by means of a Sedgwick-Rafter sand filter. One milliliter of the concentrate was placed in a Sedgwick-Rafter counting cell and enumeration of the organisms was made with the aid of a Nikon phase-contrast microscope fitted with a Whipple ocular micrometer at a magnification of 100X. Algae were identified to genus and quantitative records for each genus, major class, and total number present were recorded. Enumeration was made in standard areal units (s.a.u.), where one s.a.u. equaled 400 square

microns. The use of low magnification (100X) coupled with the sand concentration technique used in this method, undoubtedly result in a significant loss of the algal cell units recorded during the enumeration process, and may have led to an underestimation of actual phytoplankton values. It has been well documented that many waters contain a larger volume of minute nanoplankton than of the larger forms readily seen under low magnification (Palmer and Maloney 1954). Nevertheless, the s.a.u. method has historically been the preferred algal enumeration method by water supply utilities since it has helped in the past to determine the most effective time for treating a reservoir with an algicide (Whipple 1948). The total area of algae present, particularly diatoms, was useful information for determining the relationship of plankton to the length of water treatment plant filter runs (Palmer 1959). The City of New York Bureau of Water Supply has continued using the standard areal unit enumeration method, as opposed to direct cell counts, for two reasons: (1) to preserve continuity in its long-term phytoplankton database; and (2) it was generally believed the standard areal unit counting method adequately measured total algal biomass and characterized floristic composition. Since the objective of this study was to characterize the spatial and temporal variability of algal biomass within the reservoir, it was determined that the standard areal unit method of phytoplankton enumeration

would adequately describe the relative biomass of phytoplankton classes present over time and space, and that little additional information would be gained by converting from areal units to cell counts. Such a conversion would be possible since phytoplankton cell surface area is directly related to cell volume (Reynolds 1984), however, it would nevertheless be difficult procedure to implement since it would require the collection of a large amount of coincident phytoplankton cell count data on a species level over time for comparative purposes. These temporal collections would be necessary since cell dimensions of a phytoplankton species can vary greatly from season to season (Wetzel and Likens 1979).

The different time periods referred to in this chapter are as follows: spring: March-June; summer: July-September; fall: October-December; and growing season: July-October. The growing season period was used in the analysis of hydraulic residence time effects upon algal biomass since it was observed as being a period of great biological importance within Croton Reservoir. During this period the impoundment generally exhibited pronounced thermal stratification, light penetration, phytoplankton accumulation, and shifts in phytoplankton composition.

Beginning in 1986, zooplankton collection was performed at Sites 1, 4, and 8 during each monthly survey. In 1988 zooplankton collection was performed biweekly at Sites 1, 4,

6, and 8. Collection was performed by vertical hauls through the water column with a 62 μ m mesh Nitex net. The animals were preserved in 70% ethanol, and later counted, identified, and measured (Wetzel and Likens 1979). Zooplankton biomass was determined by the methods described by McCauley (1984), and Lawrence et al. (1987).

All statistical analyses were performed using the Statistical Analysis System (SAS Institute Inc., Version 6.04, 1988). All variables subjected to parametric statistical analysis were examined for normal distributions. Chlorophyll a concentrations, total and class phytoplankton counts, and total zooplankton biomass concentrations were normally distributed when transformed to natural logarithms. Analysis of variance with the Tukey-Kramer multiple comparison method was used to test for significant differences ($p < 0.05$, unless noted otherwise) between spatial and temporal biotic patterns observed in the reservoir during the five year study period. Before performing stepwise regression procedures data were subjected to correlation, regression, and principal component analysis to detect and remediate multicollinearity, i.e., eliminate or identify those variables from the regression model which measured similar phenomena. A procedure described by Freund and Littell (1986) was followed.

RESULTS

Spatial Patterns

Monthly Surveys

Chlorophyll a concentrations were found to be significantly different in site by site comparisons during both the 1984-1987 and the 1988 survey periods. Sites 6 and 8 both exhibited higher chlorophyll a concentrations than Site 4 in 1984-1987, and Site 8 exhibited greater chlorophyll a concentrations than Site 1 in 1988 (Table 3-1). No significant ($p=0.05$) spatial difference were noted for total phytoplankton counts in either time period.

The overall spatial pattern that emerged from the 1984-1987 monthly algal biomass data was one of greater chlorophyll a concentrations in the upper zone of the reservoir (Sites 6 and 8 being greater than Sites 1 and 4). This pattern was further confirmed in 1988, with all chlorophyll a concentrations appearing higher in comparison to the 1984-1987 period.

Biweekly Surveys

Table 3-2 lists the summarized results for chlorophyll a multiple depth epilimnetic measurements as reported biweekly for 1988. Significant spatial differences in chlorophyll a concentrations were noted between upper zone

Table 3-1. Summarized results for single depth epilimnetic chlorophyll a concentrations ($\mu\text{g L}^{-1}$) and total phytoplankton counts (standard areal units ml^{-1}) as reported monthly for the 1984-1987 and 1988 time periods. Means, lower and upper 95% confidence intervals, and sample size (n) are listed for each variable. Means with the same letter superscript, or means without superscript notation listed, are not significantly different (as determined by the Tukey-Kramer multiple comparisons test, $p=0.05$).

Site	Chlorophyll <u>a</u>	Total Phytoplankton
<u>1984-1987</u>		
1	5.18 (4.71, 7.17) (37) ^{ab}	796 (626, 1012) (37)
4	5.26 (4.18, 6.62) (42) ^a	657 (503, 846) (41)
6	7.77 (6.36, 9.21) (38) ^b	854 (633, 1153) (38)
8	7.54 (6.30, 9.03) (49) ^b	1022 (804, 1300) (48)
<u>1988</u>		
1	8.17 (5.67, 11.76) (15) ^a	1480 (1070, 2049) (16)
4	8.67 (5.21, 14.44) (10) ^{ab}	1130 (620, 2059) (11)
6	12.81 (7.17, 22.87) (9) ^{ab}	1652 (1002, 2724) (9)
8	17.64 (10.80, 28.79) (9) ^b	1978 (1274, 3072) (10)

sites and lower zone sites (Site 8>Sites 1, and 4; and Site 6>Site 1). Trends evident in both the 1984-1987 and 1988 monthly survey data were more pronounced in the 1988 biweekly survey data, with the reservoir's upper zone exhibiting higher chlorophyll a concentrations than the reservoir's lower zone.

Depth Analysis

Table 3-3 presents the summarized results listed by depth for chlorophyll a as reported biweekly from March to December 1988 for Sites 1, 4, 6, and 8. No significant "within site" differences between mean annual (all sampling dates combined) chlorophyll concentrations with depth were detected at any site. However, when all sites were grouped together, analysis of variance revealed a significant difference in chlorophyll a concentration with depth ($F=3.33$, $p<0.01$, $n=249$), with 9 m chlorophyll a concentrations being less than 1 m, 3 m, and 5 m concentrations. Chlorophyll a concentrations at Sites 1 and 4 were homogeneous at all depths during spring, summer, and fall (Figure 3-1). However, Site 6 had lower chlorophyll a concentrations at 9 m than at 1, 3, 5, and 7 m during the summer, and Site 8 had lower chlorophyll a concentrations at 9 m than 1 m during the summer (Figure 3-2). Figures 3-3, 3-4, and 3-5 present the information contained in Figures 3-1 and 3-2 from a different perspective. Each Figure

Table 3-2. Summarized results for chlorophyll a ($\mu\text{g L}^{-1}$), multiple depth epilimnetic measurements as reported biweekly for 1988 from March to December. Means, lower and upper 95% confidence intervals, and sample size are listed. Means with the same letter superscript are not significantly different (as determined by the Tukey-Kramer multiple comparisons test, $p=0.05$).

Site	Chlorophyll <u>a</u>
1988 Biweekly Surveys, Multiple Depths	
1	8.58 (6.89, 10.70) (52) ^a
4	10.70 (8.58, 13.33) (52) ^{ab}
6	15.33 (12.06, 19.49) (44) ^{bc}
8	17.29 (14.30, 20.91) (51) ^c

Table 3-3. Summarized results listed by depth for chlorophyll a ($\mu\text{g L}^{-1}$) as reported biweekly from March to December 1988 for Sites 1, 4, 6, and 8. Means, lower and upper 95% confidence intervals, and sample size (n) are listed. No significant within site differences between depths (as determined by the Tukey-Kramer multiple comparison test, $p=0.05$) were noted. Analysis of variance of all sites grouped together revealed significant differences in chlorophyll a concentration with depth ($F=3.33$, $p<0.01$, $n=249$, depth differences: $3>9$, $1>9$, and $5>9$ at $p=0.05$).

Depth (m)	Site			
	1	4	6	8
1	8.33 (6.05, 13.74) (13)	10.07 (6.23, 16.28) (13)	16.12 (9.93, 27.66) (11)	20.91 (10.07, 43.38) (12)
3	9.03 (5.81, 14.07) (13)	11.70 (6.96, 19.69) (13)	17.46 (11.59, 26.31) (11)	17.46 (11.82, 25.79) (13)
5	8.00 (4.75, 14.01) (13)	11.13 (6.75, 18.36) (13)	15.33 (8.08, 29.08) (11)	17.64 (11.59, 26.84) (13)
7	9.03 (5.16, 15.80) (13)	10.18 (6.62, 15.64) (13)	12.94 (7.39, 22.65) (11)	14.30 (9.88, 20.70) (13)
9	5.93 (3.16, 11.13) (13)	7.10 (4.18, 12.06) (13)	7.39 (3.53, 15.49) (11)	11.36 (6.89, 19.30) (13)

illustrates the vertical and horizontal distribution of chlorophyll a concentrations within the reservoir seasonally, i.e., spring, summer, and fall. Spring chlorophyll a concentrations were uniform throughout the reservoir with no significant differences between sites or depths being detected (Figure 3-3). During the summer, an algal biomass gradient began to develop with significantly higher chlorophyll a concentrations being present within the upper zone of the reservoir. This gradient was most evident at a depth of 1 meter. In addition, as noted in Figure 3-2, upper zone Sites 6 and 8 had significantly lower chlorophyll a concentrations at 9 meter depths (Figure 3-4). In the fall, chlorophyll a concentrations were vertically homogeneous at each individual site. In addition, a longitudinal gradient of algal biomass from headwater to dam had also developed. This gradient was more pronounced than that observed during the summer. Upper zone sites exhibited significantly greater chlorophyll a concentrations than lower zone sites both at discrete depths, and for all individual site depths combined as mean epilimnetic chlorophyll a concentrations (Figure 3-5).

Temporal Patterns

Yearly Patterns

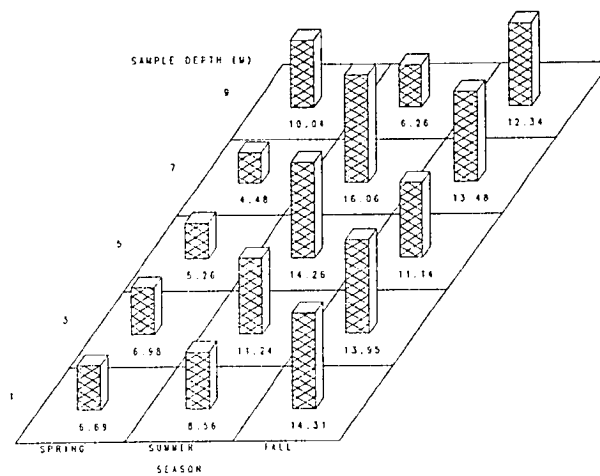
Chlorophyll *a* concentrations were greater in 1984 and 1988, with 1985 and 1986 exhibiting the lowest concentrations (Figure 3-6). Similarly, 1988 exhibited elevated total phytoplankton counts, being significantly greater than 1984 and 1985. The lowest phytoplankton counts were measured during 1985. Correlation analysis revealed a weak relationship between chlorophyll *a* concentration and total phytoplankton counts. During 1984-1987 chlorophyll and total phytoplankton had a correlation coefficient (*r*) of 0.24 ($p < 0.002$, $n = 164$), and during 1988 *r* equaled 0.37 ($p < 0.07$ $n = 26$).

In addition, regression analysis using chlorophyll *a* as the dependent variable and total phytoplankton as the independent variable revealed that total phytoplankton only explained 12% of the variability in chlorophyll *a* concentrations ($R^2 = 0.12$, $F = 27.22$, $p < 0.0001$, $n = 206$). The regression equation describing the relationship between the two variables is listed below:

$$\ln \text{chlorophyll } a = 0.282(\ln \text{ total phytoplankton}) + 0.04 \quad (1)$$

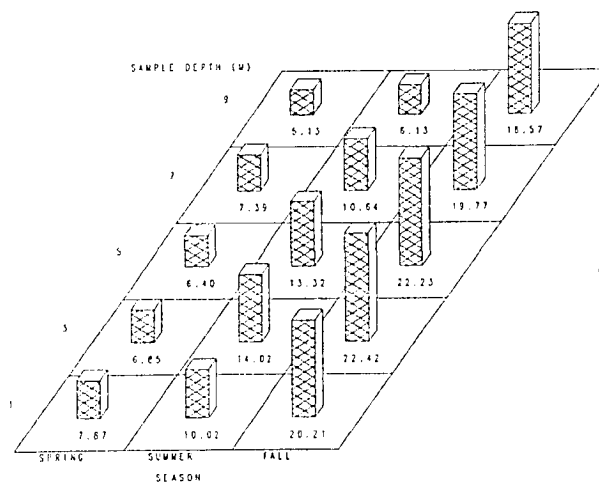
Figure 3-1. Mean seasonal chlorophyll a ($\mu\text{g L}^{-1}$) concentration by depth as measured biweekly from March to December 1988. Significant within season differences with depth (by Tukey-Kramer multiple comparison test $p=0.05$) noted with arabic letters (depths with the same letters are significantly different); (a) Site 1; (b) Site 4.

1988 BIWEEKLY SURVEYS: SITE 1
MEAN SEASONAL CHLOROPHYLL *a* ($\mu\text{g/L}$) BY DEPTH (m)



a.

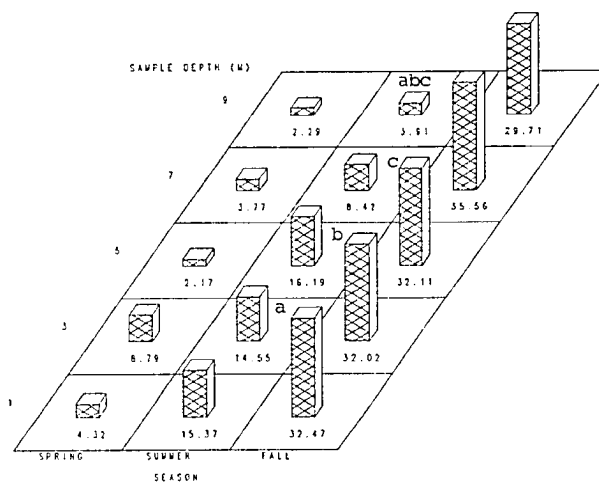
1988 BIWEEKLY SURVEYS: SITE 4
MEAN SEASONAL CHLOROPHYLL *a* ($\mu\text{g/L}$) BY DEPTH (m)



b.

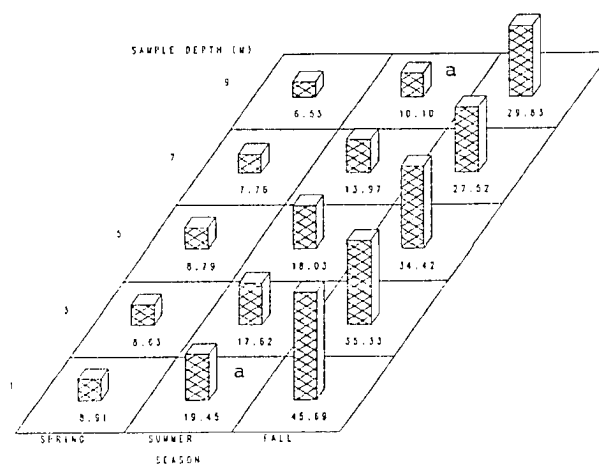
Figure 3-2. Mean seasonal chlorophyll *a* ($\mu\text{g L}^{-1}$) concentration by depth as measured biweekly from March to December 1988. Significant within season differences with depth (by Tukey-Kramer multiple comparison test $p=0.05$) noted with arabic letters (depths with the same letters are significantly different); (a) Site 6; (b) Site 8.

1988 BIWEEKLY SURVEYS: SITE 6
MEAN SEASONAL CHLOROPHYLL *a* ($\mu\text{g/L}$) BY DEPTH (M)



a.

1988 BIWEEKLY SURVEYS: SITE 8
MEAN SEASONAL CHLOROPHYLL *a* ($\mu\text{g/L}$) BY DEPTH (M)



b.

Figure 3-3. Mean chlorophyll a ($\mu\text{g L}^{-1}$) concentration by depth for Sites 1, 4, 6, and 8 as measured biweekly during the Spring of 1988. Significant within site differences with depth (by Tukey-Kramer multiple comparison test $p=0.05$) noted with arabic letters (depths with the same letters are significantly different). Significant difference between sites at specific depths (rows) is noted to the right of the chart. Significant differences between sites for all depths combined is noted with asterisks at the bottom of chart.

1988 BIWEEKLY SURVEYS: SPRING

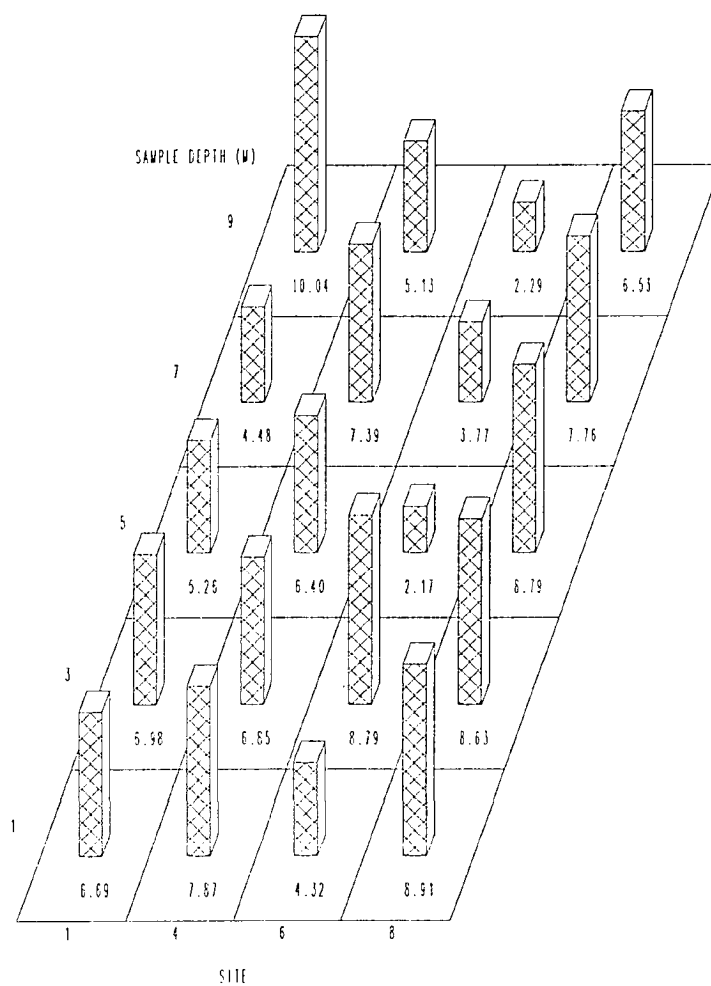
MEAN CHLOROPHYLL *a* ($\mu\text{g/L}$) BY SITE BY DEPTH (m)

Figure 3-4. Mean chlorophyll *a* ($\mu\text{g L}^{-1}$) concentration by depth for Sites 1, 4, 6, and 8 as measured biweekly during the Summer of 1988. Significant within site differences with depth (by Tukey-Kramer multiple comparison test $p=0.05$) noted with arabic letters (depths with the same letters are significantly different). Significant difference between sites at specific depths (rows) is noted to the right of the chart. Significant differences between sites for all depths combined is noted with asterisks at the bottom of chart.

1988 BIWEEKLY SURVEYS: SUMMER

MEAN CHLOROPHYLL *a* (ug/L) BY SITE BY DEPTH (m)

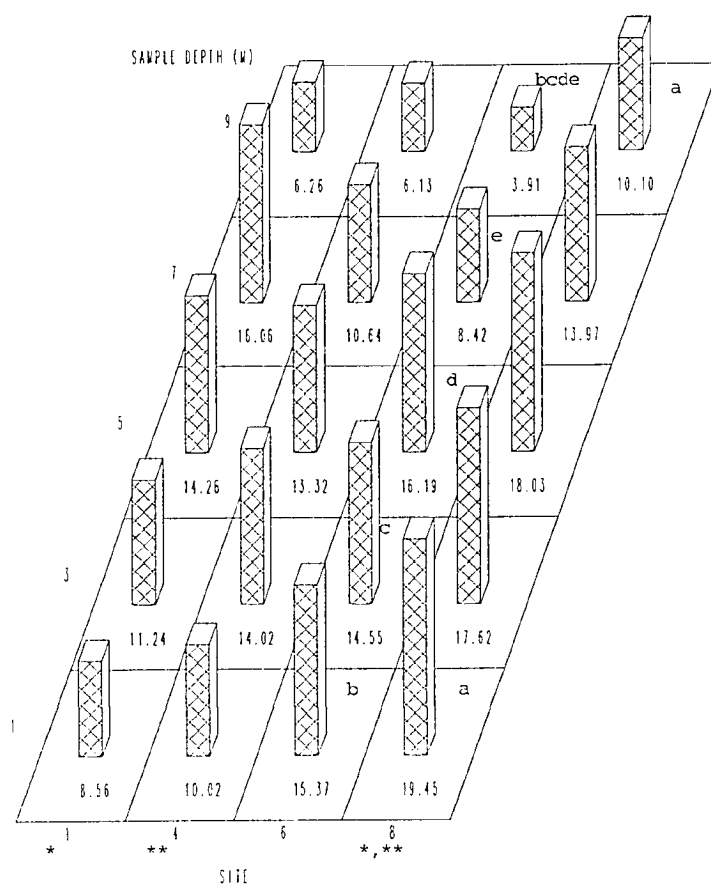
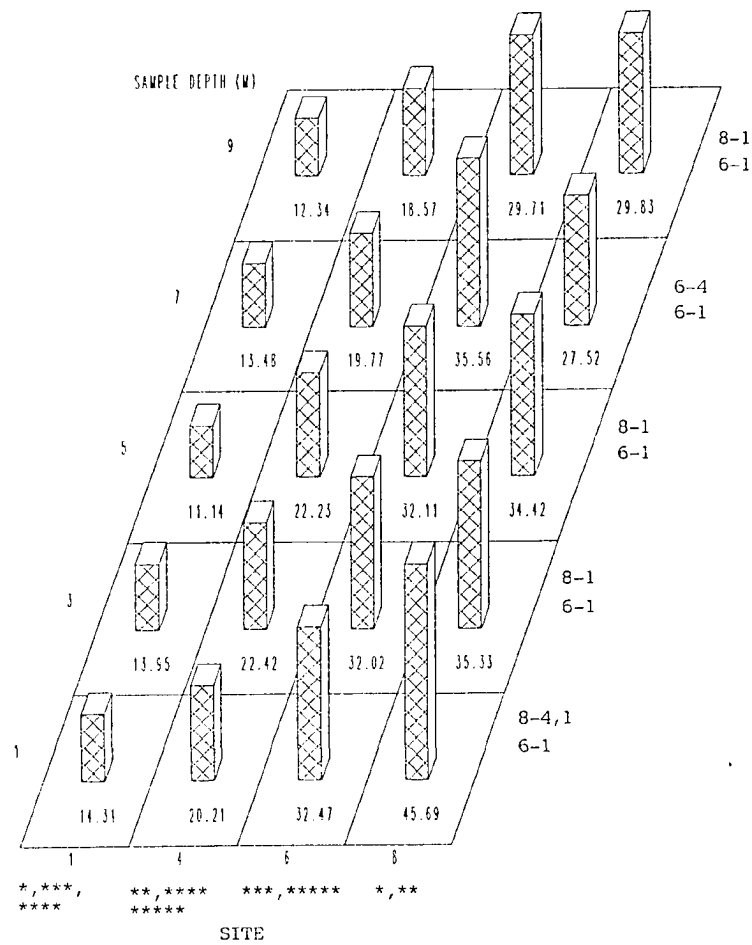


Figure 3-5. Mean chlorophyll a ($\mu\text{g L}^{-1}$) concentration by depth for Sites 1, 4, 6, and 8 as measured biweekly during the Fall of 1988. Significant within site (columns) differences with depth (by Tukey-Kramer multiple comparison test $p=0.05$) noted with arabic letters (depths with the same letters are significantly different). Significant difference between sites at specific depths (rows) is noted to the right of the chart. Significant differences between sites for all depths combined is noted with asterisks at the bottom of chart.

1988 BIWEEKLY SURVEYS: FALL

MEAN CHLOROPHYLL *a* ($\mu\text{g/L}$) BY SITE BY DEPTH (m)



The weak relationship between chlorophyll a and total phytoplankton measurements may explain the lack of agreement between the two charts illustrated in Figure 3-6. See the Methods Section of this chapter for a further explanation of the methodological deficiencies concerning each of these variables with respect to their being efficient estimators of algal biomass.

Figure 3-7 illustrates yearly spatial pattern observed during the five year study period for chlorophyll a concentrations and total phytoplankton counts. Chlorophyll a gradients were noted in both 1986 and 1988, however no significant algal biomass gradients were observed during 1984, 1985, and 1987. In addition, 1988 consistently displayed the highest chlorophyll a concentration at each site, while 1986 displayed the lowest concentration at each site. With the exception of 1984, the 1988 mean epilimnetic chlorophyll a concentration at Site 8 was the highest observed for that site during all years. No significant total phytoplankton gradients were observed for any year during the study period. With the exception of Site 4, 1985 exhibited the lowest total phytoplankton counts at each site of all years. This was particularly evident within the upper zone of the reservoir.

Figure 3-6. Mean yearly chlorophyll a concentrations and total phytoplankton counts as measured monthly from 1984 to 1988. Significant differences between years (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (years with the same letters are significantly different). (a) mean yearly chlorophyll a, 1984-1988; (b) mean yearly total phytoplankton 1984-1988.

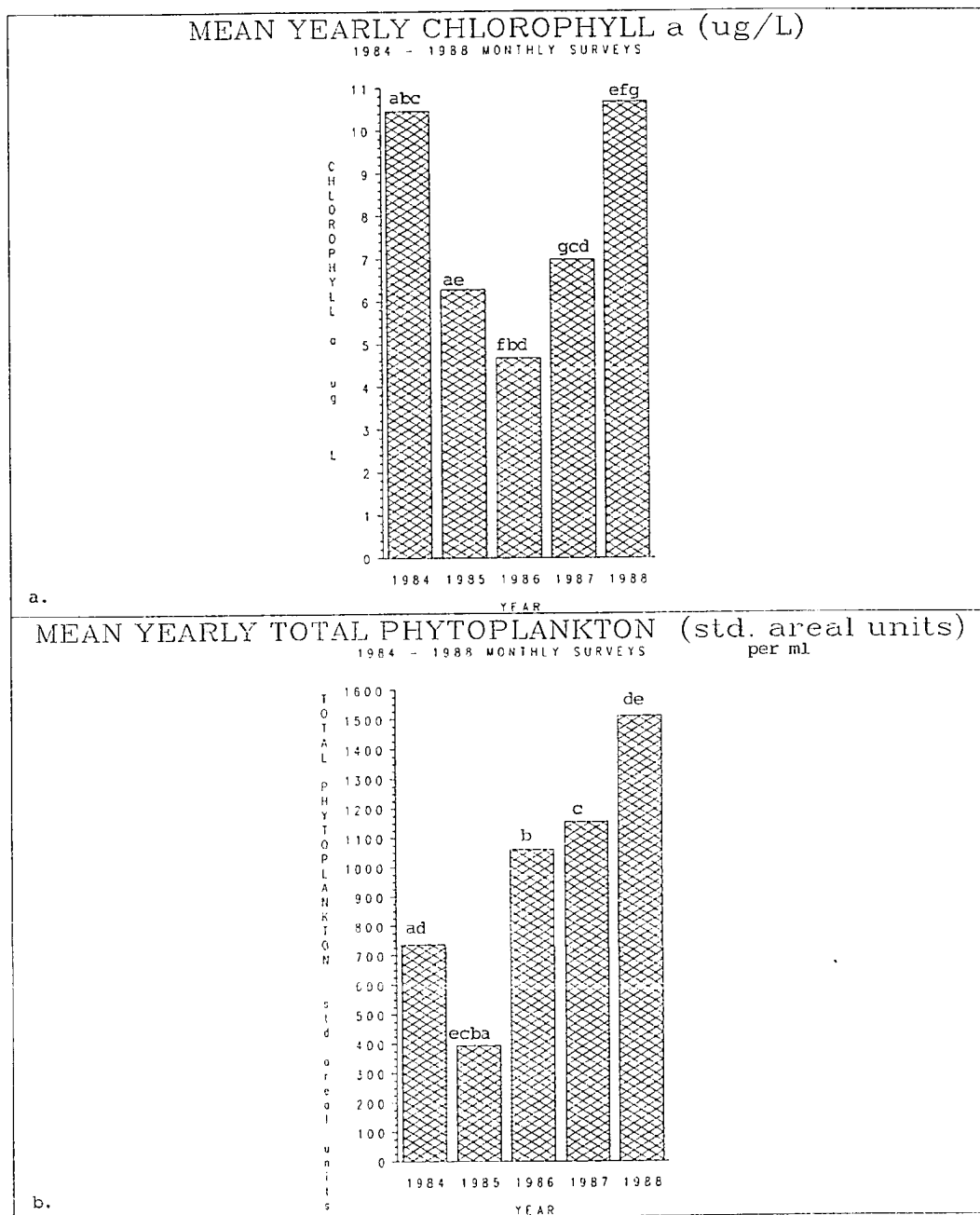
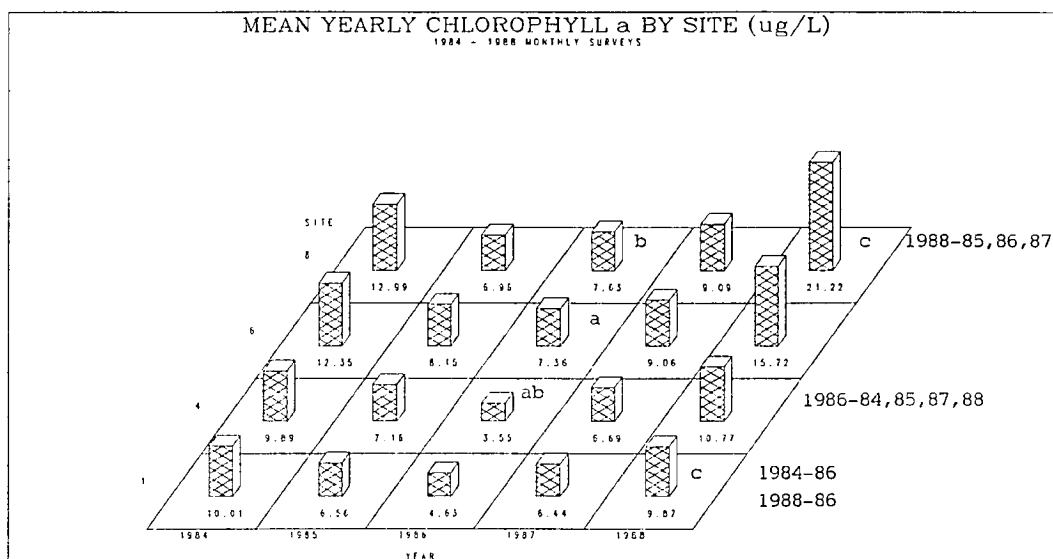
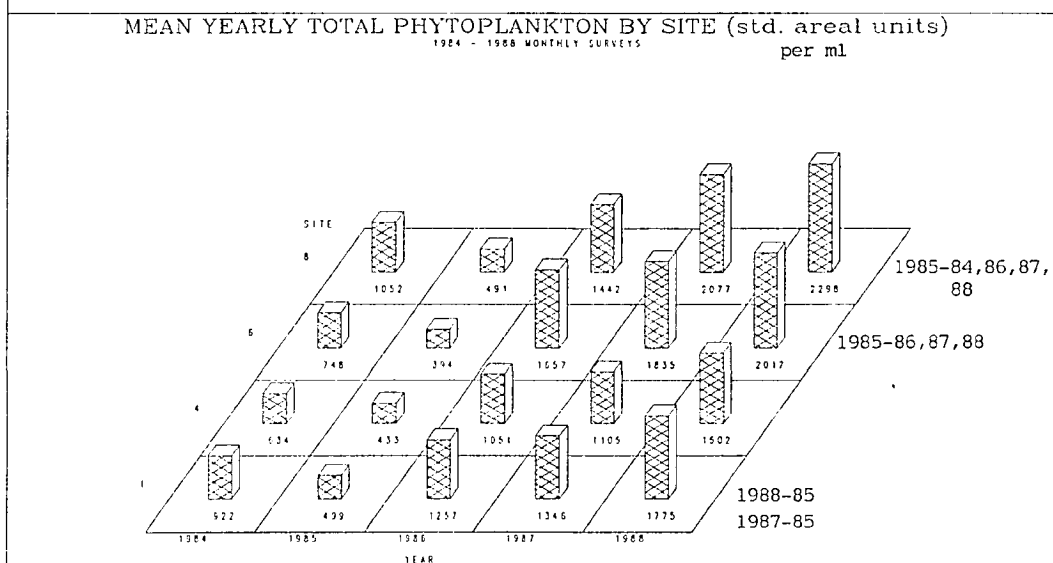


Figure 3-7. Mean yearly spatial chlorophyll a concentrations and total phytoplankton counts as measured monthly from 1984 to 1988. Significant within year differences between sites (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (sites with the same letters are significantly different). Significant differences between years at specific sites (rows) are noted to the right of the chart. (a) mean yearly chlorophyll a by site, 1984-1988; (b) mean yearly total phytoplankton by site, 1984-1988.



a.



b.

