ALGAE-TEMPERATURE-NUTRIENT RELATIONSHIPS AND DISTRIBUTION IN LAKE ERIE 1968

ENVIRONMENTAL PROTECTION AGENCY
WATER QUALITY OFFICE
REGION V
LAKE ERIE BASIN

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AND DISTRIBUTION IN LAKE ERIE

By
Robert P. Hartley
and
Chris P. Potos

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TABLE OF CONTENTS

	Page
SUMMARY AND CONCLUSIONS	1
INTRODUCTION	8
PHOSPHORUS DISTRIBUTION IN LAKE ERIE	11
Western Basin	
Soluble Phosphorus	12
Particulate Phosphorus	19
Central Basin	
Soluble Phosphorus	26
Particulate Phosphorus	28
NITROGEN DISTRIBUTION IN LAKE ERIE	30
Western and Central Basins	
Organic Nitrogen	31
Ammonia Nitrogen	36
Nitrate Nitrogen	40
Organic-Inorganic Nitrogen Ratios	45
WATER TEMPERATURE	46
AIR TEMPERATURE	50
SUNSHINE AND SOLAR RADIATION	50
WIND	52
PHYTOPLANKTON	52
DISSOLVED OXYGEN	58
CHEMICAL OXYGEN DEMAND	61
CORRELATION OF FACTORS AFFECTING ALGAL PRODUCTIVITY	61
Centric Diatoms	
Water Temperature	62
Soluble Phosphorus and Temperature	63
Inorganic Nitrogen	64

TABLE OF CONTENTS

Pennate Diatoms	Page
Water Temperature	70
Soluble Phosphorus and Temperature	70
Inorganic Nitrogen and Temperature	72
Green Coccoid Algae	
Water Temperature	73
Soluble Phosphorus and Temperature	75
Inorganic Nitrogen and Temperature	76
Blue-green Coccoid Algae	
Water Temperature	78
Soluble Phosphorus and Temperature	80
Inorganic Nitrogen and Temperature	80
Blue-green Filamentous Algae	
Water Temperature	82
Soluble Phosphorus and Temperature	82
Inorganic Nitrogen and Temperature	84
FUTURE INVESTIGATIONS	86

LIST OF TABLES

Table No.	Title	Page
1	Summary of Water Intake Physical Data	10
2	Average Seasonal Concentration of Soluble Phosphorus in Various Sectors of the Western Basin of Lake Erie	15
3	Average Seasonal Concentrations of Particulate Phosphorus in Various Sectors of the Western Basin of Lake Erie	22
4	Average Seasonal Concentrations of Soluble Phosphorus in Various Sectors of the Central Basin of Lake Erie	27
5	Average Seasonal Concentrations of Particulate Phosphorus in Various Sectors of the Central Basin of Lake Erie	29
6	Average Seasonal Concentrations of Organic Nitrogen in Various Sectors of the Central Basin of Lake Erie	34
7	Average Seasonal Concentrations of Organic Nitrogen in Various Sectors of the Central Basin of Lake Erie	37
8	Average Seasonal Concentrations of Nitrate Nitrogen in Various Sectors of the Western Basin of Lake Erie	43
9	Average Seasonal Concentrations of Nitrate Nitrogen in Various Sectors of the Central Basin of Lake Erie	43
10	Concentrations of Inorganic Nitrogen and Phosphorus Required to Produce Various Populations of Centric Diatoms during Warming Months	68
11	Concentrations of Inorganic Nitrogen and Phosphorus Required to Produce Various Populations of Pennate Diatoms during Warming Months	73
12	Concentrations of Inorganic Nitrogen and Phosphorus Required to Produce Various Populations of Green Coccoid Algae during Warming Months	76
13	Concentrations of Inorganic Nitrogen and Soluble Phosphorus Required to Produce Various Populations of Blue-green Coccoid Algae	82
14	Concentrations of Inorganic Nitrogen and Soluble Phosphorus Required for Various Populations of Blue-green Filamentous Algae	86

LIST OF FIGURES

Figure No.	Title	Page
1	Lake Erie Surveillance Stations	9
2	Nearshore Soluble Phosphorus Distribution in Lake Erie	13
3	Nearshore Seasonal Distribution of Soluble Phosphorus	14
4	Midlake Seasonal Distribution of Soluble Phosphorus	17
5	Nearshore Particulate Phosphorus Distribution in Lake Erie	20
6	Nearshore Seasonal Distribution of Particulate Phosphorus	21
7	Midlake Seasonal Distribution of Particulate Phosphorus	23
8	Nearshore Organic Nitrogen Distribution	32
9	Midlake and Nearshore Seasonal Distribution of Organic Nitrogen	33
10	Nearshore Ammonia Nitrogen Distribution in Lake Erie	38
11	Nearshore and Midlake Seasonal Distribution of Ammonia Nitrogen	39
12	Nearshore Nitrate Nitrogen Distribution in Lake Erie	41
13	Nearshore Seasonal Distribution of Nitrate Nitrogen	42
14	Midlake Seasonal Distribution of Nitrate Nitrogen	44
15	Comparison of Organic and Inorganic Nitrogen in Central Basin Nearshore for One-year Cycle	47
16	Comparison of Organic and Inorganic Nitrogen in Western Basin Nearshore for One-year Cycle	47
17	Nearshore Temperature Distribution in Lake Erie	48
18	Water Temperature at Put-in-Bay	49
19	Monthly Averages of Various Physical Factors Affecting Lake Erie	51

LIST OF FIGURES

Figure No.	Title	Page
20	Nearshore Centric Diatom Distribution in Lake Erie	53
21	Nearshore Pennate Diatom Distribution in Lake Erie	54
22	Nearshore Coccoid Green Algae Distribution in Lake Erie	55
23	Nearshore Coccoid Blue-green Algae Distribution in Lake Erie	56
24	Nearshore Filamentous Blue-green Algae Distribution in Lake Erie	57
25	Nearshore Dissolved Oxygen Distribution in Lake Erie	59
26	Nearshore COD Distribution in Lake Erie	60
27	Centric Diatoms vs. Temperature in Lake Erie Central Basin Nearshore	65
28	Centric Diatoms vs. Temperature in Lake Erie Western Basin Nearshore	65
29	Centric Diatoms as Related to Water Temperature, Soluble Phosphorus and Inorganic Nitrogen in Lake Erie Nearshore Waters	67
30	Estimated Requirements of Solar Radiation at Lake Erie Water Temperature for Centric Diatoms	69
31	Pennate Diatoms as Related to Water Temperature, Soluble Phosphorus and Inorganic Nitrogen in Lake Erie Nearshore Waters	71
32	Green Coccoid Algae vs. Water Temperature in Nearshore Waters of Central Basin	74
33	Green Coccoid Algae vs. Water Temperature in Nearshore Waters of Western Basin	74
34	Green Coccoid Algae as Related to Water Temperature, Soluble Phosphorus, and Inorganic Nitrogen in Lake Erie Nearshore Waters	77
35	Blue-green Coccoid Algae vs. Water Temperature in Nearshore Waters of Central Basin	79

LIST OF FIGURES

Figure No.	Title	Page
36	Blue-green Coccoid Algae vs. Water Temperature in Nearshore Waters of Western Basin	79
37	Blue-green Coccoid Algae as Related to Water Temperature, Soluble Phosphorus and Inorganic Nitrogen in Lake Erie Nearshore Waters	81
38	Blue-green Filamentous Algae vs. Water Temperature in Nearshore Waters of Central Basin	83
39	Blue-green Filamentous Algae vs. Water Temperature in Nearshore Waters of Western Basin	83
40	Blue-green Filamentous Algae as Related to Water Temperature, Soluble Phosphorus and Inorganic Nitrogen in Lake Erie Nearshore Waters	85

SUMMARY AND CONCLUSIONS

Data gathered in the Lake Erie surveillance program by the Federal Water Quality Administration Lake Erie Basin Office provide the basis for discussion of the distribution of algal types and some of the physical and chemical factors which control algal populations in the western and central basins of the lake. Sufficient data are not available to include the eastern basin.

For three seasons of the year, spring, summer, and fall, soluble phosphorus is remarkably uniform at any one place in Lake Erie, although there are occasional substantial variations. Concentrations generally decrease from shore lakeward and from west to east in the lake. It can be stated for generalization that for those three seasons midlake western basin soluble phosphorus as P averages about 30 μg/l compared to 50 μg/l near shore. The central basin nearshore averages 30 μg/l, about the same as the western basin midlake, while in the central basin midlake soluble phosphorus drops to about 15 μg/l.

In winter, a season when adequate data have not previously been available, soluble phosphorus more than doubles in all nearshore areas and in the western basin midlake. Limited non-nearshore data show very little winter rise in soluble phosphorus at the outlet end of the western basin and in the western portion of central basin midlake. This indicates considerable winter tributary* input, nearshore sediment resuspension, limited dispersion, and low utilization by algae in winter.

Particulate phosphorus exhibits an erratic distribution throughout the year and at any one time in the nearshore area, although it generally

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* *In this text the word tributary refers to total inputs, municipal, industrial, and agricultural.*

is less than soluble phosphorus. The erratic nearshore distribution, not so evident in midlake waters, most likely is controlled by variability in productivity and by variability in runoff and wind-induced sediment resuspension. Particulate phosphorus shows no definable seasonal pattern except for a slight rise in winter.

Organic nitrogen, which should reflect fluctuations in biological productivity is remarkably uniform on the average throughout the lake during all seasons at 300-400 µg/l. An exception is a slightly higher concentration in nearshore waters of the western basin in spring. Organic nitrogen does not correlate with algal numbers although it may with total biomass, a parameter not being determined in the present program.

Ammonia nitrogen shows no clear seasonal pattern and concentrations in midlake are not far from those in the nearshore area, generally at 200 µg/l or less. Since nearshore short-term nutrient dispersion is minimal, it is indicated that the sediments are an important source of midlake ammonia, although it is not implied that sediment inputs necessarily cause the approach to uniformity.

Nitrate nitrogen, however, does show a clear seasonally changing annual pattern in both nearshore and midlake waters. Nearshore area nitrate nitrogen is generally more than twice that of midlake. During winter and spring there is a significant decrease from west to east throughout the lake.

Nitrate nitrogen climbs to levels greater than 1,500 µg/l in winter in the nearshore waters of the western basin, most likely due to higher tributary inputs, the introduction of interstitial ammonia during sediment resuspension with subsequent conversion to nitrate, and low nutrient utilization by limited algal populations. The winter rise is progressively less eastward until at Conneaut, Ohio, it is insignificant.

A conspicuous drop in nitrate nitrogen occurs in spring, correlative with high algal populations. However, in the east half of the central basin, nitrate nitrogen increases in spring. Summer and fall are characterized by low concentrations of nitrate nitrogen (200 µg/l or less) after strong algal uptake in both nearshore and midlake waters.

Organic nitrogen exceeds inorganic between July and November in Lake Erie. The excess of organic nitrogen indicates that inorganic nitrogen is being biologically converted faster than it is being supplied. The sustenance of such a condition would eventually result in the complete depletion of ambient inorganic nitrogen and thus create the potential for nitrogen limitation of certain algal genera. Blue-green algae, certain species being nitrogen fixers, are dominant during this period.

Nearshore data correlations with respect to nutrients and algae have been made at various temperatures. During the year of concern (1968-69) an investigation of physical factors revealed that water temperature, air temperature, solar radiation, and percent of possible sunshine were above average in early spring, below average in late spring and early summer, and at or above average for the remainder of the year. Precipitation was below average the first half of the year and above average the last half. The winds throughout were lighter than normal and lake levels were above normal. All nutrient-algal relationships most likely are affected by the variations in the physical factors described above, however, except for water temperature these effects are not defined in this report.

Various types of algae show preference for particular temperature ranges, and within those ranges there are optimum growth temperatures. There are no important Lake Erie algal types which prefer freezing temperatures. Diatoms prefer temperatures between 2°C (36°F) and 10°C (50°F), green algae between 10°C and 20°C (68°F) and blue-green algae prefer temperatures in excess of 20°C. The following observations are based on ambient water nutrient concentrations and phytoplankton populations at the time of sample collection. The measurement of algal metabolic rates was never attempted, consequently any and all correlations are indirect, and can only be considered indications. In general and in opposition to what one might normally expect, it is indicated that for any algal species nutrient requirements increase as temperatures depart from the optimum. In addition increases in temperature do not necessarily result in increases in populations of algae. In fact, except for the occasional and sometimes massive blue-green bloom, which is not fully documented by the present biweekly sampling program but based on many individual observations, lower populations are characteristic of the warmest season of the year. However, total algal biomass during both spring and summer may be equivalent as suggested by the comparable organic nitrogen concentrations during both seasons.

Diatoms, the first algae to appear in great numbers in late winter or early spring, appear to require relatively low concentrations of nitrogen and phosphorus at their optimum temperature although these nutrients generally are at or near their highest concentrations. As temperatures increase the nitrogen and phosphorus requirement appears to increase while the actual nutrient concentration is diminishing. Thus it appears that control of the nutrient supply is most critical at optimum temperatures.

To reduce the population of green algae at their preferred temperature range it appears that any reduction of nutrients would be somewhat effective. If the objective were to keep populations below 200 organisms/ml, about 25 percent reduction of inorganic nitrogen or 80 percent reduction of soluble phosphorus, at the time of green algal dominance, would be required. Unlike diatoms, it appears that the duration of green algae dominance would not change but that the amplitude (maximum population) of the pulse would be decreased.

At temperatures above 20°C (68°F) blue-green populations most likely would not be reduced by the control of inorganic nitrogen, since blooms occur at present after this nutrient has all but disappeared from the lake in summer. It appears however that maximum populations, but not the period of dominance, can be limited by soluble phosphorus control. If concentrations of soluble phosphorus as P can be maintained below 40 ug/l it appears that blue-green populations can be controlled to less than 500 organisms/ml. This would be essentially a 25 percent reduction in soluble phosphorus. However the control of blue-green algae is complicated by the fact that these organisms, possibly more than any other algae, apparently are largely stimulated by nutrients regenerated from bottom sediments. Since the regeneration process is not presently controllable, compensation for this nutrient source must be accomplished by further tributary input reduction. The necessary additional reduction is not known, but a total of 80 to 90 percent does not seem unreasonable to effectively reduce blue-green populations.

Based on limited environmental relationships, of the two nutrients which are or may be controllable, phosphorus appears to be the one offering the most feasibility and practicality. Furthermore blue-green algae cannot be controlled by nitrogen tributary input limitation. Diatoms also cannot be controlled effectively with less than extreme nitrogen limitation. The probable effective nitrogen control of green algae may extend blue-green dominance for even longer periods due to minimized ecological competition and since as mentioned above, blue-greens cannot be controlled by waterborne nitrogen limitation. The blue-green algal ability to fix atmospheric nitrogen precludes dependence on waterborne nitrogen. Finally, if as indicated by this study a 90 percent input phosphorus reduction can be made to limit diatoms, apparently there is little doubt that with that same control, all algae can be limited greatly in their abundance. An 80 percent reduction of soluble phosphorus will limit the duration but not the maximum population of the diatom pulse. This reduction will also reduce the magnitude but not the duration of the green pulse, and may reduce the magnitude of the blue-green pulse but unfortunately not the duration.

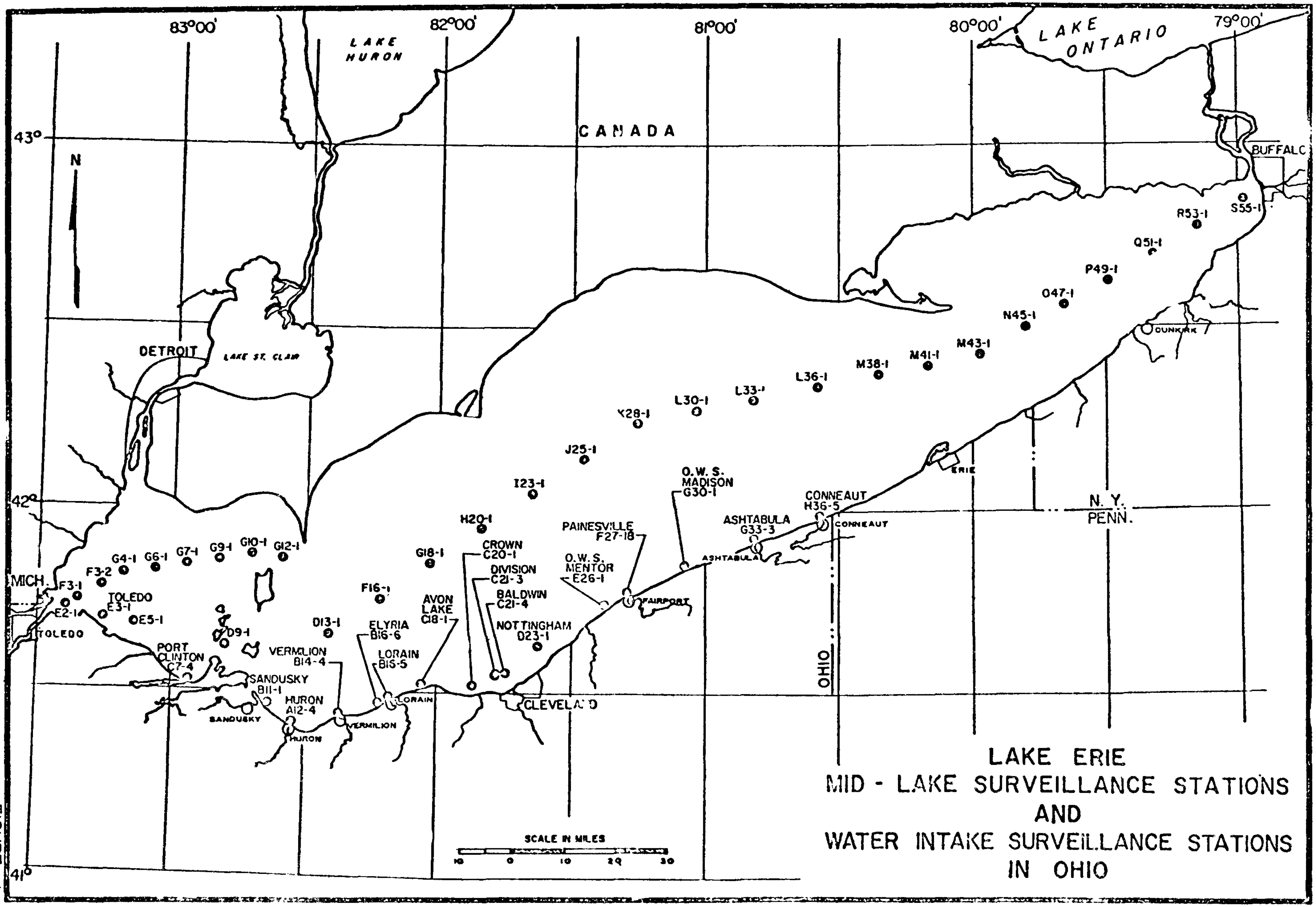
The limited correlation analysis made for this report is only a beginning but it has shown that an adequate algal response prediction system can be made for Lake Erie with perhaps considerably less effort than apparently first thought possible. The model most likely will not have optimum practicality since the effected correlations do not consider exact algal nutrient use as measured by metabolic uptake, nor do they consider nutrient storage in cell bodies, a most likely cause for any delayed ambient algal-nutrient response. As previously mentioned correlations were made using ambient water nutrient concentrations and prevalent algal populations. However a comparison of organic and inorganic nutrient forms does not reveal significant luxuriant consumption allowing for some degree of confidence in the nutrient concentration versus biological populations approach. Thus, it is indicated that a working model formulated with the technique described in this report can be made somewhat less than optimumly effective with but slight "over-engineering" to compensate for any undefined biological vagaries.

DISTRIBUTION OF CHEMICAL, PHYSICAL, AND BIOLOGICAL FACTORS IN LAKE ERIE

INTRODUCTION

The following report describes the time and space distribution of measured chemical, physical, and biological factors for a one-year cycle in the western and central basins of Lake Erie. The nearshore descriptions are based upon data gathered in a biweekly sampling program at 17 Ohio domestic water supply intakes from March 1968 through March 1969. *It should be emphasized that the Cleveland area sampling locations are relatively a great distance from shore, up to 20,000 ft., and for this reason the water quality in this area is of higher quality especially when compared to other Ohio nearshore areas where samples were retrieved as little as 1,100 ft. from shore.* The midlake descriptions are based upon data gathered at 20 midlake stations sampled four times between May 1967 and January 1968. Sampling locations, depths and distance from shore are shown on Fig. 1 and Table 1. Although the sampling times for nearshore and midlake were one year apart, for the purposes of this report the data are assumed to be comparable.

The data are certainly not so abundant nor so precise that the conclusions are indisputable. Conclusions drawn from data gathered over a one-year period are subject to argument on several grounds, not the least of which are sampling frequency, measurement technique, living systems idiosyncrasies and even the unique whims of nature during any one year. Even further danger exists in comparing midlake data for one year with nearshore data for the following year, not only for the above reasons


LAKE ERIE
MID - LAKE SURVEILLANCE STATIONS
AND
WATER INTAKE SURVEILLANCE STATIONS
IN OHIO
LAKE ONTARIO
LAKE HURON
LAKE ST. CLAIR
CANADA
BUFFALO
DUNKIRK
ERIE
N. Y.
PENN.
OHIO
MICH.
DETROIT
TOLEDO
SANDUSKY
HURON
VERMILION
LORAIN
CLEVELAND
FAIRPORT
ASHTABULA
CONNEAUT
79°00'
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41°
N
S55-1
R53-1
Q51-1
P49-1
O47-1
N45-1
M43-1
M41-1
M38-1
L36-1
L33-1
L30-1
K28-1
J25-1
I23-1
H20-1
G18-1
F16-1
D13-1
G12-1
G10-1
G9-1
G7-1
G6-1
G4-1
F3-2
F3-1
E2-1
TOLEDO
E3-1
E5-1
D9-1
PORT CLINTON
C7-4
SANDUSKY
B11-1
HURON
A12-4
VERMILION
B14-4
ELYRIA
B16-6
LORAIN
B15-5
AVON LAKE
C18-1
CROWN
C20-1
DIVISION
C21-3
BALDWIN
C21-4
NOTTINGHAM
D23-1
O.W.S. MENTOR
E26-1
PAINESVILLE
F27-18
O.W.S. MADISON
G30-1
ASHTABULA
G33-3
CONNEAUT
H36-5
SCALE IN MILES
10
0
10
20
30

FIGURE 1

TABLE 1

SUMMARY OF WATER INTAKE PHYSICAL DATA

Location Number	Intake	Latitude	Longitude	Total** Depth (ft.)	Intake** Depth (ft.)	Intake Line Diameter (In.)	Intake Line Type	Distance from shore (ft.)	%WA	%WB
E3-1	Toledo	41°42'00"	83°15'32"	17	10±5	108	C	11,000	50	50
C7-4	Port Clinton	41°31'22"	82°56'21"	8	4	30	C	2,000	75	25
B11-1	Sandusky	41°27'51"	82°38'50"	21	16	42	S	2,900	100	0
A12-4	Huron	41°24'23"	82°33'24"	15	10	36	C	2,100	100	0
B14-4	Vermilion	41°25'42"	82°22'09"	11	7	18	S	1,200	100	0
B16-6	Elyria	41°27'26"	82°13'15"	20	11	42	I	1,200	100	0
B16-5	Lorain	41°28'21"	82°11'41"	24	11	48	I	1,100	95	5
C18-1	Avon Lake	41°30'46"	82°02'36"	21	18	36	C	2,000	100	0
C20-1	Cleveland-Crown	41°31'08"	81°52'46"	44	19*	96	C	13,000	100	0
C21-3	Cleveland-Division	41°32'50"	81°45'50"	50	34	120	C	20,000	100	0
C21-4	Cleveland-Baldwin	41°32'54"	81°45'02"	47	17±9	108	C	17,000	50	50
D23-1	Cleve.-Nottingham	41°37'05"	81°37'02"	49	38	120	C	18,000	100	0
E26-1	O.W.S. - Mentor	41°43'34"	81°22'05"	17	14	36	C	2,000	100	0
F27-18	Painesville	41°45'24"	81°17'53"	11	6	24	I	1,100	50	50
G30-1	O.W.S. - Madison	41°50'00"	81°04'38"	20	16	24	I	1,800	95	5
G33-3	Ashtabula	41°54'30"	80°48'38"	23	20	30	C	1,600	95	5
H36-5	Conneaut	41°57'54"	80°34'38"	19	13	24	I	2,000	100	0

Notes:

* Depth of Intake as of 9/17/68. Previous depth was 54 feet.
** All depths referred to mean low water level (568.6 feet).

Abbreviations:

C - Concrete
I - Iron
S - Steel
%WA - Percent of raw water from above center line of inlet port.
%WB - Percent of raw water from below center line of inlet port.

but because the overall quality of lake waters may change noticeably from one year to the next. For the purposes of this report however it will be assumed that no significant changes occurred between 1967 and 1968.

In addition to describing a one-year distribution of various factors an attempt has been made herein to describe the interrelationships of these factors. Although much has been written on the general biochemical relationships in a lake system, the applicability of these relationships to the general pollution control effort in Lake Erie has nearly always been questionable. The correlation of any two analytical measurements, such as algal population and phosphorus content, more often than not leads to erroneous or conflicting conclusions, thus weekening the defensibility or justification for pollution control expenditures. This report attempts to point out the fallibility of some two parameter correlations. Also it demonstrates with a few examples of multiple-parameter correlations that it is possible to predict an adequate biological response to a given set of physical and chemical factors.

It is difficult to clearly describe the details of parameter distributions in the lake and their changes with time. For this reason some rather novel graphic approaches have been devised to simplify explanations. Most of the illustrations attempt to show three related factors simultaneously. Scales have been arbitrarily chosen, with graphics showing distance, not necessarily to scale.

PHOSPHORUS DISTRIBUTION IN LAKE ERIE

The most important nutrient by reason of rapidly increasing accumulation in Lake Erie, is phosphorus. An abundance of phosphorus is generally considered as the cause for the remarkably high biological productivity in Lake Erie. The acceptance of this as fact does not lead to the unequivocal conclusion that cessation of phosphorus inputs will produce a predictable result. Not only are the mechanics of phosphorus utilization by biological systems still unclear, but the temporal and spatial distribution have been largely undetermined. Without a basic knowledge of phosphorus distribution in Lake Erie the mechanics of its quantitative utilization offer little hope of being fully understood, much less predictable.