Monthly Patterns

Sites exhibited a late spring chlorophyll peak followed by a midsummer dormant period and late summer peak (Figure 3-8). During 1988, all sites exhibited a pronounced late summer peak which was higher than those observed in all other study years. In addition, a pronounced fall peak occurred at all sites during 1988. The fall peak first developed in the reservoir's upper zone and latter in the lower zone. With the exception of 1985, Site 8, and to a lesser extent, Site 6 exhibited a fall chlorophyll peak every year. Sites 1 and 4 only exhibited a fall chlorophyll a peak in 1988. Fall chlorophyll a peaks appear to be restricted to the upper zone of the reservoir (Figure 3-8).

Total phytoplankton peaks generally mimicked chlorophyll peaks, i.e., late spring peak followed by a late summer peak with the lower zone sites exhibiting lower phytoplankton counts (Figure 3-9). Phytoplankton counts were highest during the spring and summer of 1988.

Seasonal Patterns

Figure 3-10 illustrates seasonal spatial patterns observed during the 1984-1987 monthly survey period, the 1988 monthly survey period, and the 1988 biweekly survey period for epilimnetic chlorophyll a concentrations. The 1984-1987 monthly survey data revealed that epilimnetic chlorophyll a concentrations were significantly greater

Figure 3-8. Mean epilimnetic chlorophyll a concentrations ($\mu\text{g L}^{-1}$) as measured monthly from 1984-1987 and biweekly during 1988 for: (a) Site 1, (b) Site 4, (c) Site 6, and (d) Site 8. Note the different scales on the vertical axes; a reference line has been draw at chlorophyll a= $10 \mu\text{g L}^{-1}$ to facilitate site comparisons.

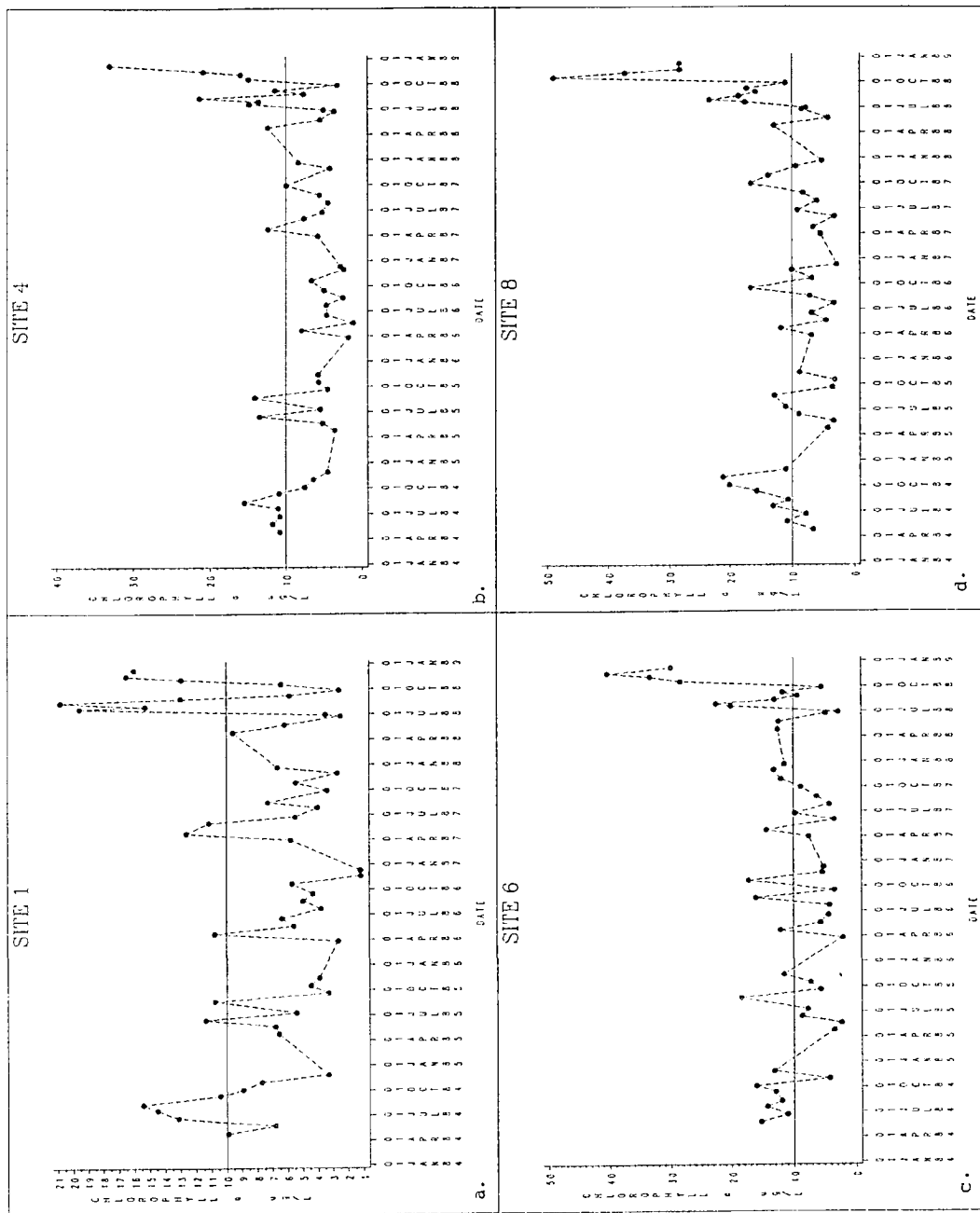
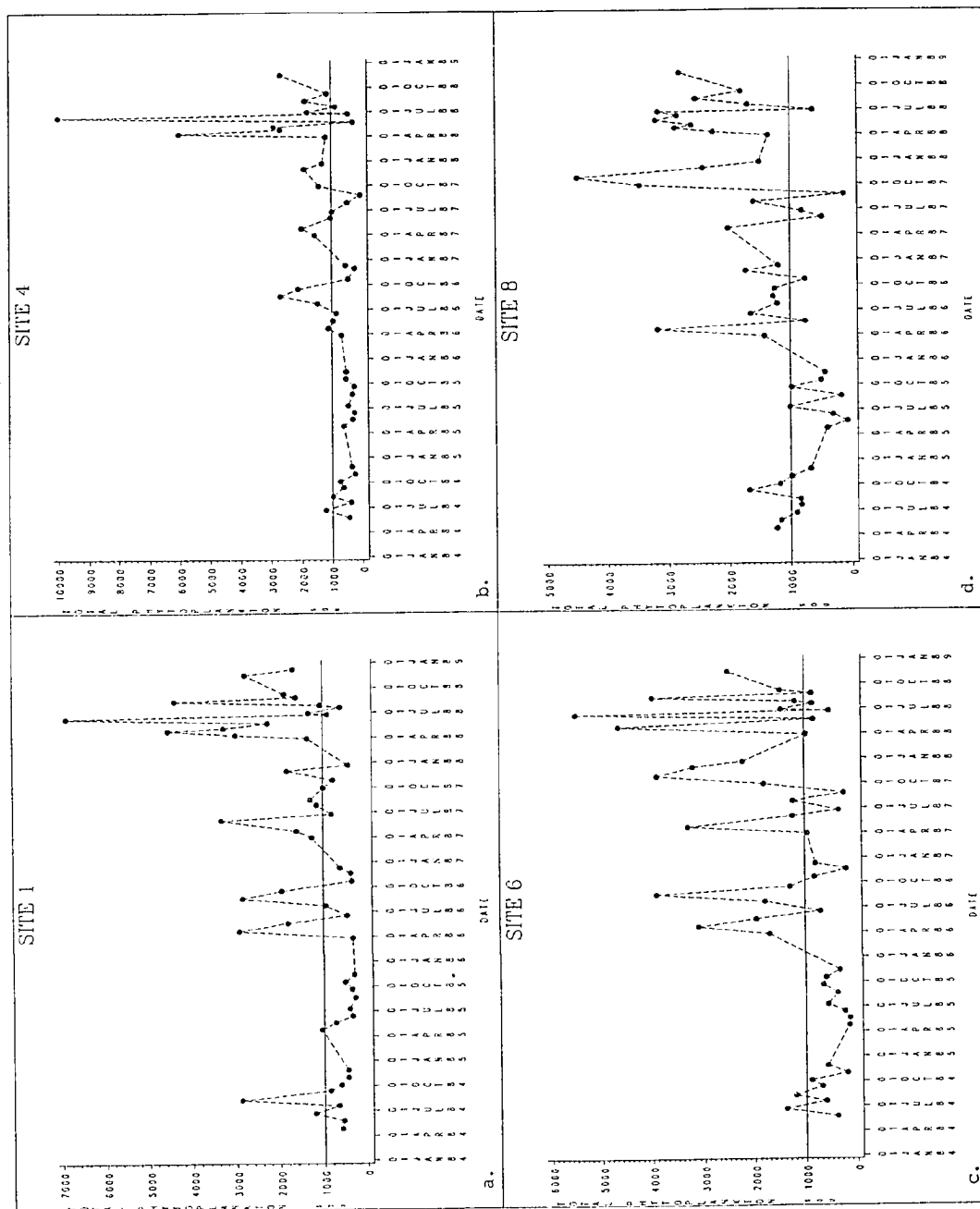


Figure 3-9. Mean epilimnetic total phytoplankton counts (standard areal units-s.a.u.) as measured monthly from 1984-1988 for: (a) Site 1, (b) Site 4, (c) Site 6, and (d) Site 8. Note the different scales on the vertical axes; a reference line has been draw at total phytoplankton=1000 s.a.u to facilitate site comparisons.



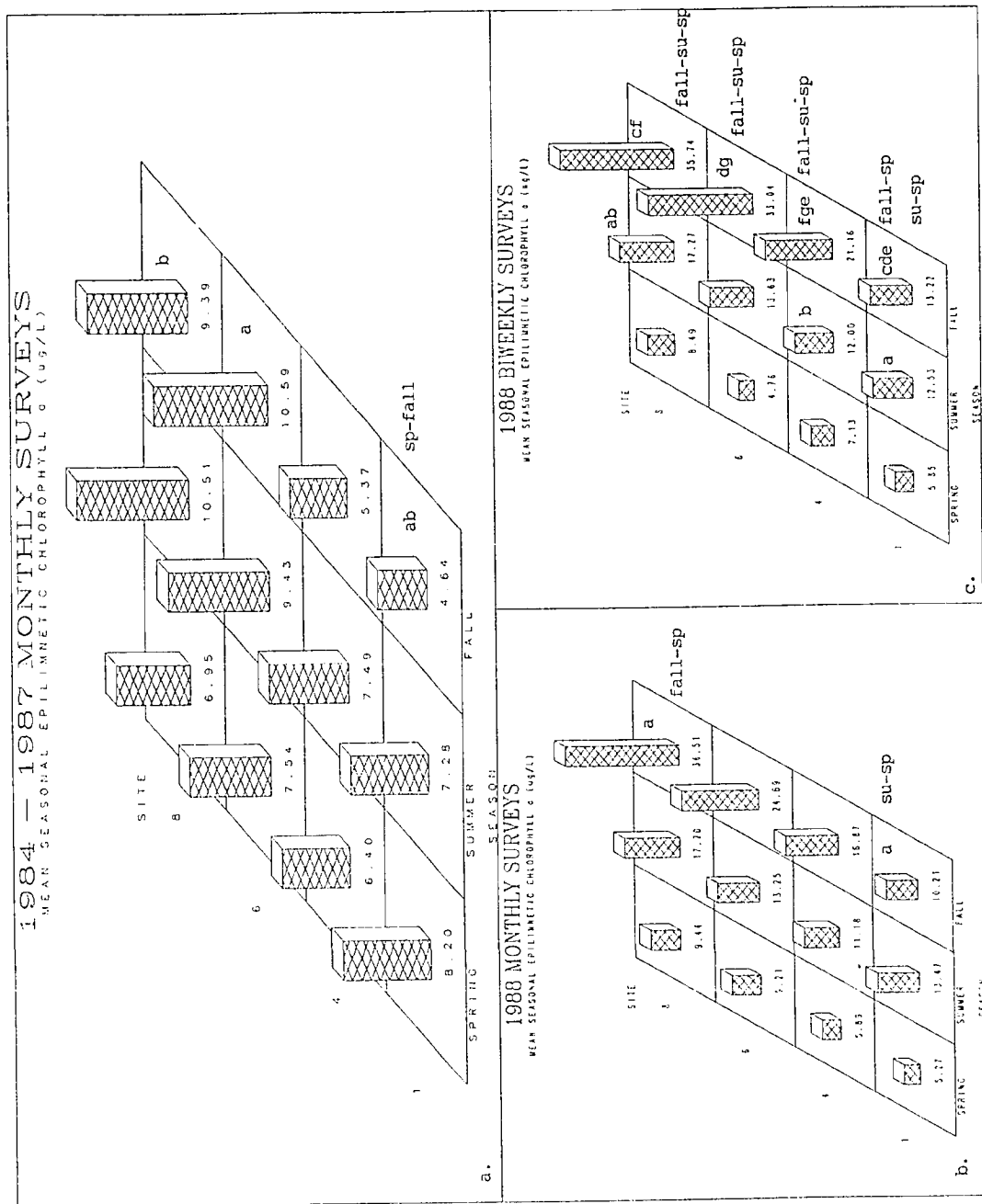
within the upper zone of the reservoir during the fall months. This pattern was also observed in the 1988 monthly and biweekly survey data. The fall peak displayed by the 1988 biweekly survey data was much more pronounced than the fall peaks noted in the monthly survey data of 1984-1987, and 1988. In addition, the 1988 biweekly surveys also revealed the existence of a summer chlorophyll gradient, with Site 8 having higher chlorophyll a concentrations than Sites 1 and 4. This summer gradient was not evident in the 1988 monthly survey data.

The 1984-1987 monthly survey data indicated that chlorophyll a concentrations were higher in the lower zone of the reservoir during the spring as opposed to the fall. However, in 1988, spring generally exhibited lower chlorophyll a concentrations than summer or fall. The 1988 biweekly survey data exhibited marked seasonal differences in chlorophyll a concentrations at all sites, with fall concentrations being greater than summer (except at Site 1), and summer concentration being greater than spring.

The 1988 monthly survey data did not show as many within site seasonal differences (at the $p=0.05$ significance level) as did the 1988 biweekly data.

Figure 3-11 illustrates seasonal spatial patterns observed during the 1984-1987 monthly survey period, and the 1988 monthly survey period for total phytoplankton counts.

Figure 3-10. Seasonal spatial patterns of mean seasonal epilimnetic chlorophyll a concentrations ($\mu\text{g L}^{-1}$) observed during: (a) the 1984-1987 monthly survey period, (b) the 1988 monthly survey period, and (c) the 1988 biweekly survey period. Significant within season differences between sites (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (sites with the same letters are significantly different). Significant differences between seasons at specific sites (rows) are noted to the right of the chart.



The same pattern of higher phytoplankton counts being present in the upper zone of the reservoir during the fall was present in both the 1984-1987, and 1988 survey periods. These elevated fall phytoplankton counts observed within the upper zone of the reservoir agree with the previously described elevated fall upper zone chlorophyll a concentrations observed during 1984-1987, and 1988.

Both survey periods failed to exhibit within site seasonal differences for total phytoplankton counts.

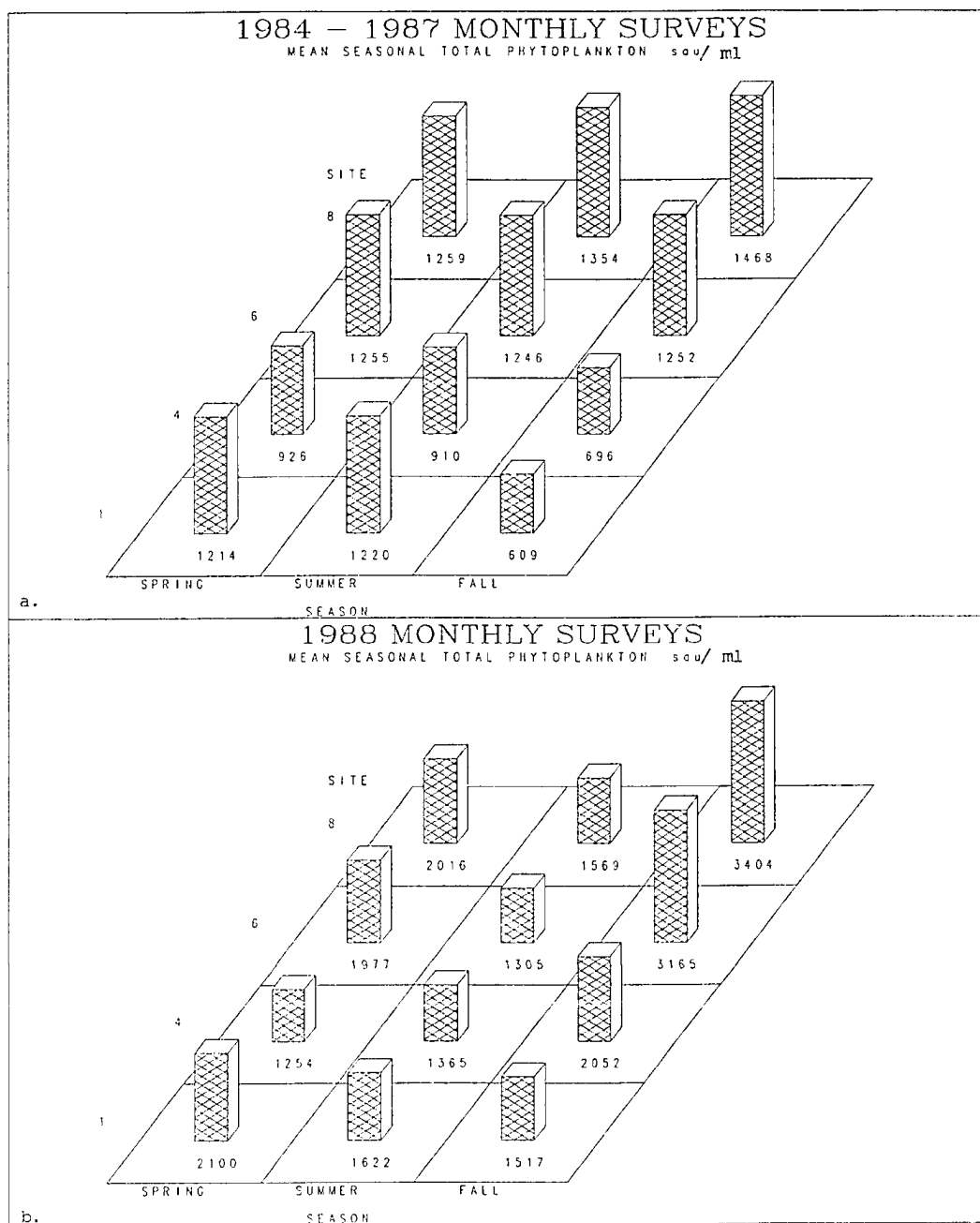
Zooplankton Biomass Dynamics

Spatial and Temporal Patterns

Zooplankton biomass levels recorded at each site generally peaked in the spring, slowly declined to minimum levels by late summer, then rebounded slightly in the fall (Figure 3-12). A secondary summer zooplankton biomass peak was noted at Sites 1, 4, and 8 during 1986. Such a peak also occurred in 1987, but only at Site 4. Unlike 1986 and 1987, Site 8 exhibited a pronounced spring zooplankton biomass peak in 1988.

Figure 3-13 depicts the copepod and cladoceran composition of the total zooplankton biomass measured monthly during 1986 and 1987 and biweekly during 1988 for Sites 1, 4, and 8. The composition of the zooplankton biomass present at Site 6 beginning June 1988 is

Figure 3-11. Seasonal spatial patterns of mean seasonal total phytoplankton counts (standard areal units-s.a.u.) observed during: (a) the 1984-1987 monthly survey period, and (b) the 1988 monthly survey period. Significant within season differences between sites (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (sites with the same letters are significantly different). Significant differences between seasons at specific sites (rows) are noted to the right of the chart.



also illustrated. The copepods were primarily composed of nauplii, copepodites, and the genera *Acyclops* and *Acanthocyclops*. The cladocerans consisted of *Bosmina*, *Ceriodaphnia*, *Daphnia*, *Chydorus*, *Diaphanosoma*, and *Holopedium*. The spring peak observed in all years was composed almost entirely of copepods. This peak was usually followed by a summer peak composed of cladocerans.

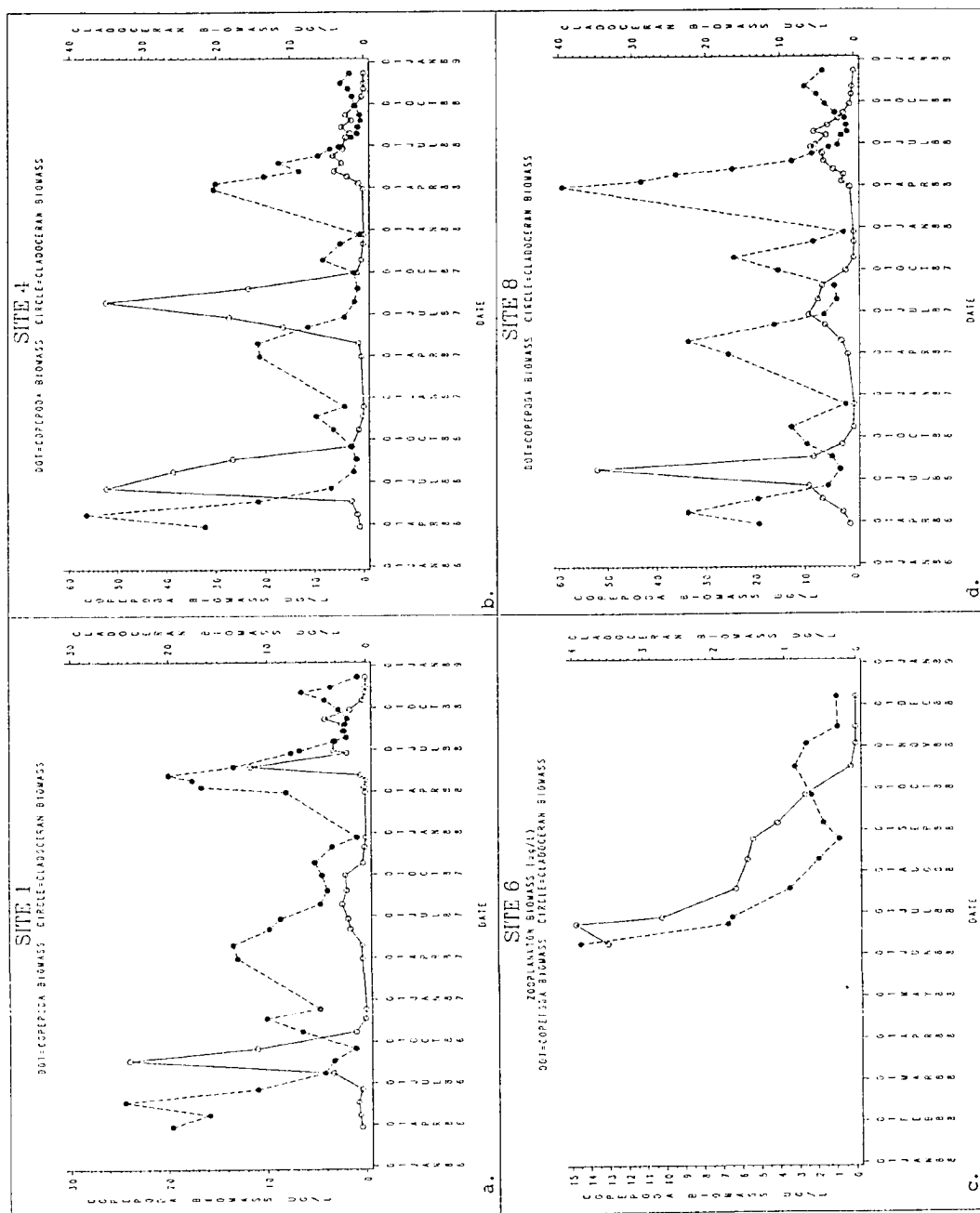
Sites 1, 4, and 8 exhibited a pronounced cladoceran peak in the summer of 1986. A similar peak was noted in 1987, but at Site 4. The genus *Holopedium* accounted for a large part of the biomass present in the cladoceran summer peaks. The less pronounced fall peaks were dominated by copepods.

Figure 3-14 illustrates mean seasonal total zooplankton biomass by year for the 1986-1988 period with all site values combined. No significant differences between yearly spring total zooplankton biomass levels were observed over the three year period. Similarly, no significant differences between yearly fall zooplankton biomass levels were noted as well. However, during the summer, both 1986 and 1987 had greater zooplankton biomass levels than in 1988.

Figure 3-15 depicts seasonal spatial patterns in total zooplankton biomass observed during 1986, 1987, and 1988. During 1986 and 1987, Sites 4 and 8 generally exhibited a greater spring zooplankton biomass peak than Site 1, and spring zooplankton biomass levels were greater

Figure 3-12. Temporal patterns of total zooplankton biomass ($\mu\text{g L}^{-1}$) as measured monthly during 1986 and 1987, and biweekly during 1988 for: (a) Site 1, (b) Site 4, (c) Site 6 (biweekly measurements began June 1988), and (d) Site 8. Note the different scales on the vertical axes.

Figure 3-13. Temporal patterns of copepod and cladoceran biomass ($\mu\text{g L}^{-1}$) as measured monthly during 1986 and 1987, and biweekly during 1988 for: (a) Site 1, (b) Site 4, (c) Site 6 (biweekly measurements began June 1988), and (d) Site 8. Note the different scales on the vertical axes. Copepod biomass is represented by dots, and cladoceran biomass is represented by circles.



than fall levels. The patterns exhibited in 1988 were different than those exhibited in 1986 and 1987. No significant difference was noted between spring zooplankton biomass levels measured at any site. However, Site 8 had a greater zooplankton biomass than Sites 4 and 6 during the summer, and Site 6 during the fall. This peak at Site 8 was chiefly composed of cladocerans. All sites exhibited highest 1988 zooplankton biomass levels in the spring.

Figure 3-14. Mean seasonal total zooplankton biomass ($\mu\text{g L}^{-1}$) by year for the 1986-1988 period with Site 1, 4, and 8 values combined on a seasonal basis. Significant within season (column) differences between years (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (years with the same letters are significantly different).

MEAN SEASONAL TOTAL ZOOPLANKTON BIOMASS ($\mu\text{g/L}$) ALL SITES COMBINED 1986-1988

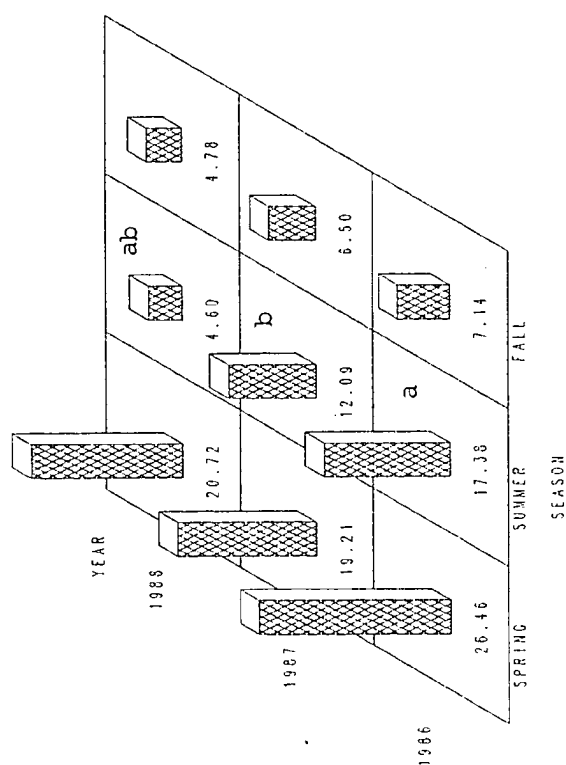
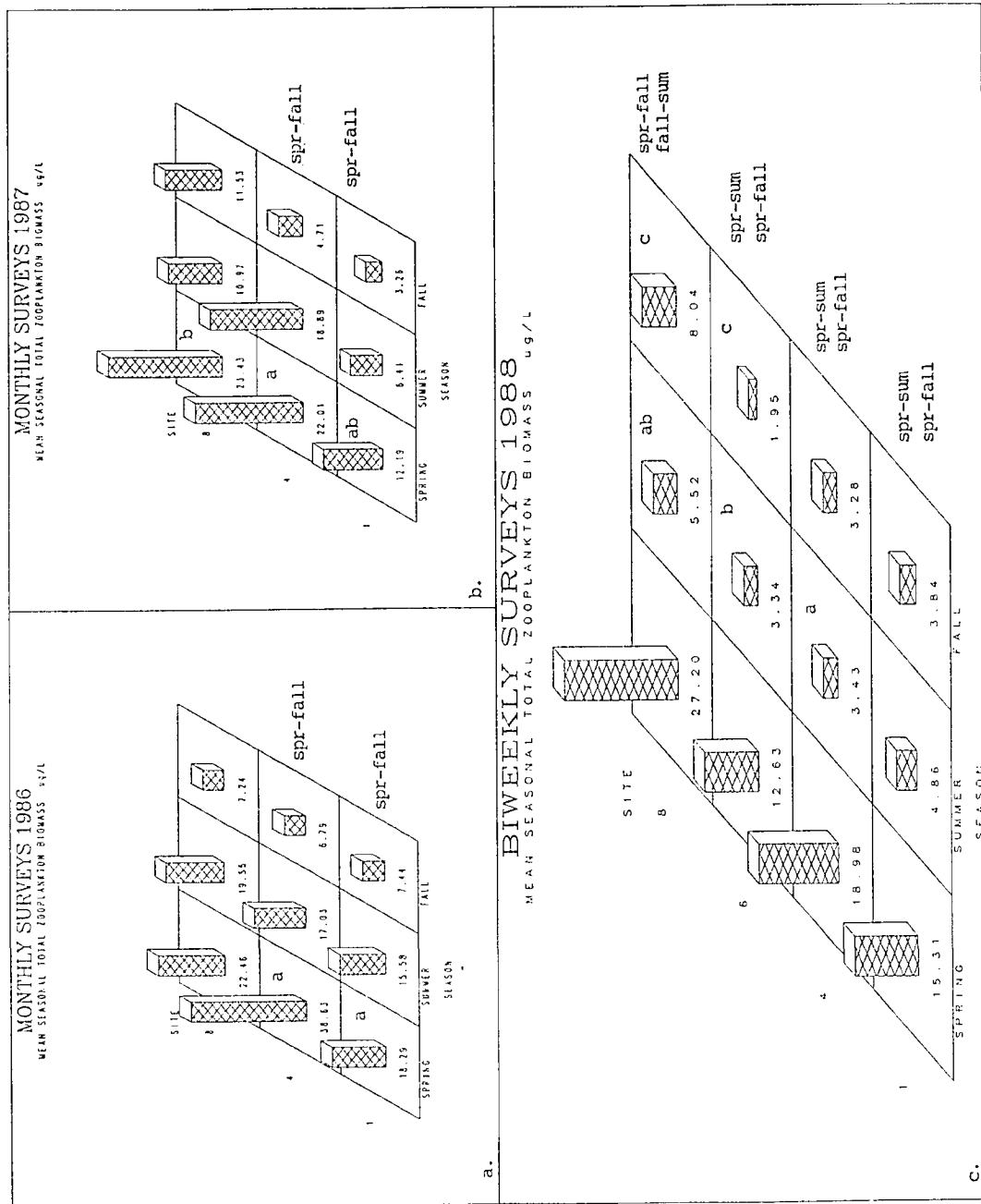


Figure 3-15. Seasonal spatial patterns of mean seasonal total zooplankton biomass ($\mu\text{g L}^{-1}$) observed during: (a) the 1986 monthly survey period, (b) the 1987 monthly survey period, and (c) the 1988 biweekly survey period. Significant within season differences between sites (by Tukey-Kramer multiple comparison test $p=0.05$) are noted with arabic letters (sites with the same letters are significantly different). Significant differences between seasons at specific sites (rows) are noted to the right of the chart.