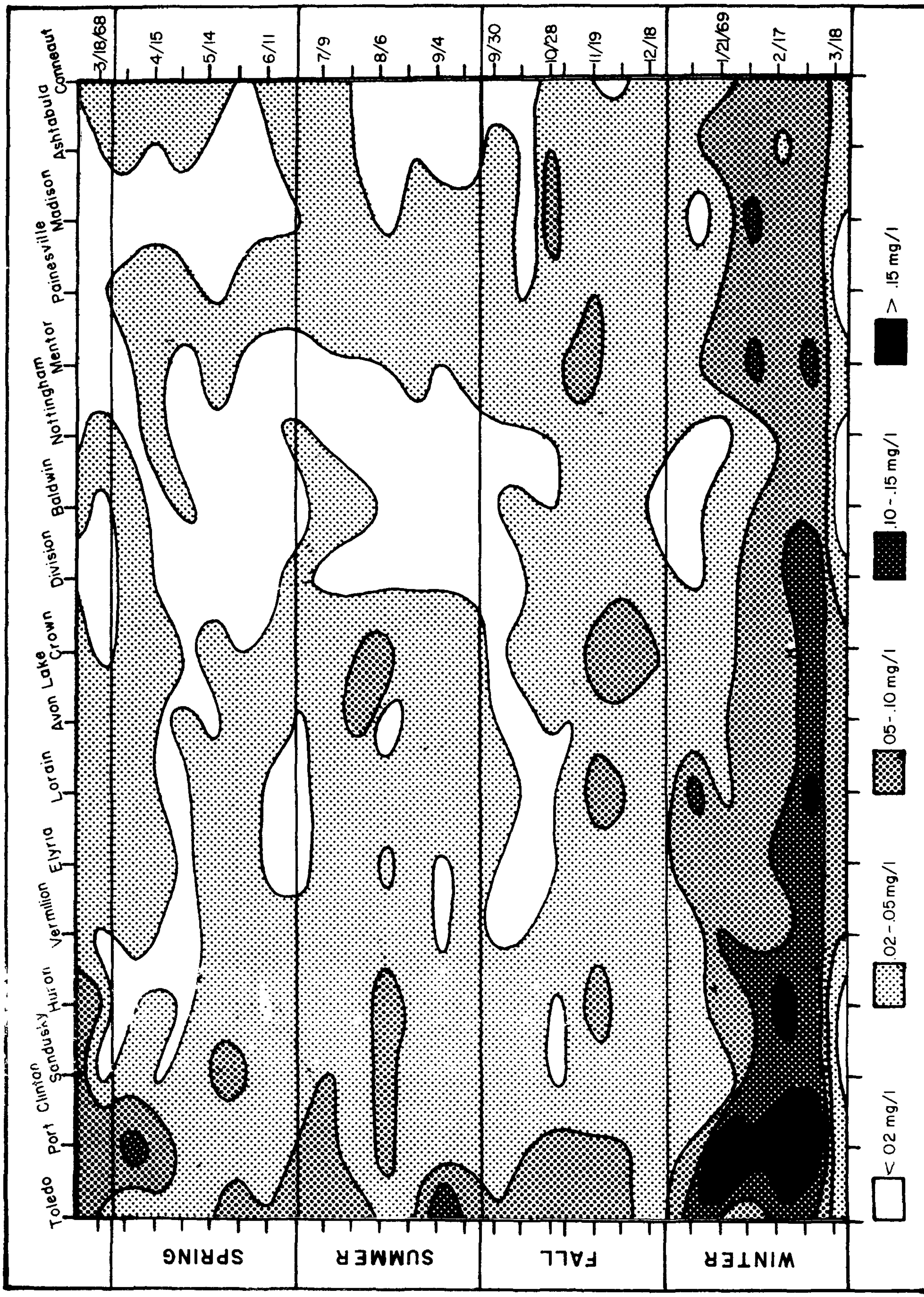
Phosphorus is described herein as soluble phosphorus and particulate phosphorus. Particulate phosphorus is simply the difference between the soluble phosphorus and total phosphorus forms. It is that portion of total phosphorus retained on fluted Whatman filter paper No. 12 while soluble phosphorus is that portion which passes. Particulate phosphorus is assumed to be either chemically or biologically bound to inorganic or organic particulate matter.

WESTERN BASIN

Soluble Phosphorus

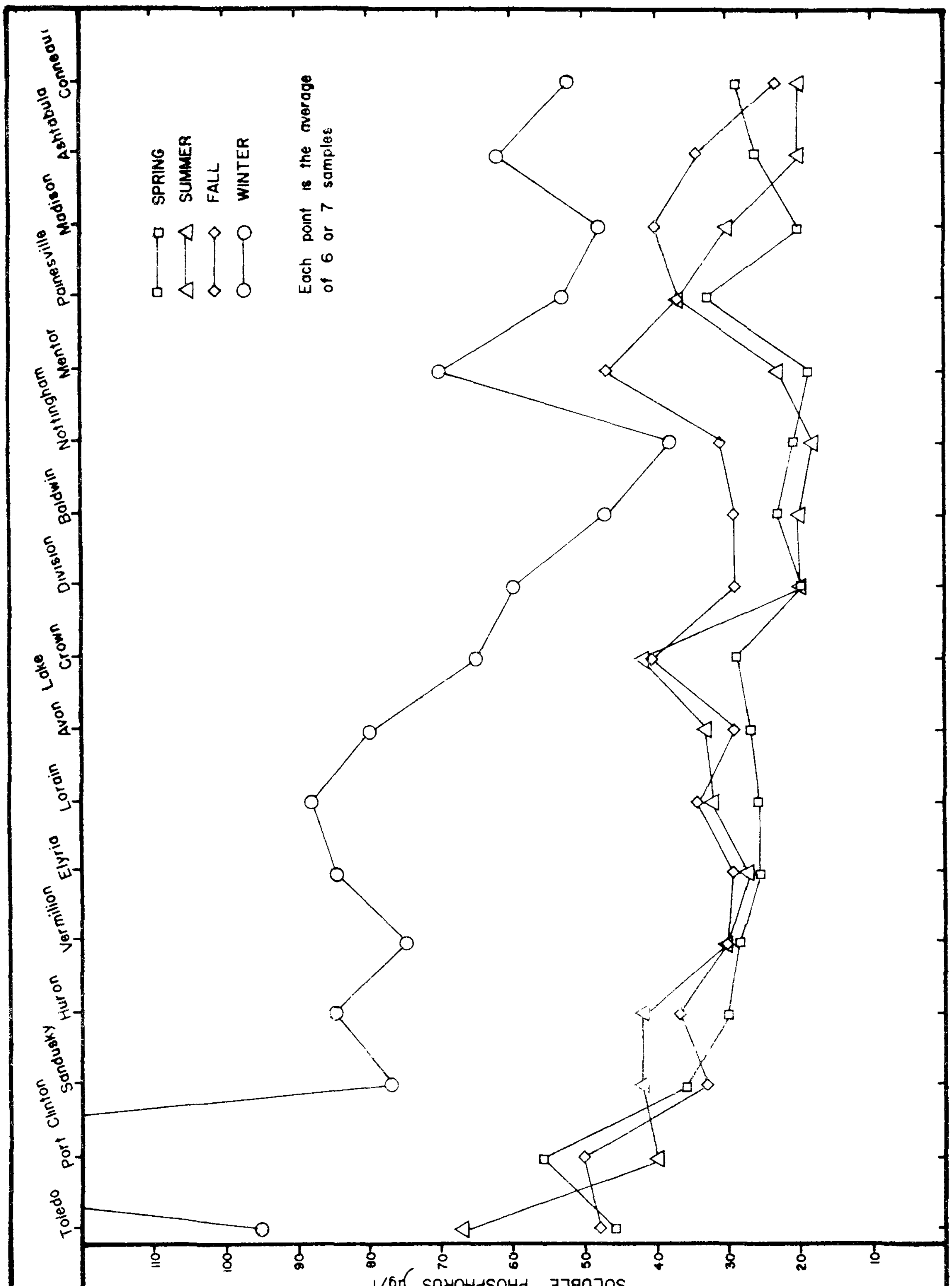
The time - space distribution of soluble phosphorus as P in near-shore waters for one year is shown in Fig. 2. The distance axis from Toledo to Conneaut is not to scale.

Examination of soluble phosphorus data from Toledo and Port Clinton water intakes has revealed a remarkable consistency at near 50 μg/l for much of the year (Fig. 3 and Table 2). *Winter however departs dramatically from the previous three seasons, apparently affected by higher tributary inputs, the introduction of interstitial soluble phosphorus*



Nearshore Soluble Phosphorus Distribution in Lake Erie 1968 - 1969

FIGURE 2



Nearshore Seasonal Distribution of Soluble Phosphorus

FIGURE 3

TABLE 2

AVERAGE SEASONAL CONCENTRATIONS OF SOLUBLE PHOSPHORUS (As P)
IN VARIOUS SECTORS OF THE WESTERN BASIN OF LAKE ERIE (μg/l)

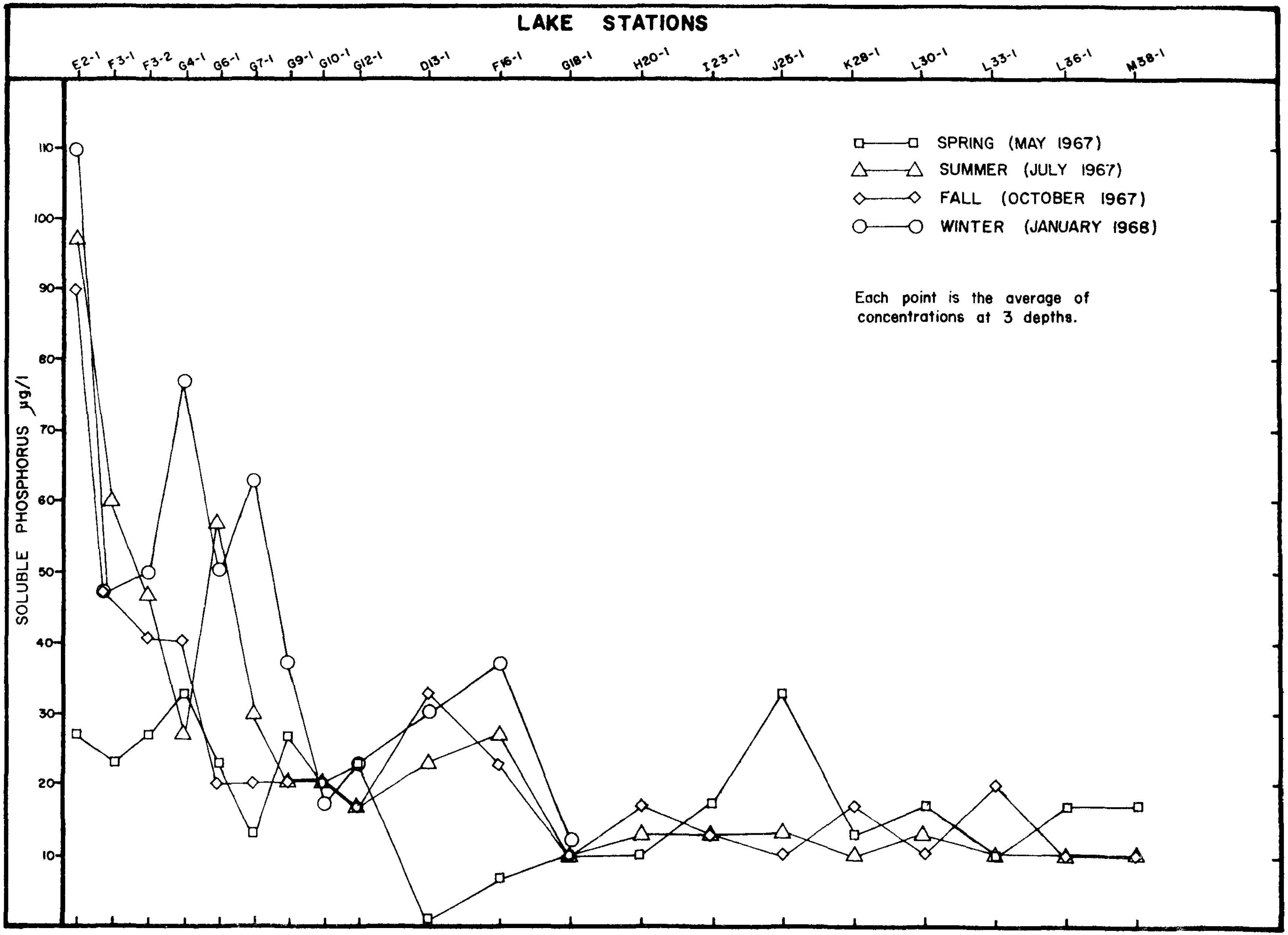
Season	Maumee Bay	Southern Nearshore	Mid-basin	Northeast sector (outlet)
Winter	110	150	55	20
Spring	25	50	25	20
Summer	95	50	40	20
Fall	90	50	30	20

during wind-induced sediment resuspension and low utilization by limited algal populations. Concentrations above 150 µg/l are probably common in January and February. The abrupt rise in concentration at the beginning of the winter season is followed by an equally abrupt decline at the end of the winter season.

Soluble phosphorus data gathered on each of four quarterly cruises during the year preceding that of the intake data are characterized by a rather wide variability between stations and between cruises except in the northeast quarter of the basin (Fig. 4 and Table 2). In this area a soluble phosphorus concentration of about 20 µg/l appears to prevail throughout the year. In contrast the Maumee Bay area seems to average near 100 µg/l in summer, fall and winter, but drops to 25 µg/l in spring In spring soluble phosphorus may be lower and fairly evenly distributed throughout the basin. Summer and fall are characterized by a predictable decline across the basin from southwest to northeast. In winter the cross-basin decline also occurs but shows more erratic and higher values in the central portion of the basin. This characteristic is also apparent to a less extent in summer.

The somewhat erratic behavior of midlake soluble phosphorus concentrations in the western basin is undoubtedly influenced by the mid-channel flow of the Detroit River. That flow, containing relatively low amounts of phosphorus, can be expected to meander over a period of time under the influence of wind and water density differences. Of course the mid-channel flow is bounded on either side by water of higher phosphorus content.

From the above description emerge some characteristics of seasonal patterns of phosphorus distribution in the western basin, along with some



Midlake Seasonal Distribution of Soluble Phosphorus

inferences as to the causes for the observed variability.

In winter, soluble phosphorus concentrations along shore rise rapidly. The rise is not impeded at this time of year by significant biological uptake of phosphorus because of low temperature. Low temperatures also slow the processes of chemical reaction. These conditions allow an accretion in phosphorus load, due mainly to increased tributary inputs and to the early winter introduction of interstitial soluble phosphorus during wind-induced sediment resuspension. The soluble phosphorus accretion is enhanced in late winter under the disruption reducing conditions of ice cover and the rather stable temperature-density barriers to mixing. The phosphorus accretion diminishes toward the center of the basin and does not reach to the northeast part of the basin. The central and northeastern portions of the basin are occupied largely by low phosphorus water from the high-volume main flow of the Detroit River. This mass of water also helps to confine the high phosphorus water to the western and southern parts of the basin.

In early spring, concurrent with the breakup and disappearance of ice cover, the high soluble phosphorus content is rapidly reduced and approaches uniformity throughout the basin. The reduction is accompanied by a tremendous increase in diatom population. In general the areas which had the greatest soluble phosphorus accretion develop the highest diatom populations. The populations decrease northeastward across the basin, so that where soluble phosphorus had not increased significantly neither had diatoms increased greatly.

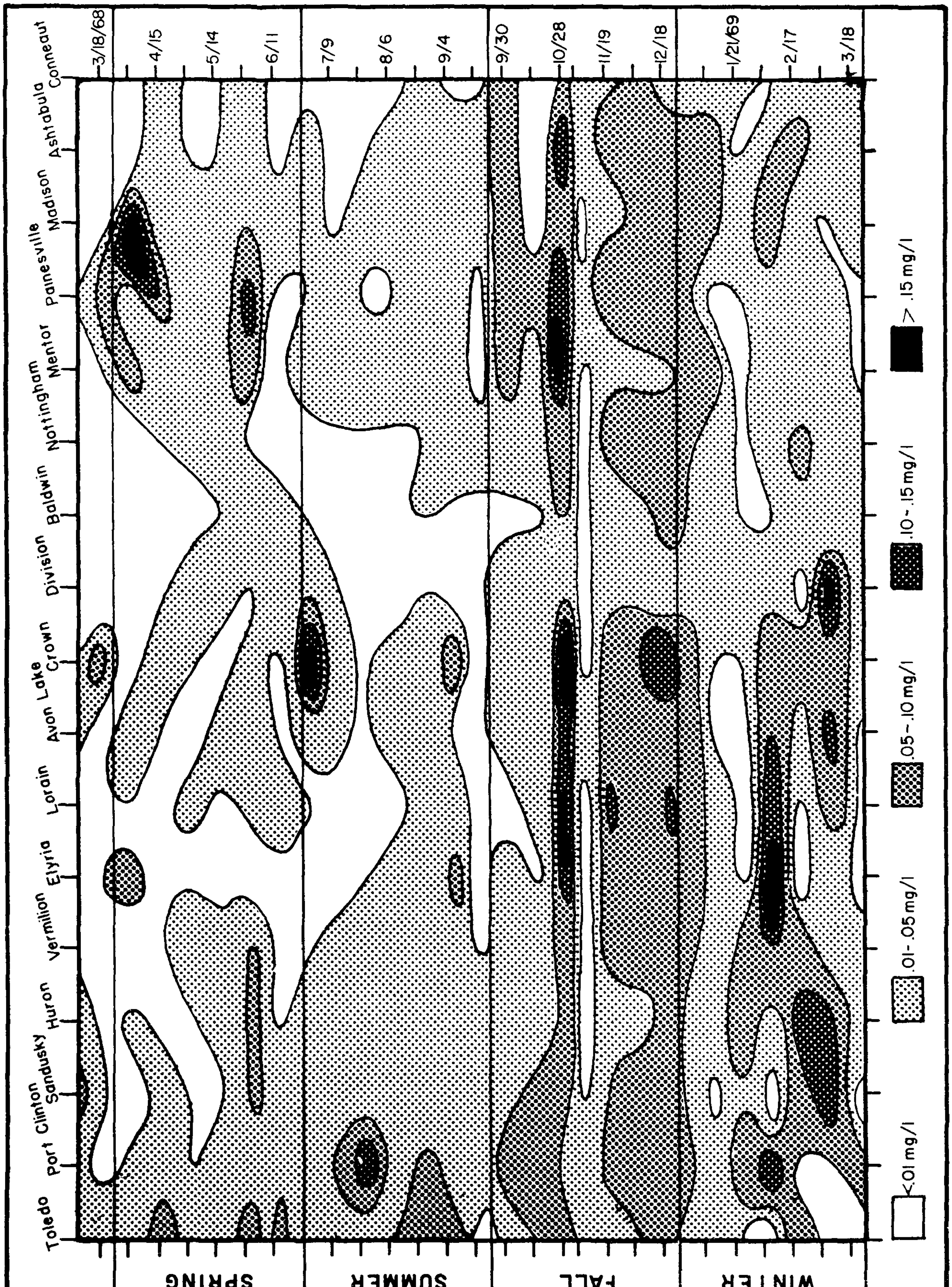
The preceding description suggests at least a general relationship between diatom populations and soluble phosphorus in western basin water.

However a detailed examination reveals that the expected immediate inverse correlation is in fact delayed. *The rapid spring reduction of soluble phosphorus occurs, not simultaneously with a great rise in plankton, but prior to it.* The highest plankton populations occur just after the soluble phosphorus content has been reduced to the average level of spring and summer. This suggests that one or both of two things have occurred: (1) luxury consumption of phosphorus by diatoms in their early bloom stages or (2) the sedimentation of soluble phosphorus at the time of ice breakup. Examination of particulate phosphorus should reveal which of these is more likely.

Particulate Phosphorus

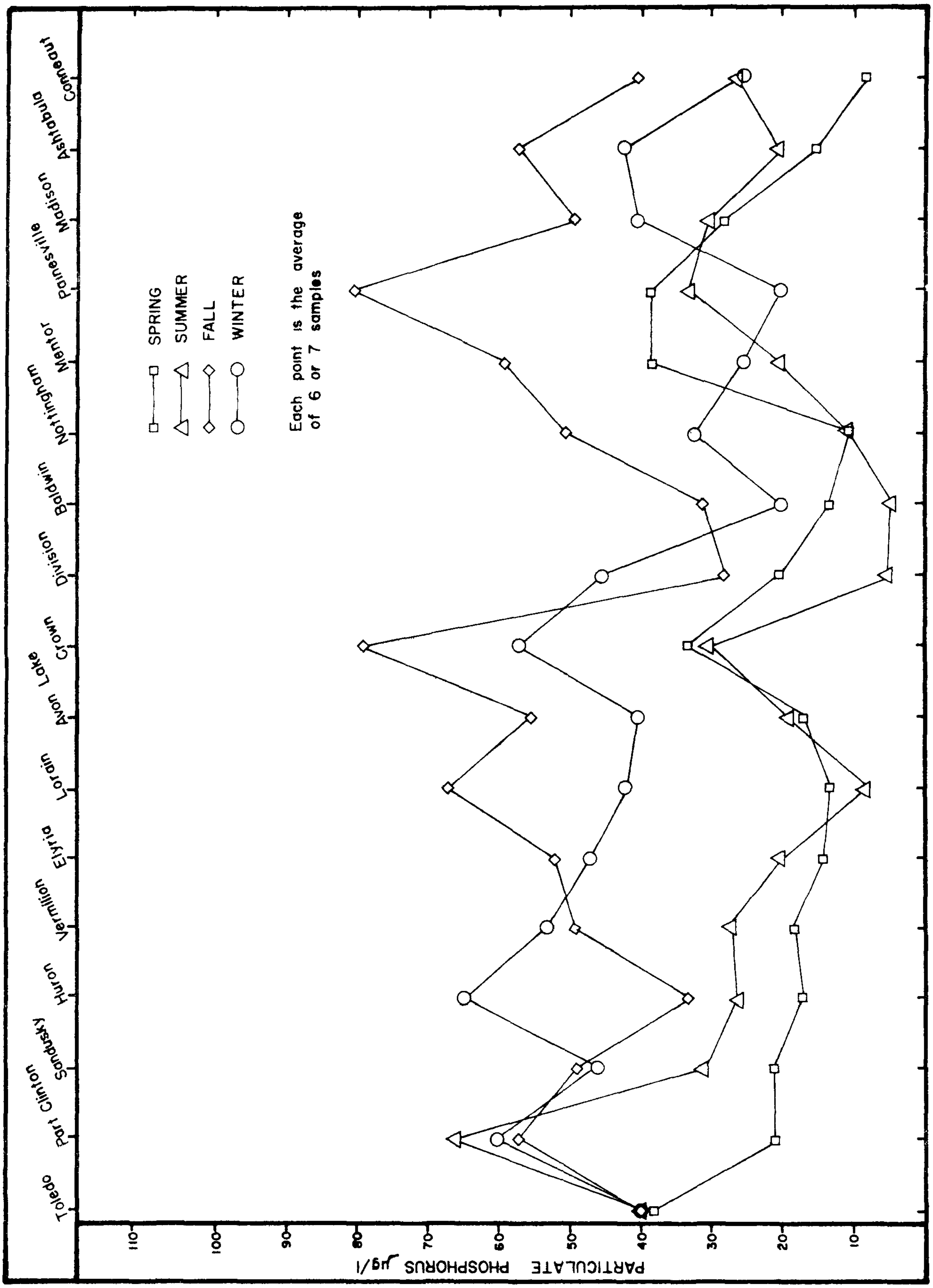
The particulate phosphorus as P time-space distribution in nearshore waters of the western and central basins of Lake Erie is shown in Fig. 5. *Western Basin particulate phosphorus is more erratic and variable over the short-term than soluble phosphorus although the annual particulate phosphorus range and average concentration are less.*

In spring nearshore particulate phosphorus (Fig. 6 and Table 3) averages about 30 µg/l, and is considerably less than soluble phosphorus. The concentration drops steadily across the lake to about 10 µg/l in the northeast quarter of the basin (Fig. 7). Particulate phosphorus rises in summer in the nearshore area to greater than 50 µg/l. Toward midlake it falls off rapidly to values of 10 to 15 µg/l and these values are characteristic of most of the basin. The fall distribution of particulate phosphorus is similar to that of summer with only a slight decline in nearshore waters. In winter however midlake values rise to more than 30 µg/l while nearshore concentrations remain essentially unchanged at an average of 50 µg/l. As with soluble phosphorus, particulate phosphorus



Nearshore Particulate Phosphorus Distribution in Lake Erie 1968 - 1969

FIGURE 5



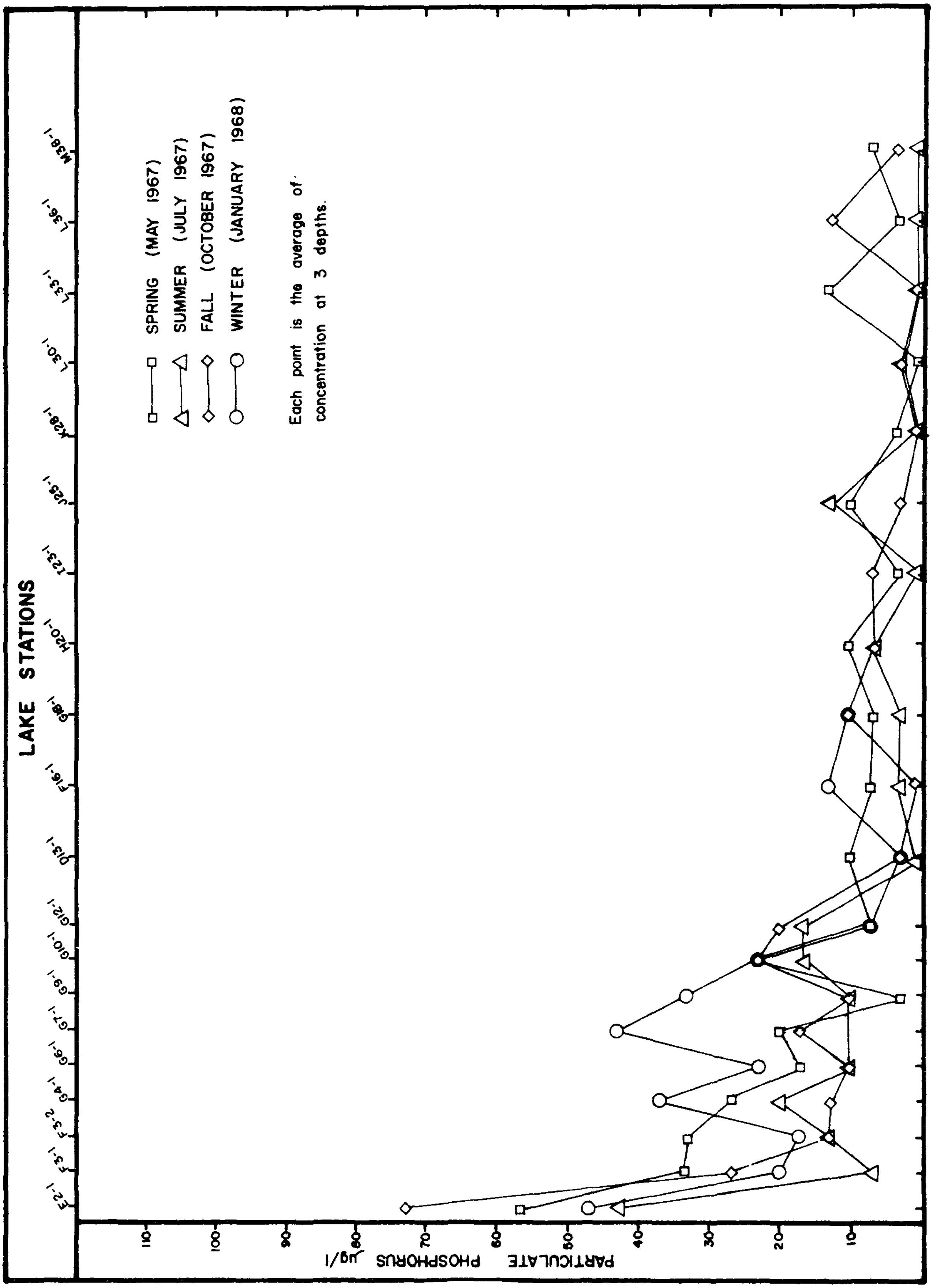
Nearshore Seasonal Distribution of Particulate Phosphorus

FIGURE 6

TABLE 3

AVERAGE SEASONAL CONCENTRATIONS OF PARTICULATE PHOSPHORUS (As P) IN VARIOUS SECTORS OF THE WESTERN BASIN OF LAKE ERIE (μg/l)

Season	Maumee Bay	Southern Nearshore	Mid-basin	Northeast sector (outlet)
Winter	45	50	30	20
Spring	55	30	25	10
Summer	40	55	15	20
Fall	70	50	15	20



Midlake Seasonal Distribution of Particulate Phosphorus

FIGURE 7

in the northeast quarter of the basin does not change substantially throughout the year.

Integrating the distribution of soluble and particulate phosphorus leads to several possible conclusions. *During the winter soluble phosphorus increases dramatically while particulate phosphorus does not.* This indicates that particulate phosphorus from tributary inputs and sediment resuspension settles quickly while soluble phosphorus from the same two sources remains in solution and rapidly accretes. Lack of plankton uptake and limited chemical activity involving phosphorus most likely allows the accretion.

At the end of winter more than half of the dissolved phosphorus and at least one-third of the particulate phosphorus disappear from the waters of the western basin. Flushing from the basin can be discounted because of the seasonal uniformity of the basin phosphorus discharge and because inputs of phosphorus via runoff have probably increased. It is indicated that in great part phosphorus is precipitated to the western basin bottom sediments through a biological intermediary. However since the loss appears to occur slightly before the height of the spring diatom pulse, the possibility exists, that simultaneous with the luxurious consumption of nutrients by algae, phosphorus removal from water to the sediments may be additionally accomplished by physical adsorption on clay and silt particles in suspension. The lake turbidity at this time of year is especially high due to a combination of much runoff and wave stirring of bottom sediments. Apparently physical adsorption and biological utilization account for an efficient, natural, phosphorus removal process. In fact the removal mechanism is so efficient that in spring the total phosphorus content of western basin waters reaches its lowest level.

Again it should be emphasized that phosphorus is not lost from the basin in unusual quantities as indicated by its stability of concentration at the main outflow in the northeast corner of the basin. Rather it is stored in the sediments through the mechanisms described above.

A moderate accretion in waterborne total phosphorus, both soluble and particulate, occurs in summer, while a slight reduction occurs in the fall. The summer increase is correlative with a reduction in plankton populations, while the fall decrease most likely is the result of an increase in plankton. It would appear that a fair balance is maintained in summer and fall, and also late spring, between inputs to the basin and precipitation to the lake bottom.

Although not completely documented in the intake data, but based on many individual observations, in late summer blue-green algae populations increase dramatically throughout the basin and even in places such as the northern island area, far removed from tributary inputs. This suggests recycling of nutrients, including phosphorus, from the bottom sediments. The suggestion is supported by a temporary increase in midlake phosphorus without a concomitant increase near shore. However, the increase is short-lived and phosphorus returns to moderate levels, remaining there throughout the fall and until the beginning of the winter phosphorus accretion in December.

CENTRAL BASIN

The central basin phosphorus distribution, both soluble and particulate, is more easily described because concentrations are generally less, short-term and long-term variations are more subdued, and areal differences are diminished. The tendency toward uniformity can be ascribed to the damping effects of a larger less easily disturbed basin and the smaller input to the basin. The general annual distribution of soluble phosphorus in the central basin is shown in Fig. 2.

Soluble Phosphorus

Central basin nearshore average soluble phosphorus is remarkably stable for seven months of the year, including the spring and summer seasons and part of the fall (Fig. 3 and Table 4). The average concentration during this period is about 30 μg/l - only 60 percent of the nearshore concentration in the western basin. During this period nearshore soluble phosphorus is similar from one end of the basin to the other.

In midlake central basin, from spring through fall, soluble phosphorus averages 10 to 15 μg/l or less than one-half that of nearshore (Fig. 3 and Table 4). There is little change areally except in spring when concentrations are lowest in the western part of the basin.

In October, central basin nearshore soluble phosphorus begins to rise and by January 1 is averaging 40 μg/l. A relatively rapid rise then occurs, reaching more than 100 μg/l at the beginning of March. This peak is followed by a rapid decline to 30 μg/l again at the advent of spring. *The winter increase in soluble phosphorus is less than half the concurrent increase in western basin nearshore waters.* The high winter period in the central basin nearshore is also characterized by a general west to east decrease which is not apparent throughout the remainder of the year.

Winter phosphorus data from midlake central basin is scarce but it

TABLE 4

AVERAGE SEASONAL CONCENTRATIONS OF SOLUBLE PHOSPHORUS (As P)
IN VARIOUS SECTORS OF THE CENTRAL BASIN OF LAKE ERIE (μg/l)

Season	Southwest Nearshore	Southeast Nearshore	Western Midlake	Eastern Midlake
Winter	80	55	25	-
Spring	30	25	10	15
Summer	35	25	15	10
Fall	30	30	20	15

appears that an increase in soluble phosphorus occurs, although relatively insignificant (Fig. 4 and Table 4). *The average concentration in midlake may never exceed 25 μg/l, that value being approached only in winter.*

Particulate Phosphorus

In central basin nearshore, as in the western basin, particulate phosphorus is much more erratic in its time and space distribution (Figs. 5 and 6). *The average concentration, except in midsummer, is comparable in both western and central basin nearshore areas.*

In the central basin nearshore, particulate phosphorus averages about 20 μg/l in spring and summer, considerably less than in the fall and winter when an average of about 40 μg/l prevails (Fig. 6 and Table 5). Fall and winter levels however are much more variable. They range from 30 to 80 μg/l in fall and from 20 to 65 μg/l in winter. In winter there is a west to east decrease in particulate phosphorus, not apparent during the other seasons.

In central basin midlake particulate phosphorus apparently averages less than 10 μg/l the year-round with perhaps slightly higher values in spring than during the other seasons (Fig. 7 and Table 5). Compared to nearshore, the *midlake has a remarkably narrow range in particulate phosphorus content.* Central basin midlake also differs radically in this respect from the widely variable western basin midlake.

The areal and time distribution of soluble and particulate phosphorus in the central basin roughly parallels the distribution in the western basin but with considerably lower values. This indicates that the same factors of biological uptake, wind-induced sediment resuspension, and inputs are operating in a manner similar to that in the western basin, but on a reduced scale. One important difference is the lack of variation in

TABLE 5

AVERAGE SEASONAL CONCENTRATIONS OF PARTICULATE PHOSPHORUS (As P) IN VARIOUS SECTORS OF THE CENTRAL BASIN OF LAKE ERIE (μg/l)

Season	Southwest Nearshore	Southeast Nearshore	Western Midlake	Eastern Midlake
Winter	50	35	10	-
Spring	15	20	10	5
Summer	20	20	5	<5
Fall	50	50	5	5

phosphorus in summer, in the central basin, indicating perhaps a general damping effect on all phosphorus input factors.

The winter soluble phosphorus accretion in both the central basin nearshore and midlake is depleted very rapidly near the beginning of spring. As in the western basin *more than half is lost to the bottom sediments.* The western part of the central basin seems to "over-react" in spring (Fig. 4) when compared to the other portions of the basin, and concentrations reach their annual low. As in the western basin the loss of soluble phosphorus in the western portion of the central basin, accompanied also by a loss of more than half the particulate phosphorus, indicates rapid biological utilization or adsorption on eroded or resuspended clays, or both, followed by rapid precipitation to the sediments.

NITROGEN DISTRIBUTION IN LAKE ERIE

Nitrogen in Lake Erie has been measured in three forms, organic nitrogen, ammonia, and nitrate. Nitrite is normally present in insignificant quantities, and therefore has not been measured as such, but is included as part of the total nitrate analysis.

Organic nitrogen is that portion of the total nitrogen combined in organic compounds. Organic nitrogen should be more or less proportional to the total biological mass. Data from Lake Erie indicate that time and spatial variations are not as great as one might expect.

Although organic nitrogen should reflect biological productivity in Lake Erie, it is the inorganic nitrogen forms which are essential to promote that productivity. The inorganic forms, particularly nitrate nitrogen, follow a more predictable pattern of concentration throughout the year and are more easily relatable to plankton abundance than is organic nitrogen. However the classical materials balance, relating one form to the other, is not readily apparent.

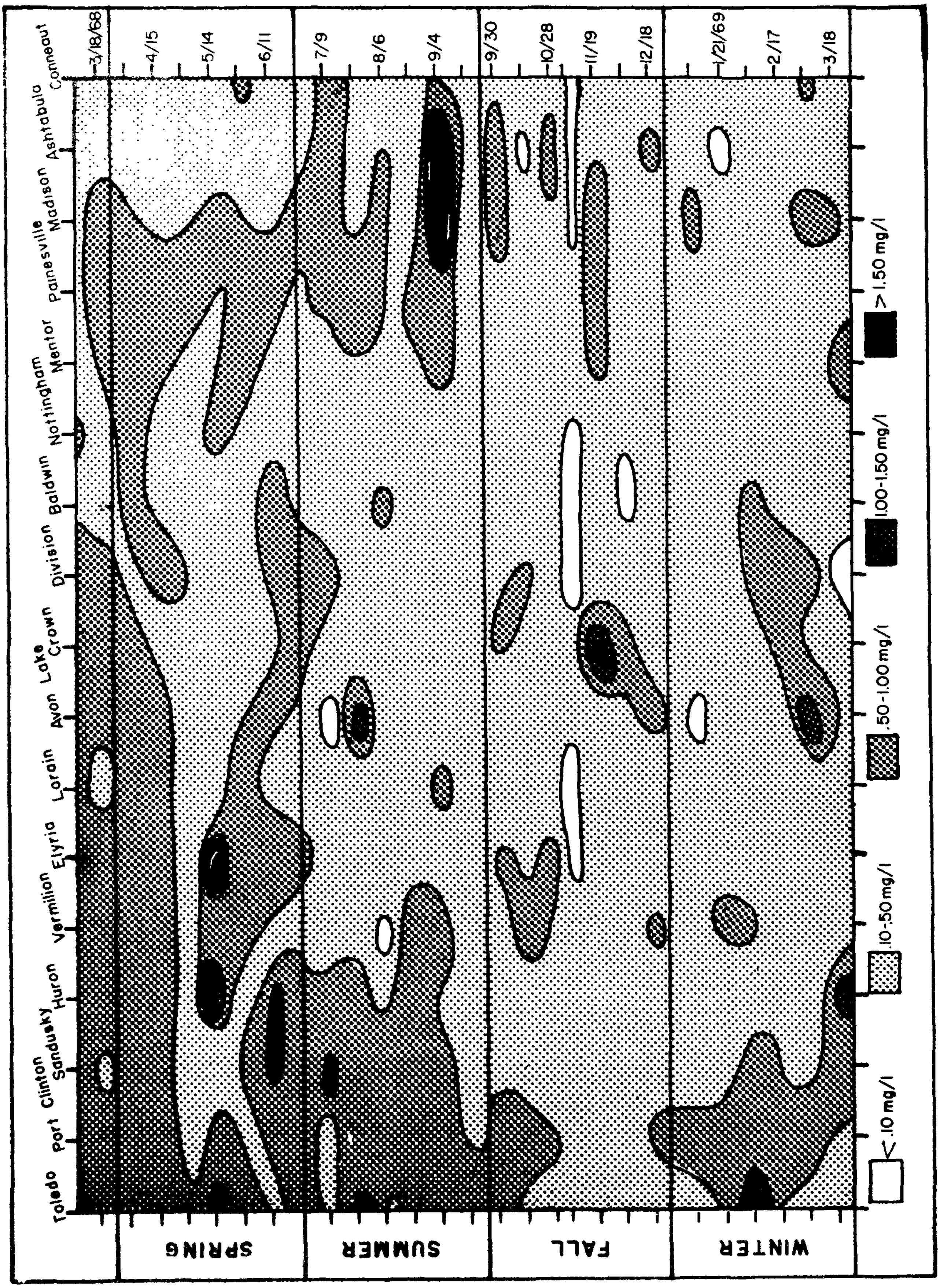
Nitrogen is vital to algal productivity, its deficiency in a marine environment often being a limiting factor to algal biomass. Although both ammonia and nitrate are utilized as nutrients the content of nitrate normally shows greater depletion characteristics. It is not clear however that nitrate is the preferred nutrient since during high algal use periods, ammonia is continually being replenished from the sediments while nitrate is not. In addition, the conversion of ammonia to nitrate most likely is hampered by the lower oxidation-reduction potentials prevalent during the summer high nutrient use periods.

WESTERN AND CENTRAL BASINS

Organic Nitrogen

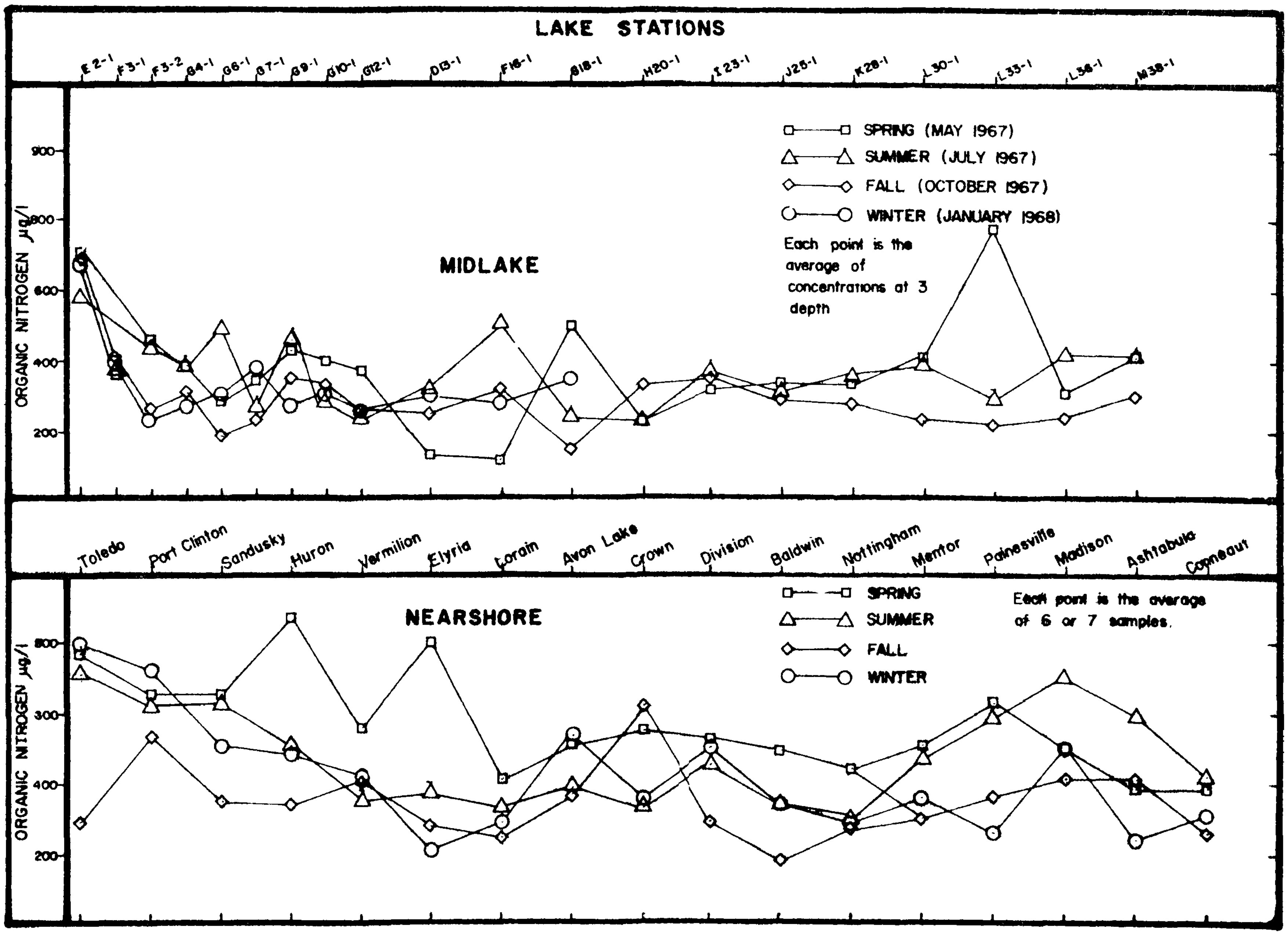
The time-space distribution of organic nitrogen for one year in the nearshore waters of the western and central basins of Lake Erie is shown in Fig. 8.

In the western basin nearshore area, organic nitrogen in winter, spring and summer averages approximately 700 µg/l but drops to about 400 µg/l in the fall (Fig. 9 and Table 6). In western basin midlake organic nitrogen in spring and summer averages about one-half those of the nearshore area or about 350 µg/l. Fall and winter concentrations in western basin midlake average about 300 µg/l. In the fall organic nitrogen approaches uniformity throughout the basin at relatively low concentrations. Occasional rather precipitous rises in organic nitrogen in the nearshore throughout the year are probably due mainly to stirring and resuspension of bottom sediments during periods of higher wind velocity and precipitation.



Nearshore Organic Nitrogen Distribution 1968 - 1969

FIGURE 8



Midlake and Nearshore Seasonal Distribution of Organic Nitrogen

FIGURE 9

TABLE 6

AVERAGE SEASONAL CONCENTRATIONS OF ORGANIC NITROGEN
IN VARIOUS SECTORS OF THE WESTERN BASIN OF LAKE ERIE (μg/l)

Season	Maumee Bay	Southern Nearshore	Mid-basin	Northeast sector (outlet)
Winter	500	750	300	250
Spring	550	700	350	400
Summer	500	650	400	250
Fall	500	400	250	250

Limited available data indicate that the concentration of organic nitrogen in the northeast part of the basin, in the Pelee Passage outlet, is relatively low and uniform at near 250 to 400 μg/l (Fig. 9 and Table 6). This suggests since inorganic nitrogen is also lower in these areas, that nitrogen is accumulating significantly in western basin sediments.

When examined as averages of all stations during each sampling period, central basin nearshore organic nitrogen has a rather stable annual pattern, averaging 500 μg/l in spring, and decreasing steadily throughout the summer to less than 200 μg/l in November (Fig. 9 and Table 6). It then begins to rise and continues to rise gradually until the beginning of spring.

The pattern of organic nitrogen in nearshore waters is more complex when examined as variations between sampling sites during a season and from one season to the next. For example in spring nearshore organic nitrogen west of Lorain averages about 700 μg/l or approximately the same as western basin nearshore. At Lorain and eastward however, organic nitrogen averages less than 500 μg/l and at Conneaut about 400 μg/l. In summer nearshore organic nitrogen drops even more quickly from 600 μg/l at Sandusky, again near the level in western basin nearshore, to about 350 μg/l at Vermilion. This concentration prevails relatively well throughout the Cleveland area in summer but rises dramatically east of Cleveland to 700 μg/l at Madison. It then decreases again eastward.

In fall organic nitrogen is more consistent throughout central basin nearshore at between 300 and 400 μg/l. The extremes are in the Cleveland area with a high averaging 600 μg/l at the westernmost Crown intake and a low of 200 μg/l at the Baldwin intake.

In central basin midlake organic nitrogen appears to average about 300 µg/l throughout the year (Fig. 9 and Table 7). This is not greatly less than nearshore except in spring. At this time the lowest concentrations are found in the western half of the basin at less than 200 µg/l. However they rise to the east to more than 400 µg/l and may reach 700 µg/l near the east end of the basin. The west to east pattern in spring in midlake is the reverse of that in nearshore. Organic nitrogen in midlake, as in the nearshore, is on an average lowest in fall and the most consistent areally, averaging 250 to 300 µg/l (Table 7).

Ammonia Nitrogen

The distribution of ammonia nitrogen, with distance and time, in nearshore waters of the western and central basins for one year is shown in Fig. 10.

Spring ammonia nitrogen in western basin nearshore averages about 200 µg/l and does not show great variability during the season (Fig. 11). In early summer it begins to decline and continues to do so, except for a brief rise in October, until the middle of November when it reaches its lowest level of less than 100 µg/l. However ammonia nitrogen then rises dramatically to more than 400 µg/l in early December, remaining at this level through January, then declining to spring levels.

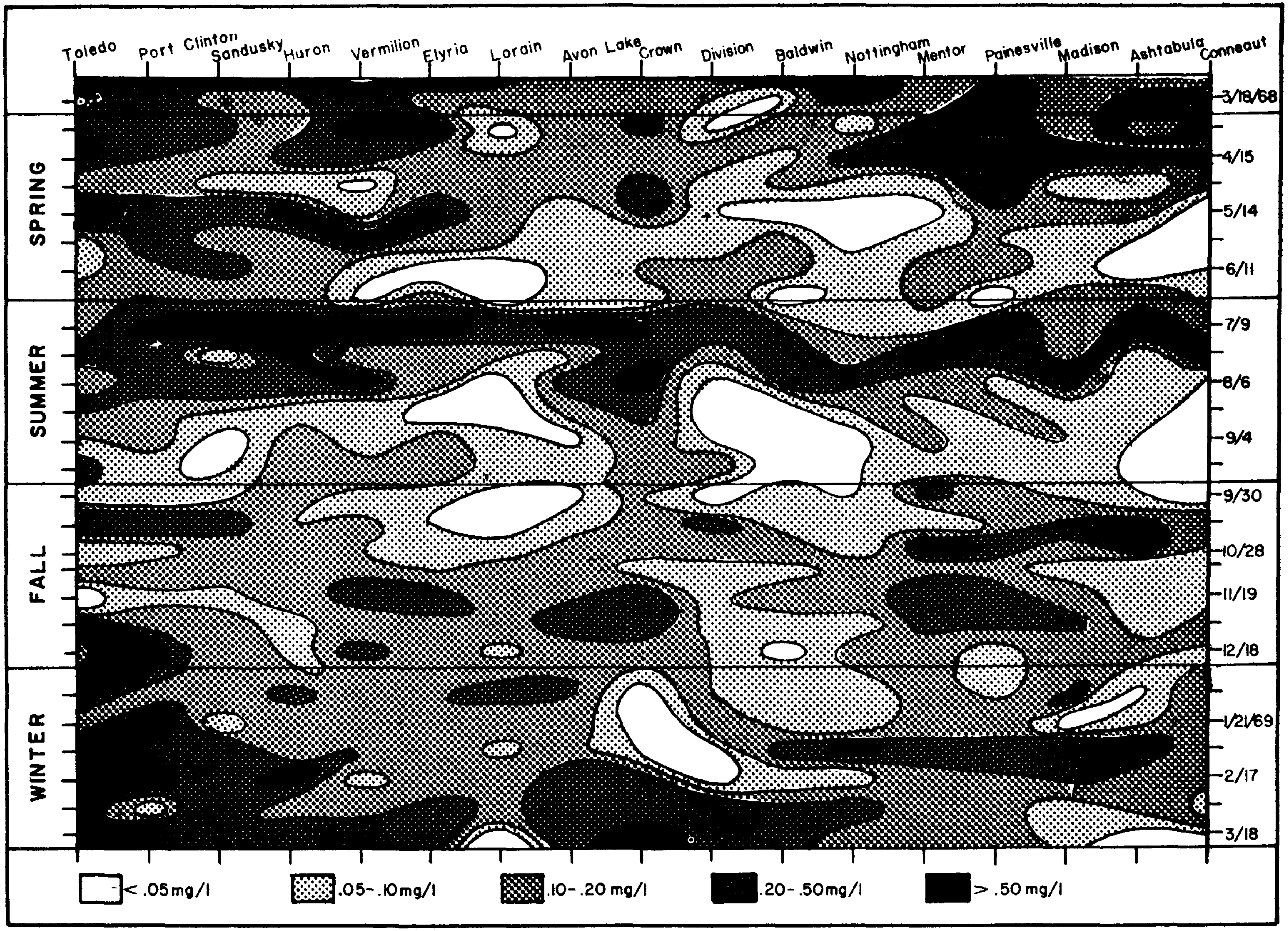
In western basin midlake ammonia nitrogen is highest in summer, averaging more than 200 µg/l (Fig. 11). It drops to about 100 µg/l in fall, and rises to about 150 µg/l in winter. It then drops again to about 100 µg/l in spring.