*Interrelationships: Algal Biomass, Environmental
Variables, and Zooplankton*

Information concerning the hydrology and physiography of Croton Reservoirs and the spatial and temporal variability of the physical and chemical processes occurring within the impoundment were evaluated during both 1984-1987, and 1988 (Chapter 1, and Chapter 2). These data were examined in conjunction with the spatial and temporal algal biomass information, measured during the same period, in order determine possible interrelationships.

Regression Analysis

1984-1987 Monthly Surveys:

Multiple linear regression analysis was performed on the 1984-1987 monthly survey data using chlorophyll a as the dependent variable and temperature, reactive silica, nitrite+nitrate-nitrogen, ammonia-nitrogen, total phosphorus, thermocline depth, and both Secchi disc depth and compensation depth measurements (in separate analyses) as independent variables for water transparency and light penetration respectively. Table 3-4 describes the multiple linear regression model derived from stepwise variable selection relating 1984-1987 annual, growing season (July-October), and fall epilimnetic chlorophyll a concentrations to environmental variables with Secchi disc depth as the

independent variable for water transparency. Table 3-5 describes a similar regression model, except compensation depth was used instead of Secchi disc depth as the independent variable for light penetration. The model presented in Table 3-4 more realistically described the variability in epilimnetic chlorophyll a concentration in all longitudinal zones of the reservoir since Secchi disc depth was consistently measured at all sample sites since 1984, and compensation depth was not. A combined total of 132 Secchi disc depth measurements were made at Sites 1, 4, 6, and 8 during the 1984-1987 period. However, compensation depth was only measured at Site 1 during 1984 and 1985. Beginning in 1986 compensation depth was measured at Sites 1, 4, and 8. This would make 1984-1987 compensation depth measurements more biased toward the reservoir's lower zone, i.e., Sites 1 and 4. It was therefore concluded that Secchi disc depth would be a more representative variable than compensation depth for assessing water transparency and chlorophyll a relationships along longitudinal axis of the reservoir during the 1984-1987 period. The 1984-1987 compensation depth data were useful for assessing light penetration and chlorophyll a relationships within the lower zone of the reservoir.

Variance in epilimnetic chlorophyll a concentrations was partially explained by differences in environmental conditions that existed during three different, overlapping

time periods: annual, growing season, and fall (Table 3-4). The annual model was the weakest ($R^2=0.26$) of the three, with silica and Secchi disc depth each explaining 10% of the variability in annual epilimnetic chlorophyll a concentrations. Total phosphorus and nitrite+nitrate nitrogen had smaller contributions. Both epilimnetic silica and nitrite+nitrate nitrogen concentrations tend to be elevated in the spring and gradually become depleted by summer as phytoplankton populations, chiefly composed of diatoms, increase. Concentrations of both these nutrients tend to increase again in the late fall as phytoplankton populations decrease. During the growing season, Secchi disc depth became important, accounting for 31% of the variability in chlorophyll a concentrations. Here, as the negative slope indicated, Secchi disc depth measurements most likely reflected the light attenuating properties of the phytoplankton biomass. The fall model was the strongest of the three 1984-1987 time period models ($R^2=0.50$). Fall was also the time period in which a chlorophyll a gradient was observed in the impoundment, with chlorophyll a concentrations being highest in the upper zone of the reservoir. These chlorophyll a concentrations typically peaked in October-November and declined in December. In addition, the upper zone of the reservoir generally exhibited a rise in nitrite+nitrate nitrogen concentrations toward the end of the fall season (Chapter 2). Epilimnetic

nitrite+nitrate nitrogen concentrations accounted for 28% of the variance in fall epilimnetic chlorophyll a concentrations, with Secchi disc depth, and silica playing lesser roles. The negative LOG NO₃ coefficient depicted in Table 3-4 supports the pattern of rising nitrite+nitrate nitrogen concentrations with a concurrent decline in chlorophyll a concentrations within the upper zone of the reservoir as described above.

The annual and growing season models which described chlorophyll a in relation to compensation depth and other environmental variables (Table 3-5) were similar to the annual and growing season models described above which used Secchi disc depth as the independent variable for water transparency. Both silica concentrations, and some measure of light penetration were important in accounting for chlorophyll a variability in both regression analyses. However, compensation depth accounted for 41% of the variability in epilimnetic chlorophyll a concentrations measured during the 1984-1987 growing season period; this is 10% greater than what Secchi disc depth measurements accounted for. As noted previously, compensation depth measurements during the 1984-1987 period were weighted toward the lower zone of the reservoir. Chlorophyll a, or phytoplankton biomass would tend to have a greater effect on light attenuation within the reservoir's more transparent lower zone as the chlorophyll a-compensation depth model

indicated. The light extinction coefficient is often a linear function of the chlorophyll *a* concentration and the effect of algal biomass on the extinction coefficient must be carefully considered whenever turbidities remain low (<5.0 NTU), since algae may become the dominant influence on light attenuation (Megard et al. 1980, Brown 1984). In order to remove the light attenuating effect of phytoplankton biomass from the analysis, and test the importance of nonalgal light attenuation in explaining chlorophyll *a* variability, a technique developed by Canfield and Hodgson (1983), which represented water transparency depth as determined by nonalgal light attenuation as the residuals from the Secchi depth or compensation depth (dependent variable)-chlorophyll *a* (independent variable) regression, was utilized. When the nonalgal light attenuation depth was used as an independent variable, in the stepwise regression compensation depth-chlorophyll *a* model, nutrients became more important in explaining growing season chlorophyll *a* variability with total phosphorus and silica concentrations explaining 14%, and 8% of the variability respectively. However, this model was weaker ($R^2=0.22$) than the original model ($R^2=0.58$).

The fall chlorophyll *a*-compensation depth model showed thermocline depth and silica concentrations as being important factors in explaining chlorophyll *a* variability. As thermocline depth increases during late summer-fall

Table 3-4. Multiple linear regression equations derived from stepwise variable selection relating 1984-1987 annual, growing season (July-October), and fall epilimnetic chlorophyll *a* concentration to environmental variables. Secchi disc depth (ZSD) was used as the independent variable for water transparency in this analysis. See text for explanation. Si-reactive silica concentration (mg L^{-1}); ZSD-Secchi disc depth (m); ZTH-thermocline depth (m); TP-total phosphorus concentration ($\mu\text{g L}^{-1}$); NO_3 -nitrate+nitrite nitrogen concentration (mg L^{-1}); n=sample size. All models were significant at $p < 0.01$.

Period	R^2 (n)	Model Description: Secchi Disc 1984-1987				
		Independent Variable	Coefficient	% Variance Explained	F	p
Annual	0.26 (132)	Si	-0.167	10%	16.07	<0.0001
		ZSD	-0.486	10%	13.87	<0.0003
		LOG TP	0.173	3%	4.29	<0.04
		LOG NO_3	-0.087	3%	4.75	<0.03
Growing Season	0.40 (67)	ZSD	-0.601	31%	43.84	<0.0001
		ZTH	0.038	9%	9.87	<0.0025
Fall	0.50 (42)	LOG NO_3	-0.279	28%	17.11	<0.0002
		ZSD	-0.584	15%	18.11	<0.0001
		Si	-0.256	7%	4.96	<0.03

Table 3-5. Multiple linear regression equations derived from stepwise variable selection relating 1984-1987 annual, growing season (July-October), and fall epilimnetic chlorophyll *a* concentration to environmental variables. Compensation depth (COMP) was used as the independent variable for light penetration in this analysis. See text for explanation. Si-reactive silica concentration (mg L^{-1}); COMP-compensation depth (m); ZTH-thermocline depth (m); TP-total phosphorus concentration ($\mu\text{g L}^{-1}$); n=sample size. All models were significant at $p < 0.01$.

Period	R^2 (n)	Model Description: Comp. Depth 1984-1987				
		Independent Variable	Coefficient	% Variance Explained	F	P
Annual	0.25 (75)	Si	-0.185	8%	16.46	<0.0001
		COMP	-0.284	16%	15.83	<0.0001
Growing Season	0.58 (32)	COMP	-0.319	41%	21.79	<0.0001
		ZTH	0.032	13%	8.15	<0.008
		LOG TP	0.184	4%	3.19	<0.09
Fall	0.31 (24)	ZTH	-0.034	20%	6.93	<0.015
		Si	-0.239	11%	3.37	<0.08

thermal stratification, chlorophyll *a* concentrations begin to drop. This pattern is particularly evident within the lower zone of the impoundment. Silica concentrations appeared to be important in both the chlorophyll *a*-compensation depth, and the chlorophyll *a*-Secchi disc depth models, but the chlorophyll *a*-compensation depth model did not contain the nitrite+nitrate nitrogen variable as the chlorophyll *a*-Secchi disc depth model did. Nitrite+nitrate nitrogen concentrations appeared to be important in explaining fall chlorophyll *a* concentration variability in the upper zone of the reservoir, while silica concentrations were more important in explaining fall chlorophyll *a* variability in the lower zone of the impoundment.

1988 Biweekly Surveys

Table 3-6 describes the multiple linear regression model derived from stepwise variable selection relating annual, growing season, and fall epilimnetic chlorophyll *a* concentrations in 1988 to environmental variables. This model used compensation depth corrected for algal light attenuation, as the independent variable for water transparency. Total nitrogen (TN), volatile solids (VS), and nonvolatile solids (NVS) were also used as independent variables. All four of these variables were not included in the 1984-1987 analysis. The annual model indicated that TN alone explained 36% of the epilimnetic chlorophyll *a*

variability, with temperature and turbidity explaining a lesser portion. The role of TN in explaining chlorophyll *a* variability became more important during the growing season, when TN explained 41% of the algal biomass variability. These findings suggest that TN had an important influence on algal abundance both during the 1988 growing season and throughout the 1988 survey year. This is not uncommon in temperate eutrophic lakes and reservoirs, like Croton Reservoir which have relatively high phosphorus concentrations, and experience summer peaks of cyanobacteria (Reynolds 1978, Wetzel 1983, Stewart 1973). Water transparency and temperature also became important during the growing season.

However, during the fall of 1988, when the longitudinal chlorophyll *a* gradient was most pronounced in the reservoir, total phosphorus (TP) concentrations accounted for 57% of the variability in chlorophyll *a* concentrations. In addition, TP had a highly significant positive correlation ($r=0.76$, $p<0.0001$) with chlorophyll *a*.

Water transparency was also important in the fall model in that it accounted for 22% of the variability in chlorophyll *a* concentrations. Nonalgal light attenuation appeared to be important in influencing water transparency within the reservoir's upper zone, whereas algal light attenuation appeared more important in the lower zone of the

Table 3-6. Multiple linear regression equations derived from stepwise variable selection relating 1988 annual, growing season (July-October), and fall epilimnetic chlorophyll *a* concentration to environmental variables. TN-total nitrogen (mg L^{-1}); T-water temperature ($^{\circ}\text{C}$); TURB-turbidity (ntu); LIGHT-water transparency corrected for algal light attenuation, see text for explanation; NO_3 -nitrite+nitrate nitrogen (mg L^{-1}); NH_3 -ammonia nitrogen (mg L^{-1}); TP-total phosphorus (ug L^{-1}); n=sample size; n.s.=not significant at $p < 0.05$; % = percent variance explained by independent variable. All models were significant at $p < 0.001$.

Period	R^2 (n)	Model Description: Chlorophyll <i>a</i>				
		Variable	Coefficient	%	F	p
Annual	0.64 (42)	LOG TN	0.741	36	3.88	<0.06
		T	-0.080	8	19.29	<0.0001
		TURB	0.962	9	16.07	<0.0003
		LIGHT	1.680	3	6.44	<0.02
		LOG NO_3	-0.228	4	3.35	<0.08
		LOG NH_3	0.367	3	4.82	<0.03
Growing Season	0.80 (23)	LOG TN	2.104	43	4.55	<0.05
		LIGHT	3.489	12	20.53	<0.0003
		T	-0.066	16	6.89	<0.02
		LOG NH_3	0.397	3	6.82	<0.02
		TURB	0.615	6	5.23	<0.03
Fall	0.95 (15)	LOG TP	1.878	57	147.13	<0.0001
		T	-0.098	12	49.33	<0.0001
		LIGHT	1.388	22	19.59	<0.001
		LOG NO_3	-0.415	3	6.96	<0.02

reservoir. A large portion of the annual variability in turbidity measurements observed in the upper zone of the reservoir were explained by nonvolatile solids (31%), while only 6% of the turbidity variability could be attributed to chlorophyll a concentrations (a similar relationship existed in the growing season) (Principe, in prep.). Turbidity within the water column can be a determinant of increased chlorophyll a content within the cells of effected algae. Soballe and Kimmel (1987) suggested that larger cell sizes or increased chlorophyll per cell (or both) predominate in rivers and rapidly flushed, somewhat turbid, lentic systems. It has been well documented that larger cell size is expected in high nutrient systems where turbulence reduces algal sinking losses (Smayda 1970; Reynolds 1984), and cell chlorophyll content generally increases in situations having high turbidity (light-limitation) and high nutrient concentrations (Harris 1978). Therefore, the fall model predicts that as water transparency increased, most likely as a result of a lessening in nonalgal light attenuation, algal biomass (chlorophyll a) levels may have increased accordingly.

A spatial analysis of the relationship between 1988 photic zone depth (Z_p) and mixed layer depth (Z_m) (Figure 3-16) revealed that during the early summer stratification period Z_p exceeded Z_m . It was also noted that the $Z_p:Z_m$ ratio accounted for 10% of the variability in 1988 growing season

chlorophyll a concentrations when substituted for the "LIGHT" variable in the multiple linear regression model described in Table 3-6. Overall, the "LIGHT" variable was found to account for greater variability in 1988 chlorophyll a concentrations than the $Z_p:Z_m$ ratio. Furthermore, beginning in late August, Z_p was less than Z_m at all sites, thus suggesting that light may have been limiting in a portion of the mixed layer at each location. This transition from $Z_p > Z_m$ to $Z_p < Z_m$ was noted as being more gradual in the lower zone than in the upper zone of the reservoir. In addition, photoautotrophic production (as measured as percent oxygen saturation) was found to be significantly greater at Site 1 than at Site 8 during the late spring period ($F=2.63$ $n=43$ $p=0.05$) (Figures 3-17 and 3-18). These findings are in agreement with the productivity zonation model proposed by Kimmel et al. (1990) in which levels of productivity and $Z_p:Z_m$ ratios found in the reservoir's lower zone exceed those measured in the upper zone.

Table 3-7 presents three regression models which relate fall epilimnetic chlorophyll a concentrations measured within different zones of the reservoir to a number of important environmental variables measured at multiple depths at Sites 1, 4, 6, and 8. As noted in Table 3-6, Table 3-7 illustrates that when all sites are considered, TP concentrations still explain 39% of the variability in

Figure 3-16. Temporal patterns of photic depth to mixing depth ratios as measured biweekly during 1988 for: (a) Site 1, (b) Site 4, (c) Site 6, and (d) Site 8. Ratio values less than one indicate possible light limitation within the mixed layer.

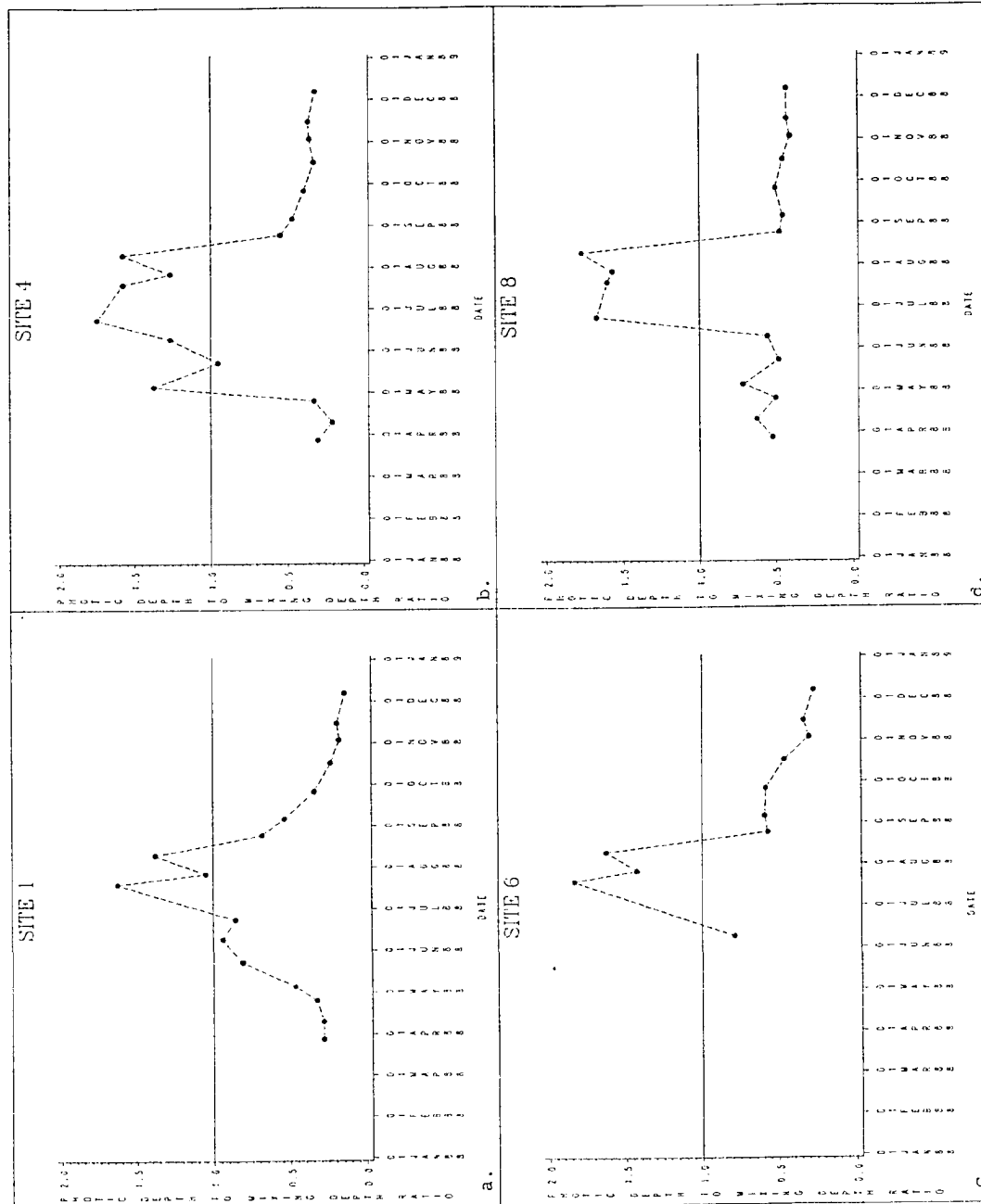


Figure 3-17. Temporal patterns of mean epilimnetic percent oxygen saturation as measured biweekly during 1988 for: (a) Site 1, (b) Site 4, (c) Site 6, and (d) Site 8.

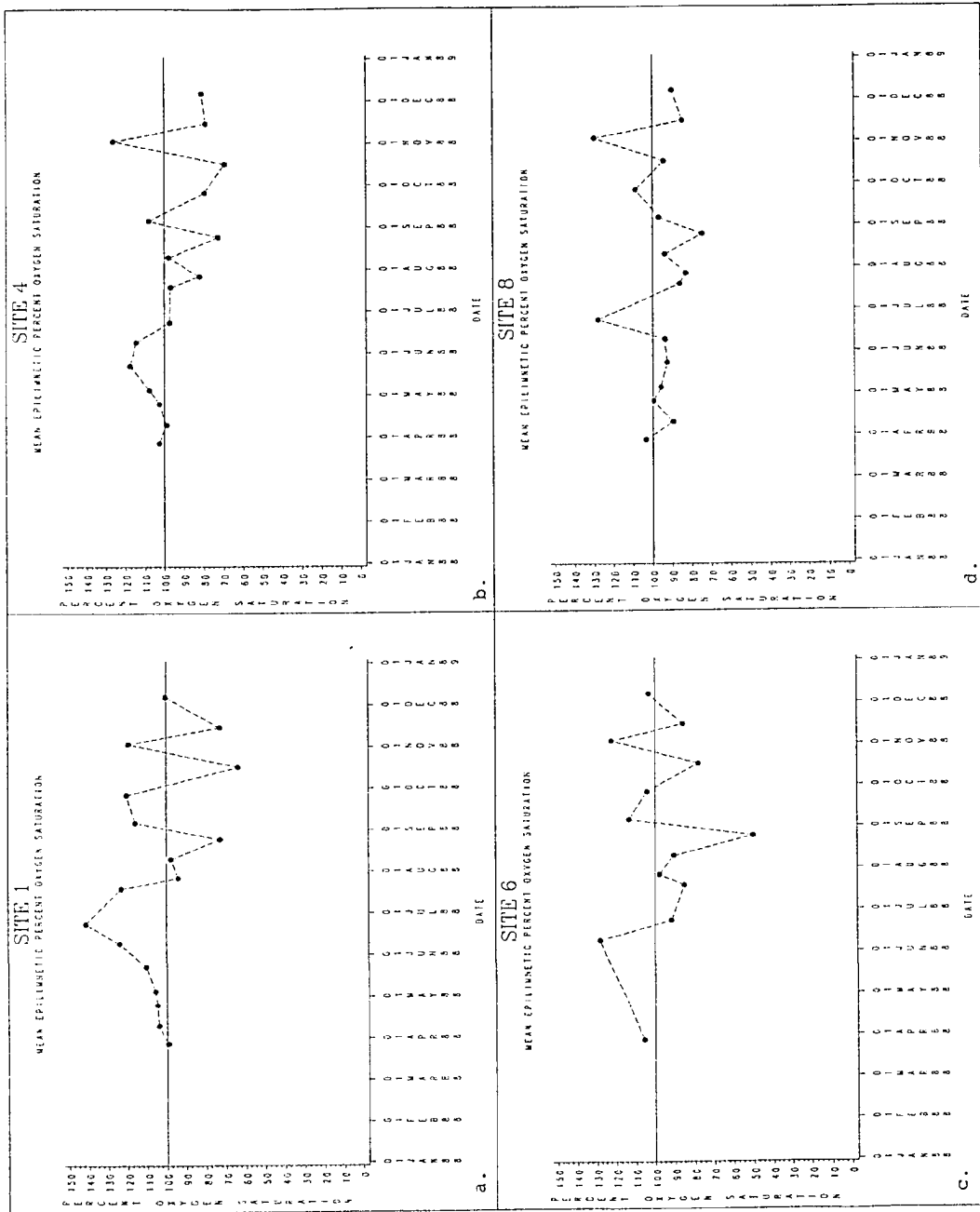
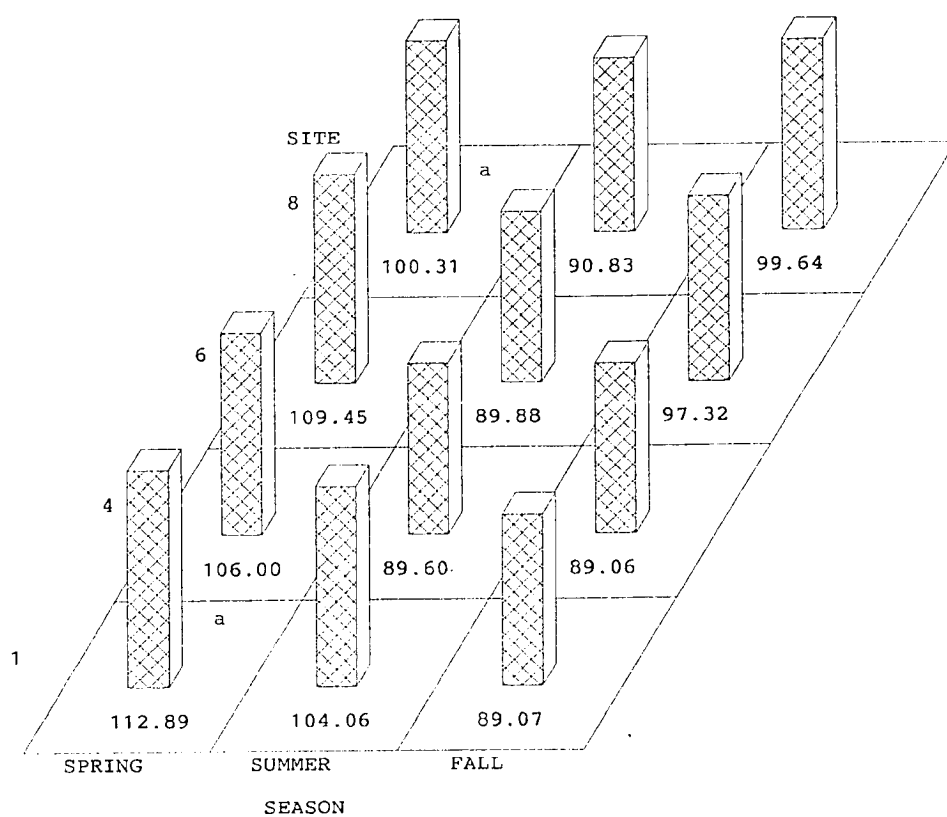


Figure 3-18. Mean seasonal percent dissolved oxygen saturation as measured biweekly during 1988 for Sites 1, 4, 6, and 8. Significant within season differences (column) between sites (by Tukey-Kramer multiple comparison test ($p=0.05$) are noted with arabic letters (sites with the same letters are significantly different).

1988 BIWEEKLY SURVEYS

MEAN SEASONAL PERCENT DISSOLVED OXYGEN SATURATION



epilimnetic chlorophyll *a* concentrations. However, within the upper zone of the reservoir, dissolved inorganic nitrogen (DIN) was important in explaining 30% of the chlorophyll *a* variability. A steady increase in DIN concentrations at Sites 6 and 8 beginning in October coupled with stable TP concentrations and a coincident decline in the October–November chlorophyll *a* peak, may have accounted for the negative DIN coefficient. At the same time, temperature accounted for 47% of the variability in chlorophyll *a* concentrations in the lower zone of the reservoir. Unlike, the upper zone, chlorophyll *a* concentrations peaked in November–December within the lower zone, thus explaining the negative relationship between increasing algal biomass levels and gradually decreasing epilimnetic temperatures.

As mentioned above, TP and chlorophyll *a* concentrations both exhibited pronounced longitudinal gradients in the fall of 1988. This explains the strong relationship between TP and chlorophyll *a* when viewed from the "all site" or spatial perspective, as noted in Tables 3-6 and 3-7. However, this relation was not evident, as presented in Table 3-7, when the upper and lower zone of the reservoir were assessed separately. TP had less variability within each zone as opposed to along the reservoir's longitudinal gradient.

Table 3-7. Multiple linear regression equations derived from stepwise variable selection relating 1988 Fall epilimnetic chlorophyll a concentration to environmental variables as measured within different zones of Croton Reservoir. TP-total phosphorus concentration ($\mu\text{g L}^{-1}$); NO_3 -nitrate+nitrate nitrogen concentration (mg L^{-1}); T-water temperature ($^{\circ}\text{C}$); DIN-dissolved inorganic nitrogen (mg L^{-1}); VS-volatile solids (mg L^{-1}); NVS-nonvolatile solids (mg L^{-1}); n-sample size. All models were significant at $p < 0.01$.

Zone	R ² (n)	Model Description				
		Independent Variable	Coefficient	% Variance Explained	F	P
All Sites	0.79 (62)	LOG VS	0.159	19%	32.15	<0.0001
		LOG TP	0.582	39%	7.91	<0.007
		LOG NO ₃	-0.545	10%	27.51	<0.0001
		T	-0.874	7%	44.76	<0.0001
		NVS	0.256	4%	14.92	<0.0003
Upper Zone	0.54 (31)	LOG DIN	-0.738	30%	37.11	<0.0001
		LOG TN	0.909	25%	6.12	<0.02
Lower Zone	0.52 (31)	LOG TP	0.873	5%	2.81	<0.10
		T	-0.108	47%	26.51	<0.0001

Zooplankton-Chlorophyll *a* Relationships

Many of empirical models (Sakamoto 1966; Dillon and Rigler 1974, Vollenweider 1976) attempt to predict annual changes in algal biomass by analyzing various aspects of nutrient loading, in-lake nutrient concentration, and lake morphometry and hydrology. Most of these models utilize a regression in which chlorophyll *a* (dependent variable) is regressed against total phosphorus (independent variable). Dillon and Rigler (1974) have pointed out that the confidence limits associated with these models are wide, and there is a good chance other variables may help to explain some of the variability associated with these models (Smith 1982). Shapiro (1980) has shown that biotic factors have an impact on the chlorophyll to total phosphorus relationship. When large cladoceran zooplankton become abundant in lakes the concentration of chlorophyll is reduced independent of changes in total phosphorus (Shapiro and Wright 1984). Pace (1984) noted that the manipulation of community composition and biomass of zooplankton could possibly be employed as a lake restoration technique, i.e., ameliorate the effects of eutrophication without the expensive programs to reduce nutrient loading. Pace (1984) investigated whether zooplankton biomass and zooplankton community composition could both be used as significant additional independent variables in total phosphorus-chlorophyll models. He hypothesized that high zooplankton biomass should be

associated with underestimates of chlorophyll a as predicted by total phosphorus-chlorophyll a models. He found that zooplankton biomass was not significant in explaining residual variation in the total phosphorus-chlorophyll a relationship of any data set studied, and that a zooplankton community index derived from the slope of log abundance-log weight regressions was significant in explaining residual variation in total phosphorus-chlorophyll a relationships, i.e., lakes with higher macrozooplankton:microzooplankton abundance ratios generally have less chlorophyll a per unit total phosphorus.

A multiple linear regression analysis was performed to assess the impact of zooplankton grazing upon chlorophyll a concentrations within Croton Reservoir. Table 3-8 relates 1986-1988 growing season epilimnetic chlorophyll a concentration to total zooplankton biomass and other key environmental variables within different zones of Croton Reservoir. The growing season period was studied since this was the period that cladocerans were observed to be most abundant. Zooplankton biomass was found to be negatively correlated with chlorophyll a concentrations at all sites. In addition, while zooplankton biomass accounted for 13% and 6% of the variability in epilimnetic chlorophyll a concentrations at all sites and within the upper zone respectively, it accounted for 26% of the variability of chlorophyll a concentrations within the reservoir's lower

zone. This finding agrees with the conceptual reservoir zonation model proposed by Kimmel and Groeger (1984) in which phytoplankton cell losses by grazing are much more important in the lacustrine zone than in the riverine zone. These findings also suggest that abiotic factors alone cannot account for levels of phytoplankton biomass within Croton Reservoir.

Table 3-8. Multiple linear regression equations derived from stepwise variable selection relating 1986-1988 growing season (July-October) epilimnetic chlorophyll *a* concentration ($\mu\text{g L}^{-1}$) to total zooplankton biomass (TBIOMASS) concentration ($\mu\text{g L}^{-1}$) and other key environmental variables as measured within different zones of Croton Reservoir. T-water temperature ($^{\circ}\text{C}$); NO_3 -nitrite+nitrate nitrogen (mg L^{-1}); NH_3 -ammonia nitrogen (mg L^{-1}); ZTH-thermocline depth (m); TP-total phosphorus ($\mu\text{g L}^{-1}$); n=sample size; % = percent variance explained by independent variable; All models were significant at $p < 0.05$.

Zone	R^2 (n)	Model Description: Chlorophyll <i>a</i>				
		Variable	Coefficient	%	F	p
All Sites	0.48 (51)	LOG NH_3	0.255	15	4.26	<0.04
		LOG TBIOMASS	-0.501	13	20.67	<0.0001
		LOG TP	0.399	10	7.91	<0.007
		ZTH	-0.065	10	8.85	<0.005
Upper Zone	0.44 (24)	LOG TP	0.648	38	12.23	<0.001
		LOG TBIOMASS	-0.225	6	2.51	<0.1275
Lower Zone	0.55 (26)	LOG TBIOMASS	-0.523	26	16.00	<0.0001
		ZTH	-0.050	23	10.30	<0.004
		LOG NH_3	0.310	6	3.15	<0.09

DISCUSSION

Croton Reservoir exhibited a longitudinal gradient of algal biomass from headwater to dam during both the 1984 - 1987, and the 1988 study periods. This gradient was consistent with those described by current reservoir zonation models which depict a high flow or rapidly flushed impoundment with a large, less pronounced, or mediated "riverine" zone and a limited "transitional" zone (Thornton et al. 1981, Kimmel and Groeger 1984). However, Croton Reservoir failed to conform to the parameters of the "idealized" 3-zone model, which describes well defined riverine, transitional, and lacustrine gradations. The gradient only appeared during the summer-fall periods of increased hydraulic residence time. The spatial and temporal algal biomass patterns observed during 1984-1987 were confirmed in the 1988 "test" year, although some of the patterns that occurred in 1988 were unique to that year. The overall spatial pattern that emerged from both the 1984-1987 monthly algal biomass data and the 1988 monthly and biweekly algal biomass data, was one of greater chlorophyll a and total phytoplankton concentrations in the upper zone of the reservoir. Trends evident in both the 1984-1987 and 1988 monthly survey data were found to be more pronounced in the 1988 biweekly survey data, with the reservoir's upper zone exhibiting higher chlorophyll a concentrations than the

reservoir's lower zone. During the 1984-1988 study period, 1984 and 1988 exhibited the greatest chlorophyll a concentrations of all years, with 1985 and 1986 exhibiting the lowest concentrations. Longitudinal gradients in chlorophyll a were only noted in 1986 and in 1988. 1988 also exhibited elevated total phytoplankton counts which were greater than those measured in 1984 and 1985. The lowest phytoplankton counts were observed in 1985.

Seasonally, the 1984-1987 monthly survey, and the 1988 monthly and biweekly survey measurements of epilimnetic chlorophyll a concentrations were significantly greater within the upper zone of the reservoir during the fall, with fall being, with the exception of 1988, the only season in which a longitudinal gradient of algal biomass occurred during the study period. This pattern was particularly evident in the fall of 1988 when all sample sites exhibited pronounced chlorophyll a peaks. The lower zone sites only exhibited a fall chlorophyll a peak in 1988, in all other years, fall chlorophyll a peaks were restricted to the upper zone of the reservoir. In addition, late summer chlorophyll a and total phytoplankton peaks were also observed at all sites in 1988, with both of these peaks being higher than those observed in all other study years; in fact, 1988 was the only year in which both summer and fall algal biomass longitudinal gradient appeared.

Sampling performed at monthly intervals during 1988 failed to uncover seasonal spatial patterns in chlorophyll *a* concentrations that were detected by biweekly sampling, e.g., the summer algal biomass gradient (Figure 3-10). These results suggest that sampling performed at monthly intervals may not be adequate when it comes to the detection of seasonal patterns of algal biomass.

Chlorophyll a with Depth

Results obtained from the analysis of the multiple depth epilimnetic chlorophyll *a* data collected during the biweekly surveys of 1988 revealed no significant annual or seasonal differences with depth within the epilimnion of Croton Reservoir for chlorophyll *a* concentrations at depths above 9 meters. Significant differences with depth were only detected during the summer when the shallower sites (6 and 8) exhibited lower chlorophyll *a* concentrations at 9 m than at shallower depths. These vertical differences in chlorophyll *a* concentration during the summer months were most likely attributable to fluctuations in the vertical mixing regime, and variations in light availability or photic zone depth. Biomass levels tend to dropoff in the "shallower" zones of an impoundment where the depth of the mixed layer often exceeds the depth of the photic zone (Kimmel et al., 1990).

It was concluded that all chlorophyll *a* measurements made at less than 9 meters would be representative of epilimnetic concentrations. Differences in chlorophyll *a* concentration among sites for single epilimnetic samples were assumed to be due to true epilimnetic differences in chlorophyll *a* concentrations over time, and that differences in algal biomass concentrations with depth were not significant.

Interrelationships Between Abiotic and Biotic Factors

Some of the general patterns that emerged from the analysis of the interrelationships between the abiotic and biotic factors that occurred within the Croton Reservoir during the 1984-1988 study period are summarized below. Both silica and TN concentrations were important in explaining the variability in annual chlorophyll *a* concentrations, with TN being more important during the growing season period. Algal light attenuation effects were most pronounced in the lower zone of the reservoir during both the growing season and the fall periods. Nonalgal light attenuation had its greatest influence on algal abundance during the fall within the upper zone of the reservoir. TP concentrations were most important in explaining the variability in algal abundance at all sites during the fall. It was only during the fall period in which a longitudinal gradient in both TP concentrations and algal biomass consistently occurred

within the impoundment. Croton Reservoir exhibited a pronounced longitudinal TP, and Secchi depth gradient during the fall of 1988 (Chapter 2). However, on a zonal basis, fall algal biomass was most influenced by light limitation, and DIN concentrations within the upper zone, and by temperature in the lower zone. The intensity of this 1988 TP and Secchi depth gradient may have been attributable to the heavier than normal November precipitation levels during that year (21.59 cm). These anomalous precipitation levels most likely enhanced the flushing action within Muscoot Reservoir, thus increasing the allochthonous input of sediment and nutrients into Croton Reservoir. During this period TP was highly correlated with turbidity ($r=0.95$, $p<0.0001$) and suspended solids ($r=0.90$, $p<0.0001$), and Secchi depth levels within the upper zone of the reservoir were depressed. Algal biomass may have been advected from the Muscoot Reservoir into the Croton Reservoir, thereby contributing to the higher algal biomass levels observed within the upper zone of the reservoir. This hypothesis needs to be further investigated, although such phenomena have been observed in a number of contiguous or interconnected impoundments (Brook and Rzoska 1954, Shiel and Walker 1984, Petts 1984).

During the growing season, zooplankton biomass was found to be negatively correlated with chlorophyll a concentrations at all sites. Zooplankton biomass, primarily

composed of cladocerans, explained the greatest amount of variability in epilimnetic chlorophyll a concentrations within the reservoir's lower zone. These findings suggest that phytoplankton losses by grazing may be more important within the reservoir's lower zone, and that abiotic factors alone cannot account for levels of phytoplankton abundance within the reservoir.

Residence Time and Algal Biomass Relationships

Table 3-9 presents a correlation matrix relating algal abundance to monthly hydraulic residence time and reservoir volume levels measured during the 1984-1988 growing season periods for all sites combined. As mentioned previously a weak relationship existed between total phytoplankton counts (standard areal units-s.a.u. ml⁻¹) and chlorophyll a concentrations (ug L⁻¹). There was also a weak relationship between areal counts of cyanobacteria (s.a.u. ml⁻¹) and chlorophyll a. Croton Reservoir exhibited high counts of cyanobacteria during the growing season (Chapter 4), yet chlorophyll a concentrations did not display any appreciable rise during this period. This may explain why chlorophyll a concentrations did not exhibit any significant correlation with residence time or reservoir volume, and may have partially been a result of the deficiencies inherent in the chlorophyll extraction and phytoplankton enumeration methodologies used throughout this study (see Methods

Table 3-9. Correlation matrix relating algal abundance variables to monthly hydraulic residence time and reservoir volume values measured during the 1984-1988 growing season periods (July-October) for all sites combined. All variables were logarithmically transformed before analysis to comply with the assumptions of correlation analysis. TPLK-total phytoplankton (standard areal units m^{-1}); CYANO-cyanobacteria (standard areal units m^{-1}); CHLA-chlorophyll *a* ($\mu\text{g L}^{-1}$); TW-hydraulic residence time (years); V-reservoir volume ($10^6 \times \text{m}^3$). The Pearson correlation coefficient (*r*), the sample size (*n*), and the *p*-value are listed for each variable relationship. n.s.=not significant at $p < 0.05$.

<u>Growing Season Measurements 1984-1988</u>			
	TW	V	CHLA
TPLK	0.32 (60) $p < 0.01$	0.67 (60) $p < 0.0001$	n.s.
CYANO	0.32 (54) $p < 0.02$	0.73 (54) $p < 0.0001$	0.38 (54) $p < 0.004$
CHLA	n.s.	n.s.	1.0 (60)

Section). However, both total phytoplankton and cyanobacteria counts were positively correlated with residence time and exhibited a strong positive correlation with reservoir volume. This finding suggests that during periods of short residence time and low reservoir volume levels, both total plankton and cyanobacteria numbers may decrease, and conversely during periods of long residence time, and high reservoir volume levels, total plankton and cyanobacteria numbers may elevate. Both of these patterns were observed during the five year study period. During a drought period which occurred in 1985, the reservoir experienced its lowest volume level (71%), and its shortest growing season hydraulic residence time (0.20 years), and all sites exhibited their lowest total phytoplankton counts of the five year period, with reduced numbers of cyanobacteria (Chapter 4). In contrast, during 1988, reservoir volume levels were elevated and stable (from 90-100%) for the year, and growing season hydraulic residence time was the longest (0.46 years) of the five year study period. Each sampling site exhibited its highest summer phytoplankton peak of the five year period during 1988, and each of these peaks was primarily composed of cyanobacteria. Residence time may play an important role in influencing chlorophyll *a* concentrations within the upper zone of the reservoir (Figures 3-19 and 3-20). With the exception of the 1985 drought year, the upper zone exhibited a late summer-

early fall chlorophyll a peak during all years, particularly when summer residence time exceeded 90 days (0.22 years). This pattern was most pronounced in 1988.

In addition, although the reservoir generally behaved as a rapidly flushed transitional system during the five year study period, it sometime exhibited the characteristics of a reduced flow, "lake-like" system during the summer months (Chapter 1). In particular, the summer-fall hydraulic residence times for 1986 and 1988 were 0.40 and 0.46 years, respectively. These were the two longest summer residence times observed during the 1984-1988 period. Both these years also experienced elevated precipitation levels during November (ca. 14 cm in 1986, and 20 cm in 1988). This rainfall caused residence time to decrease abruptly, and thus changed the reservoir's flow regime. It was during the fall of both these years, that the reservoir exhibited a longitudinal gradient of algal biomass. No other year exhibited such a pattern. This finding suggests that a period of prolonged summer-fall reservoir residence time, followed by a period of intense watershed runoff/Muscoot Reservoir inflow, may be the primary hydrologic factors responsible for the development of a longitudinal gradient in algal biomass within Croton Reservoir.

Both the seasonal and spatial algal biomass variations observed within the reservoir may have been attributable to the hydrologic factors mentioned above which facilitated

Figure 3-19. Chlorophyll *a* as measured monthly in $\mu\text{g L}^{-1}$ during the growing season (July-October) from 1984-1988 under varying reservoir hydraulic residence times for (a) the upper zone, (b) the middle zone, and (c) the lower zone. Residence time=circle, and chlorophyll *a*=dot.

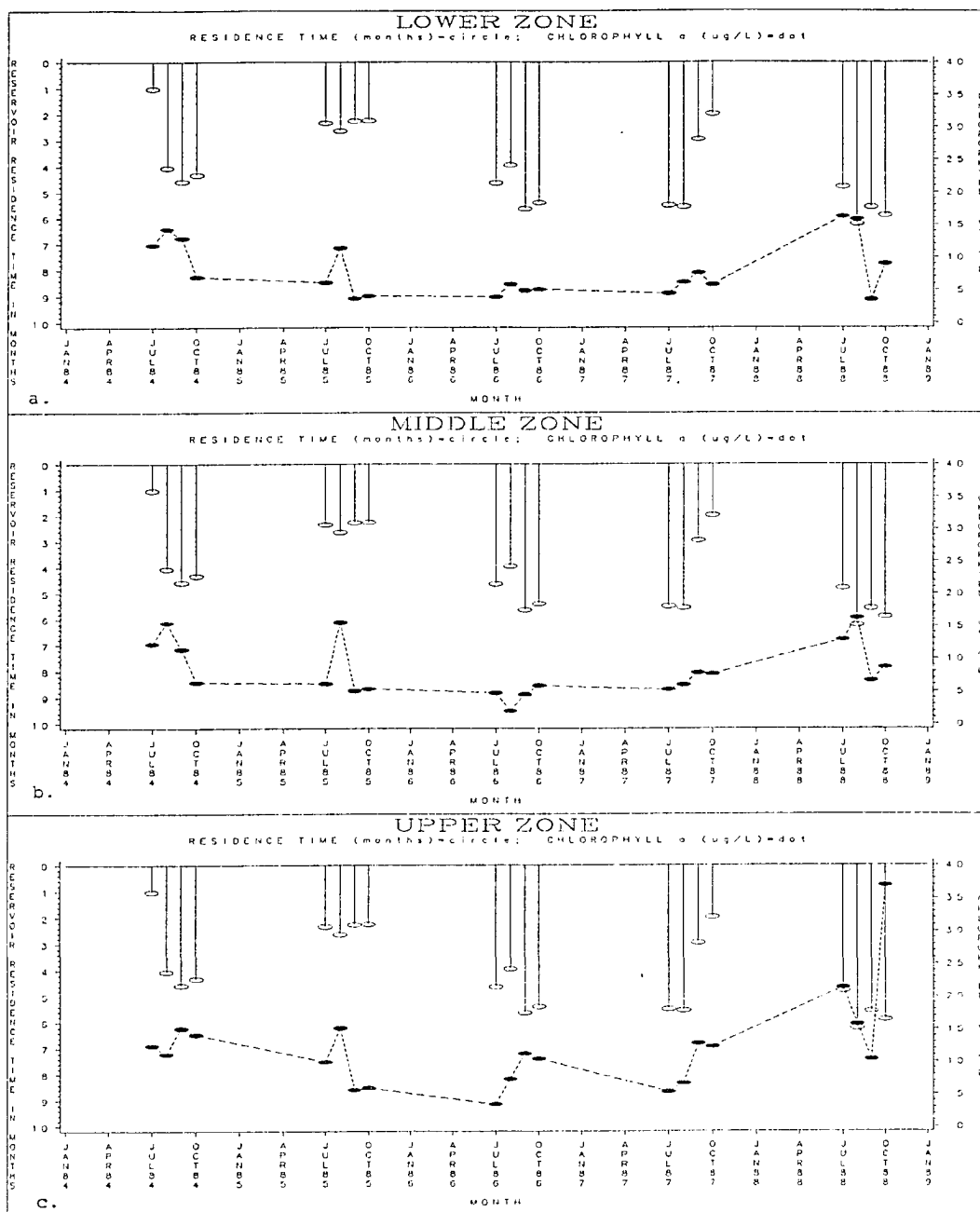
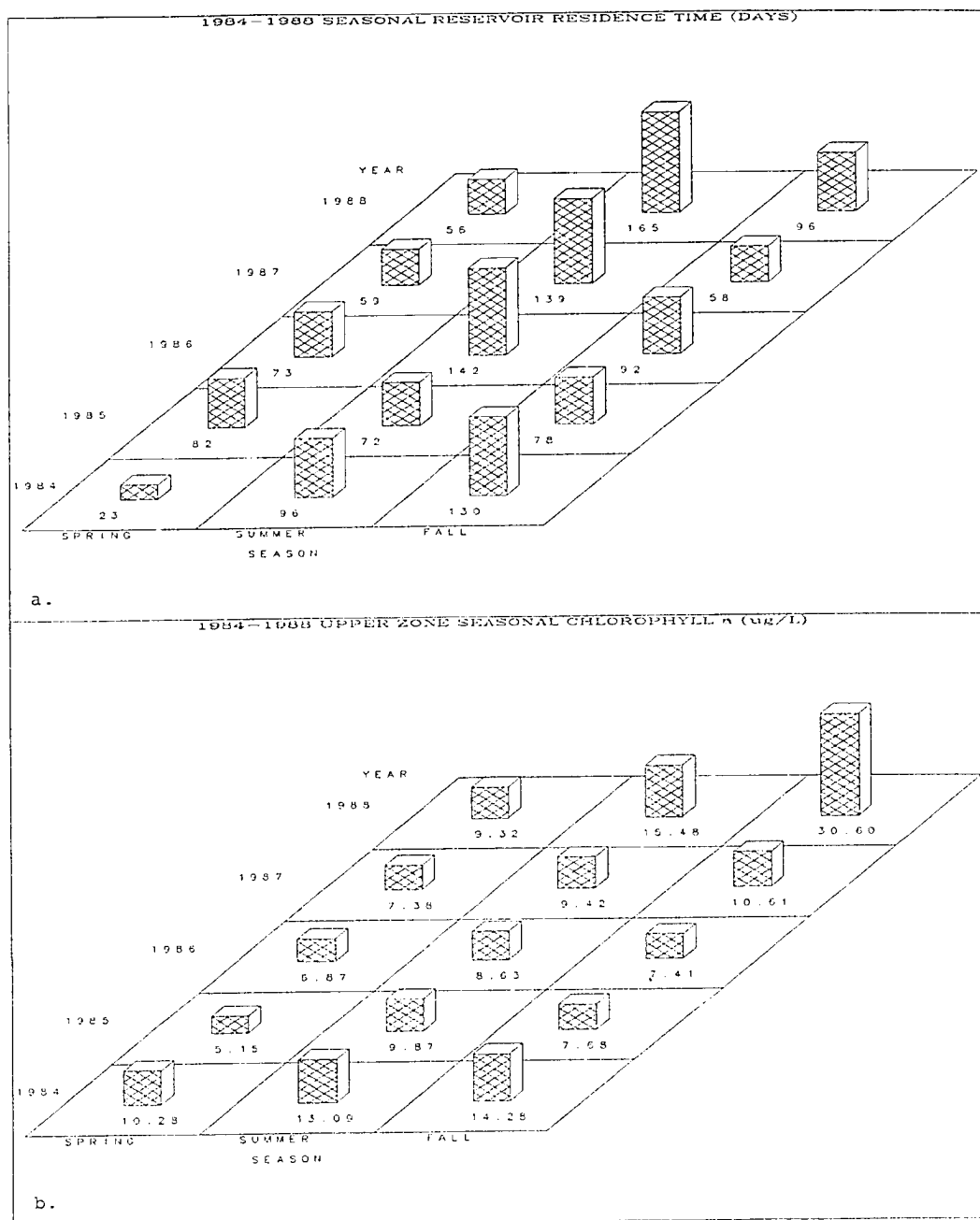


Figure 3-20. (a) mean seasonal hydraulic residence time as calculated monthly and measured in days during the 1984-1988 study period; and (b) mean seasonal chlorophyll a concentrations measured in $\mu\text{g L}^{-1}$ within the upper zone of the reservoir during the 1984-1988 study period.



both nutrient availability and increased mixing of the water column. Study results indicated that the variations in phytoplankton biomass within Croton Reservoir were not completely governed by nutrient limitation. With the exception of late summer DIN depletions, nutrient concentrations were usually at or above their respective detection limits within the Croton Reservoir water column (see Chapter 2). However, the relative proportions and concentrations of these nutrients varied both spatially and temporally within the reservoir. There are clearly other factors (many of which were not measured during this investigation), beside nutrient availability that play an important role in shaping the phytoplankton community both spatially and temporally. Such factors, as described by Reynolds (1984), may include: day-length, total irradiance, water column light availability, temperature, flow regime, the abundance of herbivorous animals, the inhibitory and stimulatory effect of trace metals, and phytoplankton antibiosis. In addition, the interaction of these factors often makes it difficult to determine which mechanism(s) primarily affected phytoplankton composition and biomass. Nevertheless, the relative proportions (ratios) or concentrations of the nutrients present can be a strong selective force in both shaping phytoplankton communities, as well as determining levels of biomass yield per unit of limiting nutrient (Hecky and Kilham 1988).

DIN:TP and Si:TP ratios exhibited considerable annual variation within the Croton Reservoir during the study period. Both ratios were highest in the spring and lowest in the summer (Chapter 2). These variations usually resulted from decreasing DIN and Si concentrations, and stable or increasing TP concentrations. Seasonal patterns of algal biomass appeared to coincide with the variability of these nutrient concentrations and water temperature. Both silica and TN concentrations were important in explaining the variability in annual chlorophyll a concentrations, with TN being more important during the growing season period. TP concentrations were most important in explaining the variability in algal abundance at all sites during the fall. As mentioned previously, it was during the fall period in which a longitudinal gradient in both TP concentrations and algal biomass consistently occurred within the impoundment during the study period. The fall was often noted as being a dynamic period for Croton Reservoir. As observed in the fall of 1988, the sequential upper to lower zone reservoir overturn in combination with November's higher than normal precipitation, and its resultant allochthonous sediment, nutrient, and algal biomass input from a thoroughly "flushed" Muscote Reservoir, may have lead to the marked differences in TP concentrations, Secchi depths, and chlorophyll a concentrations measured along the impoundment's 13.8 km length during that period.

Further research concerning the minimization of advective nutrient and organic matter input from Muscoot Reservoir is essential to an understanding of Croton Reservoir phytoplankton ecology. Two areas that warrant further investigation include: (1) the fate and transport of nutrients and organic material through the Muscoot-Croton Reservoir continuum; and (2) the importance of the biotic linkage between Muscoot and Croton Reservoirs with respect to the advective input of planktonic organisms. It was noted in Chapter 2, that the elevated TP concentrations present within the upper zone of Croton Reservoir in the fall were most likely the result of the combination of the massive late summer die-off and decomposition of the dense stands of *Myriophyllum spicatum* that thrive throughout much of Muscoot Reservoir and portions of the upper zone of Croton Reservoir, and the 5000 kg yr^{-1} load of TP Muscoot Reservoir receives from sewage treatment plants (STP) discharges within its 189.09 km^2 sub-basin. It was also suggested that the fall TP and algal biomass gradient within Croton Reservoir became more pronounced in 1988 as a result of heavier than normal November precipitation which enhanced the flushing action within Muscoot Reservoir, thus increasing allochthonous input of sediments, nutrients, and organic material to the upper reaches of Croton Reservoir. As noted earlier in this Chapter, multiple regression analysis revealed that TP accounted for 57% of the

variability in chlorophyll *a* concentrations within the reservoir during this period. In addition, TP had a highly significant correlation ($r=0.76$, $p<0.0001$) with chlorophyll *a*. These findings suggest that TP may be one of the important factors influencing phytoplankton abundance during the reservoir's autumnal circulation period. This type of relationship between algal biomass and total phosphorus is consistent with the predictions of the "yield limitation" nutrient-limitation models of both Dillon and Rigler (1974), and Vollenweider (1976) which estimate elevated levels of biomass based upon nutrient enrichment. Since Croton Reservoir receives 80% of its water input from Muscoot Reservoir, it is critical that water quality management practices be targeted at reducing advective outputs of nutrients, and organic matter from Muscoot Reservoir to Croton Reservoir, and that both reservoirs be managed as integrated systems in the future. Water quality remediation efforts should include a program aimed at reducing STP total phosphorus inputs to all reservoirs within the Croton River Watershed, through implementation of best available phosphorus removal technologies. Particular emphasis should be given to those wastewater treatment facilities which discharge into tributaries of the Muscoot and Croton Reservoirs. In addition, there is a need for a better understanding of phosphorus retention efficiency of the Muscoot ecosystem, and the influence of interreservoir

nutrient transfers upon Croton Reservoir algal abundance. Particular attention should be given to the structure and function of the Muscoot Reservoir macrophyte community and its role in nutrient cycling.

Similarly, further research is warranted concerning the biotic linkage between Muscoot and Croton Reservoirs with respect to the advective input of planktonic organisms. As was previously noted in this Chapter, algal biomass could have been advected from the Muscoot Reservoir into the Croton Reservoir during the fall, thereby contributing to the higher algal biomass levels observed within the upper zone of the reservoir.

The findings of this study suggest that there are a multitude of factors governing the temporal variability of phytoplankton abundance within a reservoir ecosystem, many of which are often interrelated and difficult to determine. The analysis of phytoplankton biomass variation within Croton Reservoir, proved to be challenging since the impoundment was generally not nutrient limited. In this case, it became critical to examine reservoir nutrient dynamics, hydraulic residence time effects, light and temperature variations, and zooplankton biomass dynamics in order to correctly interpret the spatial and temporal patterns of the reservoir's phytoplankton biomass. Croton Reservoir provided a unique environment to study the effects of flow regime and its associated physical and chemical

influences upon algal abundance. The impoundment essentially behaved as a rapidly flushed nutrient-rich system which occasionally exhibited longitudinal algal biomass gradients due to the combined sequential effect of increased growing season residence time coupled with intense fall precipitation. It appears likely that reservoir flow through rates were generally too rapid during a large portion of the year to allow for the accumulation of algal biomass. Kimmel et al. (1990) noted that as in a chemostat, if the flushing rate exceeds the phytoplankton doubling rate, the accumulation of biomass can be limited by advective losses (washout) of cells. Carmack et al. (1979) have indicated that phytoplankton washout can exert a major influence upon the accumulation of biomass in reservoirs with intermediate residence times (60-100 days) when the flushing rate of the photic zone is high, as in the spring. As such, the close examination of phytoplankton dynamics within Croton Reservoir during both slow and rapid flow regimes, helped to further clarify the distinction between patterns of phytoplankton abundance as observed within both low flow, "steady-state", nutrient-limited lacustrine environments, and hydrologically dynamic, nutrient enriched reservoirs.

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CHAPTER 4**The Floristic Composition of the Phytoplankton Within
Croton Reservoir, New York**

ABSTRACT

The spatial heterogeneity and temporal variability of phytoplankton floristic composition was studied in Croton Reservoir, New York, initially from 1984-1987, and more intensively during 1988. Croton Reservoir exhibited the same classic pattern of phytoplankton succession during both the 1984-1987, and the 1988 study periods, as that observed in most northern temperate mesotrophic-eutrophic lakes. Diatoms predominated in the spring and fall, whereas cyanobacteria occurred in great numbers during the late summer.

Chryosphyceae were coincident with the diatoms in the spring and fall, whereas the Chlorophyta and the Dinophyceae were present during the summer months. These temporal patterns of floristic composition appeared to be fairly consistent across all sites. No significant spatial differences in phytoplankton community structure were detected when phytoplankton counts were analyzed on a seasonal basis during both the 1984-1987, and the 1988 study periods.

Spring and fall diatom dominance was positively correlated with silica (Si) concentrations, dissolved inorganic nitrogen (DIN) concentrations, and DIN:total phosphorus (TP) ratios, and negatively correlated with epilimnetic temperature. Summer cyanobacteria dominance was negatively correlated with Si and DIN concentrations, and DIN:TP ratios, and positively correlated with epilimnetic

temperature.

Reservoir hydraulic residence time, and volume appeared to affect floristic composition. Growing season (July - October) reservoir volume and hydraulic residence time were positively correlated with the abundance of cyanobacteria, as well as the abundance of Chlorophyta. The rapid 1985 summer flushing rate may have inhibited the usual proliferation of slow-growing cyanobacteria within the reservoir. In contrast, the longer 1988 summer hydraulic residence time may have led to the more pronounced presence of Cyanobacteria observed during that period.

Findings from the study suggested that when studying phytoplankton dynamics within a hydrologically complex, nutrient-rich system, it was not only important to consider reservoir nutrient dynamics, hydraulic residence time effects, and light and temperature variations, but it was also essential to examine the individual ecological characteristics of the dominant phytoplankton. Such an approach allowed for a more accurate interpretation of the spatial and temporal patterns of phytoplankton succession and composition within the Croton Reservoir ecosystem.

INTRODUCTION

Kalff and Knoechel (1978) have noted that, although research concerning the composition of phytoplankton communities and the relative abundances of component species which undergo continuous changes on varying scales has resulted in an enormous amount of literature, progress in understanding and prediction has been very slow. Reynolds (1984) pointed out that there are still no widely-accepted explanations either of the mechanisms that drive the seasonal waxing and waning of phytoplankton, or the factors that condition long-term floristic changes. However, consideration of a particular body of water's trophic state, morphometry, geography, and hydrology, does allow one generalize both successional and compositional phytoplankton communal patterns.

One of the simplest descriptions of phytoplankton succession/composition was that of Findenegg (1943), who observed an increase in phytoplankton volume from spring to a maximum in July and a decrease the subsequent months to a minimum in winter in the Carinthian Lakes. Similar studies were performed by Birge and Juday (1922), Ruttner (1930), Pearsall (1932), and Grim (1939). Work of Whipple (1894) demonstrated in Lake Cochituate that there normally was a great increase in the number of Bacillariophyceae (diatoms) in the spring which subsequently disappeared in the early

summer. In the late summer the abundance of cyanobacteria (blue-green algae) may appear in great quantities, which are in turn followed by an autumnal diatom rise. This is the classic pattern of phytoplankton succession found in northern temperate mesotrophic-eutrophic lakes. This pattern has also been described by Boney (1975) and Fogg (1965). Boney (1975) indicated that in Lake Windermere the diatoms *Asterionella formosa*, *Tabellaria fenestrata*, and *Fragilaria crotonensis* tended to dominate the spring diatom bloom. *Melosira italica* had shown a growth period not synchronous with the spring outburst, but early in March. During the summer, after stratification became firmly established, the region above the thermocline lost nutrients and experienced a rise in the zooplankton population which at that time were actively grazing. As a result, phytoplankton numbers began to decline but diversity increased along with competition. Quite often, Dinophyceae (dinoflagellates) such as *Ceratium* sp. and *Peridinium* sp. appeared at this time. In late summer conditions became favorable for such cyanobacteria as *Anacystis cyanea*, *Anabaena flos-aquae*, *Aphanizomenon flos-aquae*, and *Gomphosphaeria lacustris*. Many of the spring diatoms persisted in the metalimnion throughout the summer and reappeared in greater numbers during the late autumn (Boney, 1975).

Wood (1979, 1981) in his studies of Cannonsville and Pepacton Reservoirs observed spring diatom increases with

summer cyanobacteria peaks in both reservoirs although the cyanobacteria peak in Cannonsville Reservoir was more pronounced. The eutrophic zones along the longitudinal trophic gradient present within each reservoir exhibited greater cyanobacteria numbers. Brown et al. (1980, 1986) found similar patterns in their study of Cannonsville Reservoir. They noted spring diatom peaks of *Asterionella formosa*, *Asterionella formosa gracillima*, *Fragilaria crotonensis*, *Melosira granulata*, and *Synedra acus*. Summer cyanobacteria peaks consisted of *Anabaena circinalis*, *Anabaena heterocysts*, *Aphanizomenon flos-aquae*, *Coelosphaerium naegelianum*, and *Microcystis aeruginosa*. Autumn diatom peaks were dominated by *Melosira granulata*, and *Melosira granulata angustissima*. Concentrations of phytoplankton were consistently highest in the riverine section of the reservoir.