Central basin nearshore ammonia nitrogen is fairly consistent throughout the year, varying around the average of about 150 µg/l. It reaches a

TABLE 7

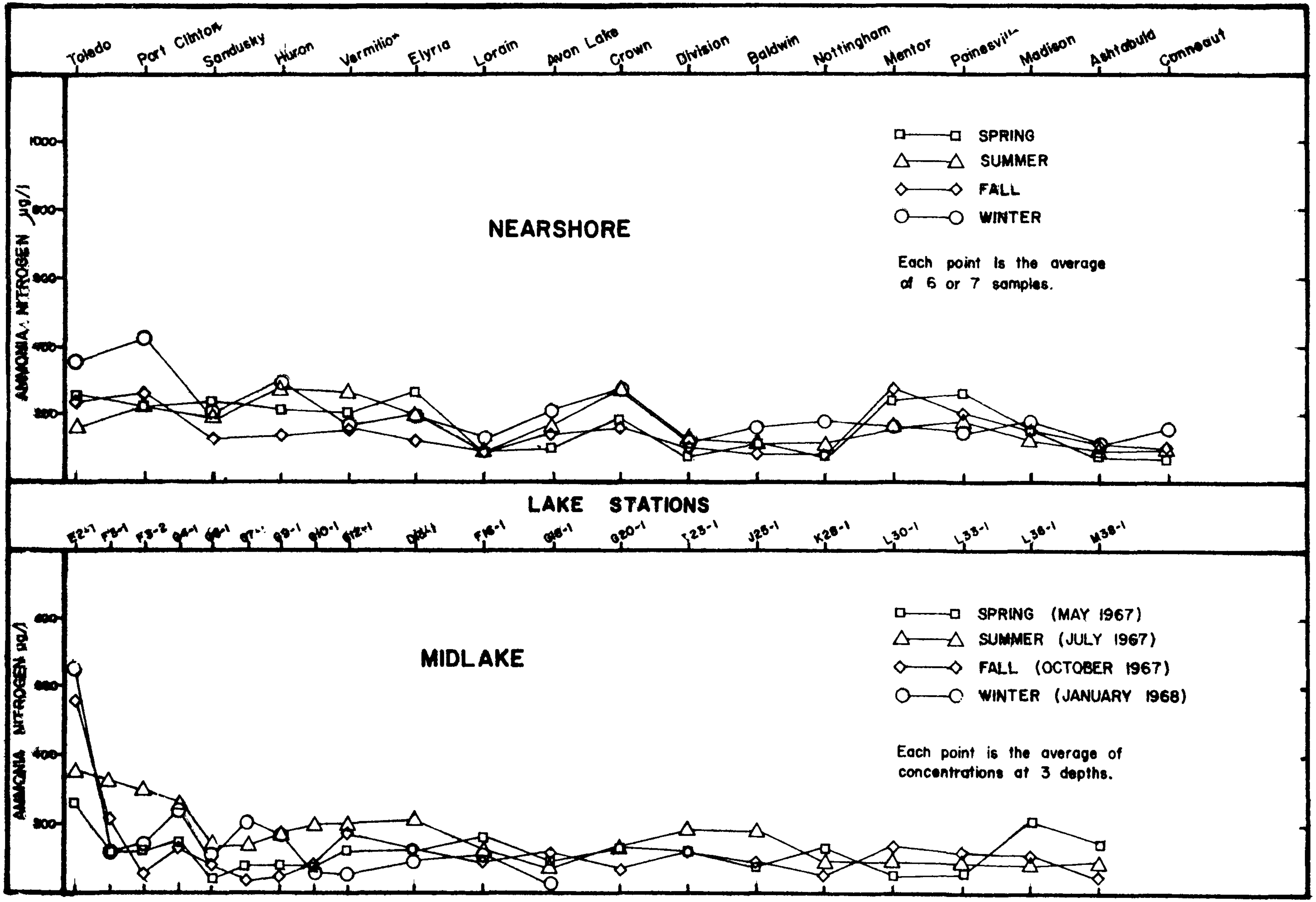
AVERAGE SEASONAL CONCENTRATIONS OF ORGANIC NITROGEN IN VARIOUS SECTORS OF THE CENTRAL BASIN OF LAKE ERIE (µg/l)

Season	Southwest Nearshore	Southeast Nearshore	Western Midlake	Eastern Midlake
Winter	400	300	300	-
Spring	600	450	250	300
Summer	450	500	300	350
Fall	350	350	250	250



Nearshore Ammonia Nitrogen Distribution in Lake Erie 1968 - 1969

FIGURE 10



Nearshore and Midlake Seasonal Distribution of Ammonia Nitrogen

FIGURE 11

temporary high in early July of more than 300 μg/l but then decreases to its annual low of less than 100 μg/l at the end of the summer.

In central basin midlake ammonia nitrogen is again remarkably consistent throughout the year averaging between 100 and 150 μg/l (Fig. 11), not much less than in nearshore. Its lowest level of less than 100 μg/l apparently occurs in winter.

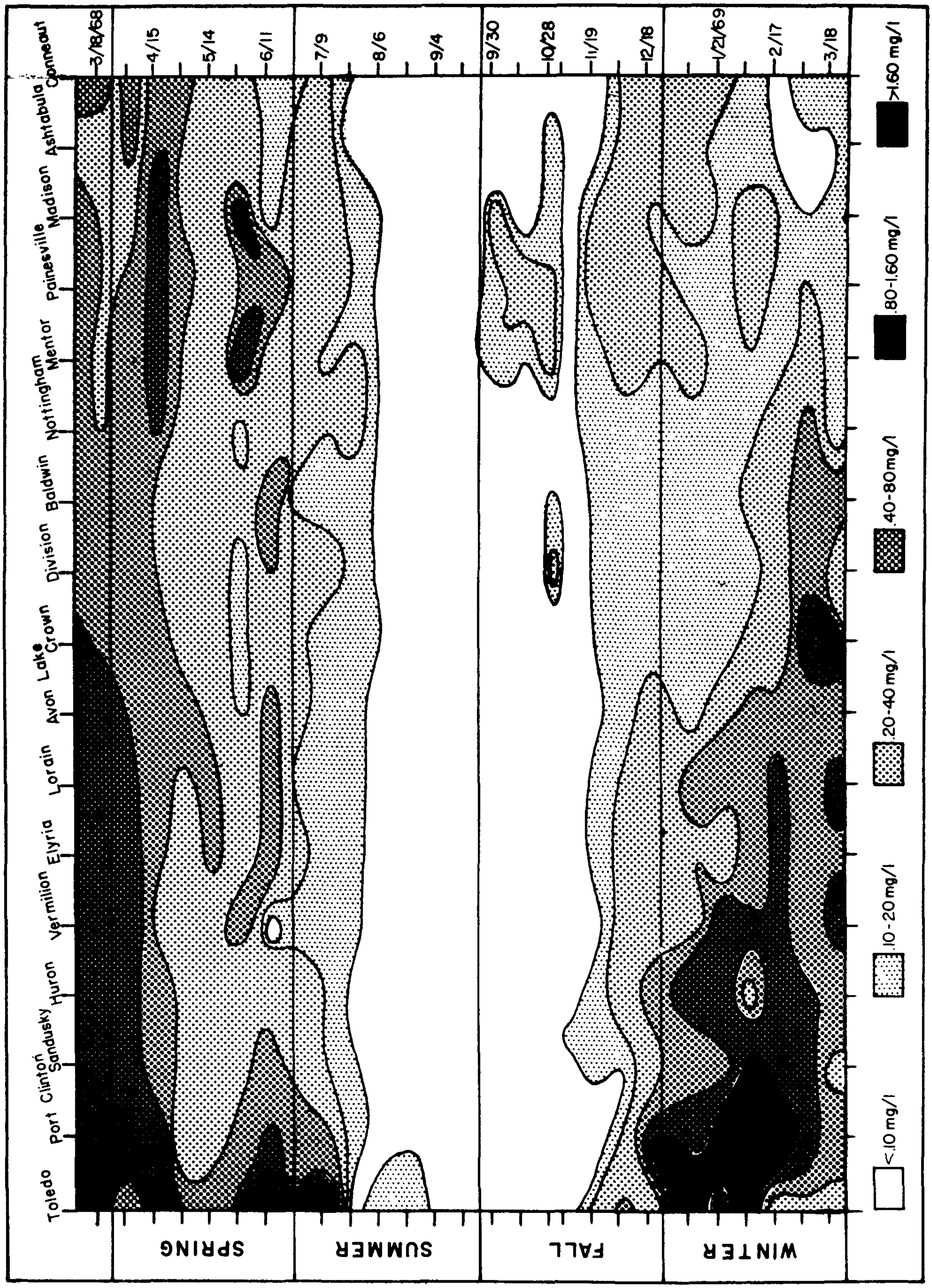
Summarizing, it appears that ammonia nitrogen does not show a very wide variation either areally or temporally throughout the year.

Nitrate Nitrogen

The time-space distribution of nitrate nitrogen in nearshore waters of Lake Erie for one year is shown in Fig. 12.

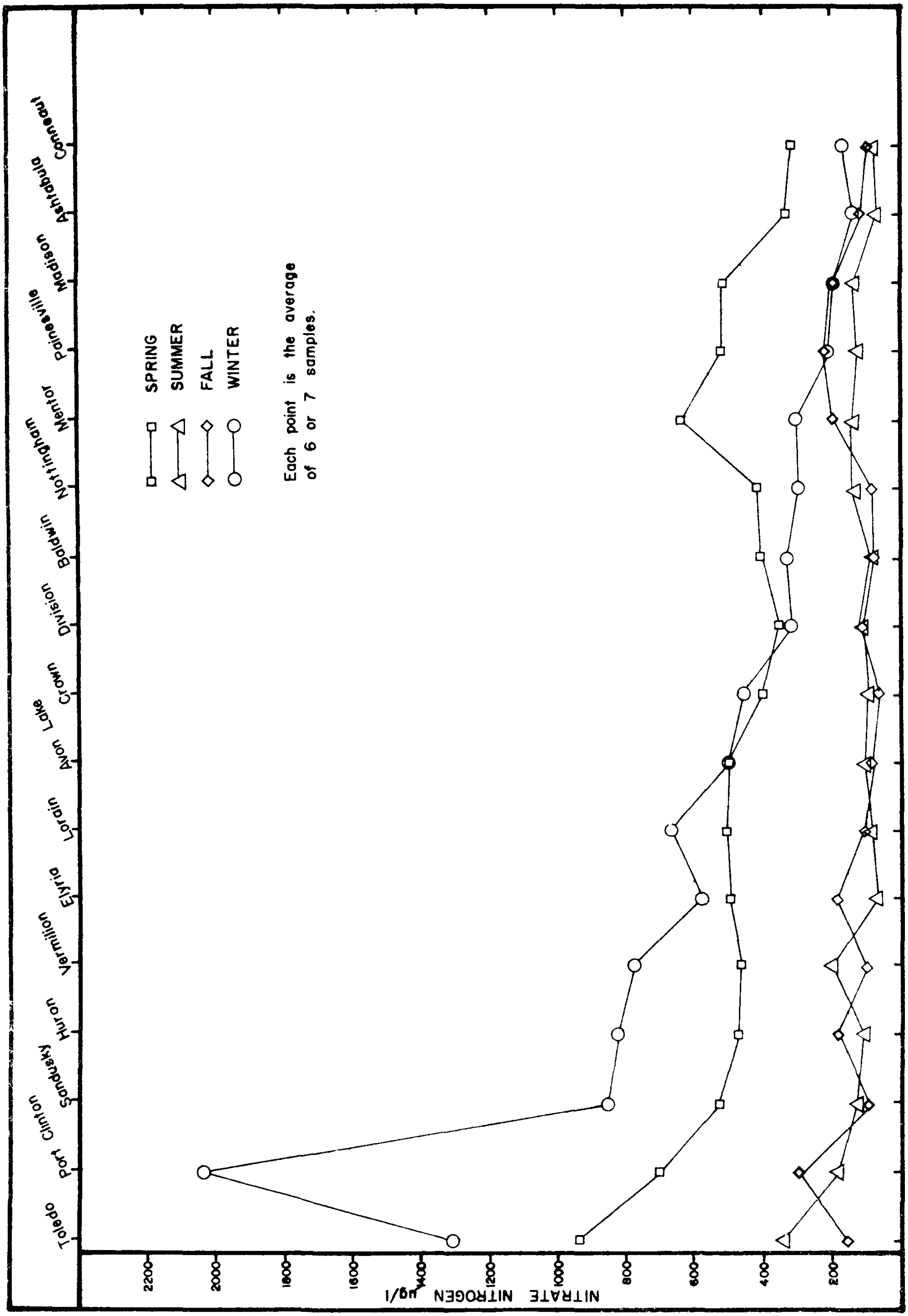
The annual pattern for western basin nearshore nitrate nitrogen parallels neither that for ammonia nor organic nitrogen (Fig. 13 and Table 8). It averages about 1200 μg/l in early spring but drops dramatically at the end of April to about 400 μg/l. Nitrate nitrogen rises again to about 800 μg/l in early July, then drops sharply to less than 100 μg/l. It virtually disappears in early fall and begins to rise again in November. The rise in late fall and early winter is remarkable, exceeding 2500 μg/l by the middle of January. In early February ritrate nitrogen begins a similar remarkable decline to spring levels.

In western basin midlake, spring nitrate nitrogen averages about 300 μg/l but shows a marked west to east decline, from more than 500 to about 200 μg/l (Fig. 14 and Table 8). The lowest midlake level of about 50 μg/l occurs in summer and then rises to about 150 μg/l in fall. As in nearshore a remarkable nitrate nitrogen rise occurs in winter to an average of about 600 μg/l, but again with a marked west to east decline, the



Nearshore Nitrate Nitrogen Distribution in Lake Erie 1968 - 1969

FIGURE 12



Nearshore Seasonal Distribution of Nitrate Nitrogen

FIGURE 13

TABLE 8

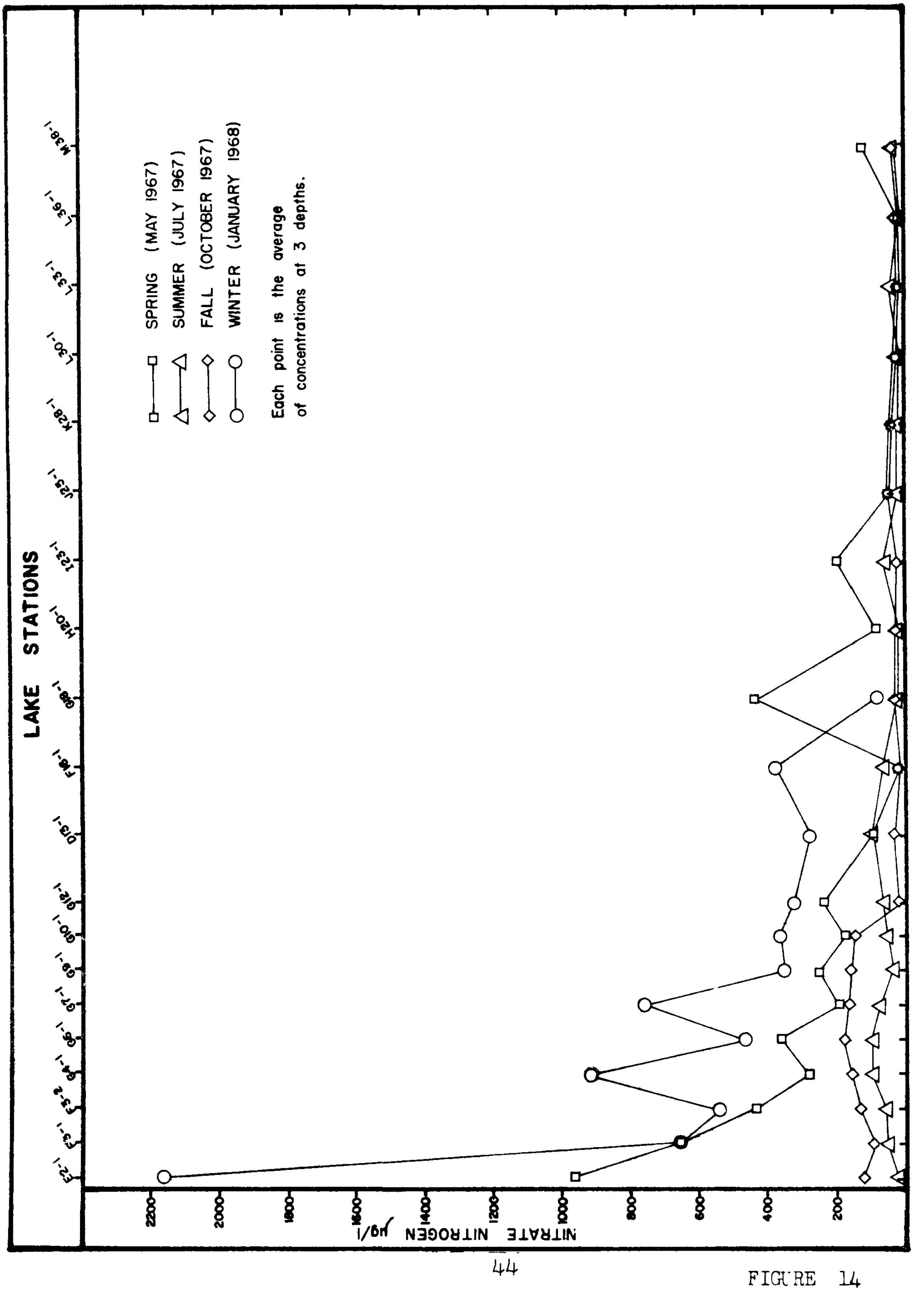
AVERAGE SEASONAL CONCENTRATIONS OF NITRATE NITROGEN
IN VARIOUS SECTORS OF THE WESTERN BASIN OF LAKE ERIE (μg/l)

Season	Maumee Bay	Southern Nearshore	Mid-basin	Northeast sector (outlet)
Winter	1,500	1,700	600	350
Spring	800	800	300	200
Summer	<50	250	75	<50
Fall	100	200	175	175

TABLE 9

AVERAGE SEASONAL CONCENTRATIONS OF NITRATE NITROGEN
IN VARIOUS SECTORS OF THE CENTRAL BASIN OF LAKE ERIE (μg/l)

Season	Southwest Nearshore	Southeast Nearshore	Western Midlake	Eastern Midlake
Winter	600	250	250	-
Spring	600	400	200	<50
Summer	100	150	<50	<50
Fall	100	175	<50	<50



Midlake Seasonal Distribution of Nitrate Nitrogen

FIGURE 14

concentration at the northeast corner of the basin being about 300 μg/l.

Central basin nearshore nitrate nitrogen follows a reasonably smooth annual curve, highest in late winter, (600 μg/l or more) and lowest in late summer (0-50 μg/l). A short, relatively sharp nitrate nitrogen decline occurs at the end of April followed by a slight rise, perhaps corresponding to the similar but generally more obvious trend in western basin nearshore.

At all times nitrate nitrogen shows significantly different areal patterns in central basin nearshore (Fig. 13 and Table 9). For example in winter, nitrate nitrogen declines from more than 800 μg/l at Sandusky to less than 200 μg/l at Conneaut. In spring it is relatively constant from Sandusky to Cleveland where it declines. Then it rises to its highest level (600 μg/l) eastward at Mentor, and declines again eastward. In summer and fall nitrate nitrogen is relatively stable throughout the entire distance at less than 200 μg/l.

A similar west to east nitrate nitrogen distribution but at lower levels, exists in central basin midlake (Fig. 14 and Table 9). In winter nitrate nitrogen decreases from about 350 μg/l at the west end of the basin to about 50 μg/l at the center of the basin. In spring nitrate nitrogen reaches its highest level (400 μg/l) at the center of the basin, declining eastward to less than 50 μg/l. In summer and fall midlake nitrate nitrogen is uniformly low throughout - less than 50 μg/l.

Organic-Inorganic Nitrogen Ratios

To determine whether nitrogen is a limiting factor in the biological productivity of any lake, in addition to actual concentrations, it is necessary to consider the proportion of inorganic to organic nitrogen existing at any one time. As long as inorganic nitrogen exceeds organic nitrogen (assuming organic nitrogen is directly related to biomass) this nutrient cannot limit biological growth. *However when organic nitrogen exceeds inorganic, it is possible for nitrogen to be a limiting factor, simply because more inorganic nitrogen is necessary for comparably continuing growth rates than is available.* Obviously such a condition cannot persist for any significant length of time.

The average concentration of inorganic and organic nitrogen for all samples in central basin nearshore for each sampling period is plotted on Fig. 15. Fig. 16 shows similar data for the western basin. *In the western basin organic nitrogen exceeds inorganic from the middle of July through the middle of November.* In the central basin organic nitrogen clearly exceeds inorganic from the middle of July through October. During these times nitrogen is potentially limiting to further algal growth except possibly for the blue-green nitrogen-fixers.

Averaging all nearshore data for the entire year, the organic and inorganic portions of the total nitrogen balance fairly well - 52% organic vs. 48% inorganic.

WATER TEMPERATURE

Figure 17 shows the temperature distribution in nearshore waters for spring 1968 through winter 1968-69. This pattern is probably similar, except for possible minor variations, for any year.

Figure 18 shows the average water temperature curve for the Ohio State Fish Hatchery at Put-in-Bay for March 1968 through March 1969, superimposed on the average annual curve (average for 45 years) at the hatchery. Although the 1968-69 curve is not far from the average, it does show departures

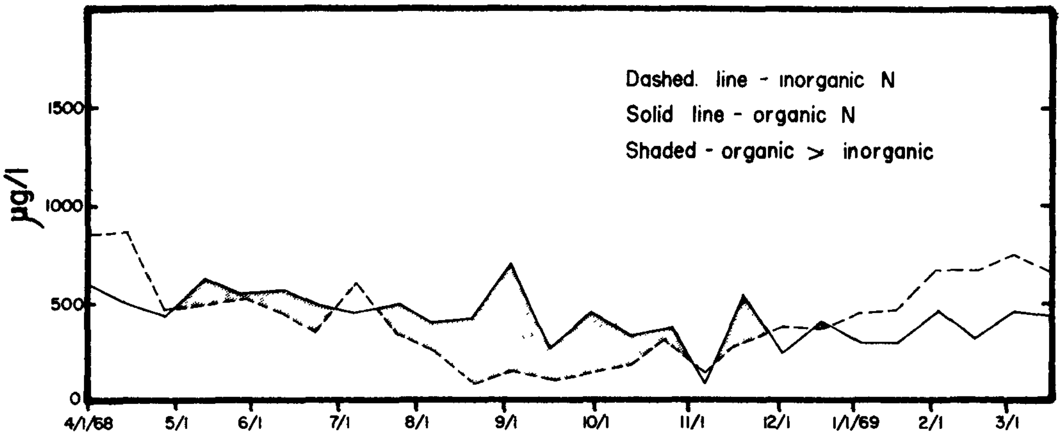


FIG. 15 COMPARISON OF ORGANIC AND INORGANIC NITROGEN IN CENTRAL BASIN NEARSHORE FOR ONE-YEAR CYCLE

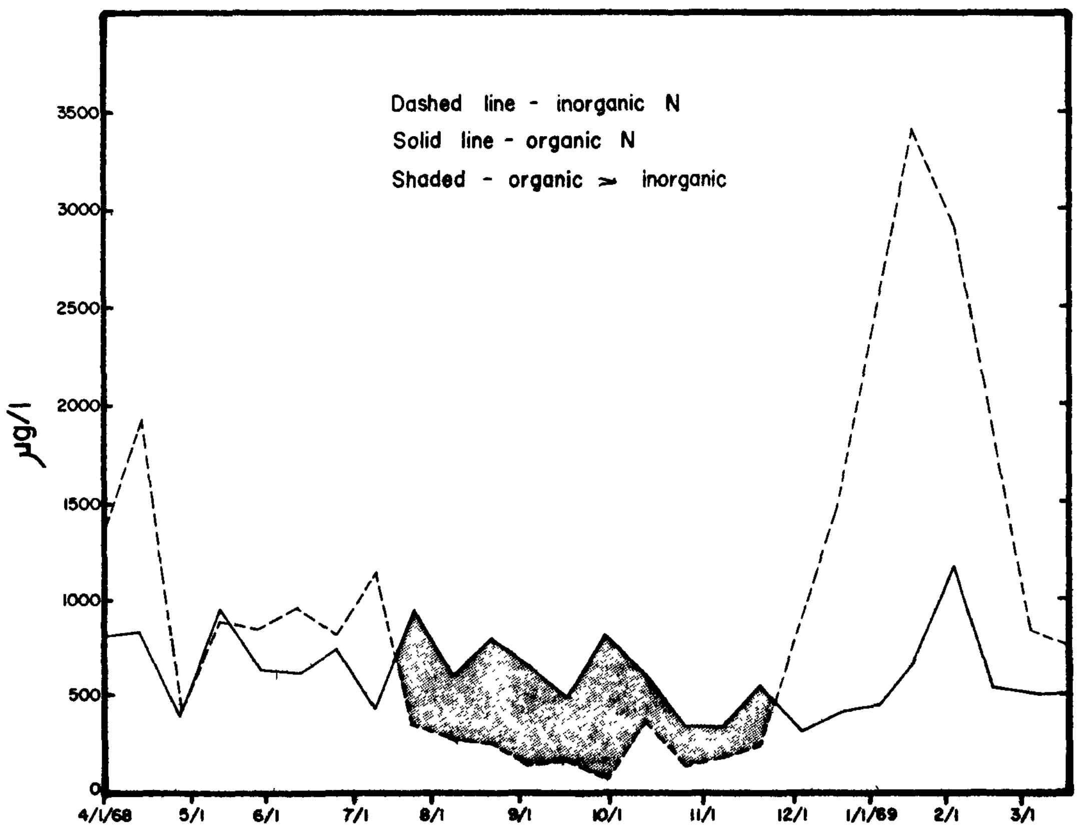
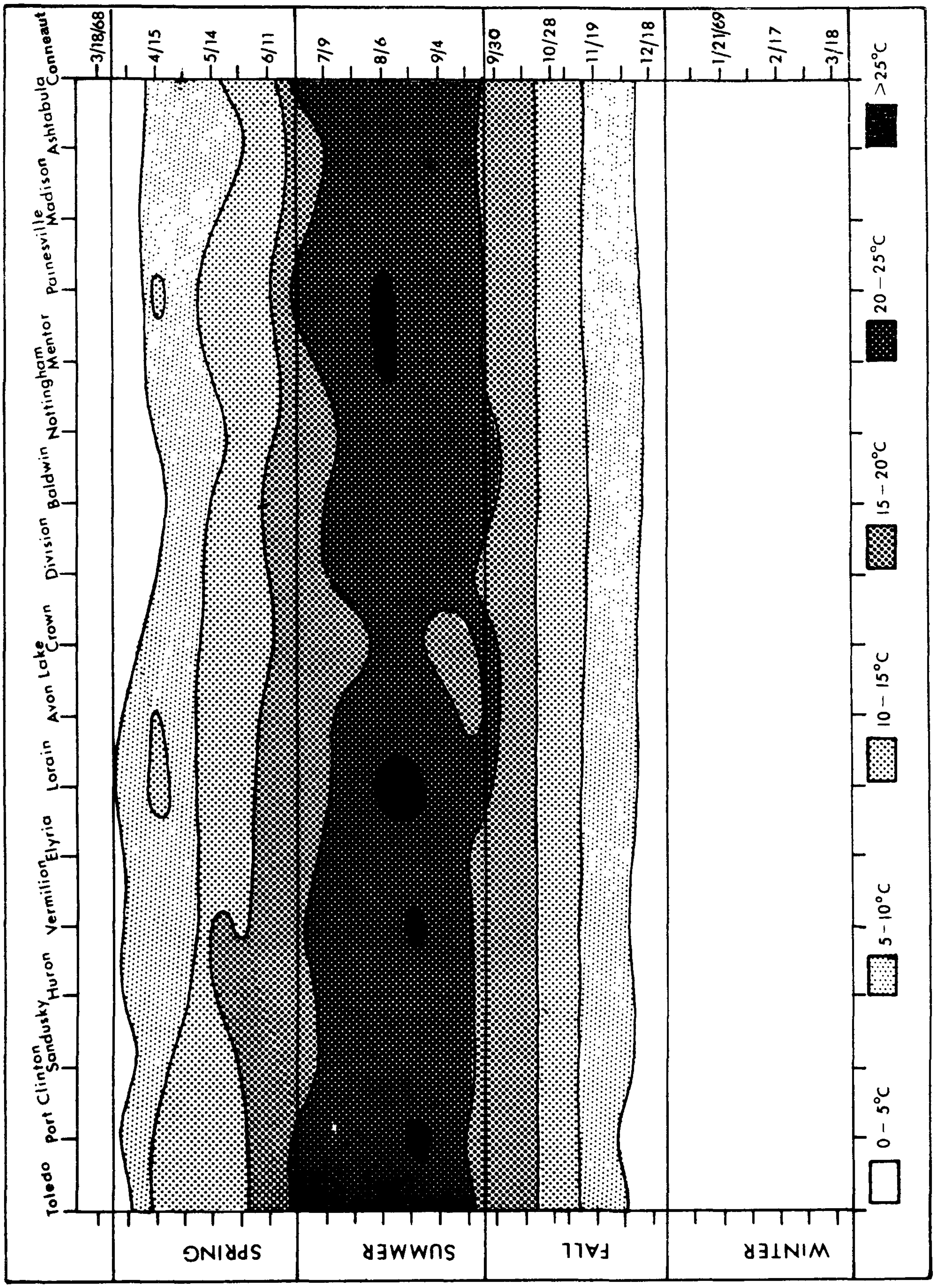