Reynolds (1982), in similar form to Hutchinson (1967), categorized and generalized phytoplankton successional pathways in lakes of different trophic status. The data used in formulating his system were obtained from a wide range of temperate lakes. He notes that in a eutrophic lake, the diatoms *Asterionella formosa*, and *Fragilaria crotonensis* dominate the spring phytoplankton. Early summer includes the chlorophytes *Volvox sp.* and *Pandorina sp.* The cyanobacteria *Anabaena sp.* and *Aphanizomenon flos-aquae* become numerous during late summer along with the dinoflagellate *Ceratium*

sp. The diatoms *Asterionella formosa*, and *Fragilaria crotonensis* reappear once again in the autumn.

Resource competition among the phytoplankton has been noted as having considerable importance in structuring the phytoplankton community (Tilman et al. 1982; Kilham and Kilham 1984; Sommer 1985). Sommer (1985) indicated that resource competition was important in determining the course of seasonal succession in Lake Constance. Kilham et al. (1986) noted that resource competition influenced the distribution and abundance of many common diatom species in the lakes of east and central Africa. In their review of phytoplankton ecology, Kilham and Hecky (1988) discuss resource competition among the phytoplankton from the r - K selection perspective. They note that r and K selected phytoplankton species differ in their ecological and physiological properties. These properties may enhance or inhibit the ability of a species to exploit available resources. r -selected organisms have high growth rates, can rapidly exploit nutrient patches that become available in the environment (have enhanced nutrient uptake rates), are small, and have high loss rates. K -selected phytoplankton have low maximum growth rates, low loss rates, low nutrient uptake rates, and are large. Many K -selected algae escape from grazing by zooplankton because they are large, colonial, and toxic while many small r -selected organisms are heavily grazed (Lehman and Sandgren 1985; Guillard and

Kilham 1977). *K*-selected algae are capable of utilizing the low ambient nutrient concentrations often found within oligotrophic waters. They take up nutrients slowly, but their growth rates are low as well. Kilham and Hecky (1988) point out that cyanobacteria such as *Anabaena flos-aquae* and *Microcystis aeruginosa* are storage specialists that appear to occupy a more intermediate position on the *r* through *K* selection continuum. These organisms are physiologically similar to *r*-selected organisms except that they grow more slowly and thus do not utilize their internal stores as rapidly. Steinberg and Hartmann (1988) pointed out that, in the presence of frequent or permanent turbulence, but with mixing depths less than the euphotic zone, cyanobacteria can outgrow normally dominant *r*-strategists under conditions of low N:P ratios, high water temperature, pH >9.0 or low light conditions.

The purpose of this study was to investigate the spatial heterogeneity and the temporal variability of the floristic composition of the phytoplankton from headwater to dam within Croton Reservoir, New York. Preliminary patterns of spatial heterogeneity and temporal variability of the phytoplankton composition present within the reservoir were first studied from 1984 to 1987, and further evaluated during 1988. Additional information concerning the hydrology and physiography of Croton Reservoir and the spatial and temporal variability of the physical and chemical processes

occurring within the impoundment were also evaluated during these time periods (Chapter 1 and Chapter 2). These data were reviewed in conjunction with the spatial and temporal algal floristic composition information in an effort to discover possible interrelationships. However, since this study was based entirely on observational data, causal assumptions were made cautiously.

The findings from this study were directly applicable to the management of Croton Reservoir as a drinking water supply, and provide a foundation for future research regarding the water quality impacts associated with the spatial and temporal variability of phytoplankton composition as it occurs within the impoundment.

STUDY AREA

Croton Reservoir is the final receiving reservoir of the Croton River. The impoundment is located in southeastern New York State ($41^{\circ} 13' 39''$ N, $73^{\circ} 51' 27''$ W), and lies 59.6 meters above mean sea level. The reservoir has a surface area of $9.13 \times 10^6 \text{ m}^2$, a volume of $90.77 \times 10^6 \text{ m}^3$, and a mean and maximum depth of 9.9 and 36.6 m, respectively. The effective drainage area of the impoundment is $152.80 \times 10^6 \text{ m}^2$, although the reservoir ultimately receives drainage from the entire Croton watershed which has a total drainage area of $971.30 \times 10^6 \text{ m}^2$. The effective $A_d:A_o$ ratio for the

reservoir is 16.70, whereas the Croton Watershed $A_d:A_o$ ratio for the reservoir is 106.40. Croton Reservoir has a dendritic shoreline development index of 4.9 which is typical of a flooded river valley caused by either natural or artificial damming (Hutchinson 1957). The reservoir is owned and operated by the City of New York, and supplies the City with approximately 10-15% of its annual drinking water supply needs. A more detailed description of the study area is contained within Chapter 1.

METHODS AND MATERIALS

Water samples were collected and analyzed for key chemical, physical, and biological variables, and field surveys were performed monthly during the ice-free season (March-December) from 1984 through 1987 at four sites located along the longitudinal axis of Croton Reservoir from the headwaters to the dam. These four sites were chosen because they were thought to represent zones of differing flow regimes in the impoundment, i.e., riverine, transitional, and lacustrine. Sites 1, 4, 6, and 8 were located 0.23, 3.95, 6.50, and 12.00 kilometers from the dam respectively. The sampling design and analytical matrix of this study were based upon a eutrophication assessment program developed by the Organization for Economic Cooperation (OECD 1982). This program was designed to

quantify the relationship between nutrient load in waters and their trophic reaction.

In addition to the monthly surveys performed during 1984-1987 and continued in 1988, more intensive biweekly sampling was carried out in 1988. Results obtained from the 1988 monthly and biweekly surveys allowed for both a further refinement and evaluation of the monthly testing performed during 1984-1987, and a confirmation of the spatial and temporal patterns observed during that same period. The dates sampling was performed during the five year study period are listed in Chapter 2.

For each of the monthly surveys, epilimnetic water samples, as determined by prior *in situ* measurements of the thermocline and photic zone depths, were collected from each of the sites with a 2.2 liter acrylic Van Dorn sampler at each site and brought back to the laboratory for analysis. For each of the 1988 biweekly surveys, water samples were collected with a Van Dorn sampler at the multiple epilimnetic depths described above, and brought back to the laboratory for analysis as well. Vertical profiles of temperature, pH, and dissolved oxygen were measured *in situ* using a Hydrolab Surveyor II (Hydrolab Corp., Austin, Texas). Physical and chemical analyses were performed as outlined in Chapter 2.

Total phytoplankton counts were determined following a method described in Standard Methods (1955,

1965). This method, or some modification of it, has been used by the New York City Water Supply Laboratories, as well as many other water supply laboratories located in the United States, since the early 1900's. During the 1984-1988 study period, water samples collected from the reservoir were immediately transported to the laboratory where a subsample was concentrated by means of a Sedgwick-Rafter sand filter. One milliliter of the concentrate was placed in a Sedgwick-Rafter counting cell and enumeration of the organisms was made with the aid of a Nikon phase-contrast microscope fitted with a Whipple ocular micrometer at a magnification of 100X. Algae were identified to genus and quantitative records for each genus, major class, and total number present were recorded. Enumeration was made in standard areal units (s.a.u.). where one s.a.u. equaled 400 square microns. The use of low magnification (100X) coupled with the sand concentration technique used in this method, undoubtedly result in a significant loss of the algal cell units recorded during the enumeration process, and lead to an underestimation of actual phytoplankton values. It has been well documented that many waters contain a larger volume of minute nanoplankton than of the larger forms readily seen under low magnification (Palmer and Maloney 1954). Nevertheless, the s.a.u. method has historically been the preferred algal enumeration method by water supply utilities since it has helped in the past to determine the

most effective time for treating a reservoir with an algicide (Whipple 1948). The total area of algae present, particularly diatoms, was useful information for determining the relationship of plankton to the length of water treatment plant filter runs (Palmer 1959). The City of New York Bureau of Water Supply has continued using the standard areal unit enumeration method, as opposed to direct cell counts, for two reasons: (1) to preserve continuity in its long-term phytoplankton database; and (2) it was generally believed the standard areal unit counting method adequately measured total algal biomass and characterized floristic composition. Since the objective of this study was to characterize the spatial and temporal variability of floristic assemblages within the reservoir, it was determined that the standard areal unit method of phytoplankton enumeration would adequately describe the relative proportions of phytoplankton classes present over time and space, and that little additional information would be gained by converting from areal units to cell counts. Such a conversion would be possible since phytoplankton cell surface area is directly related to cell volume (Reynolds 1984), however, it would nevertheless be a difficult procedure to implement because it would require the collection of a large amount of coincident phytoplankton cell count data on a species level over time for comparative purposes. These temporal collections would be necessary

since cell dimensions of a phytoplankton species can vary greatly from season to season (Wetzel and Likens 1979).

The different time periods referred to in this chapter are as follows: spring: March-June; summer: July-September; fall: October-December; and growing season: July-October. The growing season period was used in the analysis of hydraulic residence time effects upon floristic composition since it was observed as being a period of great biological importance within Croton Reservoir. During this period the impoundment generally exhibited pronounced thermal stratification, light penetration, phytoplankton accumulation, and phytoplankton diversity.

All statistical analyses were performed using the Statistical Analysis System (SAS Institute Inc., Version 6.03, 1988). All variables subjected to parametric statistical analysis were examined for normal distributions. Total and class phytoplankton counts were normally distributed when transformed to natural logarithms. Analysis of variance with the Tukey-Kramer multiple comparison method was used to test for significant differences ($p < 0.05$, unless noted otherwise) between spatial and temporal biotic patterns observed in the reservoir during the five year study period.

RESULTS

General Spatial and Temporal Patterns

Croton Reservoir exhibited the same classic pattern of phytoplankton succession during both the 1984-1987, and the 1988 study periods, as that observed in most northern temperate mesotrophic-eutrophic lakes. Bacillariophyceae (diatoms) predominated in the spring and fall, whereas cyanobacteria occurred in great numbers during the late summer. In addition, Chryosphyceae were coincident with the diatoms in the spring and fall, whereas the Chlorophyta and the Dinophyceae were present during the summer months. These temporal patterns of floristic composition appeared to be fairly consistent across all sites (Figures 4-1 and 4-2). The Chryosphyceae, Chlorophyta, Dinophyceae, and Euglenophyta are grouped as "other" phytoplankton in these figures. Total phytoplankton numbers generally peaked in late spring (diatoms), and in late summer (cyanobacteria), with the lower zone sites exhibiting lower phytoplankton counts. Phytoplankton counts were highest during the spring and summer of 1988, and lowest during 1985. Figures 4-3 and 4-4 depict percent phytoplankton abundance by class as observed from 1984 through 1988, for Sites 1 and 4, and Sites 6 and 8 respectively. With the exception of 1985, cyanobacteria made up the largest part of the phytoplankton

during the summer months. This pattern was most pronounced during the summer of 1988, when the cyanobacteria comprised from 50 to 100% of the phytoplankton from July through September at all sites. During the summer of 1985 cyanobacteria were virtually absent from the phytoplankton populations observed at each site. The spring and fall phytoplankton populations were chiefly composed of diatoms at all sites, for all years.

Figure 4-1. Phytoplankton abundance by class, as measured in standard areal units ml^{-1} from 1984 through 1988, for (a) Site 1 and (b) Site 4. Class "Other" includes genera from the Euglenophyta, Chlorophyta, Chryosphyceae, and the Dinophyceae. Note the different scales on the vertical axes.

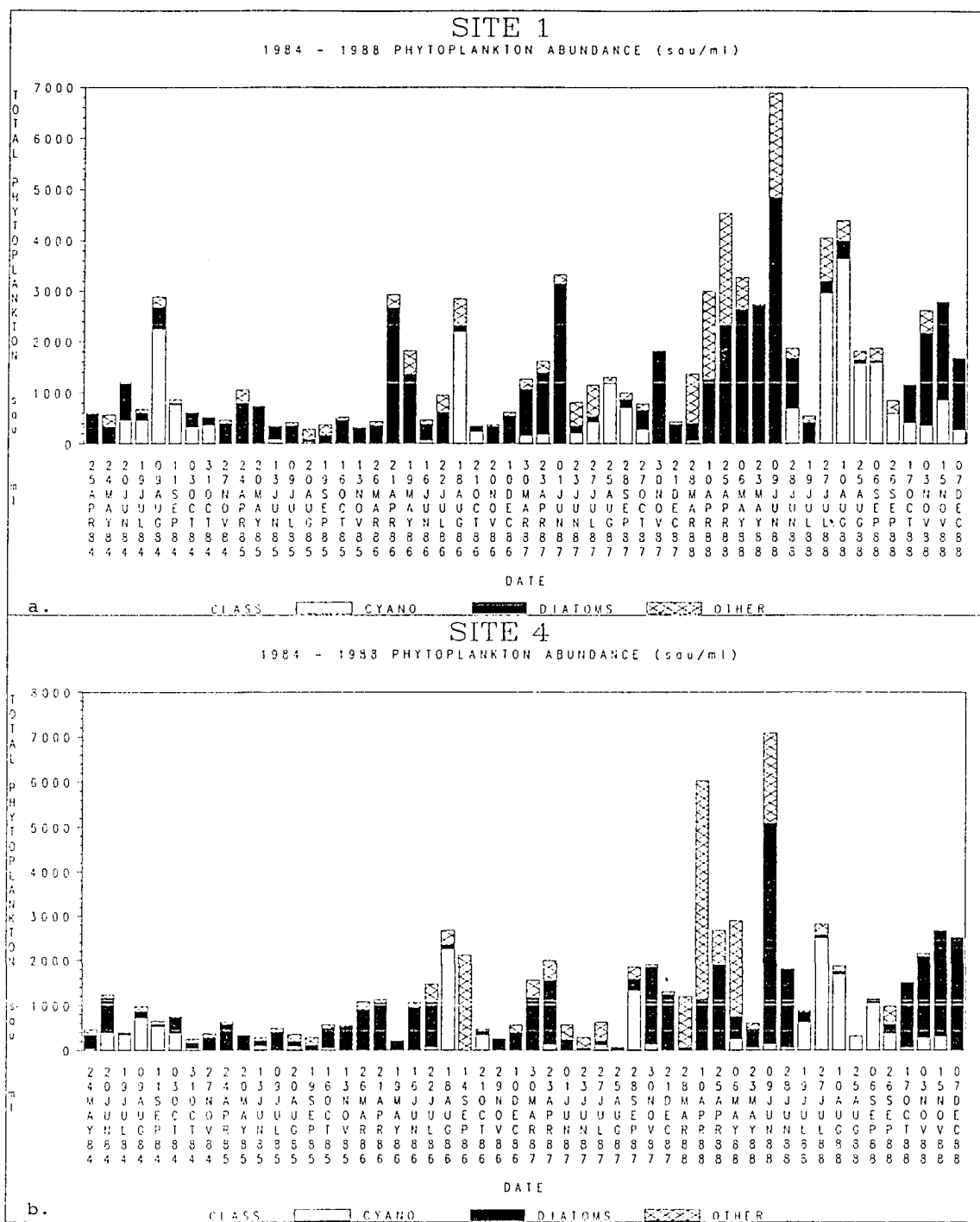


Figure 4-2. Phytoplankton abundance by class, as measured in standard areal units ml^{-1} from 1984 through 1988, for (a) Site 6 and (b) Site 8. Class "Other" includes genera from the Euglenophyta, Chlorophyta, Chryosphyceae, and the Dinophyceae. Note the different scales on the vertical axes.

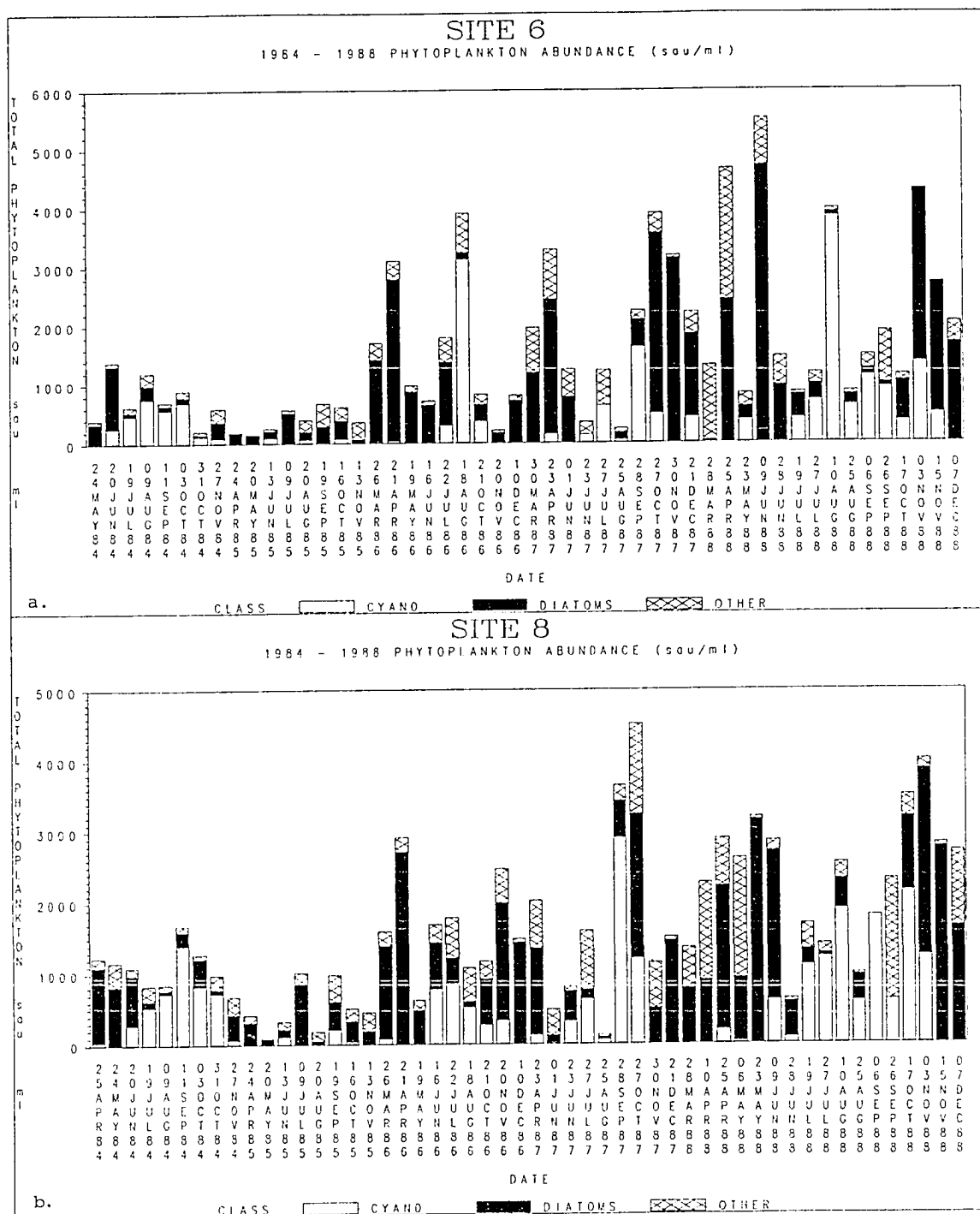


Figure 4-3. Percent phytoplankton abundance by class, as observed from 1984 through 1988, for (a) Site 1 and (b) Site 4. Class "Other" includes genera from the Euglenophyta, Chlorophyta, Chryosphyceae, and the Dinophyceae.

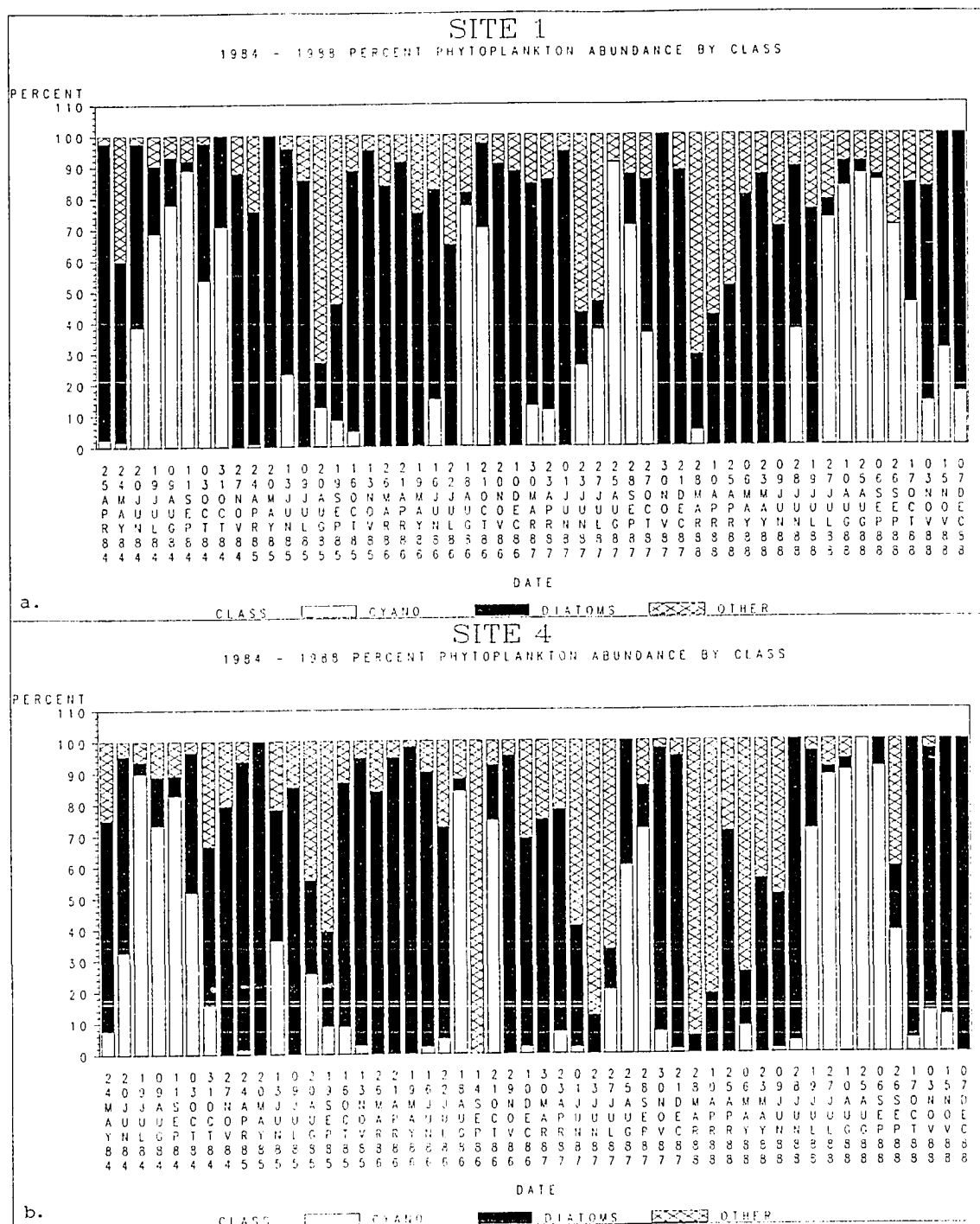
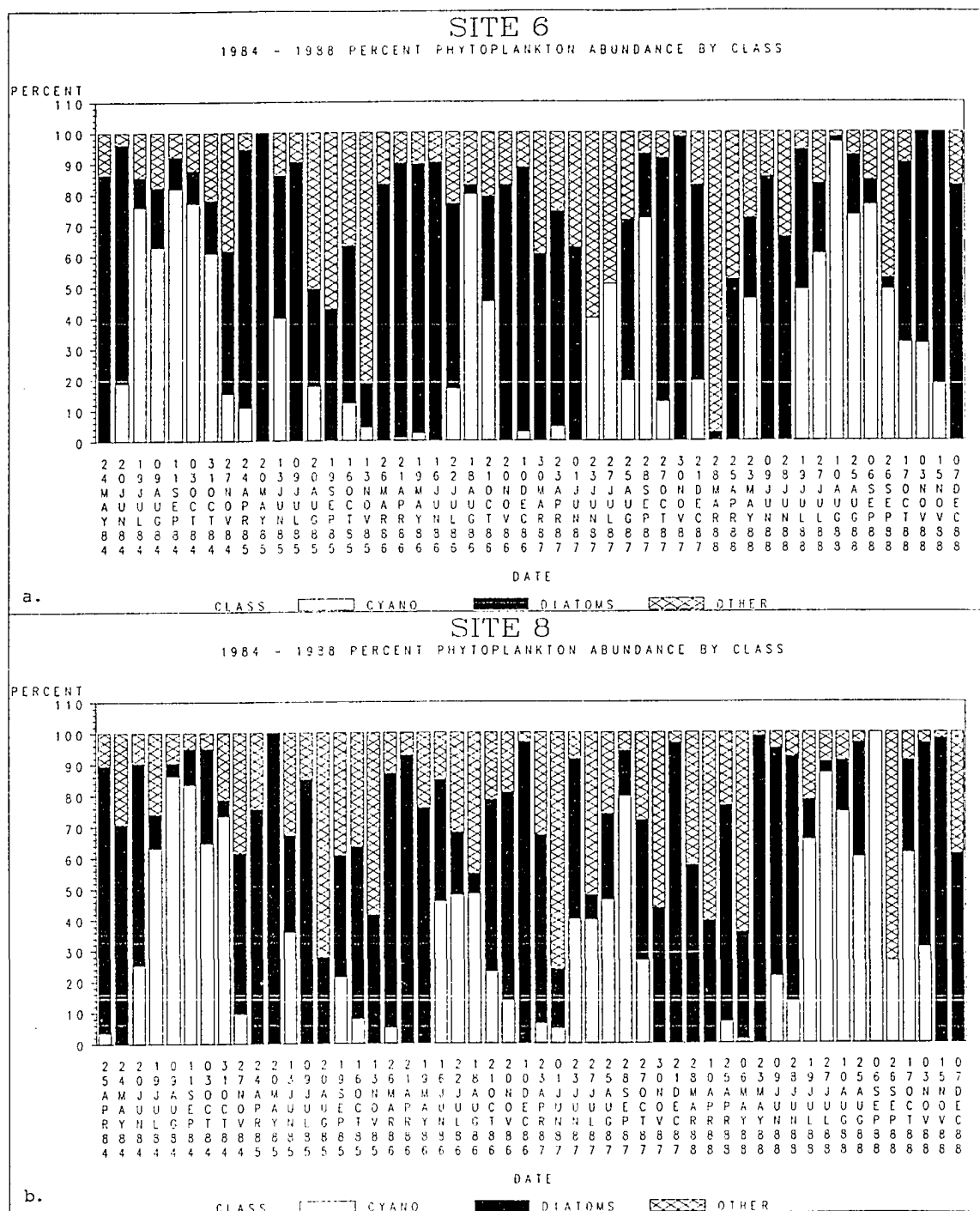


Figure 4-4. Percent phytoplankton abundance by class, as observed from 1984 through 1988, for (a) Site 6 and (b) Site 8. Class "Other" includes genera from the Euglenophyta, Chlorophyta, Chryosphyceae, and the Dinophyceae.



Seasonal Patterns

Figures 4-6 through 4-13 illustrate seasonal spatial patterns observed during the 1984-1987, and the 1988 survey periods for the mean seasonal numbers and percentages of the total phytoplankton that was composed of diatoms, cyanobacteria, and "other" phytoplankton. "Other" phytoplankton were chiefly composed of genera from the Euglenophyta, Chlorophyta, Chryosphyceae, and Dinophyceae. Table 4-1 lists significant seasonal variations in phytoplankton class abundance during the 1984-1987, and the 1988 study periods as determined by the analysis of variance procedure.

Figures 4-5 and 4-6 illustrate that the reservoir was spatially homogeneous in terms of the mean seasonal numbers and percentage composition of diatoms present during both the 1984-1987, and the 1988 study periods. No significant between site differences were detected during any season for both study periods. The same pattern of a spring and fall diatom peak was noted at all sites during both periods as well. Table 4-1 notes that during both 1984-1987, and 1988 fall and spring diatom numbers were significantly greater than summer diatom numbers.

Figures 4-7 and 4-8 depict the mean seasonal numbers and percentages of cyanobacteria present during both the 1984-1987, and the 1988 study periods. No significant

Table 4-1. Seasonal variation in phytoplankton class abundance as measured within Croton Reservoir during the 1984 - 1987 and the 1988 study periods. Significant differences between seasons were determined by the Tukey-Kramer multiple comparisons test $p=0.05$. Euglenophyta not significant during both periods.

<i>Phytoplankton Class/Period</i>	<i>Seasonal Differences</i>	<i>F</i>	<i>(n)</i>	<i>(p)</i>
<i>1984-1987</i>				
Cyanobacteria	summer>fall; summer>spring	12.91	95	0.0001
Bacillariophyceae	summer<fall; summer<spring	18.54	135	0.0001
Chlorophyta	summer>fall; summer>spring	15.39	140	0.0001
Chrysophyceae	summer<fall; summer<spring	5.67	66	0.0060
Dinophyceae	summer>spring; summer>fall; spring>fall	20.97	140	0.0001
<i>1988</i>				
Cyanobacteria	summer>fall; summer>spring; spring>fall	17.83	44	0.0001
Bacillariophyceae	summer<fall; summer<spring	29.62	61	0.0001
Chlorophyta	summer>fall; summer>spring	9.78	65	0.0002
Chrysophyceae	summer<fall; summer<spring	11.03	30	0.0030
Dinophyceae	summer>fall	3.37	65	0.0400

between site differences were detected during any season for both study periods. These findings suggest that like the diatoms, the reservoir was spatially homogeneous in terms of the abundance of cyanobacteria present on a seasonal basis. With the exception of the fall of 1988, in which fall cyanobacteria numbers appeared higher than the fall seasons of previous years, the same seasonal compositional pattern of cyanobacteria was observed during both the 1984-1987, and the 1988 study periods (Table 4-1). Summer cyanobacteria numbers were greater than both that observed during the spring and fall. During 1984-1987 fall and spring cyanobacteria numbers were significantly less than those observed during the summer. During 1988, fall and spring blue-green numbers were significantly less than those noted during the summer, and spring blue-green numbers were less than fall numbers as well. In addition, the number of cyanobacteria present during the summer of 1988 appeared to exceed the numbers observed during the summer of the 1984-1987 period. The lower 1984-1987 summer blue-green numbers most likely resulted from the bias generated by the low blue-green numbers observed during the summer of 1985, and the elevated summer of 1988 blue-green numbers. As noted above, cyanobacteria were virtually absent from the reservoir during 1985, and the summer of 1988 exhibited the greatest cyanobacteria peak of all the study years.

Figure 4-5. Seasonal spatial patterns of diatoms, as measured in standard areal units (sau) ml^{-1} , that were observed during: (a) the 1984-1987 monthly survey period, and (b) the 1988 biweekly survey period.