FIG. 16 COMPARISON OF ORGANIC AND INORGANIC NITROGEN IN WESTERN BASIN NEARSHORE FOR ONE-YEAR CYCLE



Nearshore Temperature Distribution in Lake Erie 1968-1969

FIGURE 17

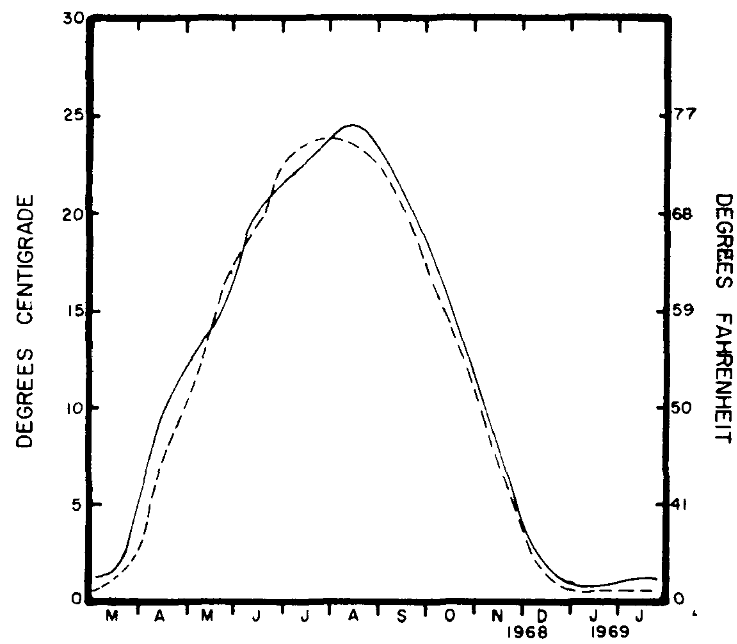


FIG. 18 WATER TEMPERATURE AT PUT-IN-BAY
Dashed line 50-year average
Solid line 1968-1969

which may have been significant in lake biological processes. Spring water temperatures were above average while in the first half of summer, water temperatures were below average. From about August 1 until mid-December, water temperatures were above average from 1 to 3°F (0.5 to 2°C). The curve of average water temperatures for all intake sampling stations closely parallels, but is slightly lower than that for Put-in-Bay. In general, nearshore water temperatures rise more slowly in the central basin than in the western basin. Lower values reflect deeper water and greater distance from shore. (See Table I).

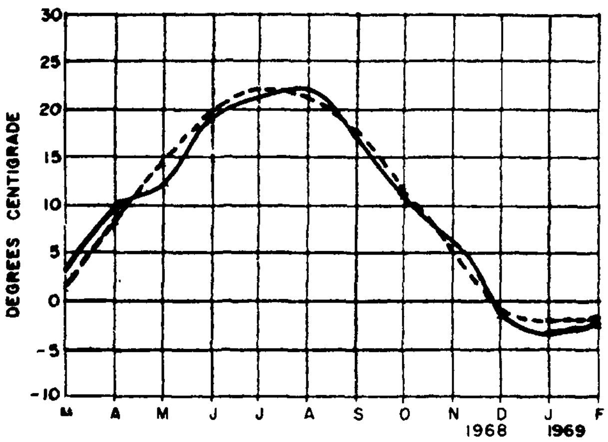
AIR TEMPERATURE

Figure 19 A indicates that the average air temperature curve at Cleveland for the year described also closely follows the long-term average but with slightly cooler temperatures in the spring and warmer in the early summer of 1968.

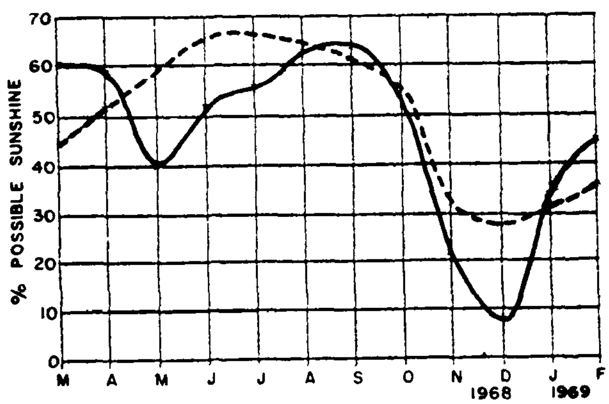
SUNSHINE AND SOLAR RADIATION

Figure 19 B, depicting average monthly percent of possible sunshine for the year of study, superimposed upon the long-term average, indicates that in this respect the year departed rather far from the average. This may have had a significant influence upon productivity during the year. Early spring had a greater than normal amount of sunshine. Late spring and early summer were rather far below the average as were late fall and early winter.

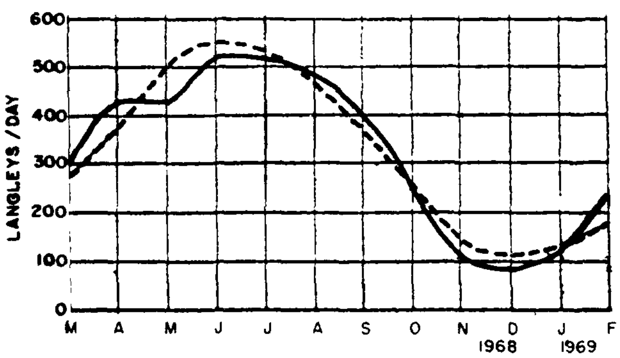
Solar radiation, Figure 19 C, was above average in early spring and below average in late spring and early summer. A particularly non-characteristic feature of the radiation curve occurred in May when the radiation was less than in April, coinciding with a significant drop in



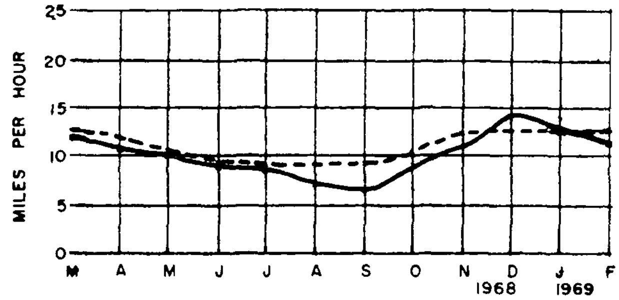
A. MONTHLY AVERAGE AIR TEMPERATURE



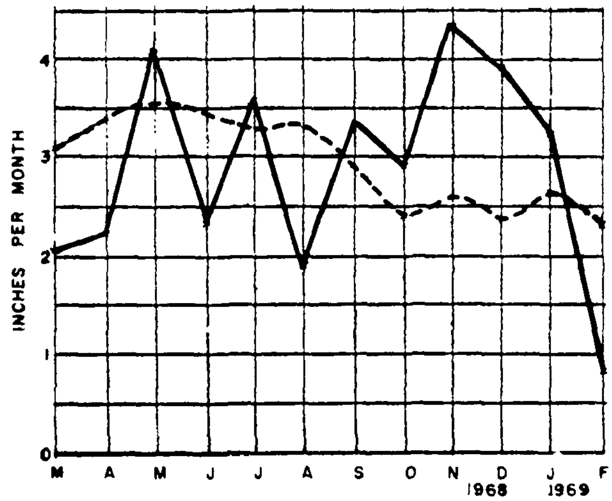
B. MONTHLY AVERAGE % POSSIBLE SUNSHINE



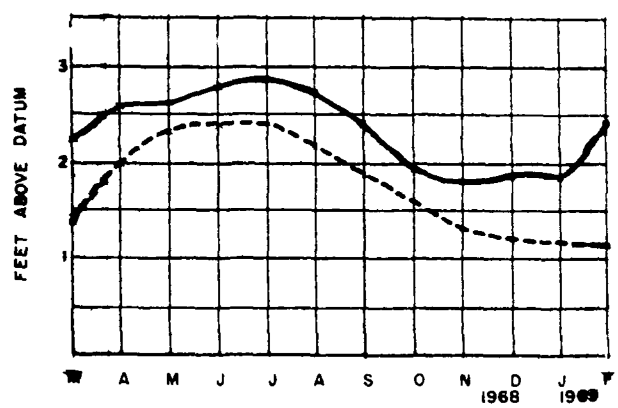
C. MONTHLY AVERAGE SOLAR RADIATION



D. MONTHLY AVERAGE WIND VELOCITY



E. MONTHLY AVERAGE PRECIPITATION



F. MONTHLY AVERAGE LAKE LEVELS
(U.S. Lake Survey Data)

FIG. 19 MONTHLY AVERAGES OF VARIOUS PHYSICAL FACTORS AFFECTING LAKE ERIE.
All data from U. S. Weather Bureau at Cleveland unless otherwise noted.
Dashed lines - longterm average. Solid lines - 1968-69.

percent of possible sunshine. A concurrent rise in inorganic nitrogen (Fig. 15 b) may be related. Radiation on the average should, and does, follow a smooth curve coinciding with seasonal expectations.

WIND

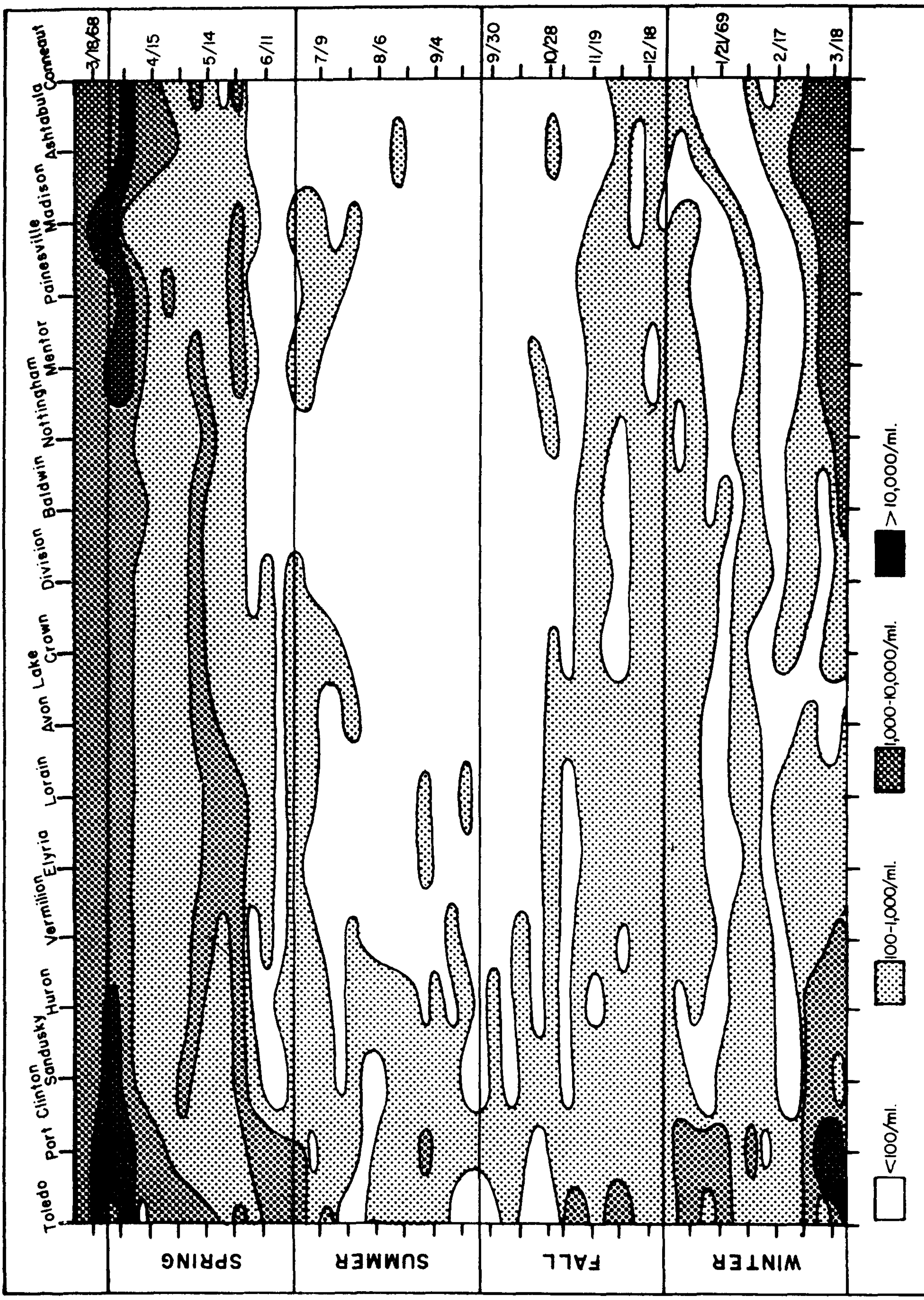
Average monthly wind velocities at Cleveland for the study period are plotted as an annual curve in Figure 19 D along with the long-term averages. The year was slightly calmer than normal, December being the only month when the long-term average was exceeded. September was very calm which may have been reflected in perhaps higher than normal blue-green phytoplankton populations.

PHYTOPLANKTON

Figures 20, 21, 22, 23, and 24 show nearshore population distribution of the dominant phytoplankton in Lake Erie western and central basins. *Diatoms (Figs. 20 and 21) are by far the dominant forms, numerically speaking, reaching their largest populations in late winter and early spring.* This maximum pulse occurs when water temperatures are 5°C or less and rising and just after nitrate has reached its maximum. Diatoms reach a minimum in summer and generally increase through fall.

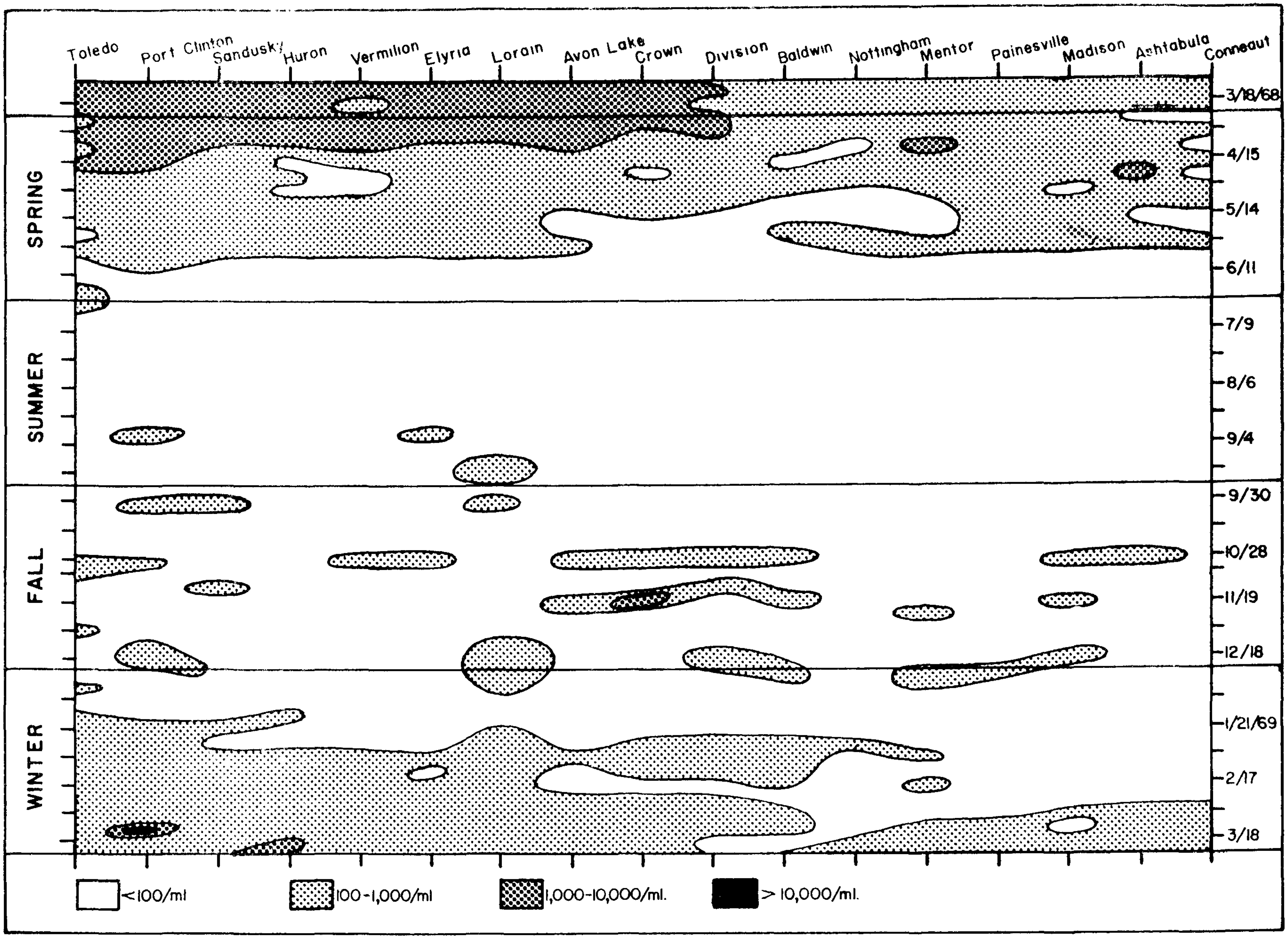
Although not reaching the extreme populations of other types, green algae uniquely exist at significant populations throughout the year (Fig. 22). *Green algae dominate the phytoplankton in late spring and early summer when the lake temperature is rising and between 10°C and 15°C, and when nitrate levels are intermediate and declining.*

The blue-greens, Figs. 23 and 24 are virtually absent much of the year but may show a growth explosion in late summer and early fall. They



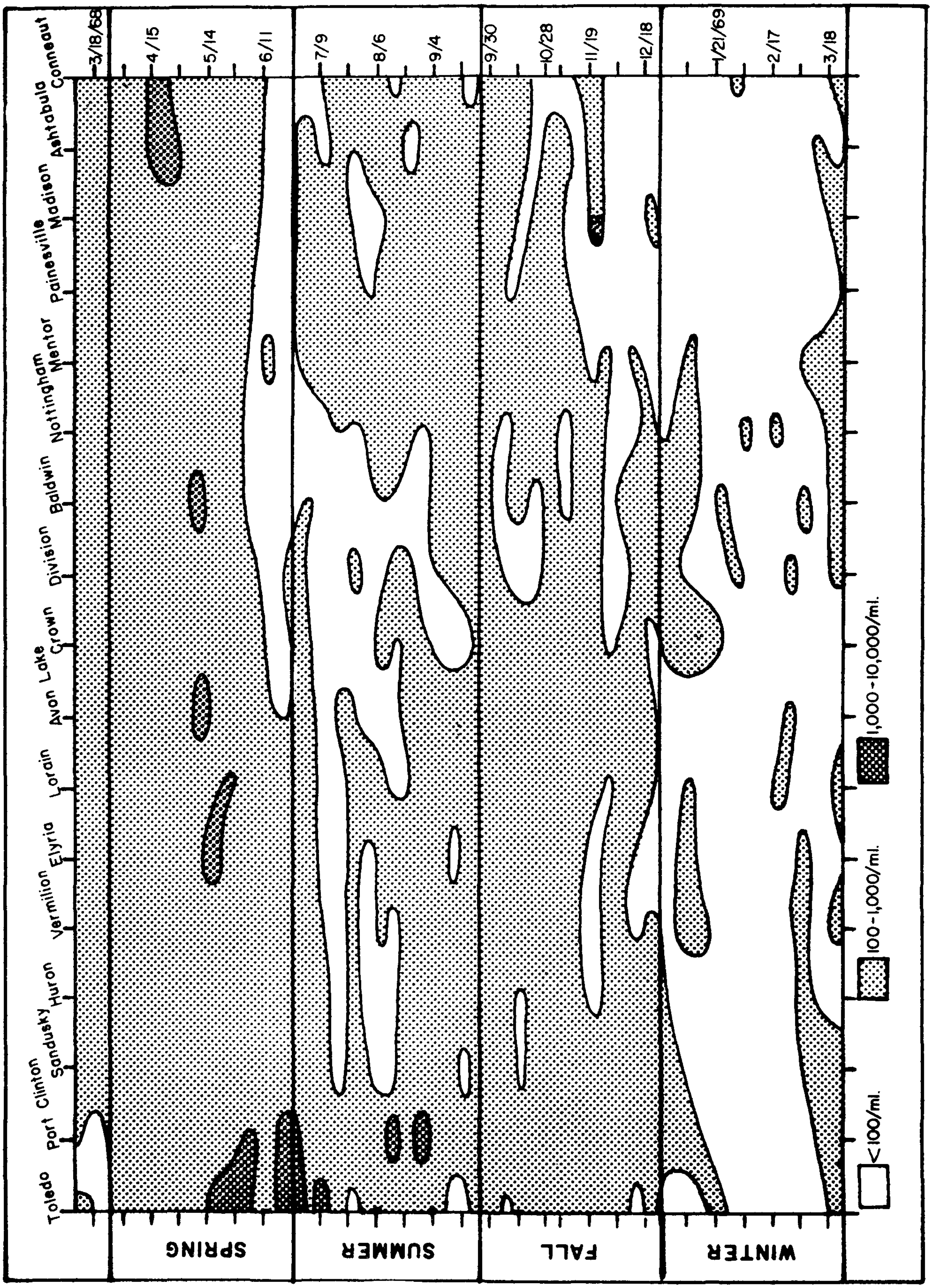
Nearshore Centric Diatom Distribution in Lake Erie 1968 - 1969

FIGURE 20



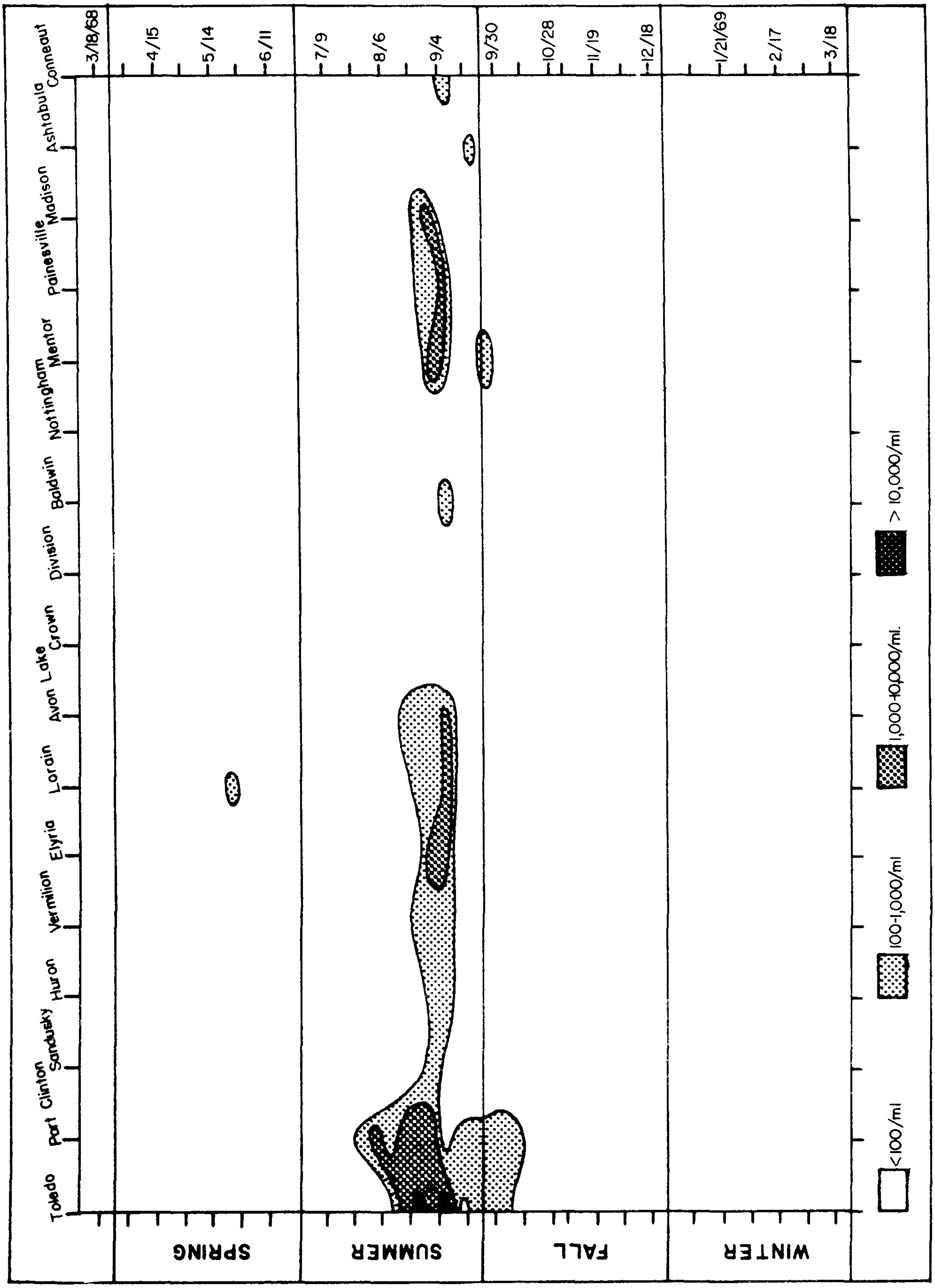
Nearshore Pennate Diatom Distribution in Lake Erie 1968 - 1969