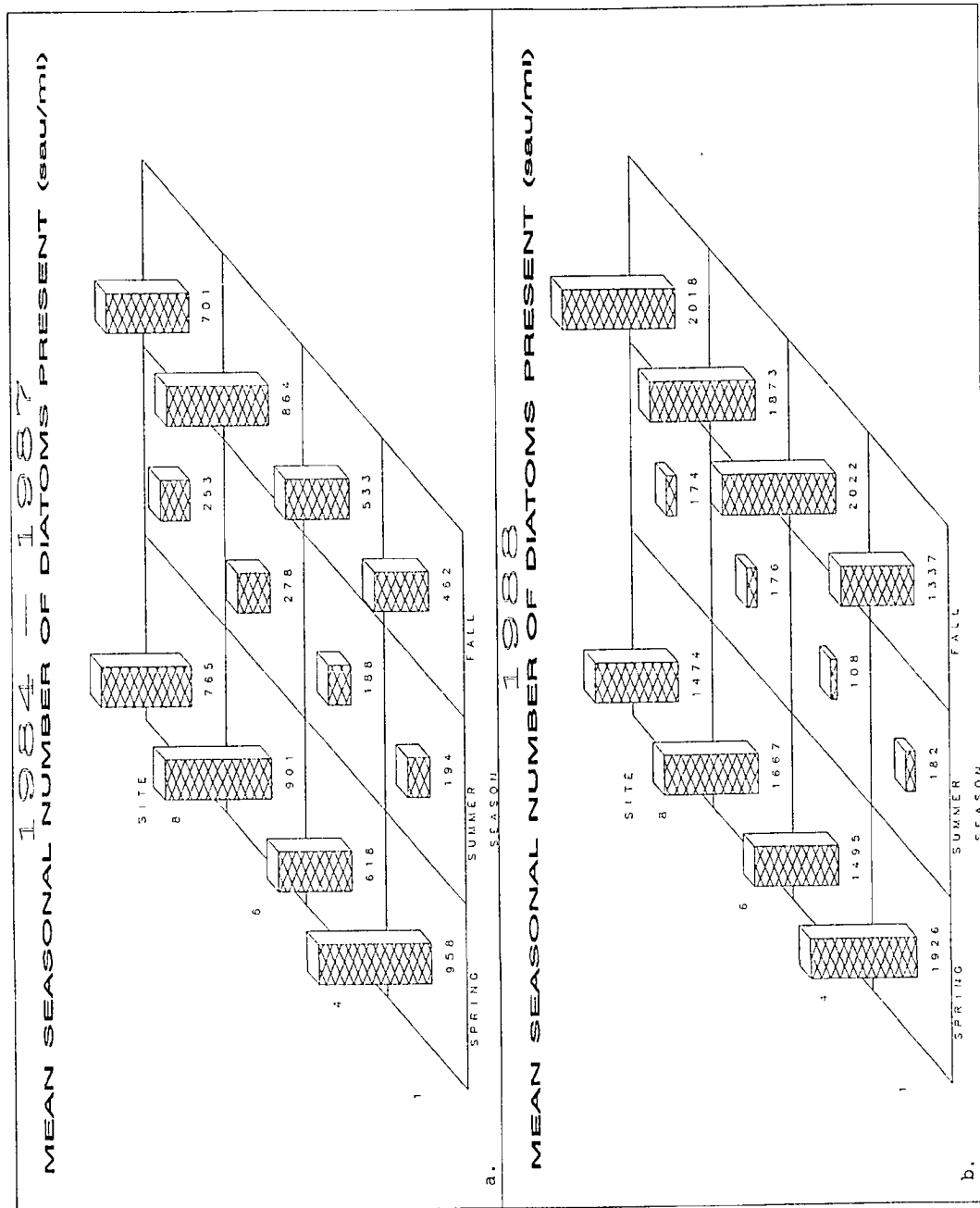


Figure 4-6. Seasonal spatial patterns of the percentage composition of the total phytoplankton present within the reservoir which were attributable to diatoms during: (a) the 1984-1987 monthly survey period, and (b) the 1988 biweekly survey period.

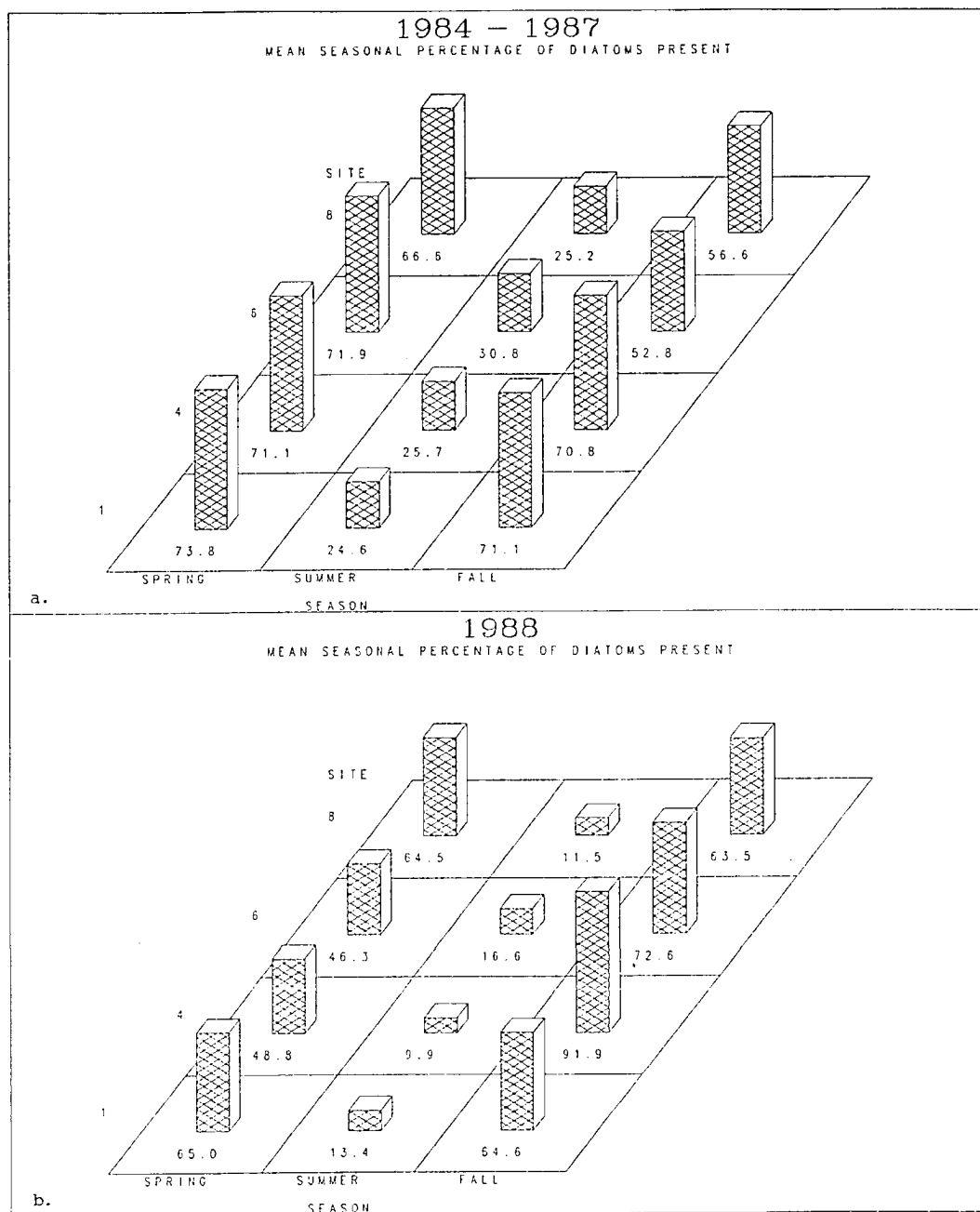


Figure 4-7. Seasonal spatial patterns of cyanobacteria, as measured in standard areal units (sau) ml⁻¹, that were observed during: (a) the 1984-1987 monthly survey period, and (b) the 1988 biweekly survey period.

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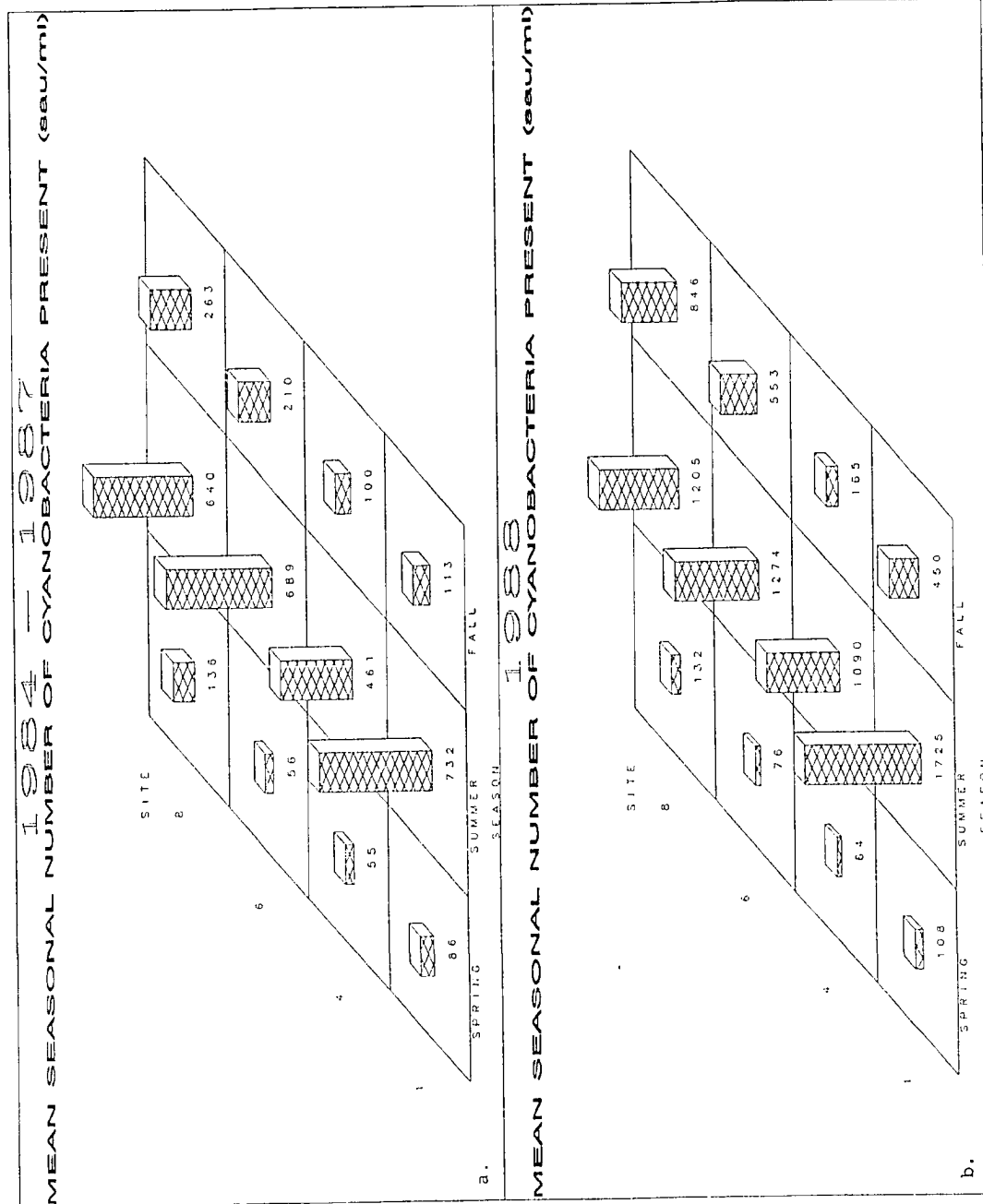


Figure 4-8. Seasonal spatial patterns of the percentage composition of the total phytoplankton present within the reservoir which were attributable to cyanobacteria during: (a) the 1984-1987 monthly survey period, and (b) the 1988 biweekly survey period.

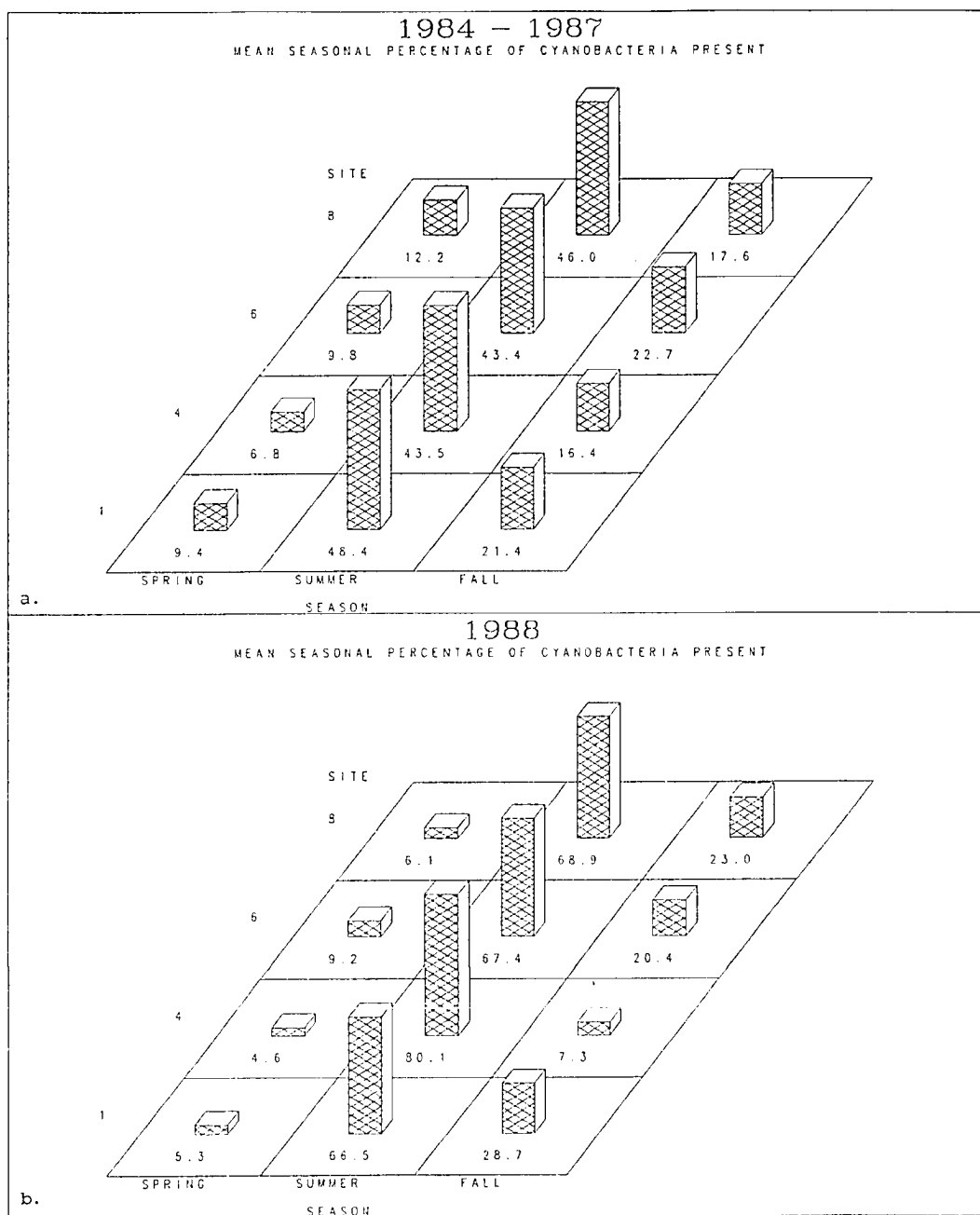
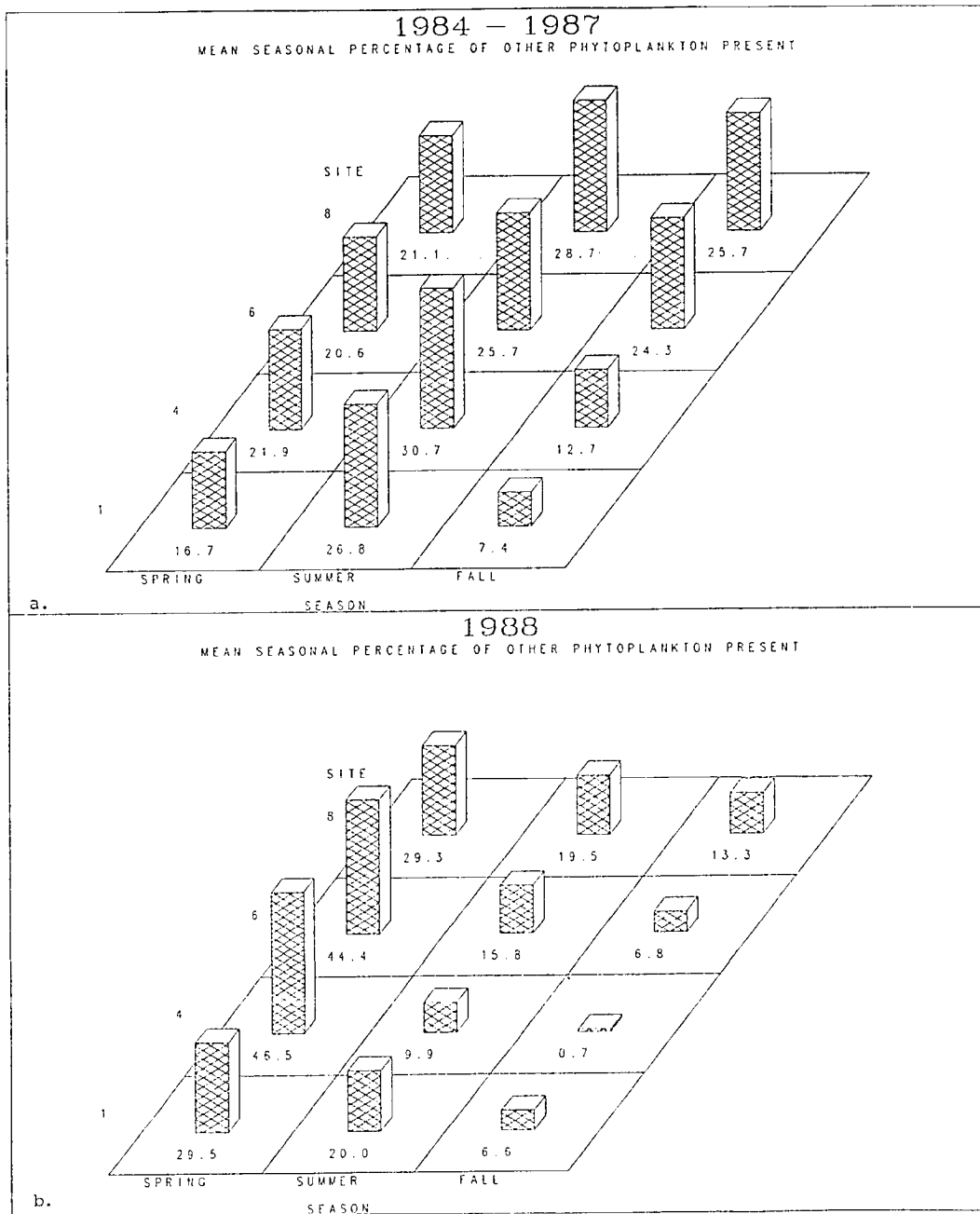


Figure 4-9 depicts the 1984-1987, and the 1988 mean seasonal percentages of "other" phytoplankton present that were not members of either the cyanobacteria or the diatoms. Figures 4-10 through 4-13 illustrate the seasonal spatial patterns observed during both the 1984-1987 and 1988 study periods for the Chryosphyceae, Chlorophyta, Dinophyceae, and Euglenophyta respectively. With the exception of the Euglenophyta, no significant between site differences were detected during any season for both the 1984-1987, and the 1988 study periods.

Figure 4-9 illustrates that seasonally, the reservoir was spatially homogeneous in terms of percent composition of the other phytoplankton. Summer percentages of other phytoplankton appeared greater than fall percentages during 1984-1987, whereas spring percentages appeared greater than fall percentages in 1988. However, fall always exhibited the lowest percentage composition values of the other phytoplankton, especially in the lower zone.

Figure 4-10 depicts the seasonal spatial pattern of Chryosphyceae numbers within the reservoir as observed during both 1984-1987, and 1988. No significant between site differences were detected during any season for both study periods. These findings suggest that the reservoir was spatially homogeneous in terms of the abundance of Chryosphyceae present on a seasonal basis. Table 4-1 notes that the same seasonal compositional pattern for

Figure 4-9. Seasonal spatial patterns of the percentage composition of the total phytoplankton present within the reservoir which were attributable to "other" phytoplankton (Euglenophyta, Chlorophyta, Chryosphyceae, and Dinophyceae) during: (a) the 1984-1987 monthly survey period, and (b) the 1988 biweekly survey period.



Chryosphyceae abundance was observed during 1984-1987, and 1988, with fall and spring numbers being significantly greater ($p=0.05$) summer numbers. This pattern mimicked that of the diatoms, although virtually no Chryosphyceae were present during the summer months. Chryosphyceae appeared to dominate the "other" phytoplankton during the spring, particularly in 1988.

Figure 4-11 depicts the seasonal spatial pattern of Chlorophyta numbers within the reservoir during both 1984 - 1987, and 1988 study periods. No significant among site differences were detected during any season. These findings suggest that the reservoir was spatially homogeneous in terms of the abundance of Chlorophyta present on a seasonal basis. The same seasonal compositional pattern for Chlorophyta abundance was observed during 1984-1987, and 1988, with fall and spring numbers being significantly less than summer numbers (Table 4-1). Chlorophyta were coincident with the cyanobacteria, and appeared to dominate the "other" phytoplankton during the summer months.

Figure 4-12 depicts the seasonal spatial pattern of Dinophyceae numbers within the reservoir during both 1984-1987, and 1988 study periods. No significant between site differences were detected during any season. These findings suggest that the reservoir was spatially homogeneous in terms of the abundance of Dinophyceae present on a seasonal basis. Table 4-1 notes that a similar seasonal compositional

pattern for Dinophyceae abundance was observed during 1984-1987 and 1988, with abundance in the fall being significantly less than in the summer. However, during 1984-1987, spring numbers were less than summer numbers, and fall numbers were less than spring numbers. Dinophyceae were coincident with the Chlorophyta, but appeared to favor the late spring-early summer period, whereas Chlorophyta appeared more abundant during the late summer-early fall.

Figure 4-12 depicts the seasonal spatial pattern of Euglenophyta numbers within the reservoir during both 1984-1987, and 1988 study periods. Euglenophyta was the only phytoplankton class to exhibit spatial difference during the study. During the 1984-1987 period, abundance of Euglenophyta in the upper zone was greater than in the reservoir's lower zone during both the summer and fall months ($F=6.15$, $n=140$, $p<0.0006$; Sites 8>1, 6>1, and 4>1 at $p=0.05$). A similar (but insignificant) pattern was noted during 1988. No significant seasonal variations in Euglenophyta numbers were noted during both the 1984-1987, and the 1988 periods. However, the observed presence of Euglenophyta within the Croton Reservoir phytoplankton community was limited, as illustrated by the low numbers of this class recorded during both the 1984-1987, and 1988 study periods.

Figure 4-10. Seasonal spatial patterns of Chryosphyceae, as measured in standard areal units (sau) ml⁻¹, that were observed during: (a) the 1984-1987 monthly survey period, and (b) the 1988 biweekly survey period.

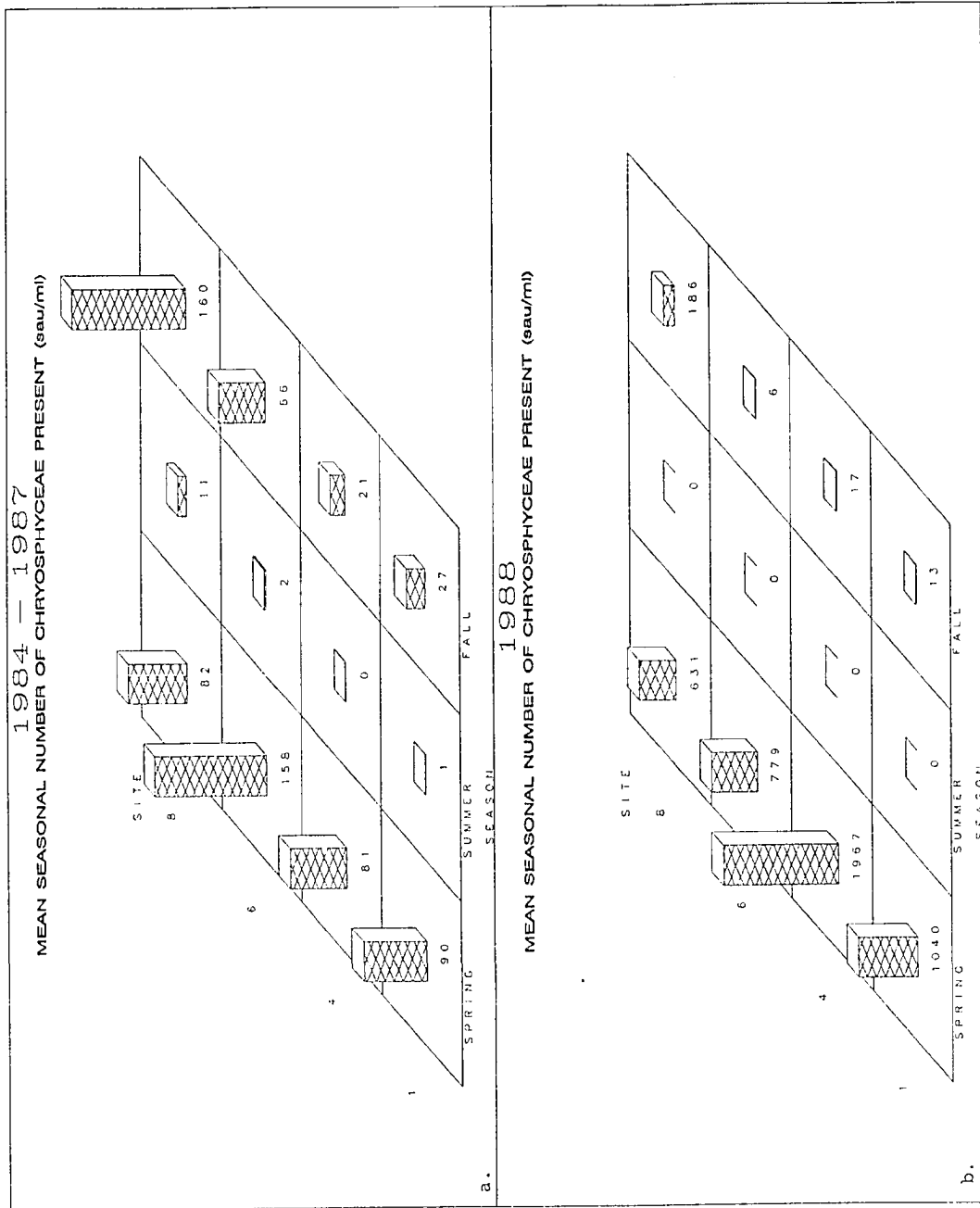


Figure 4-11. Seasonal spatial patterns of Chlorophyta, as measured in standard areal units (sau) ml^{-1} , that were observed during: (a) the 1984-1987 monthly survey period, and (b) the 1988 biweekly survey period.

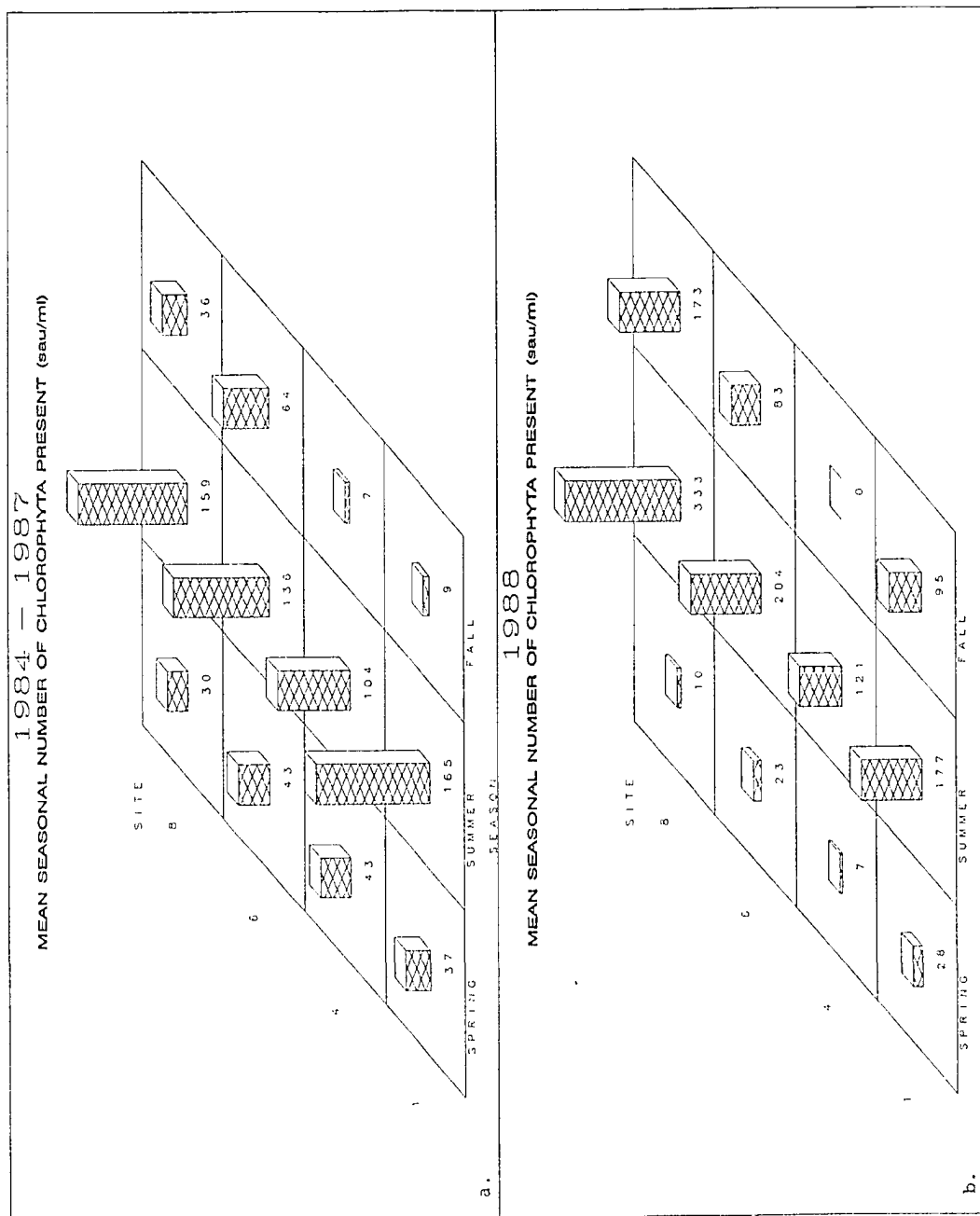


Figure 4-12. Seasonal spatial patterns of Dinophyceae, as measured in standard areal units (sau) ml^{-1} , that were observed during: (a) the 1984-1987 monthly survey period, and (b) the 1988 biweekly survey period.

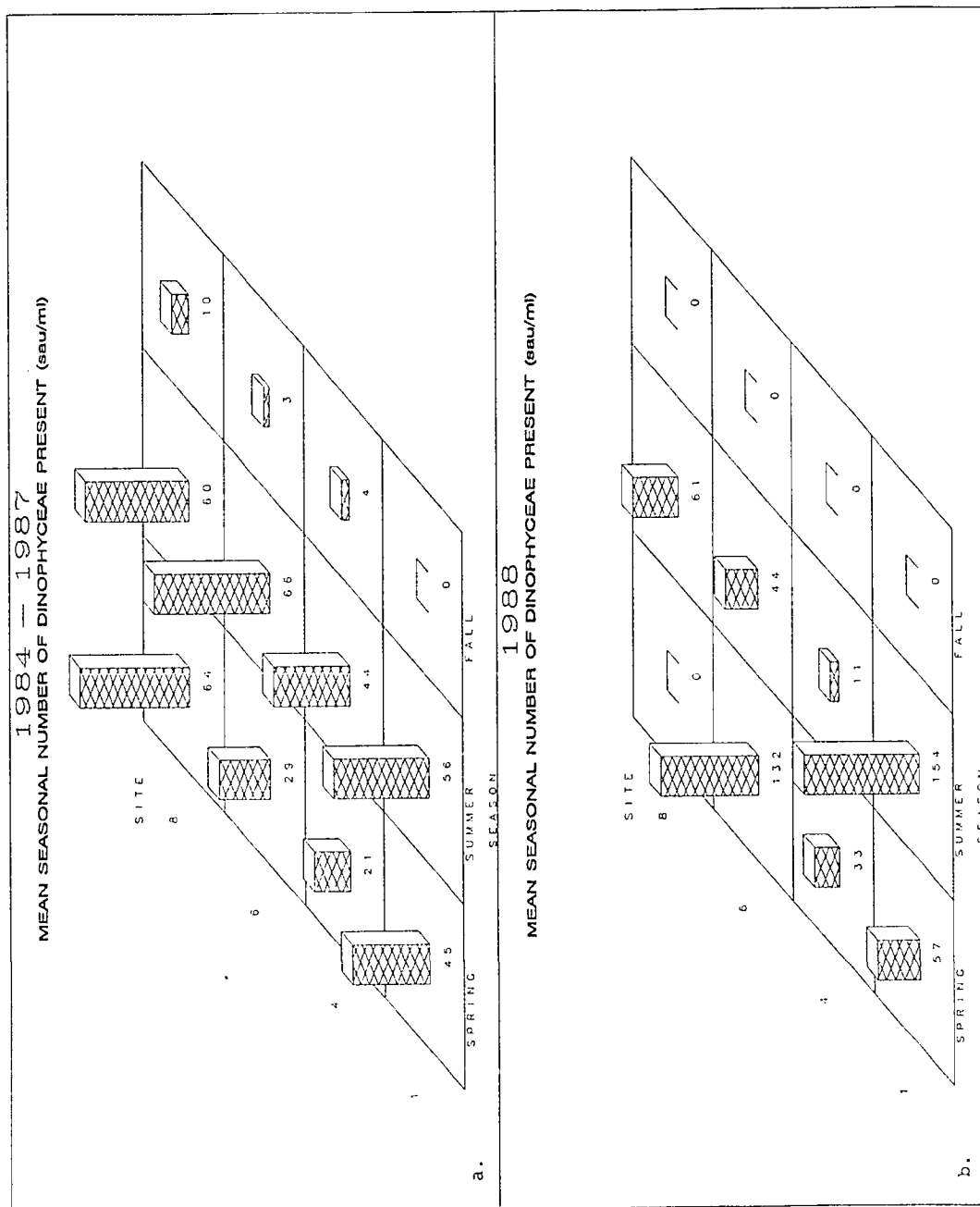
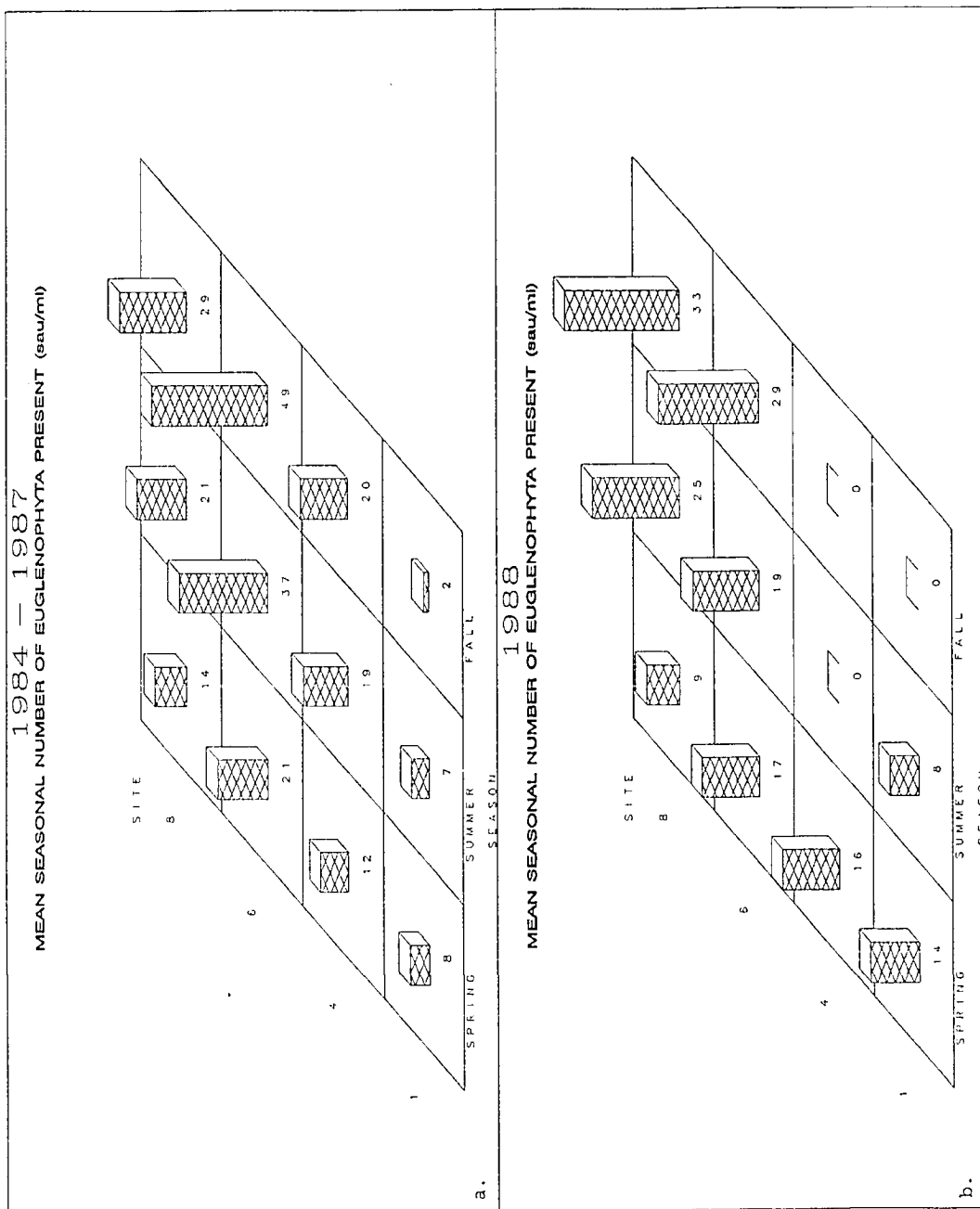


Figure 4-13. Seasonal spatial patterns of Euglenophyta, as measured in standard areal units (sau) ml^{-1} , that were observed during: (a) the 1984-1987 monthly survey period, and (b) the 1988 biweekly survey period.



Figures 4-14 and 4-15 illustrate 1988 Chlorophyta, Chryosphyceae, Dinophyceae, and Euglenophyta abundance over time for each site. Overall, the same successional pattern was exhibited at each site with Chryosphyceae dominating in the spring, followed by Dinophyceae in the early summer, and Chlorophyta in the late summer. Euglenophyta appeared to be present more frequently within the reservoir's upper zone.

Table 4-2 lists the seasonal composition of the phytoplankton by genera that was observed in the reservoir over the five year study period. During the spring the diatoms *Asterionella sp.*, *Fragilaria sp.*, and *Melosira sp.* dominated. With the exception of 1985, the summer phytoplankton population was primarily composed of the cyanobacteria *Anabaena sp.*, *Aphanizomenon sp.*, and *Gomphosphaeria sp.* During the summer of 1985, the dominant phytoplankton genera appeared to shift from the cyanobacteria to a combination of genera belonging to the Bacillariophyceae, Dinophyceae, and the Chlorophyta. The fall population was chiefly composed of the diatom *Melosira sp.*, however a number of the summer cyanobacteria usually persisted throughout the fall months. The important genera included in the "other" classes of phytoplankton which were observed during the study period include: Dinophyceae-*Glenodinium sp.*, *Peridinium sp.*, *Ceratium sp.*; Chryosphyceae-*Dinobryon sp.*, *Synura sp.*, *Uroglenopsis sp.*, *Mallomonas sp.*; Chlorophyta-*Chlorella sp.*, *Mougoetia sp.*,

Pediastrum sp., *Chlorococcus sp.*, *Palmelloccoccus*,
Sphaerocystis sp., *Pandorina sp.*; and Euglenophyta-*Euglena*
sp., *Trachelomonas sp.*

Table 4-3 presents a correlation matrix which describes the interrelationships between different phytoplankton classes during the five year study period. Trends apparent in Table 4-3 tend to corroborate those trends displayed in Table 4-1. Bacillariophyceae were coincident with Chryosphyceae in the spring, and were found in low numbers when Chlorophyta and Dinophyceae were present in the summer. Chlorophyta were coincident with both populations of cyanobacteria and Dinophyceae during the summer, but absent when the Chryosphyceae were abundant in the spring. Similarly, Chryosphyceae were found in low numbers when the Dinophyceae were present.

Figure 4-14. 1988 Chlorophyta, Chryosphyceae, Dinophyceae, and Euglenophyta abundance, as measured in standard areal units (sau) ml^{-1} , over time for (a) Site 1, and (b) Site 4. CHLORO=Chlorophyta, CHRYOS=Chryosphyceae, DINO=Dinophyceae, and EUGLEN=Euglenophyta. Note the different scales on the vertical axes.

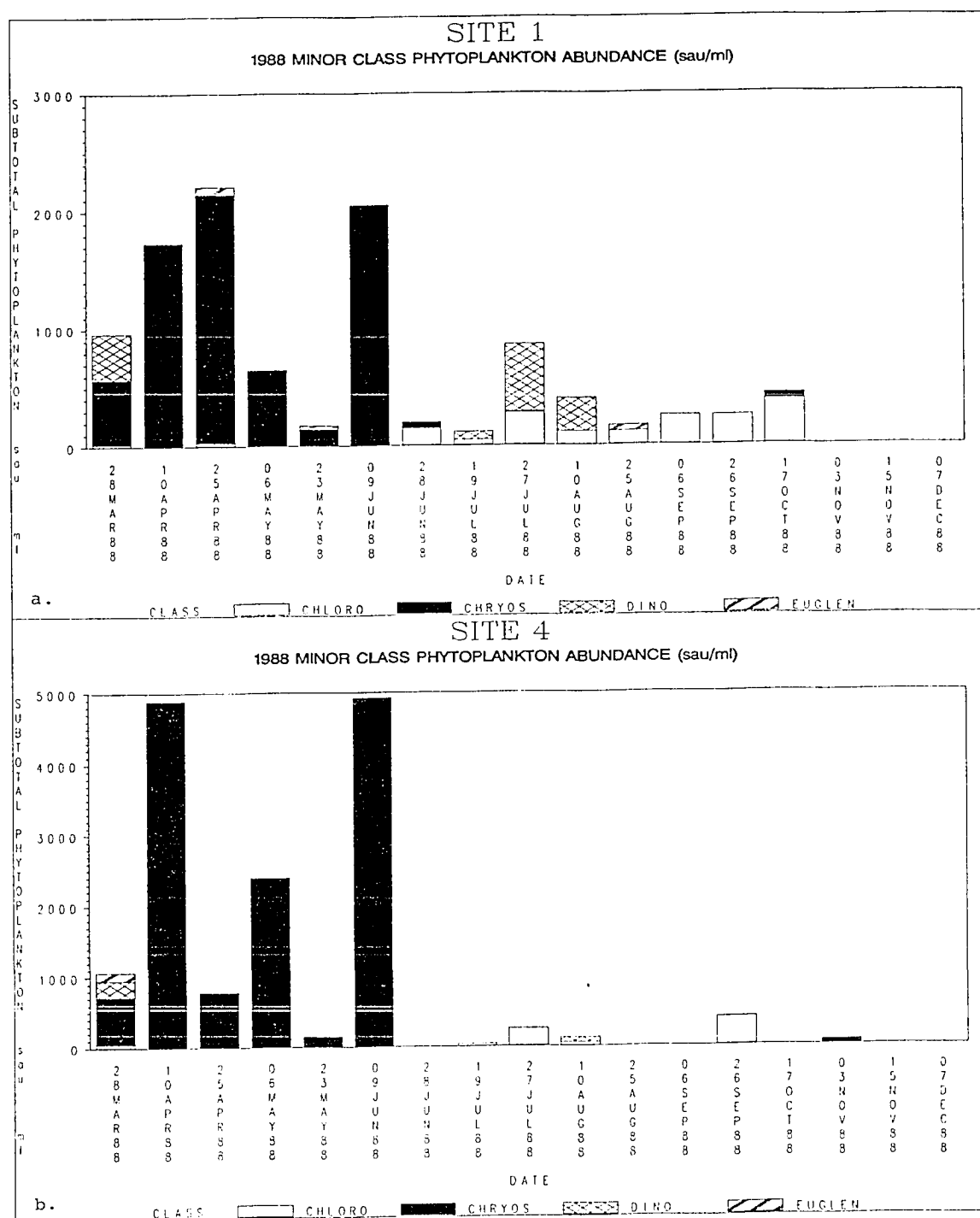


Figure 4-15. 1988 Chlorophyta, Chryosphyceae, Dinophyceae, and Euglenophyta abundance, as measured in standard areal units (sau) ml^{-1} , over time for (a) Site 6 and (b) Site 8. CHLORO=Cholorphyta, CHRYOS=Chryosphyceae, DINO=Dinophyceae, and EUGLEN=Euglenophyta. Note the different scales on the vertical axes.

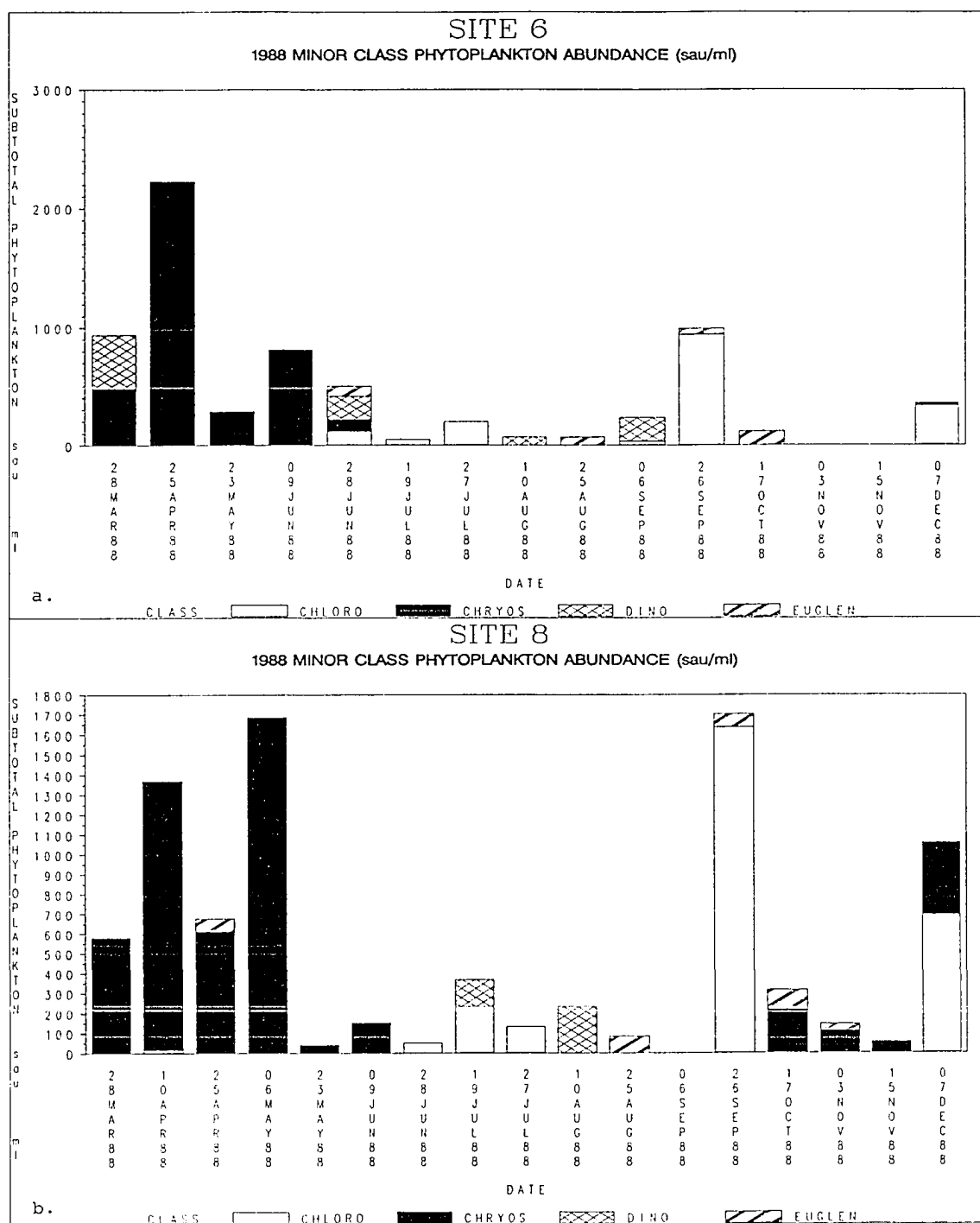


Table 4-2. Dominant phytoplankton genera, listed by season, that were observed in Croton Reservoir during the 1984 -1988 study period.

Season / Year	1984	1985	1986	1987	1988
Spring	<u>Asterionella</u> <u>Fragilaria</u> <u>Melosira</u> <u>Synedra</u> <u>Tabellaria</u>	<u>Asterionella</u> <u>Fragilaria</u> <u>Synedra</u> <u>Aphanizomenon</u> <u>Dinobryon</u>	<u>Asterionella</u> <u>Fragilaria</u> <u>Melosira</u> <u>Tabellaria</u> <u>Rhizosolenia</u>	<u>Asterionella</u> <u>Fragilaria</u> <u>Melosira</u> <u>Synedra</u> <u>Glenodinium</u>	<u>Asterionella</u> <u>Fragilaria</u> <u>Melosira</u> <u>Synedra</u> <u>Rhizosolenia</u>
Summer	<u>Anabaena</u> <u>Aphanizomenon</u> <u>Gomphosphaeria</u> <u>Anabaenopsis</u> <u>Anacystis</u>	<u>Fragilaria</u> <u>Ceratium</u> <u>Palmeilococcus</u> <u>Synedra</u> <u>Melosira</u>	<u>Anabaena</u> <u>Rhizosolenia</u> <u>Gomphosphaeria</u> <u>Anabaenopsis</u> <u>Anacystis</u>	<u>Aphanizomenon</u> <u>Gomphosphaeria</u> <u>Lynbya</u> <u>Anabaena</u> <u>Chlorococcus</u>	<u>Anabaena</u> <u>Aphanizomenon</u> <u>Gomphosphaeria</u> <u>Mougetia</u> <u>Lynbya</u>
Fall	<u>Melosira</u> <u>Aphanizomenon</u> <u>Gomphosphaeria</u> <u>Dinobryon</u> <u>Anabaena</u>	<u>Melosira</u> <u>Asterionella</u> <u>Mougetia</u> <u>Synura</u> <u>Rhizosolenia</u>	<u>Melosira</u> <u>Aphanizomenon</u> <u>Fragilaria</u> <u>Rhizosolenia</u> <u>Anabaena</u>	<u>Melosira</u> <u>Dinobryon</u> <u>Gomphosphaeria</u> <u>Aphanizomenon</u> <u>Anabaena</u>	<u>Melosira</u> <u>Aphanizomenon</u> <u>Gomphosphaeria</u> <u>Botrydiopsis</u> <u>Cyclotella</u>

Table 4-3. Correlation matrix describing interrelationships between different phytoplankton classes during the 1984 -1988 study period. The Pearson correlation coefficient (r), the sample size (n), and the p -value are listed for each variable relationship. n.s. = not significant at $p < 0.05$.

	Bacillariophyceae	Cyanobacteria	Chlorophyta	Chrysophyceae	Dinophyceae	Euglenophyta
Bacillariophyceae	1.00	n.s.	-0.34 (199) $p < 0.0001$	0.51 (98) $p < 0.0001$	-0.28 (199) $p < 0.0001$	n.s.
Cyanobacteria	n.s.	1.00	0.18 (141) $p < 0.04$	n.s.	n.s.	n.s.
Chlorophyta	-0.34 (199) $p < 0.0001$	0.18 (141) $p < 0.04$	1.00	-0.20 (98) $p < 0.05$	0.25 (207) $p < 0.0003$	n.s.
Chrysophyceae	0.51 (98) $p < 0.0001$	n.s.	-0.20 (98) $p < 0.05$	1.00	-0.21 (98) $p < 0.04$	n.s.
Dinophyceae	-0.28 (199) $p < 0.0001$	n.s.	0.25 (207) $p < 0.0003$	-0.21 (98) $p < 0.04$	1.00	n.s.
Euglenophyta	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

*Interrelationships Between Environmental Factors
and Floristic Composition*

A correlation matrix relating phytoplankton class numbers to environmental variables, as measured monthly from 1984-1988 (physical and chemical data are presented in Chapter 2), is listed in Table 4-5. Diatoms (Bacillariophyceae) were positively correlated with silica (Si) concentrations, dissolved inorganic nitrogen (DIN) concentrations, and DIN:total phosphorus (TP) ratios, but negatively correlated with epilimnetic temperature. A similar set of relationships were observed for the Chryosphyceae, except the Chryosphyceae were not correlated with DIN:TP ratios. Both the cyanobacteria and the Chlorophyta were negatively correlated with Si concentrations, DIN concentrations, and DIN:TP ratios, and positively correlated with epilimnetic temperature. The Chlorophyta were also negatively correlated with SI:TP ratios. In addition, stepwise regression analysis revealed that epilimnetic temperature and the DIN:TP ratio explained 22% and 10% respectively of the variability in cyanobacteria numbers observed during the 1984-1988 period ($F=28.28$, $n=125$, $p<0.0001$, $R^2=0.32$). The Dinophyceae were negatively correlated with both Si concentrations and epilimnetic temperatures. These results suggest that diatoms and Chryosphyceae favor the spring and fall conditions of

elevated DIN and Si concentrations, and lower epilimnetic temperatures. In contrast, the Chlorophyta and cyanobacteria appear to thrive under summer conditions of depressed DIN:TP and, lower DIN and Si concentrations, and elevated epilimnetic temperatures. The Dinophyceae appear to fall somewhere in between the Bacillariophyceae/Chryosphyceae and the Chlorophyta/Cyanobacteria groupings.

In addition, the predominance of cyanobacteria during the summer months may have been affected by changes in reservoir volume and hydraulic residence time as Table 4-5 illustrates. The abundance of cyanobacteria, as well as Chlorophyta, was positively correlated with both reservoir volume and hydraulic residence time during the growing season (July-October) months of the 1984-1988 study period. Figure 4-16 depicts the variability in cyanobacteria numbers with changes in growing season hydraulic residence time as measured within each zone of the reservoir from 1984 to 1988. During the growing season of 1985, in which the reservoir experienced it shortest hydraulic residence time of the five year study period, cyanobacteria were conspicuously absent from the reservoir's phytoplankton population.

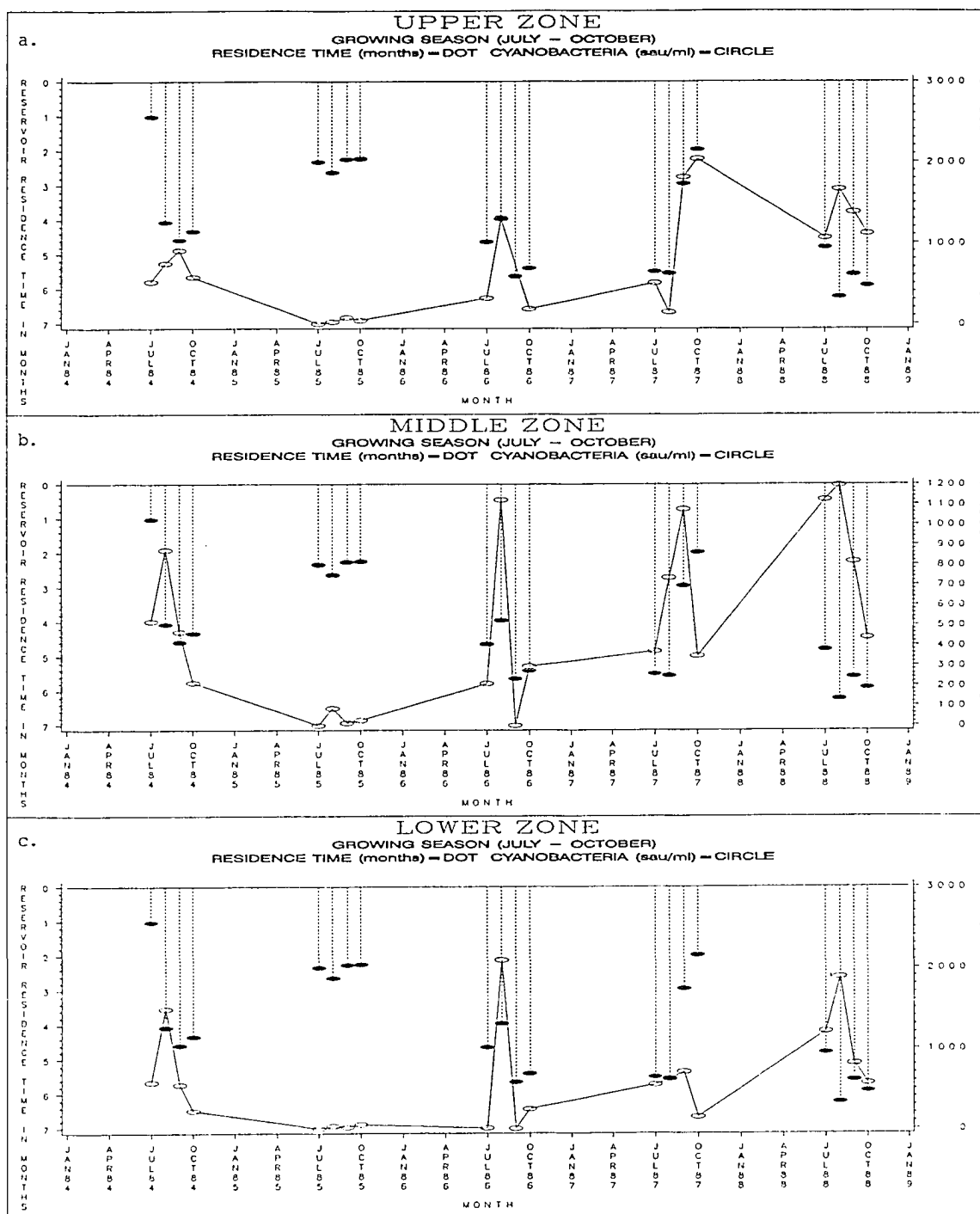
Table 4-4. Correlation matrix relating phytoplankton abundance by class to environmental variables measured monthly during the 1984 - 1988 study period for all sites combined. With the exception of temperature and reactive silica, all variables were logarithmically transformed before analysis to comply with the assumptions of correlation analysis. CYANO-Cyanobacteria (standard areal units ml^{-1}); BAC- Bacillariophyceae (standard areal units ml^{-1}); CHRYOS-Chryosphyceae (standard areal units ml^{-1}); CHLORO- Chlorophyta (standard areal units ml^{-1}); DINO-Dinophyceae (standard areal units ml^{-1}); EUGLENO- Euglenophyta (standard areal units ml^{-1}); SI- reactive silica (mg L^{-1}); TEMP- temperature ($^{\circ}\text{C}$); DIN- dissolved inorganic nitrogen (mg L^{-1}); TP- total phosphorus (ug L^{-1}); DIN:TP- dissolved inorganic nitrogen to total phosphorus ratio; SI:TP- silica to total phosphorus ratio. The Pearson correlation coefficient (r), the sample size (n), and the p - value are listed for each variable relationship. n.s. = not significant at $p<0.05$.

Monthly Measurements 1984 - 1988					
	SI	TEMP	DIN	DIN:TP	SI:TP
BAC	0.25 (144) $p<0.003$	-0.47 (174) $p<0.0001$	0.35 (162) $p<0.0001$	0.25 (154) $p<0.002$	n.s.
CYANO	-0.21 (100) $p<0.04$	0.33 (122) $p<0.0002$	-0.29 (114) $p<0.002$	-0.32 (110) $p<0.0007$	n.s.
CHLORO	-0.31 (147) $p<0.0001$	0.36 (180) $p<0.0001$	-0.24 (168) $p<0.002$	-0.28 (160) $p<0.0004$	-0.32 (139) $p<0.001$
CHRYOS	0.38 (147) $p<0.001$	-0.51 (87) $p<0.0001$	0.33 (77) $p<0.003$	n.s.	n.s.
DINO	-0.30 (147) $p<0.0002$	0.33 (180) $p<0.0002$	n.s.	n.s.	n.s.
EUGLENO	0.24 (147) $p<0.003$	n.s.	n.s.	n.s.	n.s.

Table 4-5. Correlation matrix relating phytoplankton class abundance variables to monthly hydraulic residence time and reservoir volume values measured during the 1984 - 1988 growing season periods (July - October) for all sites combined. All variables were logarithmically transformed before analysis to comply with the assumptions of correlation analysis. TPLK- total phytoplankton (standard areal units ml^{-1}); CYANO- Cyanobacteria (standard areal units ml^{-1}); BAC- Bacillariophyceae (standard areal units ml^{-1}); CHLOR- Chlorophyta (standard areal units ml^{-1}); TW- hydraulic residence time (years); V- reservoir volume ($10^6 \times \text{m}^3$). The Pearson correlation coefficient (r) and the p- value are listed for each variable relationship. Sample size = 50. n.s. = not significant at $p < 0.05$.

<u>Growing Season Measurements 1984-1988</u>			
	TW	V	TPLK
BAC	n.s.	n.s.	n.s.
CYANO	0.29 ($p < 0.04$)	0.74 ($p < 0.0001$)	0.75 ($p < 0.0001$)
CHLOR	0.31 ($p < 0.03$)	0.48 ($p < 0.0004$)	0.47 ($p < 0.0005$)
TPLK	n.s.	0.66 ($p < 0.0001$)	1.00

Figure 4-16. The abundance of cyanobacteria as measured monthly in standard areal units ml^{-1} during the growing season (July-October) from 1984 to 1988 under varying total reservoir hydraulic residence times for (a) the upper zone; (b) the middle zone; and (c) the lower zone. Note the different scales on the cyanobacteria vertical axes. Residence time = dot, and cyanobacteria abundance = circle.



DISCUSSION

Croton Reservoir exhibited the same classic pattern of phytoplankton succession during both the 1984-1987, and the 1988 study periods, as that observed in most northern temperate mesotrophic-eutrophic lakes. Bacillariophyceae (diatoms) predominated in the spring and fall, whereas cyanobacteria occurred in great numbers during the late summer. In addition, Chrysophyceae were coincident with the diatoms in the spring and fall, whereas the Chlorophyta and the Dinophyceae were present during the summer months. These temporal patterns of floristic composition appeared to be fairly consistent across all sites. No significant differences among sites were observed when phytoplankton community structure was analyzed on a seasonal basis during both the 1984-1987, and the 1988 study periods. These findings suggest that the reservoir was spatially homogeneous during the 1984-1988 study period with respect to floristic composition. One of the key findings presented in Chapter 3 was that Croton Reservoir exhibited a longitudinal gradient of algal biomass from headwater to dam during both the 1984-1987, and the 1988 study periods. This gradient consistently occurred in the fall, although a summer gradient was also observed during 1988. These findings suggest that although the season-specific floristic composition of the phytoplankton did not vary along the

longitudinal axis of the reservoir, the biomass of the observed floristic classes did vary spatially, particularly in the summer and the fall. These algal biomass variations may have been attributable to an array of physical and chemical processes which facilitated nutrient enrichment of the existent phytoplankton population.

Study results indicated that the seasonal succession, or "shifts" of the phytoplankton within Croton Reservoir was not completely governed by nutrient limitation. Both Chapters 2 and 3 suggested that with the exception of late summer DIN depletions, nutrient concentrations were usually at or above their respective detection limits within the Croton Reservoir water column. However, the relative proportions (ratios) or concentrations of these nutrients did vary both spatially and temporally within the reservoir. There are clearly other factors, beside nutrient concentrations that play an important role in shaping the phytoplankton community both spatially and temporally. Such factors, as described by Reynolds (1984), may include: day-length, total irradiance, water column light availability, temperature, flow regime, the abundance of herbivorous animals, the inhibitory and stimulatory effect of trace metals, and phytoplankton antibiosis. In addition, the interaction of these factors often makes it difficult to determine which mechanism was responsible for phytoplankton succession and composition. Nevertheless, the relative

proportions or concentrations of the nutrients supplied to the phytoplankton could be a strong selective force in both shaping phytoplankton communities, as well as determining levels of biomass yield per unit of limiting nutrient (Hecky and Kilham 1988).