FIGURE 21



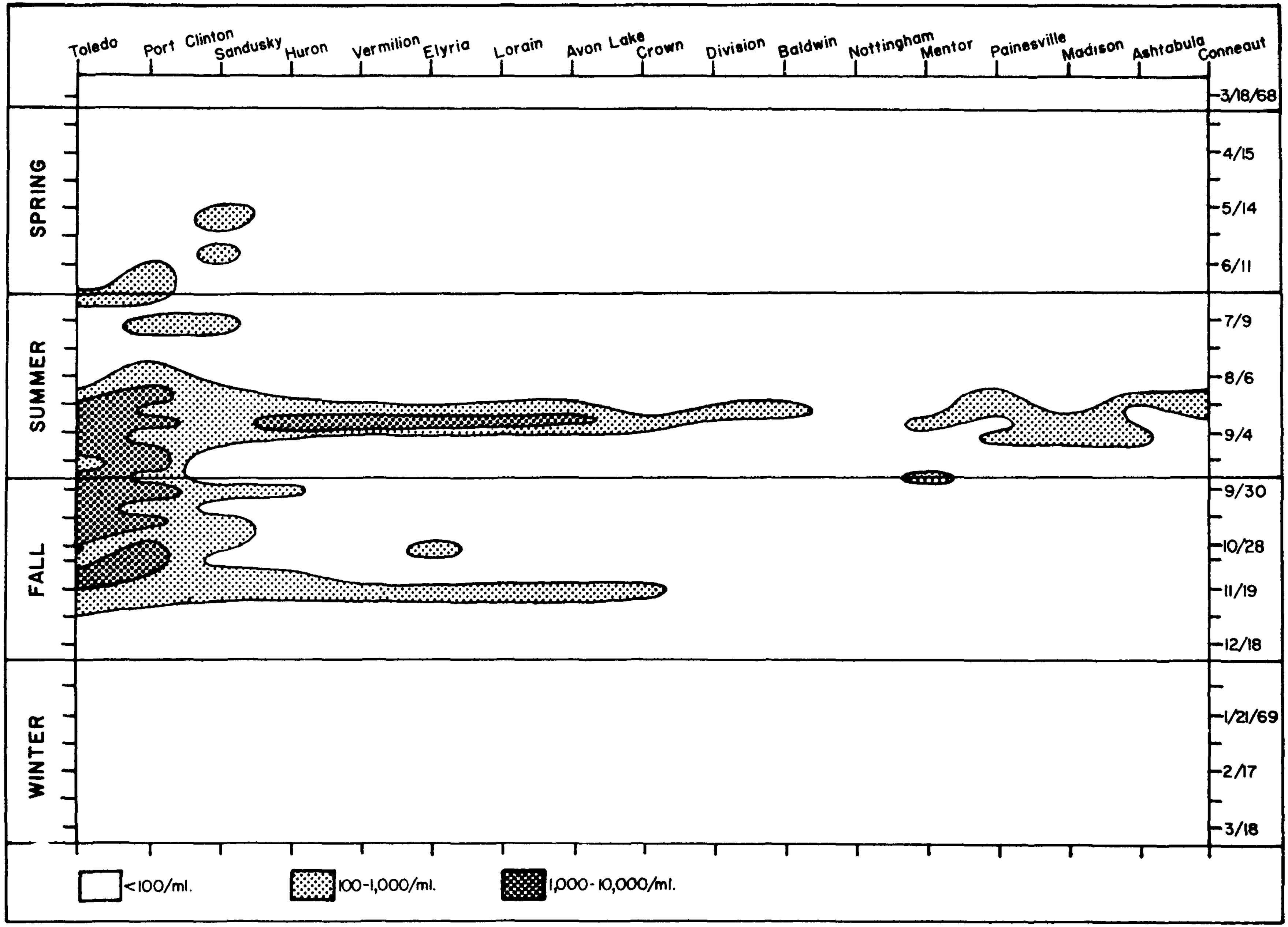
Nearshore Coccoid Green Algae Distribution 1968-1969

FIGURE 22



Nearshore coccoid Blue-green Algae Distribution in Lake Erie 1968 - 1969

FIGURF 23



Nearshore Filamentous Blue-green Algae Distribution in Lake Erie 1968-1969

FIGURE 24

generally are dominant for a longer time in the western basin than in the central basin. *Blue-green algae reach their greatest populations when nitrate is nearly absent, when water temperature is above 20°C, and after the lake has begun to cool.*

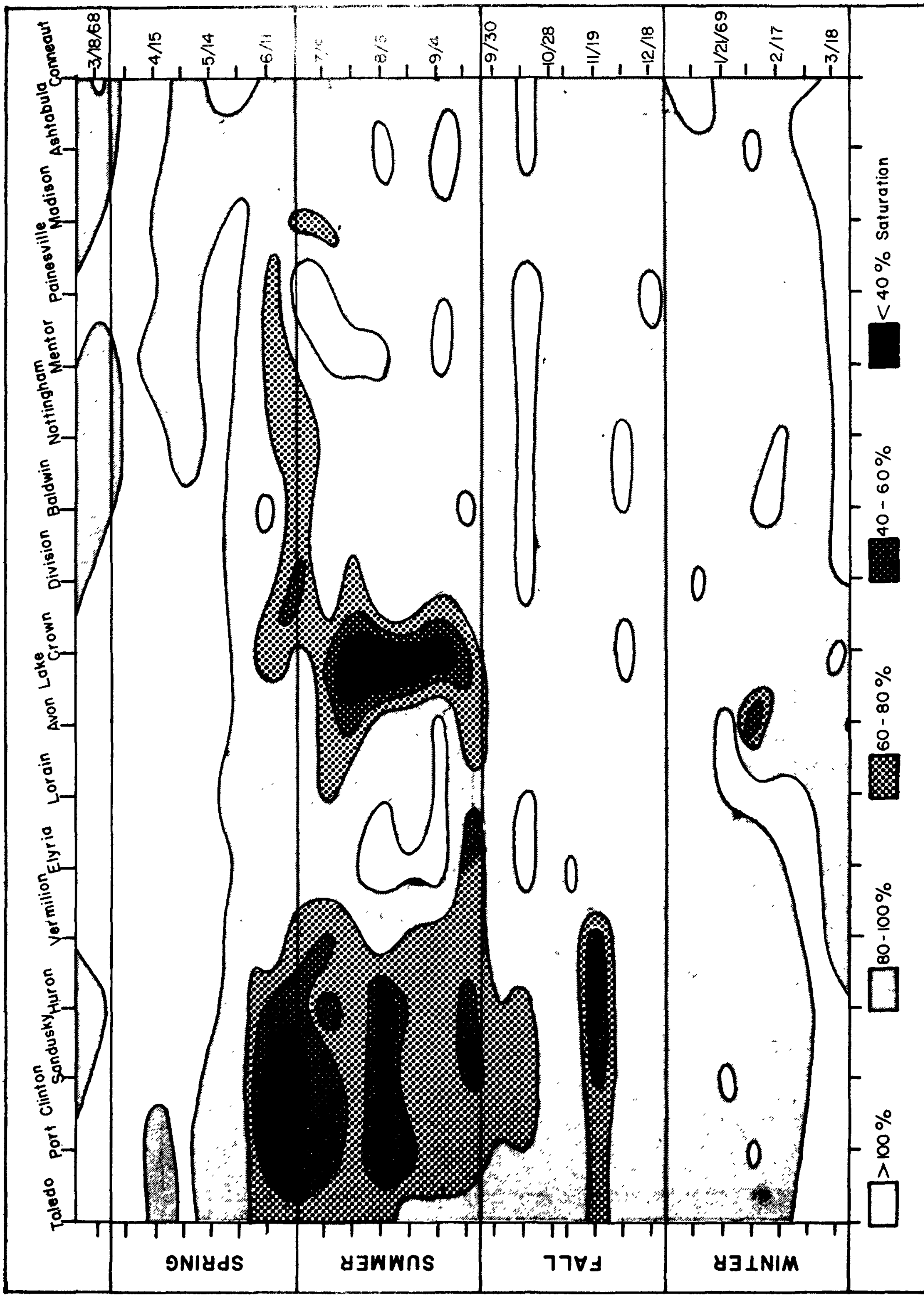
Flagellates are not dominant in nearshore waters at any time of the year.

All phytoplankton forms appear to decrease quite significantly in population from west to east in the lake. By far the largest population is found in the western basin at all times of the year.

The attached green filamentous alga Cladophora was not considered in this report. Cladophora grows profusely in Lake Erie, a suitable substrate for "hold-fast" attachment being the only limiting factor. Cursory agency study indicates that the eastern basin, because of appropriate substrate produces the largest Cladophora biomass.

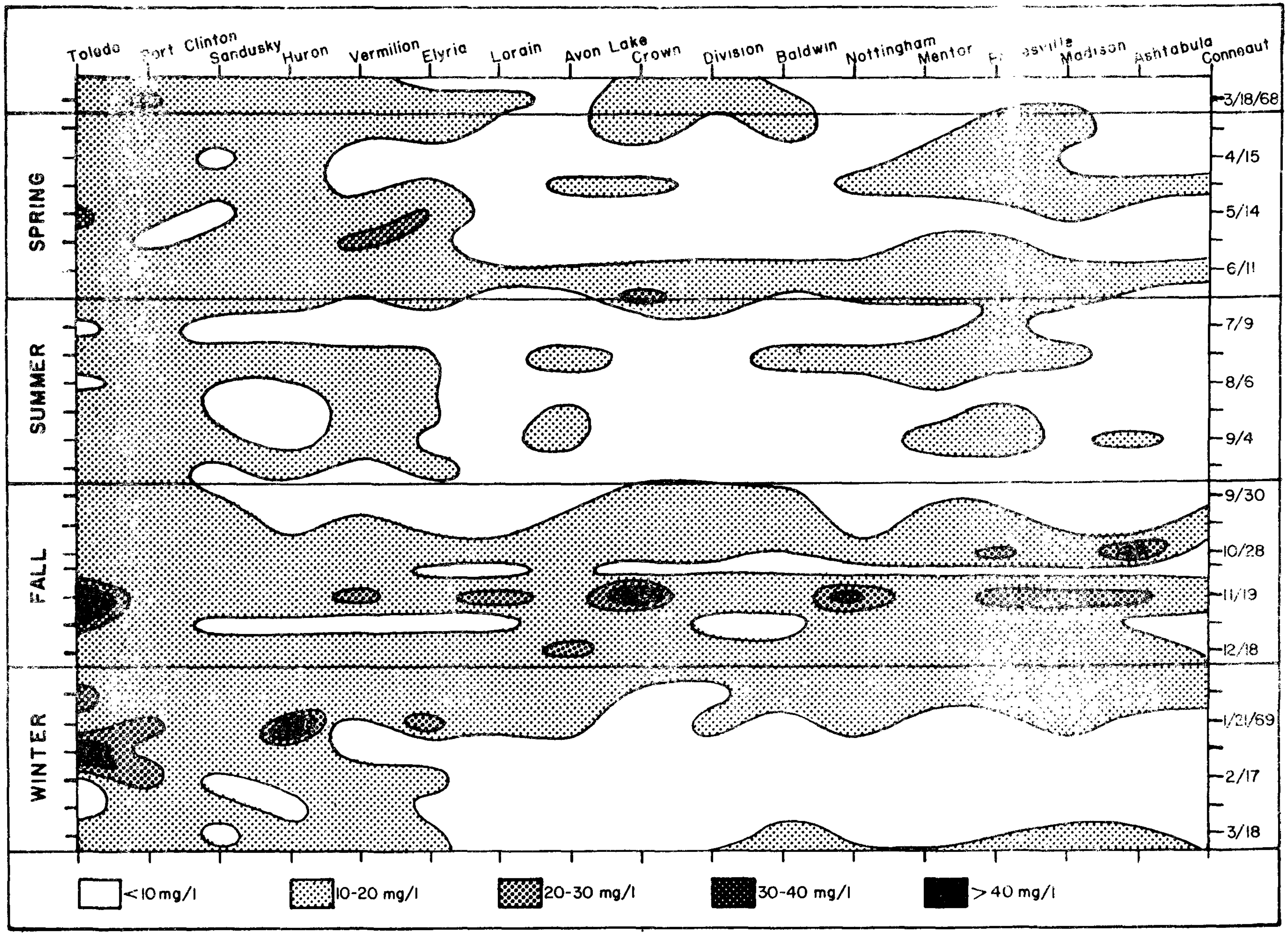
DISSOLVED OXYGEN

Figure 25 shows the time and spatial distribution of dissolved oxygen at the intake sampling stations. *Early spring is characterized by consistently higher percentages of oxygen saturation while summer is characterized by the lowest.* Fall and winter show intermediate percentages of oxygen saturation. Dissolved oxygen is apparently related to phytoplankton populations, particularly diatoms, see Figs. 20 and 21. Acute low oxygen saturation in summer in the Cleveland area primarily results from incursions of hypolimnion water into the intake sampling areas. In areas not affected by the hypolimnion less acute low oxygen saturation is most likely the result of chemical deoxygenation from nearshore resuspended sediments.



Nearshore Dissolved Oxygen Distribution in Lake Erie 1968 - 1969

FIGURE 25



Nearshore COD Distribution in Lake Erie 1968-1969

FIGURE 26

CHEMICAL OXYGEN DEMAND

Figure 26 shows the distribution of chemical oxygen demand in the nearshore waters of the western and central basins. A clear, relationship between this distribution and that of dissolved oxygen does not exist. If there is a relationship, it is a direct one. *Low dissolved oxygen concentrations in summer are associated with lower COD while higher DO concentrations in fall and winter are associated with relatively high COD.*

CORRELATION OF FACTORS AFFECTING ALGAL PRODUCTIVITY

The relationships described herein deal only with the factors described in the previous discussion. It is fully realized that algae require many kinds of nutrients in addition to nitrogen and phosphorus. It is assumed however that trace elements and vitamins necessary for sustaining primary productivity are always in adequate supply and that they do not become limiting at any time. Two other elements, silicon and carbon, necessary in relatively large quantity, have not been measured in this study. Silicon is required by diatoms in shell formation but is not a significant nutrient for other algae.

Many typical general relationships are apparent in Lake Erie. For example, various kinds of algae show preference for different temperature ranges. Populations decrease from west to east in Lake Erie correlative with a general decrease in nutrient content in that direction. Populations are higher in nearshore and other shallow waters correlative with higher nutrient content. Shifts in dominance with time are characteristic of all parts of the lake. The time shifts may not be relatable to water temperature alone. Most likely variations in solar radiation (energy) due to earth position are significant. Finally populations of planktonic algae are generally inversely correlatable with water depth.

The following discussion examines the five main groups of algae prevalent in Lake Erie, centric diatoms, pennate diatoms, green coccoid algae, blue-green coccoid algae, and blue-green filamentous algae, and their relationship to various physical, chemical, and biological factors. A glaring omission involves the enumeration of zooplankton. As phytoplankton grazers, zooplankton can have a pronounced effect on phytoplankton and consequently on the relationships to be presently described.

CENTRIC DIATOMS

Water Temperature

Centric diatoms show a definite correlation with water temperature in both the central basin nearshore (Fig. 26) and the western basin nearshore (Fig. 27). Populations increase very rapidly at the time of ice breakup following a winter period of relative dormancy. *Maximum populations in both basins occur before the temperature reaches 3°C (37°F).* Above this temperature the central basin population (>6,000 organisms/ml) declines rapidly to less than 1,000 organisms/ml at a temperature of about 7°C (45°F). In the western basin the high populations (>10,000 organisms/ml) persist longer, leveling off at less than 2,000 organisms/ml) when a temperature of about 10°C (50°F) is reached. Populations in the western basin remain fairly stable until a temperature of 20°C (68°F) is reached, then drop rapidly to less than 500 organisms/ml. In the central basin stability persists through 12.5°C (54°F) when populations drop to 200 or fewer organisms/ml.

Centric diatoms decrease to or near their minimum populations when the lake is warmest, thus showing an inverse correlation with temperature while the lake is warming. After cooling begins, one might expect another inverse correlation; however the cooling season rise in centric diatoms is non-existent in the central basin and greatly subdued in the western basin. Maximum western basin populations occur again at between 10°C (50°F) and 3°C (37°F) in fall but they are less than 10 percent of the populations in spring. This suggests that some factor other than temperature has a greater population controlling influence in fall, as will be discussed presently.

Soluble Phosphorus and Temperature

The plot of centric diatoms and soluble phosphorus reveals a variability difficult to explain. At times higher populations are associated with lower phosphorus concentrations following the classical tendencies toward depletion shown by silica and nitrate. At other times the reverse is true, suggesting the biological mechanisms of nutrient storage and delayed phytoplankton response.

A plot of centric diatoms, soluble phosphorus, and temperature (Fig. 29) reveals quite a different picture. *Although the detailed interpretation remains difficult, a definite general trend is shown during the warming season indicating that, as the water warms, progressively more phosphorus is required to maintain similar populations.* For example, to maintain a population of centric diatoms greater than 1,000 organisms per milliliter at temperatures less than 5°C (41°F), less than 10 μg/l soluble phosphorus is required, while at 20°C (68°F) the requirement increases to greater than 50 μg/l. In these types of correlation, ambient water nutrient concentration is inferred to mean a concentration associated with a specific algal population. It is not meant to mean algal metabolic requirement.

It appears that above 20°C (68°F) both temperature and soluble phosphorus are severely limiting to diatom growth in Lake Erie. This does not mean that other factors are not also limiting, but does mean that reduction of other prevailing non-limiting factors at this time is not necessary for diatom control.

After the lake begins to cool the relationship between diatoms, soluble phosphorus, and temperature becomes obscure, indicating that some other factor becomes more important to diatom production.

Although a relationship between soluble phosphorus and diatoms is apparent during the warming season, in the early part of this period the relationship in detail is not altogether clear. Below a temperature of 10°C (50°F) it appears that a concentration of about 30 μg/l soluble phosphorus is sufficient for continued diatom growth. If this is fact, it may be difficult to establish, for at this time soluble phosphorus is rapidly decreasing. The possibility exists that during this period, diatom populations are regulating soluble phosphorus rather than the reverse.

Inorganic Nitrogen and Temperature

Inorganic nitrogen appears to show a direct correlation with centric diatoms when nitrogen averages for each sampling period are plotted against average plankton numbers. Higher diatom populations are associated with higher nitrogen values and vice versa. However the correlation becomes nebulous when inorganic nitrogen and centric diatoms are considered not as nearshore wide averages but as individual station statistics. For example, while maximum populations tend to increase eastward, the inorganic nitrogen associated with these maximums progressively decreases eastward.

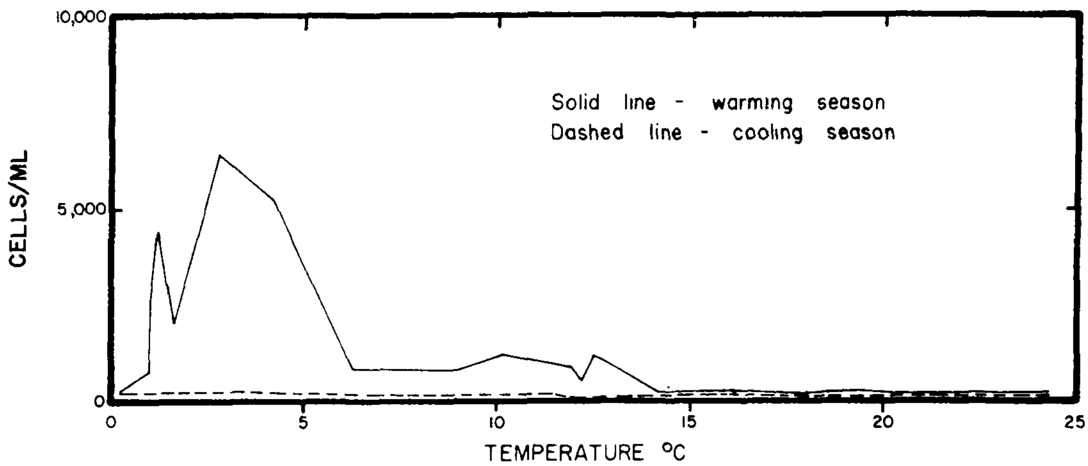


FIG. 27 CENTRIC DIATOMS VS. TEMPERATURE IN LAKE ERIE CENTRAL BASIN NEARSHORE

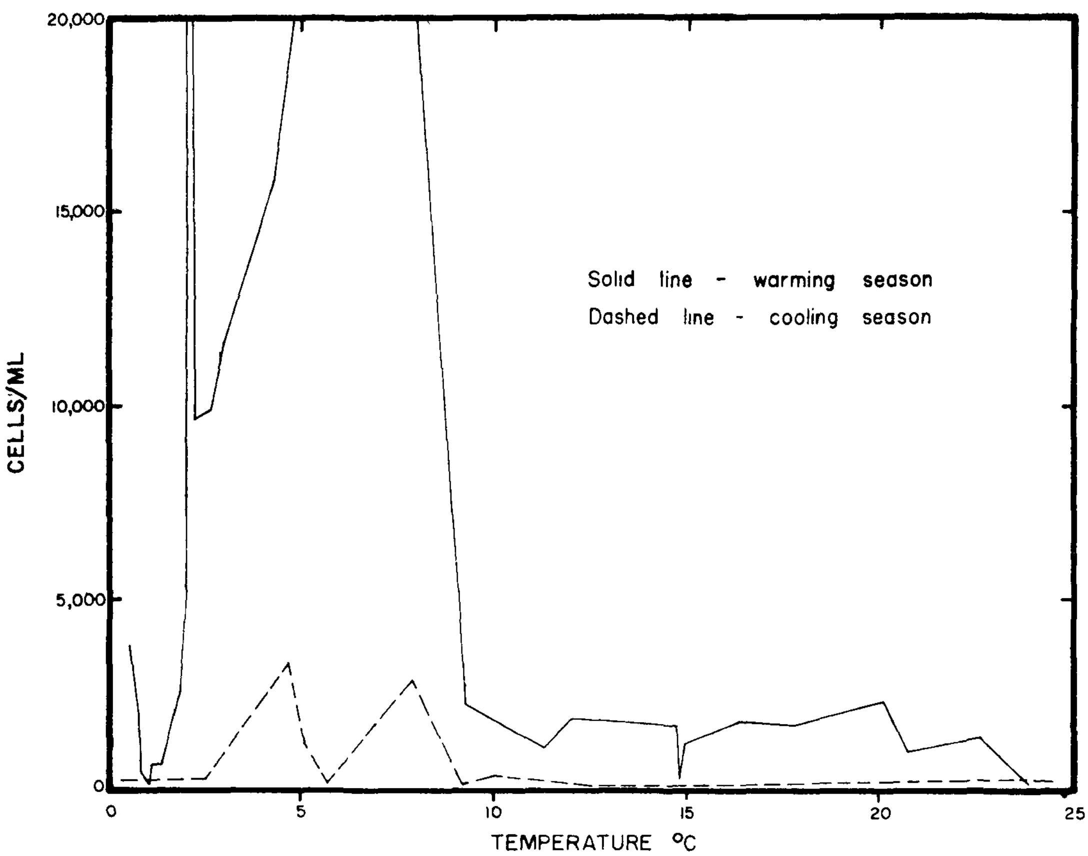
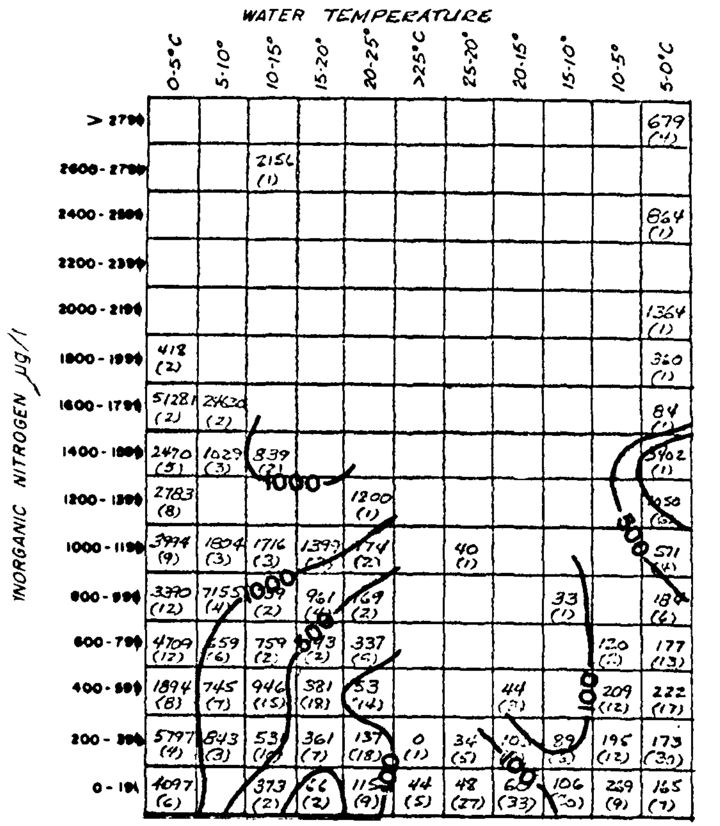


FIG. 28 CENTRIC DIATOMS VS. TEMPERATURE IN LAKE ERIE WESTERN BASIN NEARSHORE

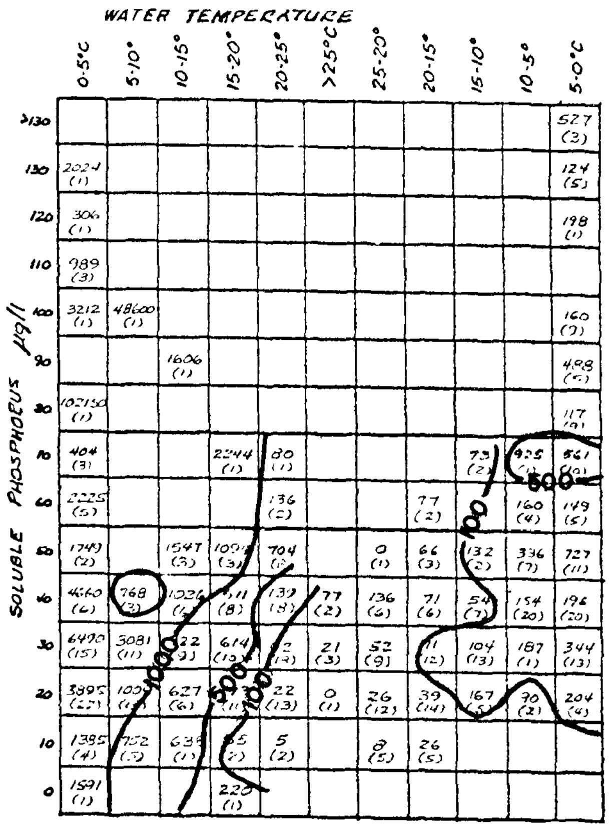
A plot of centric diatoms, inorganic nitrogen and temperature gives more insight as to cause and effect between the various considered factors (Fig. 29). *It appears that between 0°C (32°F) and 5°C (41°F) centric diatoms are virtually independent of the amount of inorganic nitrogen which exists at the time.* Above 5°C (41°F) the amount of inorganic nitrogen apparently does not greatly affect centric diatom populations as long as the nitrogen concentrations are below about 800 µg/l and within the range normally found in nearshore waters. Sporadic significant population increases occur above 800 µg/l with progressively larger ambient nutrient concentrations being required to maintain a certain population at progressively increasing water temperatures. Above 20°C (68°F) more than 1000 µg/l is needed to produce a significant diatom population (>1000 org/ml).

After the lake begins to cool centric diatoms are no longer important, showing little relation to either nitrogen or temperature, until a water temperature of about 10°C (50°F) is reached, then centrics show a slight increase, but still independent of existing nitrogen concentrations.

Integrating results for temperature, soluble phosphorus, and inorganic nitrogen during the warming season, apparent nutrient requirements for specified centric diatom populations can be inferred, as shown in Table 10.



Centric Diatoms vs. Temperature and Inorganic Nitrogen



Centric Diatoms vs Temperature and Soluble Phosphorus

FIG. 29 CENTRIC DIATOMS AS RELATED TO WATER TEMPERATURE, SOLUBLE PHOSPHORUS, AND INORGANIC NITROGEN IN LAKE ERIE NEARSHORE WATERS.

Upper numbers in each block are average populations of centrics diatoms per ml; number of samples in parenthesis.

TABLE 10

CONCENTRATIONS OF INORGANIC NITROGEN AND PHOSPHORUS REQUIRED TO PRODUCE VARIOUS POPULATIONS OF CENTRIC DIATOMS DURING WARMING MONTHS

Temp. (°C)	Inorganic N (µg/l)			Soluble P (µg/l)		
	1000 org/ml	500 org/ml	100 org/ml	1000 org/ml	500 org/ml	100 org/ml
0-5	<100	<100	<100	<10	<10	<10
5-10	800	100	<100	20	<10	<10
10-15	900	200	<100	40	<10	<10
15-20	1,000	700	200	50	30	10
20-25	1,200	1,000	100	>70	50	40

During the cooling months centric diatoms are related to temperature, increasing slightly as the lake cools. However it appears that prevailing variations in nitrogen and phosphorus are not important, suggesting that other factors may be controlling. It is possible that sunlight is a factor. Solar radiation as measured in langleys is considerably greater during the warming months at any particular water temperature. For example in early spring at ideal diatom growth temperatures below 5°C (41°F), the solar radiation is above 300 langleys/day while at the same temperatures in late fall the radiation is about 100 langleys/day (Fig. 30). It is possible that radiation of at least 300 langleys/day is optimal and that below this value solar radiation may be limiting.

Another factor, is the daily duration of sunlight as measured by hours of actual sunshine. Actual sunshine averages only about three hours per day in late fall, but more than twice that amount in early spring.

Finally, minimal shore erosion and tributary siltation due to summer meteorological calm and low precipitation may keep silica inputs to the lake at a minimum. Since silica is required in diatom skeletal formation

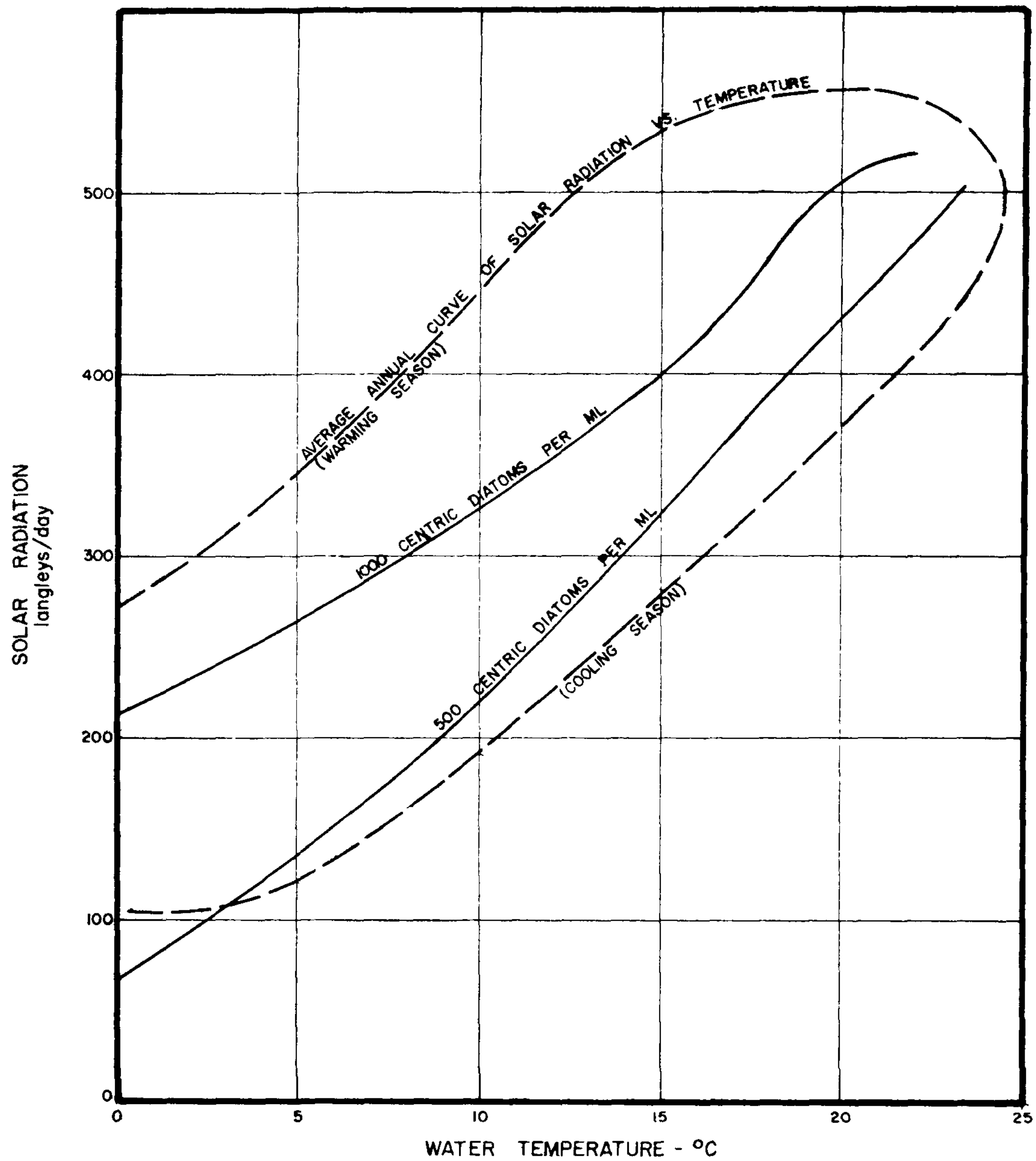


FIG. 30 ESTIMATED REQUIREMENTS OF SOLAR RADIATION AT LAKE ERIE WATER TEMPERATURES FOR CENTRIC DIATOMS.

any silica deficiency at this time of the year may be controlling diatoms in general.

PENNATE DIATOMS

Water Temperature

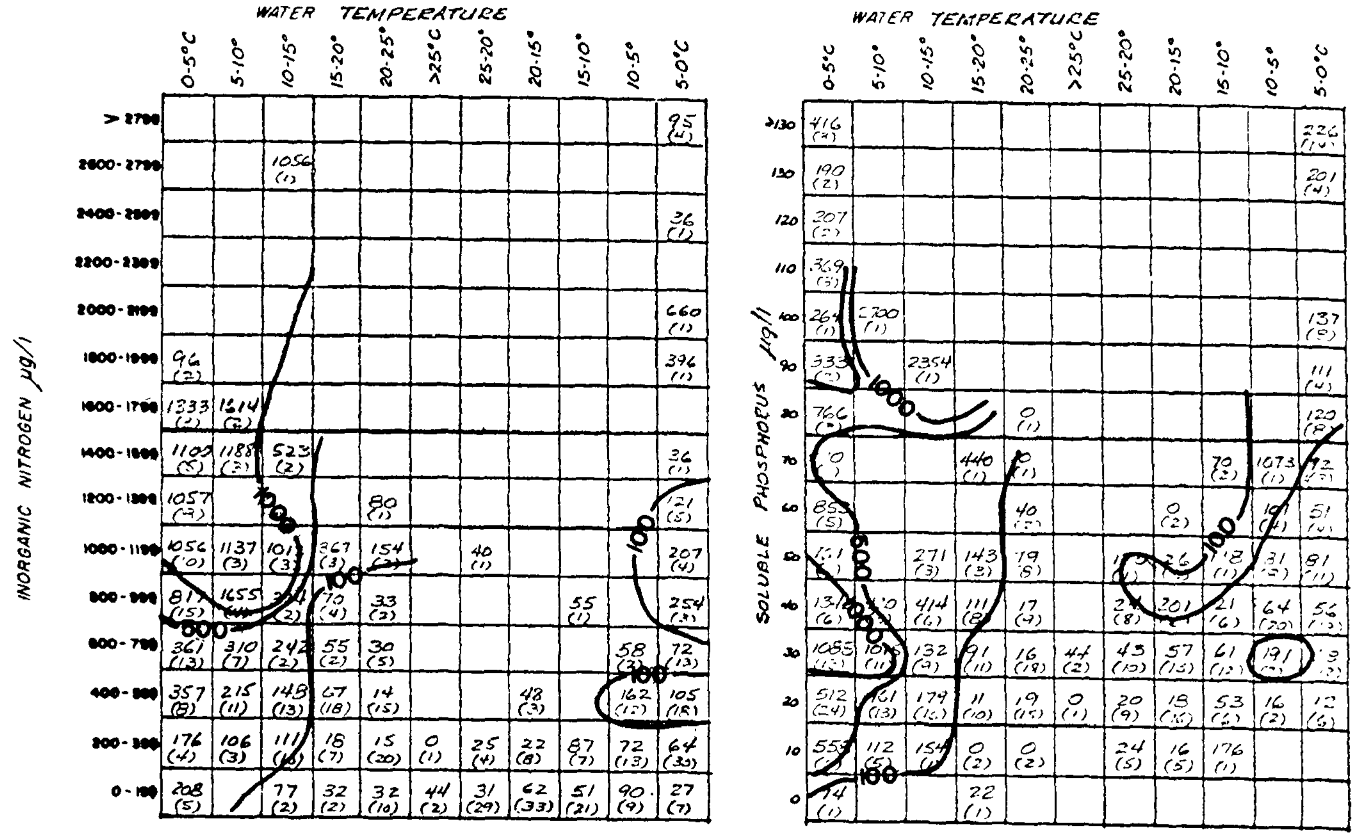
Pennate diatoms show essentially the same kind of response to temperature as do the centric diatoms with the exception that populations are usually considerably less. The large spring pulse lasts approximately the same length of time in both the western and central basins, beginning during the period of ice breakup and essentially disappearing by the time the water temperature reaches 15°C (59°F).

During the cooling season populations of pennate diatoms rise slightly but do not reach significant numbers, again suggesting, as with centrics, that they may be subdued by a lack of sufficient sunlight or silica at preferred temperatures.

Soluble Phosphorus and Temperature

As with centric diatoms, the pennates also show a variable relationship and most likely for the same reasons, with soluble phosphorus alone. When plotted against soluble phosphorus and temperature some apparently significant correlations emerge (Fig. 31). *During the warming season at temperatures below 5°C (41°F) and as evidenced by maximum populations, the pennates appear to prefer soluble phosphorus concentrations of 30 to 40 μg/l, decreasing in numbers when concentrations are above and below those levels.* This correlation prevails somewhat through 10°C (50°F) when higher concentrations of phosphorus appear to begin to stimulate the pennates.

From 10°C (50°F) through 20°C (68°F) the correlation becomes clearer



Pennate Diatoms vs Temperature and Inorganic Nitrogen

Pennate Diatoms vs Temperature and Soluble Phosphorus

FIG. 31 PENNATE DIATOMS AS RELATED TO WATER TEMPERATURE, SOLUBLE PHOSPHORUS, AND INORGANIC NITROGEN IN LAKE ERIE NEARSHORE WATERS.

Upper numbers in each block are average populations of pennate diatoms per ml; number of samples in parenthesis and is direct. However significant populations, more than 500 cells/ml, require relatively large quantities of soluble phosphorus, in excess of 70 µg/l. Above 20° (68°F) pennate diatoms, because of restricting temperatures, cannot be of great significance regardless of phosphorus concentrations.

During the cooling season there is no clear relationship between phosphorus and pennate diatoms, indicating that another factor is limiting.

Inorganic Nitrogen and Temperature

Inorganic nitrogen appears to show a direct correlation with pennate diatoms when nitrogen averages for each sampling period are plotted against average plankton numbers. Again higher diatom populations are associated with higher nitrogen values. As with centric diatoms the correlation is not altogether consistent, with occasional erratic values indicating some delayed ambient algal-nutrient response.

A plot of pennates, inorganic nitrogen, and temperature however reveals the following: Below a temperature of 10°C (50°F) pennate diatoms appear to require a concentration of more than 600 µg/l inorganic nitrogen to produce blooms of more than 500 cells/ml. Above 10°C (50°F) the requirement increases to a large degree, indicating that temperature is relatively more controlling. Above 20°C (68°F) as with phosphorus, nitrogen is no longer important to pennate diatoms in Lake Erie, the population apparently entirely controlled by some other factor, most likely temperature.

During the cooling season, a correlation is not apparent between inorganic nitrogen and pennates until a temperature of less than 10°C (50°F) is reached. They then seem to prefer an inorganic nitrogen concentration of 800-1,000 µg/l. Populations are still relatively small, however, indicating a response to insufficient sunlight or silica.

The results of nutrient-temperature-pennate diatom correlations provide some insight as to probable pertinent plankton requirements as shown in Table II.

TABLE II

CONCENTRATIONS OF INORGANIC NITROGEN AND PHOSPHORUS REQUIRED TO PRODUCE VARIOUS POPULATIONS OF PENNATE DIATOMS DURING WARMING MONTHS

Temp.	Inorganic N (μg/l)			Soluble P (μg/l)		
(°C)	1,000 org/ml	500 org/ml	100 org/ml	1,000 org/ml	500 org/ml	100 org/ml
0-5	1,000	800	200	30	10	5
5-10	800	700	200	30	30	10
10-15	1,000	900	300	80	70	10
15-20	-	1,500	900	-	80	40
20-25	-	-	1,000	-	-	-

GREEN COCCOID ALGAE

Water Temperature

The western basin nearshore green coccoid algae temperature plot (Fig. 33 shows a conspicuous rise during the course of lake warming, with maximum populations of more than 3,000 cells/ml at about 22°C (72°F). A precipitous decline in population occurs above this temperature. During the lake cooling period, populations rise again slightly to about 600 cells/ml at 10°C (50°F) and then decline again in winter.

In the central basin green coccoid algae are generally about one-half those in the western basin. The relation to temperature alone is quite different (Fig. 32). They rise from insignificance at the time of ice breakup to a maximum (600 cells/ml) at a temperature of about 12°C (54°F) then decline rapidly, so that the population minimum occurs at the same

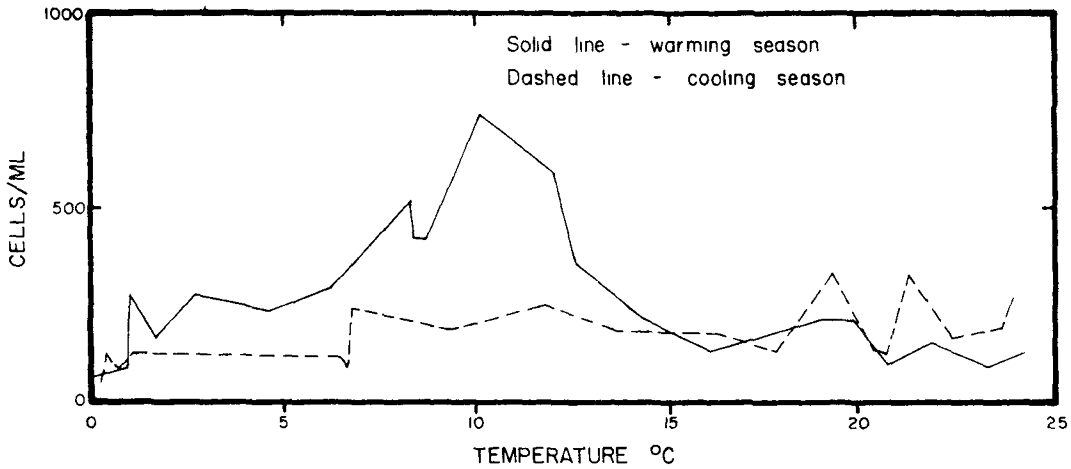


FIG. 32 GREEN COCCOID ALGAE VS. WATER TEMPERATURE IN NEARSHORE WATERS OF CENTRAL BASIN.

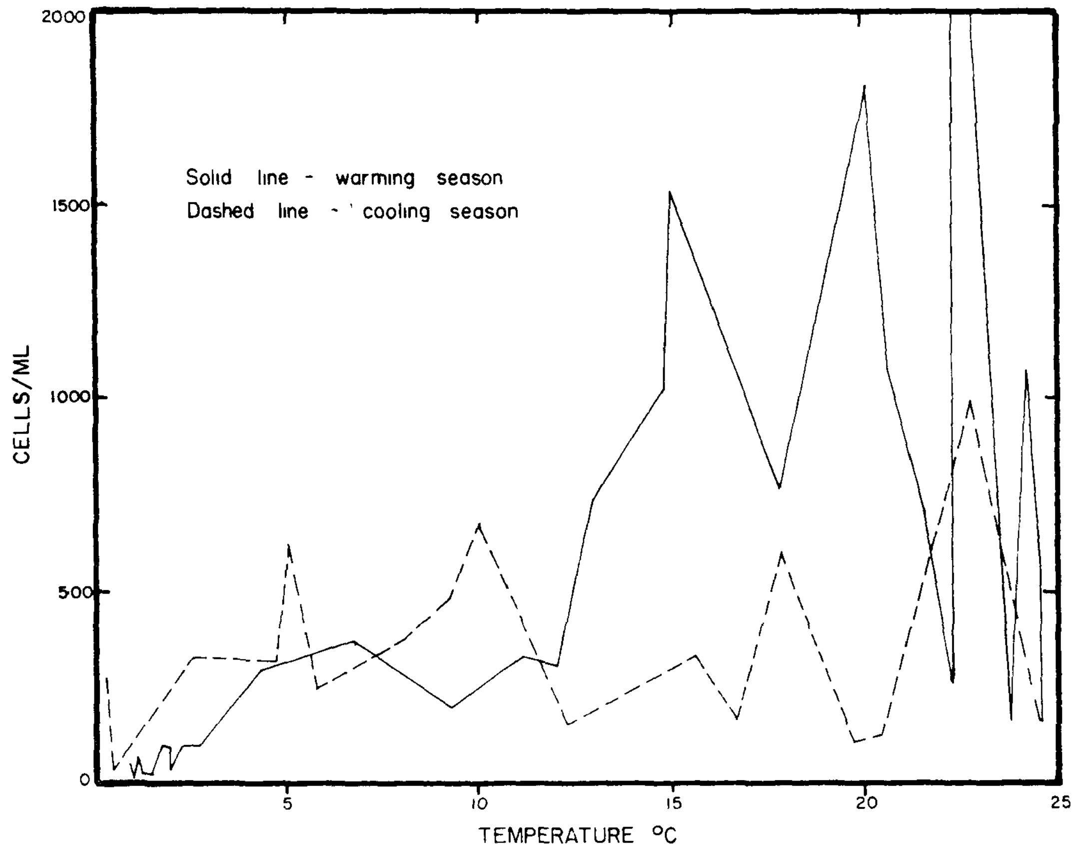


FIG.33 GREEN COCCOID ALGAE VS. WATER TEMPERATURE IN NEARSHORE WATERS OF WESTERN BASIN.

time and same temperature as the population maximum in the western basin. A secondary maximum in green coccoid algae then occurs in central basin nearshore just after the lake begins to cool at about 20°C (68°F). This is followed by a gradual decline to winter populations of less than 100 cells/ml.

Based on the description above it is indicated that temperature is most influential to green coccoid populations in winter and in the early part of the warming of the lake in spring. It is also indicated that if other factors are adequate, as in the western basin the temperature influence will be extended to the period just prior to lake cooling.

Soluble Phosphorus and Temperature

The plot of green coccoid algae and soluble phosphorus shows no discernible trend. Adding temperature to the relationship still produces no clearly defined characteristics. However a few important conclusions can be drawn. *Green coccoid algae increase as the water warms in spring through a temperature of about 12°C (54°F), while not showing any really significant preference for higher phosphorus concentrations.* Above 12°C however, green coccoid algae appear to become more phosphorus dependent. Below 12°C phosphorus concentrations of less than 30 μg/l appear adequate to sustain populations greater than 400 organisms/ml, whereas above 12°C, that requirement rises to 50 μg/l or more.

The dependence upon phosphorus continues through maximum water temperature, (25°C (77°F) and into the cooling period. In the cooling period and below 20°C (68°F) the correlation disappears and does not reappear, although the green coccoid algae do seem to prefer 50-60 μg/l of soluble phosphorus for the remainder of the year.

Inorganic Nitrogen and Temperature

A plot of inorganic nitrogen temperature (Fig. 34), and green coccoid algae shows that below 10°C (50°F) the green coccoids appear to be more related to temperature than to nitrogen. Above 10°C the influence of inorganic nitrogen becomes more apparent, the greater the nitrogen concentration, the higher the populations. As the temperature increases above 10°C (50°F) larger amounts of inorganic nitrogen are required to produce similar populations. For example at 12°C (54°F) 200 µg/l inorganic nitrogen will produce 300 green coccoid algal cells/ml, but at 22°C (72°F) 600 µg/l is needed for the same population.

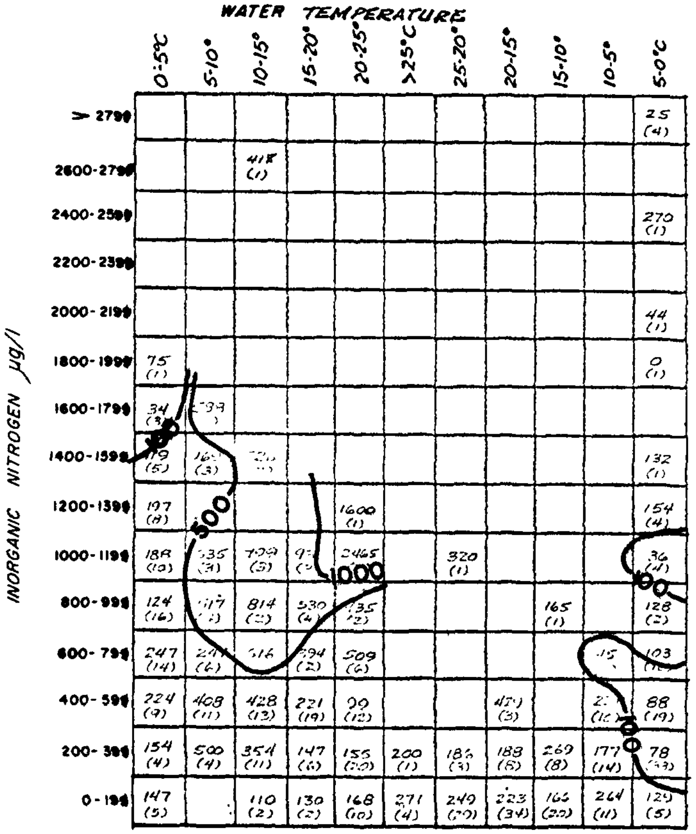
After the lake begins to cool, there appears to be no clear relation of green coccoid algae to inorganic nitrogen, the populations being relatively low regardless of concentration. If there is any preference at all, it seems to be for lower amounts of inorganic nitrogen.

The relationship between inorganic nitrogen, soluble phosphorus, and temperature with green coccoid algae is listed in Table 12.