DIN:TP and Si:TP ratios exhibited considerable annual variation within the Croton Reservoir during the study period. Both ratios were highest in the spring and lowest in the summer (Chapter 2). These variations usually resulted from decreasing DIN and Si concentrations, and stable or increasing TP concentrations. Seasonal patterns of floristic composition appeared to coincide with the variability of these nutrient concentrations and water temperature. Spring and fall diatom dominance was positively correlated with Si concentrations, DIN concentrations, and DIN:TP ratios, and negatively correlated with epilimnetic temperature. Summer cyanobacteria dominance was negatively correlated with Si and DIN concentrations, and DIN:TP, and positively correlated with epilimnetic temperature.

An understanding of factors controlling the seasonal pattern of phytoplankton succession within Croton Reservoir may be facilitated by viewing the ecology of the phytoplankton at the genus level. The spring diatom maximum observed within Croton Reservoir was consistently dominated by *Asterionella* sp. throughout the study period. Other vernal diatoms that were observed included *Fragilaria* sp.,

Synedra sp., and *Melosira* sp. Reynolds (1984) noted that *Asterionella* sp. is one of the most ubiquitous species in mesotrophic and eutrophic lakes because of its high photosynthetic efficiency, low threshold of photosynthetic saturation (low I_k), rapid growth rate, and efficient assimilation of carbon at low total irradiance levels. As such, Croton Reservoir's spring light regime would tend to favor a genus with these characteristics. In addition, the concentrations of nitrogen, phosphorus, and silicon measured within the reservoir during the spring months, corresponded well with the optimum nutrient ratios for such diatoms as *Asterionella* sp., *Synedra* sp., *Fragilaria* sp., *Tabellaria* sp., and *Melosira* sp. (Kilham and Kilham 1984). *Asterionella* sp. tend to favor high Si:P ratios (>100), and low N:P ratios (>12); such ratios were observed within the epilimnion of Croton Reservoir during the spring months.

The gradual disappearance of *Asterionella* sp. and the other vernal diatoms from the Croton Reservoir phytoplankton may have been attributable to the depletion of silicon (Chapter 2), the onset of thermal stratification and its resultant increase in the sinking rate of the diatoms, and losses due to grazing.

During late spring and mid-summer, the structurally stable, and somewhat resource-limited conditions of the reservoir's water column appeared to favor the large, unicellular Dinophyceae. It was not uncommon to find

Ceratium sp., *Glenodinium sp.* and *Peridinium sp.* throughout the impoundment during this period. However, the numbers of Dinophyceae observed within the reservoir never approached those of either the diatoms or the cyanobacteria. These large dinoflagellates represent the most extreme *K*-strategist because of their high mobility, slow growth rate, phagotrophic capabilities, and relative immunity to grazing animals (Heaney and Talling 1980). Their ability to live under resource limited conditions exceeds that of most other algal classes. Chlorophyta also tended to occur during the same period as the Dinophyceae, although they were often most abundant during late summer when DIN concentrations were most depressed.

With the exception of the summer of 1985, in which Croton Reservoir was in a drought condition, the cyanobacteria *Anabaena sp.*, and *Aphanizomenon sp.* were the dominant genera observed in late summer. During this same period, DIN concentrations, and DIN:TP ratios were consistently depressed within the epilimnion of the Reservoir (Chapter 2). Reynolds (1978) noted that nitrogen may limit phytoplankton production in temperate eutrophic lakes, especially where phosphorus concentrations are relatively high (and N:P ratios are low), and where epilimnetic nitrate concentration becomes depleted during the summer. The ability of both *Anabaena sp.* and *Aphanizomenon sp.* to fix nitrogen provides them with a

distinct ecological advantage over other phytoplankton during such periods of nitrogen limitation. In addition, Pearsall (1932) noted that the seasonal incidence of large populations of cyanobacteria was due to the previous decay of either diatom plankton or littoral plants which liberated large amounts of nitrogenous organic matter to the water column. Total nitrogen (TN) concentrations were important in explaining the variability in both annual and growing season biomass measurements within Croton Reservoir during the five year study period (Chapter 3). The late summer senescence of the dense stands of *Myriophyllum spicatum* within Muscoot Reservoir and the upper zone of Croton Reservoir may have contributed to this TN pool, and fostered cyanobacteria growth. During the summer of 1985, DIN concentrations were not as low as in the other study years, and the cyanobacteria were virtually absent from the reservoir's phytoplankton population. *Fragilaria sp.* replaced both *Anabaena sp.* and *Aphanizomenon sp.* as the dominant genus during that period. Hutchinson (1967) pointed out that the outcome of competition between *Fragilaria sp.* and *Anabaena sp.* would most likely be determined by competition going in favor of *Anabaena sp.* when the nitrogen content of the water is initially low but in favor of *Fragilaria sp.* when it is initially high.

Melosira sp. consistently dominated the fall phytoplankton community within Croton Reservoir. The

seasonal cycle of *Melosira* sp. in Croton Reservoir seems to closely parallel the cycle observed by Lund (1954, 1955) in the lakes of the English Lakes District. He noted that this heavy, filamentous diatom could not maintain itself in the water column as the water temperature increased and viscosity decreased. It would thus settle to the sediments during the summer. During fall overturn, the water column would mix, thus resuspending the *Melosira* cells from the sediments. This diatom does well in the fall and winter months since it can attain sufficient growth rates at low light intensities. In addition, this diatom has also been found to be characteristic of lakes that produce large cyanobacteria maxima (Pearsall 1932), and exhibit low N:P ratios (Kilham and Kilham 1984). Croton Reservoir displayed all the above characteristics over the course of the five year study period. As noted previously, Croton Reservoir exhibited its most pronounced longitudinal algal biomass gradient during the fall of 1988. *Melosira* was the dominant genus of the phytoplankton present at that time. Autumnal circulation was pronounced during that period because of the abnormally high levels of precipitation that occurred during the month of November (>20 cm). This enhanced mixing and sediment resuspending action may have lead to the elevated levels of *Melosira* biomass observed during that period.

In addition to the nutrient related determinants discussed above, reservoir hydraulic residence time, and

volume appeared to affect floristic composition. Reservoir volume and hydraulic residence time were positively correlated with the abundance of cyanobacteria, as well as the abundance of Chlorophyta during the growing season. The rapid 1985 summer flushing rate may have inhibited the usual proliferation of slow-growing cyanobacteria within the reservoir. This phenomena has been observed in other impoundments as well (Weiss et al. 1981, Soballe and Kimmel 1987, and Rechkow 1988). In contrast, the longer 1988 summer hydraulic residence time may have led to the more pronounced presence of Cyanobacteria observed during that period.

The findings of this study suggest that there are a multitude of factors governing the temporal variability of phytoplankton floristic composition within a reservoir ecosystem, many of which are interrelated and difficult to determine. The analysis of phytoplankton dynamics within Croton Reservoir, proved to be challenging since the impoundment was generally not nutrient limited. In this case, it was not only important to consider reservoir nutrient dynamics, hydraulic residence time effects, and light and temperature variations, but it was essential to examine the individual ecological characteristics of the endemic algal genera in order to correctly interpret the spatial and temporal successional and compositional patterns of the reservoir's phytoplankton.

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CHAPTER 5

SUMMARY DISCUSSION

The findings of this study, stated in the context of the hypotheses originally presented in the preface of this dissertation, may be summarized as follows:

(1) Croton Reservoir is *not* a spatially homogeneous system with respect to phytoplankton abundance. Longitudinal gradients of algal biomass were noted in both 1984-1987, and 1988. However, patterns of succession and floristic composition of the phytoplankton did not appear to vary spatially within the reservoir during the 1984-1988 period.

(2) Spatial variations in phytoplankton biomass *do* occur seasonally within Croton Reservoir. Algal biomass gradients were observed during the fall period, and were usually associated with periods of long hydraulic residence time which were terminated abruptly by elevated levels of precipitation. In 1988, an algal biomass gradient occurred in both the summer and fall.

(3) The factors governing phytoplankton abundance *are not* the same spatially and temporally along the entire longitudinal axis of Croton Reservoir. Overall, the upper zone of the reservoir exhibited a greater frequency of mixing, higher nutrient concentrations, higher levels of turbidity, color, and suspended solids, and lower water transparency and light penetration measurements than the reservoir's lower zone. Temporal variations, i.e., seasonal variations, of abiotic factors were also found to be heterogeneous along the reservoir's longitudinal axis.

(4) Hydraulic residence time *did* play a significant role in influencing phytoplankton abundance and floristic composition within the reservoir. Longer growing season residence times encouraged increased numbers of phytoplankton, and a greater percent composition of cyanobacteria.

(5) Differences among sampling stations for single epilimnetic samples were due to true differences in biomass over time, and differences in phytoplankton abundance with depth were not significant.

(6) The relation of phytoplankton biomass and composition with abiotic and biotic factors in different seasons *does* change when shorter time scales are examined. The more intensive 1988 phase of the study revealed that both spatial and temporal patterns for nutrients, water transparency, and algal biomass detected in the biweekly survey data, were not observed in the monthly survey data. The lack of significant ($p < 0.05$) trend detection in the monthly spatial analyses was most likely the result of the smaller sampling sizes and the lack of statistical power. Temporal trend detection in the monthly data was limited due to the longer time between sampling intervals, and thus the failure to adequately measure abiotic and biotic variability over time. This finding suggests that sampling performed on a monthly basis may not be adequate for assessing seasonal abiotic and biotic patterns over the course of a year.

(7) Abiotic factors alone *cannot* account for the variation in phytoplankton biomass. This study demonstrated that zooplankton biomass accounted for a significant portion of the variability in epilimnetic chlorophyll *a* concentrations within the reservoir's lower zone; thus suggesting that phytoplankton losses by grazing may be important in the lower zone of the reservoir.

Although the Croton Reservoir's bathymetry and water flow superficially resembled a general model for reservoirs, analysis of the flow regimes showed that the Croton Reservoir did not have the pronounced riverine zone and clearly defined transitional zone predicted by the model. Similarly, the physical, chemical, and biological gradients observed within the reservoir were not consistent with the typical well defined riverine, transitional, and lacustrine zonal pattern described by current reservoir zonation models. However, the reservoir did occasionally exhibit

longitudinal patterns typical of a high flow or rapidly flushed impoundment (as defined by Kimmel et al. 1990). This type of reservoir gradation is often demarcated by a large, less pronounced riverine zone, a limited transitional zone, and a well defined, but small lacustrine zone. The impoundment essentially behaved as a rapidly flushed nutrient-rich system, which occasionally exhibited longitudinal algal biomass gradients caused by increased residence time during the growing season (July-October) coupled with intense fall precipitation. It appeared likely that, with the exception of the summer-fall period, reservoir flow through rates were generally too rapid to allow for the accumulation of algal biomass. Kimmel et al. (1990) noted that as in a chemostat, if flushing rate exceeds phytoplankton doubling rate, the accumulation of biomass may be limited by advective losses (washout) of cells. In addition, Carmack et al. (1979) have indicated that phytoplankton washout could exert a major influence upon the accumulation of biomass in reservoirs with intermediate residence times (60-100 days), like Croton Reservoir, when the flushing rate of the photic zone is high, as in the spring. Perhaps the reservoir would have conformed more closely to the theoretical reservoir zonation model if both Muscoot and Croton Reservoirs were viewed as a continuum. The Muscoot Dam clearly has a mediating effect upon water quality within the upper zone of Croton

Reservoir. This mediation allows for a more gradual transition from a riverine to a lacustrine environment along the Croton longitudinal axis. Muscoot Reservoir has a surface area of $4.72 \times 10^6 \text{ m}^2$, a volume of $18.7 \times 10^6 \text{ m}^3$, and a mean depth of 3.9 m. It is a long, shallow, dendritic reservoir with a mean annual residence time of 0.06 years (21 days); these attributes are typical of the model's riverine zone. As such, the entire length of Muscoot Reservoir could act as the continuum's riverine zone. The transitional zone might extend from the Muscoot Dam to Site 6 (8.3 km downstream of the Muscoot Dam), and from Site 6 to the Croton Dam could represent the lacustrine zone. This hypothesis has yet to be tested, and warrants further investigation.

Seasonal succession and abundance of phytoplankton within Croton Reservoir were not completely governed by nutrient availability. With the exception of late summer DIN depletions, nutrients concentrations were usually at or above their respective detection limits within the epilimnion of Croton Reservoir. However, the relative concentrations of these nutrients did vary both spatially and temporally within the reservoir. There were clearly other factors, beside nutrient concentrations that played an important role in shaping the phytoplankton community both spatially and temporally. Such factors, as described by Reynolds (1984), may include: day-length, total irradiance,

water column light availability, temperature, flow regime, the abundance of herbivorous animals, the inhibitory and stimulatory effect of trace metals, and phytoplankton antibiosis. Not all of these factors were measured over the course of this investigation; thus many of the "causal" inferences put forth in this study were made very cautiously. In addition, the interaction of these factors often makes it difficult to determine which mechanism was responsible for phytoplankton succession and composition. Nevertheless, the relative proportions or concentrations of the nutrients present could have been a strong selective force in shaping phytoplankton community composition, particularly when either silicon (Si) or dissolved inorganic nitrogen (DIN) were at detection limits (Hecky and Kilham 1988). Seasonal patterns of floristic composition appeared to coincide with the variability of nutrient concentrations and water temperature. Spring and fall diatom dominance was positively correlated with Si concentrations, DIN concentrations, and DIN:TP ratios, and negatively correlated with epilimnetic temperature. Summer cyanobacteria dominance was negatively correlated with Si and DIN concentrations, and DIN:TP, and positively correlated with epilimnetic temperature. In addition, the concentrations of nitrogen, phosphorus, and silicon measured within the reservoir during the spring months, corresponded well with the optimum nutrient ratios for such diatoms as *Asterionella* sp.,

Synedra sp., *Fragilaria sp.*, *Tabellaria sp.*, and *Melosira sp.* (Kilham and Kilham 1984). *Asterionella sp.* tend to favor high Si:P ratios (>100), and low N:P ratios (>12); such ratios were observed within the epilimnion of Croton Reservoir during the spring months. Although the impoundment exhibited the same classic pattern of phytoplankton succession during both the 1984-1987 and the 1988 study periods as that observed in most northern temperate mesotrophic-eutrophic lakes, these patterns do not entirely agree with the predictions of the "Plankton Ecology Group" (PEG) Model as described by Sommer et al. (1986). This model was constructed based upon the succession in Lake Constance, and it was intended to provide a framework for interpretation of seasonal plankton succession in all lakes. The model assumes certain boundary conditions: a nutrient-rich lake in which nutrients are depleted in sequence P, Si, N. The model predicts the following seasonal sequence: (1), Cryptophyceae and diatoms are predominant during the spring at high Si:P ratios and cold water temperatures; (2), green algae become dominant after Si and P become depleted while N levels are still high; (3), once N levels become depleted and water temperature increases, cyanobacteria predominate; (4), increased mixing and the cooling of the water in the fall give rise to nutrient replenishment and filamentous algal forms, and the diatoms.

A possible explanation for the differing successional

patterns between those predicted by the PEG lake model and those observed within Croton Reservoir may be attributable to the different physical and chemical attributes of reservoirs as opposed to lakes. Reservoir nutrient dynamics are primarily governed by morphometry inflow-outflow regimes, and discharge depth. This is in contrast to lakes in which nutrient cycling is controlled by vertical mixing induced by wind action, and internal nutrient cycling (Baxter 1977; Kennedy 1984; Pickett and Harvey 1988). Reservoirs also receive greater areal water loads, and experience shorter hydraulic residence times than lakes. The PEG lake model predicts the sequential depletion of phosphorus and silicon as summer stratification progresses. The model also predicts the dominance of diatoms well into the summer months. Although this pattern is typical in most oligotrophic-mesotrophic lakes, it is contrary to what was observed in Croton Reservoir during this investigation. Both phosphorus and silicon concentrations were, for the most part, always present above the limit of detection, although concentrations of both of these nutrients generally dropped during the summer months. As such, contrary to the PEG model, the extent of diatom predominance was limited to the spring when Si:P ratios were high, and water temperatures were low. In addition, since N:P ratio measurements were low as the summer months began, Chlorophytes (poor N competitors), although present, never took hold as a

dominant algal class. Instead, cyanobacteria became dominant as DIN concentrations approached detection limits and hydraulic residence time increased. The N:P ratios observed within the reservoir during this period were consistent with those observed by Schindler (1975) and Levine (1983), which predict cyanobacteria dominance. Notwithstanding, Dinophyceae generally bridged the transition between diatoms and cyanobacteria as the PEG model predicts. These findings suggest that the nutrient dynamics observed within Croton Reservoir, which were primarily controlled by advective processes, may have played a significant role in shaping the successional patterns of the phytoplankton. In addition, the patterns of succession observed within the impoundment varied from those generally observed in lakes, i.e., the PEG model, in that algal populations never appeared to be limited by phosphorus availability, except during the fall of 1988 as noted below. Nitrogen and silicon may have played a more important role than phosphorus in shaping phytoplankton populations.

Biomass levels were generally greatest during the late summer-fall period. These elevated biomass levels primarily resulted from the combined sequential effect of increased growing season (July-October) residence time coupled with intense fall precipitation, which exacerbated autumnal circulation. Croton Reservoir exhibited its most pronounced longitudinal algal biomass gradient during the fall of 1988.

The filamentous diatom *Melosira sp.* was the dominant algal genus present at that time. Autumnal circulation was pronounced during that period because of the abnormally high levels of precipitation that occurred during the month of November (>20 cm). Enhanced mixing and sediment resuspension may have led to the elevated levels of *Melosira* biomass observed during that period. In addition, this heavier than normal November precipitation may have augmented the flushing action within Muscoot Reservoir, thus increasing allochthonous input of sediments, nutrients (Si, DIN, TP), and organic material to the upper reaches of Croton Reservoir. As noted in Chapter 3, multiple regression analysis revealed that TP accounted for 57% of the variability in chlorophyll a concentrations within the reservoir during this period. In addition, TP had a highly significant correlation ($r=0.76$, $p<0.0001$) with chlorophyll a. These findings suggest that TP may be one of the important factors influencing phytoplankton abundance during the reservoir's autumnal circulation period, particularly within the upper zone of the reservoir. This type of relationship between algal biomass and total phosphorus is consistent with the predictions of the "yield limitation" nutrient-limitation models of both Dillon and Rigler (1974), and Vollenweider (1975), which estimate elevated levels of biomass based upon nutrient enrichment. The utilization of laboratory biostimulation tests may be a helpful addition to

further research efforts concerning nutrient enrichment of the phytoplankton within the reservoir, in that certain external variables could be removed from the analysis, and comparisons between laboratory results and field observations could be facilitated.

In addition to nutrients, other factors that may have influenced algal abundance in the reservoir during the study period include water transparency, zooplankton grazing effects, and hydraulic residence time. The influence of these factors upon phytoplankton populations also appeared to vary spatially within the impoundment during this investigation. Biomass concentrations within the lower zone of the reservoir during the growing season were most affected by algal light attenuation and grazing effects. In addition, the lower zone's photic zone depth did not vary seasonally, and was consistently greater than upper zone levels. These results are consistent with the reservoir zonation model which predicts a lower zone with a relatively clear water column, an autochthonous organic matter supply, and cell losses by grazing. These findings also lend credence to the "top-down" (food-web interactions) phytoplankton control theory as well as the "bottom-up" (resource competition) theory. However, results indicated that biomass concentrations within the upper zone of the reservoir were influenced by limited water transparency due to the resuspension and advective input of inorganic

particulate material, particularly during periods of autumnal circulation and elevated precipitation.

Accordingly, the upper zone exhibited great seasonal variability in photic zone depth, with lowest levels being observed in the fall. These findings suggest that the upper zone of the impoundment exhibited characteristics typical of rivers, which are generally noted for having limited light availability because of high suspended solids concentrations and rapid vertical mixing (Kimmel et al. 1990).

Nevertheless, during the fall of 1988, Croton Reservoir exhibited elevated biomass levels within the upper zone of the impoundment in spite of reduced photic zone depth, i.e., light-limiting conditions. As mentioned earlier in this Chapter, Carmack et al. (1979) noted that advective losses of phytoplankton from the photic zone can be substantial when the flushing rate is high in reservoirs with intermediate residence times. However, Kimmel et al. (1990) have indicated that, if the flushing rate is less than the mean doubling time of the phytoplankton population, then increased flushing can actually increase algal abundance by increasing nutrient availability. In addition, Soballe and Kimmel (1987) suggested that larger cell sizes or increased chlorophyll per cell (or both) predominate in rivers and rapidly flushed, somewhat turbid, lentic systems. Larger cell size is expected in high nutrient systems where turbulence reduces algal sinking losses (Smayda 1970;

Reynolds 1984) and cell chlorophyll content generally increases in situations having high turbidity, light-limitation, and high nutrient concentrations (Harris 1978). Such an effect was noted by Turner et al. (1983) in Lake Tahlquin, Florida. Therefore, it seems likely that the process of nutrient enrichment of the phytoplankton population within the "light-limited" upper zone of Croton Reservoir occurred during periods of increased flushing and enhanced autumnal circulation.

Lastly, hydraulic residence time calculations indicated that Croton Reservoir was a rapidly flushed transitional system with a mean hydraulic residence time and a mean flushing rate of 0.17 years (60 days) and 6.2 flushes per year, respectively. With the exception of the drought year of 1985, growing season residence times were generally greater than annual residence times by a factor of 2.1. Annual residence time values did not significantly differ during the five year study period, but growing season residence times did differ. The shortest and longest growing season residence times were observed during 1985 (72 days) and 1988 (165 days). Hydraulic residence time and reservoir volume levels played an important role in determining the abundance and the composition of the phytoplankton, as well as affecting the extent of the physical and chemical longitudinal gradients which occurred within the impoundment over the five year study period.

Growing season reservoir volume and hydraulic residence time were positively correlated with the abundance of cyanobacteria, as well as the abundance of Chlorophyta, and total phytoplankton. The rapid 1985 summer flushing rate may have inhibited the usual proliferation of slow-growing cyanobacteria within the reservoir; small numbers of cyanobacteria were noted during the 1985 growing season. In contrast, the longer 1988 growing season hydraulic residence time may have led to the more pronounced presence of cyanobacteria observed during that period.

The accumulation of algal biomass within Croton Reservoir was influenced by both abiotic and biotic factors that varied spatially and temporally within the impoundment. With the exception of the summer-fall period, the reservoir flow-through rates were generally too rapid to allow for the accumulation of algal biomass, i.e., advective output of the phytoplankton cells exceeded gross phytoplankton production along the reservoir's entire longitudinal axis. However, during the growing season period (July-October), when advective cell losses became reduced due to increased hydraulic residence time, cell losses and reduced biomass production were most likely attributable to grazing, light-limitation and cell sedimentation. Grazing losses appeared to be more pronounced in the reservoir's lower zone, whereas nonalgal light-limitation, and sedimentation were more pronounced in the reservoir's upper zone. Nutrient

availability never appeared to be a controlling factor with respect to algal abundance, although the relative proportions or concentrations of nutrients measured corresponded with the spatial and temporal patterns of floristic composition observed within the impoundment, and agreed with current nutrient ratio theory. Nevertheless, nutrient enrichment may have influenced phytoplankton abundance during the fall of 1988 when a pronounced longitudinal algal biomass gradient was observed within the reservoir. Finally, the importance of temperature-dependent algal metabolic rates, respiration, the extracellular excretion of photosynthate, and parasitism as forces influencing gross phytoplankton production and cell losses, should not be minimized. Although these factors were not measured during this investigation, their importance as underlying controlling mechanisms with respect to algal biomass accumulation could be considerable.

This was one of the few investigations of a limnetic system that had a sufficient database to thoroughly explore the nature of temporal and spatial interactions of variables that could influence phytoplankton abundance and composition. This investigation helped to further clarify the distinction between the patterns of phytoplankton abundance observed within both low flow, "steady-state", nutrient-limited lacustrine environments, as well as those within hydrodynamic, nonequilibrium, nutrient enriched

reservoirs. The findings from this study will not only provide an additional contribution to the body of research concerning the ecological processes occurring in reservoirs, but will assist immeasurably in the implementation of the water quality management strategies described below.

*Water Quality Management Implications
and Future Research Needs*

Findings from this study suggest that the following three areas are essential to the formulation of an effective water quality management program for Croton Reservoir: (1) selection of the ideal intake location, both horizontally and vertically, based upon current water quality conditions; (2) regulation of growing season hydraulic residence time to achieve optimum water quality; and (3) minimization of advective nutrient and organic matter input from Muscoot Reservoir.

Croton Reservoir has two gatehouse locations from which water can be withdrawn. One location is situated at the dam, within the lower or lacustrine zone of the reservoir. This gatehouse has 2 intakes located at approximately 10 m and 30 m below spillway crest elevation. A second gatehouse is located in the middle, or transitional zone of the reservoir, approximately five kilometers upstream from the dam. This gatehouse has 3 intakes which are located at

approximately 5 m, 10 m, and 20 m below spillway crest elevation. These multiple intake locations provide reservoir managers with a number of options for water withdrawals over the course of the year. Clearly, water quality data collected over the five year study period indicated that withdrawals of water from the lower zone of the reservoir would be preferable because of its low turbidity, color, algal biomass levels, and suspended solids concentrations. However, it is highly likely that during late summer stratification, hypolimnetic diversions from the 30 m lower zone intake may have to be curtailed due to the development of anaerobic conditions. At this point, withdrawals from either the 10 m lower zone intake, or the mid-reservoir gatehouse may become necessary.

Growing season hydraulic residence time plays a significant role in determining both algal abundance and phytoplankton floristic composition within Croton Reservoir. As the study results indicated, longer growing season residence time provided favorable conditions for cyanobacteria, and allowed for the production of higher algal biomass levels. As a result, water quality deteriorated, thus requiring the usage of greater amounts of chlorine to adequately disinfect diverted water. It has been noted that chlorine usage at the Croton Reservoir Gatehouse increased considerably in the late summer of 1988, when growing season residence time levels were at their highest

of the 1984-1988 study period (Muursepp pers. comm.). The combination of drawdown, or decreased reservoir volume, and increased diversions to the Croton Aqueduct both act to decrease summer residence time. In contrast, if the reservoir is maintained at crest elevation during the growing season, and the aqueduct diversion is decreased, hydraulic residence time will increase. This situation may lead to increases in algal biomass, thus further substantiating decreased diversions to the aqueduct because of poorer water quality. A Croton System filtration facility is currently in the design stages. When this facility is constructed and put into operation, it is critical that aqueduct diversions to the filter plant be consistently maintained throughout the growing season so as to not cause any undue increase in reservoir hydraulic residence time. There may be a tendency to lessen flow to the facility, i.e., reduce diversions to the Croton Aqueduct, during the summer due to the shorter filter run lengths that may result from the increased levels of algal biomass usually present within the reservoir at that time. However, this reduction in aqueduct flow will only exacerbate the filter plant performance problem by increasing reservoir hydraulic residence, thus further encouraging algal growth. These findings suggest that a beneficial water quality management strategy may be to optimize reservoir volume levels and aqueduct diversions to achieve summer residence times which

stay below the threshold level beyond which cyanobacteria abundance elevates drastically, while still affording adequate residence time for sedimentation of particulates. Findings suggested that this threshold may lie within the 70-80 day range. Minimizing the generation of autochthonous material, or cyanobacteria blooms, would result in improved drinking water quality through a reduction in chlorine demand, and a coincident decline in the production of disinfection by-products and bacteriologically assimilable organic carbon.

Lastly, findings from this study strongly suggest that the Muscoot Reservoir may contribute nutrients and organic matter to the upper zone of Croton Reservoir, particularly during the fall months. Minimization of advective nutrient and organic matter input from Muscoot Reservoir is essential to controlling water quality within Croton Reservoir. Three areas that warrant further research include: (1) the fate and transport of nutrients and organic material through the Muscoot-Croton Reservoir continuum; (2) the importance of the biotic linkage between Muscoot and Croton Reservoirs with respect to the advective input of planktonic organisms; and (3) the biological transformation of the organic material present within Croton Reservoir and its susceptibility to the formation of disinfection by-products or trihalomethanes.

It was noted in Chapter 2, that the elevated TP

concentrations present within the upper zone of Croton Reservoir in the fall were most likely the result of the combination of the massive late summer die-off and decomposition of the dense stands of *Myriophyllum spicatum* that thrive throughout much of Muscoot Reservoir and portions of the upper zone of Croton Reservoir, and the 5000 kg yr⁻¹ load of TP Muscoot Reservoir receives from sewage treatment plants (STP) discharges within its 189.09 km² sub-basin. It was also suggested that the fall TP and algal biomass gradient within Croton Reservoir became more pronounced in 1988 as a result of heavier than normal November precipitation which enhanced the flushing action within Muscoot Reservoir, thus increasing allochthonous input of sediments, nutrients, and organic material to the upper reaches of Croton Reservoir. As noted earlier in this Chapter, multiple regression analysis revealed that TP accounted for 57% of the variability in chlorophyll a concentrations within the reservoir during this period. In addition, TP had a highly significant correlation ($r=0.76$, $p<0.0001$) with chlorophyll a (Chapter 3). These findings suggest that TP may be one of the important factors influencing phytoplankton abundance during the reservoir's autumnal circulation period. This type of relationship between algal biomass and total phosphorus is consistent with the predictions of the "yield limitation" nutrient-limitation models of both Dillon and Rigler (1974), and

Vollenweider (1975) which estimate elevated levels of biomass based upon nutrient enrichment. Since Croton Reservoir receives 80% of its water input from Muscoot Reservoir, it is critical that water quality management practices be targeted at reducing advective outputs of nutrients, and organic matter from Muscoot Reservoir to Croton Reservoir, and that both reservoirs be managed as integrated systems in the future. Water quality remediation efforts should include a program aimed at reducing STP total phosphorus inputs to all reservoirs within the Croton River Watershed, through implementation of best available phosphorus removal technologies. Particular emphasis should be given to those wastewater treatment facilities which discharge into tributaries of the Muscoot and Croton Reservoirs. In addition, there is a need for a better understanding of phosphorus retention efficiency of the Muscoot ecosystem, and the influence of interreservoir nutrient transfers upon Croton Reservoir algal abundance. Particular attention should be given to the structure and function of the Muscoot Reservoir macrophyte community and its role in nutrient cycling.

Similarly, further research is warranted concerning the biotic linkage between Muscoot and Croton Reservoirs with respect to the advective input of planktonic organisms. It was suggested in Chapter 3 that during the fall of 1988 Muscoot Reservoir could have acted as an algal biomass

advective mechanism to Croton Reservoir, thereby contributing to the higher algal biomass levels observed within the upper zone of the reservoir. Such a phenomenon has been observed in a number of contiguous or interconnected impoundments (Brook and Rzoska 1954, Shiel and Walker 1984, Petts 1984).

There is, and has been for a number of years, great concern within the both the public health field, and the drinking water supply industry regarding the formation of trihalomethanes (THMs) within chlorinated drinking water supplies. The ultimate goal of a water supplier has been to adequately disinfect the water being sent to consumers while minimizing the formation of THMs. The standard water quality management approach has been to minimize or eliminate THM precursor concentrations within the water to be chlorinated. Such an approach often includes filtration, or stricter watershed management measures to control source water quality. Cooke and Carlson (1989) have noted that although much of the organic matter, including precursors of THMs, that passes through a reservoir is refractory to chemical reactions, including chlorination, some is highly reactive. They suggest that increased reservoir detention time may lead to the biological transformation of the organic material present within a reservoir making it more susceptible to the formation of THMs. Accordingly, the origin, fate, and transport of THM precursors present within

Croton Reservoir, and their relation to reservoir hydraulic residence time warrants further investigation.

In conclusion, the success of water quality management initiatives within the Croton basin are contingent upon the continued production of technologically advanced water quality information of sufficient scope and detail. This study has provided a strong foundation for the research needs described above, as well as some recommendations for immediate management actions to be taken to improve Croton Reservoir water quality. Above all, this investigation emphasized the need to both study and manage the Croton and Muscoot impoundments as closely linked and integrated ecosystems.

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