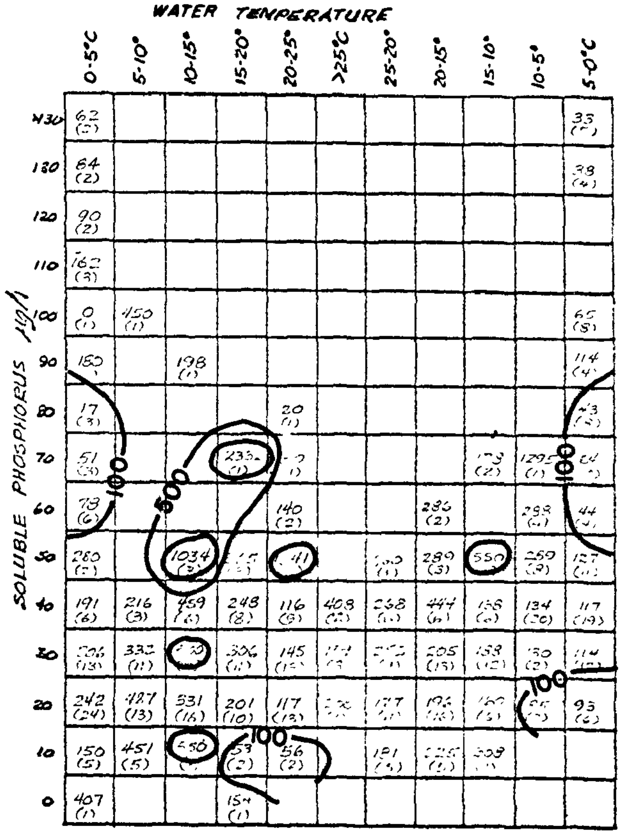
TABLE 12

CONCENTRATIONS OF INORGANIC NITROGEN AND PHOSPHORUS REQUIRED TO PRODUCE VARIOUS POPULATIONS OF GREEN COCCOID ALGAE DURING WARMING MONTHS

Temp.	Inorganic N (µg/l)			Soluble P (µg/l)		
(°C)	1,000 org/ml	500 org/ml	100 org/ml	1,000 org/ml	500 org/ml	100 org/ml
0-5	-	-	400	-	-	10
5-10	-	300	100	-	20	<10
10-15	>900	600	200	50	10	<10
15-20	>1,000	850	400	60	50	20
20-25	1,100	900	600	50	50	40



Green Coccoid Algae vs. Temperature and Inorganic Nitrogen



Green Coccoid Algae vs. Temperature and Soluble Phosphorus

FIG. 34 GREEN COCCOID ALGAE AS RELATED TO WATER TEMPERATURE, SOLUBLE PHOSPHORUS, AND INORGANIC NITROGEN IN LAKE ERIE NEARSHORE WATERS.

Upper numbers in each block are average populations of green coccoid algae per ml; number of samples in parenthesis

BLUE-GREEN COCCOID ALGAE

Water Temperature

Lake Erie water temperature and blue-green coccoid algae are clearly related (Figs. 35 and 36). It is well-known that blue-greens proliferate above a temperature of 20°C (68°F) and this study is further confirmation of that fact. In Lake Erie however, maximum populations do not occur when the water temperature is rising. *Rather the maximum nearly always occurs just after the lake reaches peak temperature and begins to cool in August and September.* Apparently when the lake temperature begins to drop, some undetermined phenomenon occurs which in turn stimulates or allows increased blue-green growth.

It is possible that during the cooling period the actual water temperature, or even the rate of water temperature decline, may trigger the extensive blue-green coccoid algal growths. It is also possible that the algal grazers, the zooplankton which were not considered in this study, were primarily affected by the temperature downswing killing the grazers and indirectly allowing the blue-green accretion. Most likely, however, blue-green blooms are stimulated and sustained by nutrients diffused or resuspended from the bottom sediments, especially where those blooms occur at a great distance from tributary inputs, such as the northern island area or midlake. *It would appear that sediment nutrient recycling to overlying waters is enhanced by surface cooling, resulting in top-to-bottom convective mixing.* Under conditions of cooling the lake waters are readily mixed even without additional wind-induced agitation. Winds however can induce upwelling, such as commonly occurs in the northwestern part of the central basin, making the situation even more ideal for nutrient recycling

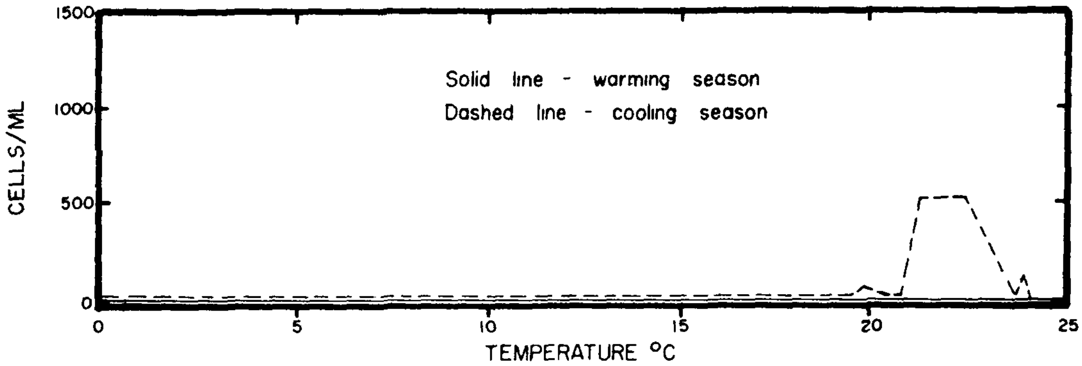


FIG. 35 BLUE-GREEN COCCOID ALGAE VS. WATER TEMPERATURE IN NEARSHORE WATERS OF CENTRAL BASIN.

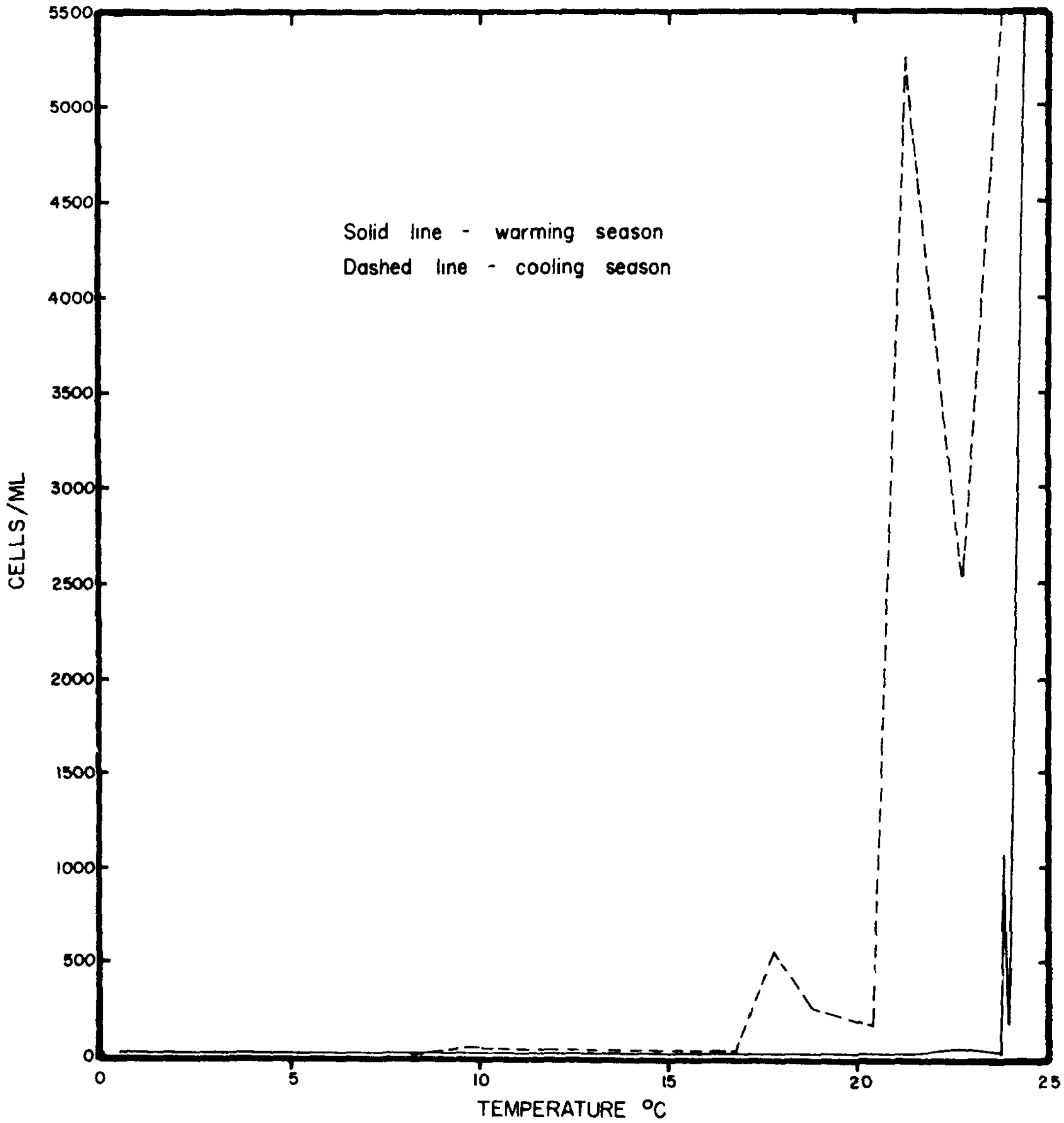


FIG. 36 BLUE-GREEN COCCOID ALGAE VS. WATER TEMPERATURE IN NEARSHORE WATERS OF WESTERN BASIN.

and blue-green blooms.

Soluble Phosphorus and Temperature

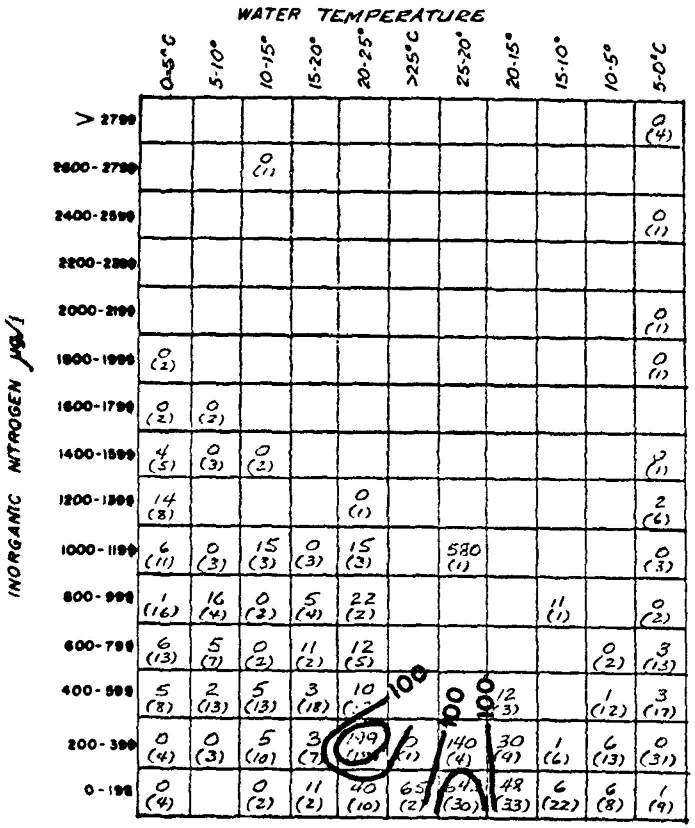
A plot of blue-green coccoid algae and soluble phosphorus also shows no discernible trend. A relation does develop however when blue-green coccoids are correlated with phosphorus and temperature together (Fig. 37). *Below a temperature of 25°C (77°F), when the lake is warming, blue-green coccoid algae respond neither to temperature nor to phosphorus.* But, as noted previously, when the lake begins to cool, they appear, often in great numbers and as shown in Fig. 37 are responsive to soluble phosphorus. The highest populations appear when soluble phosphorus is 50 µg/l or more.

When the temperature falls, during the cooling season, to below 20°C (68°F), blue-green coccoid algae decline. By the time the lake has reached 15°C (59°F) these algae are no longer significant. Although blue-green coccoid algae can be found in very small numbers at almost any time of the year, they are restricted in importance to late summer and very early fall.

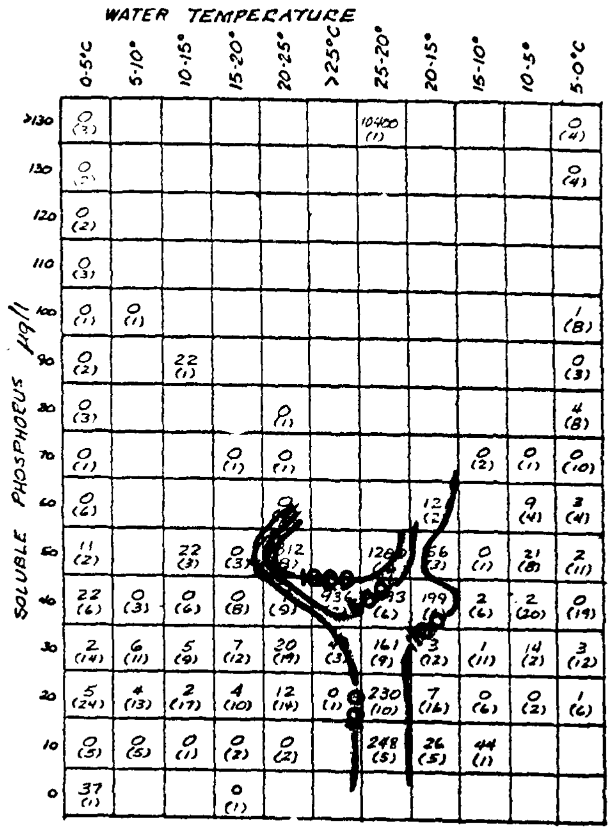
Inorganic Nitrogen and Temperature

Fig. 37 shows the correlation of inorganic nitrogen to blue-green coccoids. If a correlation exists it is inverse, higher populations existing at low concentrations of inorganic nitrogen.

Since some blue-green algae can fix atmospheric nitrogen, it is assumed that this nutrient cannot limit all blue-green productivity in Lake Erie. However the possibility remains that if inorganic nitrogen were plentiful at this time of the year, green algae might continue to dominate with blue-greens subordinate. *It is indicated that limited populations of green algae due to nitrogen starvation minimize ecological competition thus*



Blue-Green Coccoid Algae vs. Temperature and Inorganic Nitrogen



Blue-Green Coccoid Algae vs. Temperature and Soluble Phosphorus

FIG. 37 BLUE-GREEN COCCOID ALGAE AS RELATED TO WATER TEMPERATURE, SOLUBLE PHOSPHORUS, AND INORGANIC NITROGEN IN LAKE ERIE NEARSHORE WATERS.

Upper numbers in each block are average population of blue-green coccoid algae per ml; number of samples in parenthesis *allowing the dominance of nitrogen fixing blue-green algae.*

TABLE 13

CONCENTRATIONS OF INORGANIC NITROGEN AND SOLUBLE PHOSPHORUS REQUIRED TO PRODUCE VARIOUS POPULATIONS OF BLUE-GREEN COCCOID ALGAE

Temp. (°C	Inorganic N (μg/l) 1,000 org/ml	500 org/ml	100 org/ml	Soluble P (μg/l) 1,000 org/ml	500 org/ml	100 org/ml
0-5	-	-	-	-	-	-
5-10	-	-	-	-	-	-
10-15	-	-	-	-	-	-
15-20	-	-	-	-	-	-
20-25	-	-	-	-	50	40
25-20	-	>200	>200	50	40	10

BLUE-GREEN FILAMENTOUS ALGAE

Water Temperature

Blue-green filamentous algae show the same general correlation with temperature as do the blue-green coccoids. That is that maximum populations occur after the lake begins to cool (Figs. 38 and 39). It is assumed that this response is for the same reasons as described for blue-green coccoids. *However in the western basin the blue-green filamentous pulse dies out more slowly than in the central basin persisting at significant populations (>1,000 cells/ml) to a temperature of 10°C (50°F) in autumn.* This probably is a result of a generally higher nutrient supply in the western basin, perhaps in turn a result of easier mixing in the basins shallow waters.

Soluble Phosphorus and Temperature

Fig. 40 shows blue-green filamentous algae plotted against soluble phosphorus and temperature. From the time of their dominance, at the period of warmest water, 25°C ±, down to a temperature of 10°C (50°F) or less, the

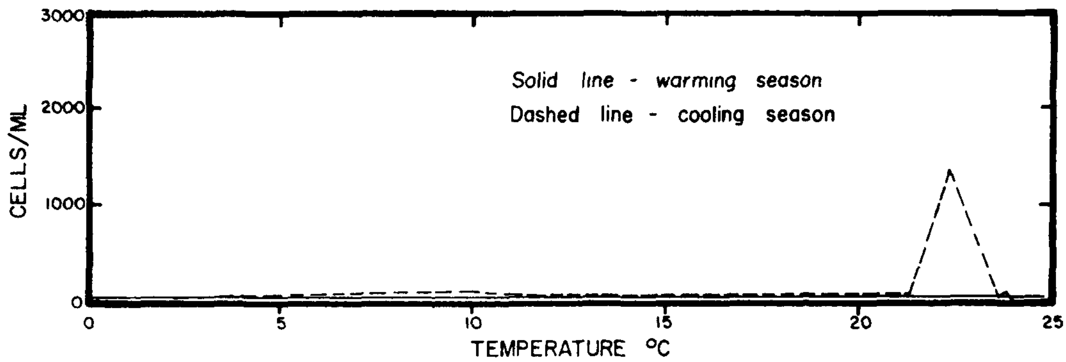


FIG.38 BLUE-GREEN FILAMENTOUS ALGAE VS WATER TEMPERATURE IN NEARSHORE WATERS OF CENTRAL BASIN.

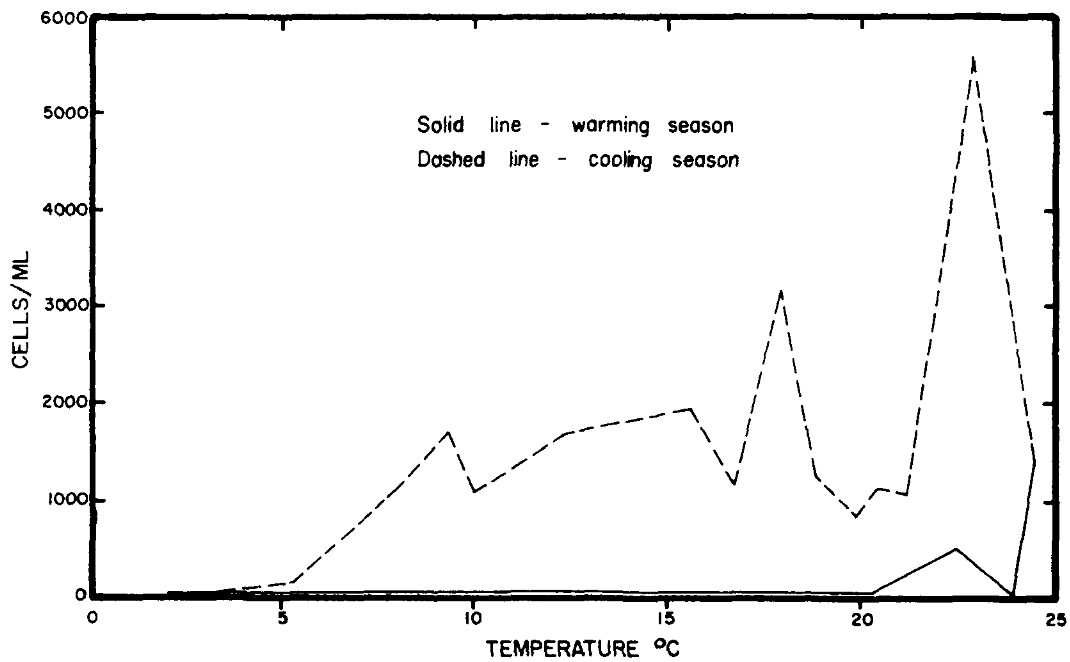


FIG.39 BLUE-GREEN FILAMENTOUS ALGAE VS. WATER TEMPERATURE IN NEARSHORE WATERS OF WESTERN BASIN.

blue-green filamentous algae show a rather clear and direct relation to soluble phosphorus. At concentrations of 30 µg/l or less the filamentous types are not significant but above this level populations increase greatly.

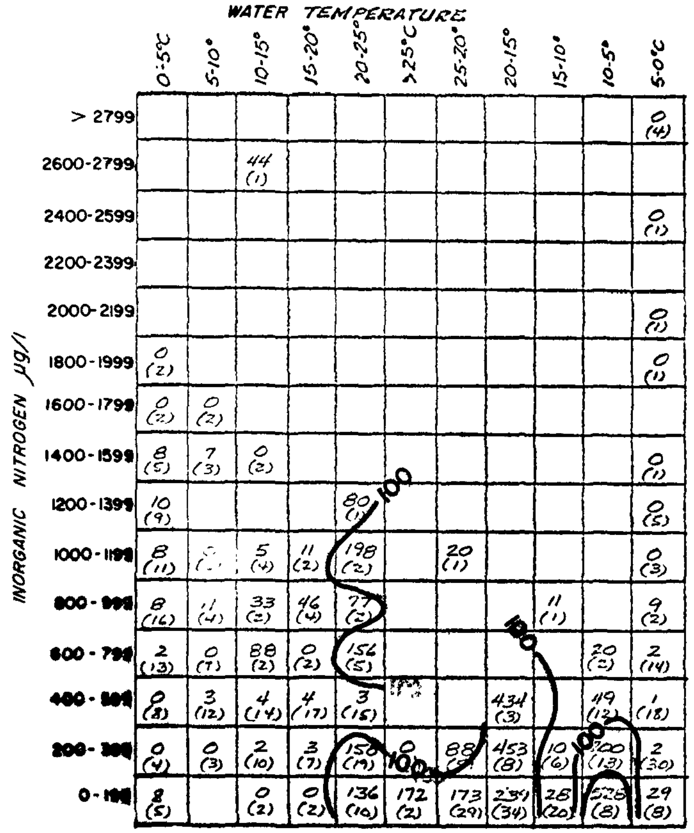
In fall after the temperature decreases below 10°C (50°F) and until it reaches above 20°C (68°F), the following year, blue-green filamentous algae are not an important component of the algal population regardless of the phosphorus concentration.

Inorganic Nitrogen and Temperature

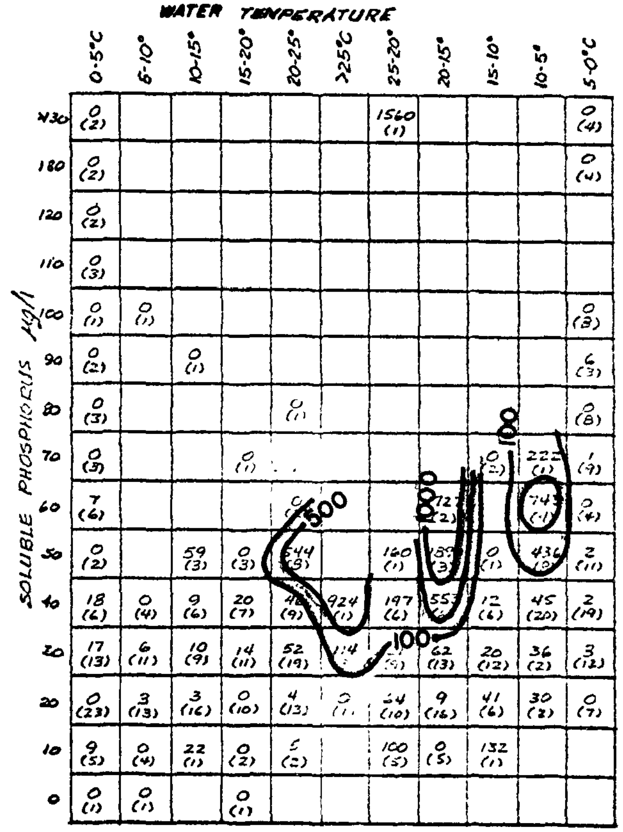
Fig. 40 also shows the relation of blue-green filamentous algae populations to temperature and inorganic nitrogen. As with the blue-green coccoids if a relationship exists, it is inverse, higher populations occurring with lower nitrogen concentrations. Again the ability to fix atmospheric nitrogen allows the blue-green filaments to proliferate during periods of water inorganic nitrogen depletion.

As with soluble phosphorus, inorganic nitrogen shows no relation to blue-green filamentous algae during winter and spring, populations being insignificant the entire period regardless of nutrient concentration.

Table 14 gives requirements for various blue-green filamentous populations.



Blue - Green Filamentous Algae vs. Temperature and Inorganic Nitrogen



Blue - Green Filamentous Algae vs. Temperature and Soluble Phosphorus

FIG. 40 BLUE-GREEN FILAMENTOUS ALGAE AS RELATED TO WATER TEMPERATURE, SOLUBLE PHOSPHORUS, AND INORGANIC NITROGEN IN LAKE ERIE NEARSHORE WATERS.

Upper numbers in each block are average populations of blue-green filamentous algae per ml; number of samples in parenthesis

TABLE 14

CONCENTRATIONS OF INORGANIC NITROGEN AND SOLUBLE PHOSPHORUS REQUIRED FOR VARIOUS POPULATIONS OF BLUE-GREEN FILAMENTOUS ALGAE

Temp. (°C)	Inorganic N (μg/l) 1,000 org/ml	500 org/ml	100 org/ml	Soluble P (μg/l) 1,000 org/ml	500 org/ml	100 org/ml
0-5	-	-	-	-	-	-
5-10	-	-	-	-	-	-
10-15	-	-	-	-	-	-
15-20	-	-	-	-	-	-
20-25	-	-	200	-	50	40
25-20	-	-	200	-	-	20
20-15	-	<500	200	45	40	20
15-10	-	-	-	-	-	-
10-5	-	<200	200	-	55	40

FUTURE INVESTIGATIONS

This study represents the beginning of the preparation of an algal response analysis system for Lake Erie. By present-day analytical standards it is rather crude. However it has demonstrated that such a system most likely can be designed and at minimum expense. It appears that it can be designed without an elaborate, sophisticated program of sampling and analysis.

At this point an effective algal response prediction system does not appear to demand that we determine the part played by trace elements, nor does it demand that high frequency sampling and analyses be accomplished during pulses of any particular algal species. Such determinations might refine the system, but presently appears unnecessary as long as the gross features of the system have not been fully defined.

This study lacks information with respect to the factors governing algal metabolism. This information deficiency includes the algal capacity for nutrient storage and subsequent stimulation from dormancy by extraneous phenomena.

Furthermore some additional parameters presently appear necessary namely carbon, silica, and zooplankton. It appears that the role of carbon is important and at times may be limiting to algae. It is possible that spring diatom repression could limit Lake Erie carbon content especially in midlake, to the point where green algae and subsequently blue-green algae would become insignificant.

Silica is necessary for diatom skeletal formation. It may be diatom limiting during certain parts of the year. Although silica limitation for winter and early spring diatom repression is a long way from consideration, a knowledge of the silica cycle could be most useful in understanding other pertinent chemical and biological cycles.

The role of zooplankton must be considered. As algal grazers they can affect algal populations to the point where phytoplankton-nutrient relationships can be easily misunderstood and subsequently misrepresented.

Perhaps the most difficult segment of a response analysis system, is the determination of bottom sediment nutrient contribution. Quantification of recycled nutrients should lead to greater confidence in the prediction of the results of input control in both immediate and long-term effects on all algal species.

Future study will involve the refinement of the biological, chemical, and physical factors so rudimentally presented in this report. In addition new relationships including carbon, silica, and zooplankton will be studied. At the same time the second year of data will be added to the one year described herein. It is expected also that computer programs will be designed to facilitate the project.

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