THE DYNAMICS OF ZOOPLANKTON POPULATIONS IN WESTERN LAKE ERIE INCLUDING THE EFFECT OF THERMAL EFFLUENT

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ABSTRACT

THE DYNAMICS OF ZOOPLANKTON POPULATIONS IN WESTERN LAKE ERIE INCLUDING THE EFFECT OF THERMAL EFFLUENT

By

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The result of the dynamics of zooplankton populations in western Lake Erie from 1970 to 1975, including the effect of thermal effluent on the aquatic ecosystem are presented. The study area included four different habitats: lake shore area, a discharge canal, a shallow marsh creek, and a highly polluted river. In general, the total zooplankton population decreased from 1971 to 1973 and started to increase somewhat in 1974. The zooplankton population in 1975 followed the typical pattern of the spring increase at that time of the year. In terms of the precent composition of the three major groups, cladocerans were the least in abundance as compared with the other two groups, rotifers and copepods. Significant changes in the mean density and the mean biomass in the three major groups were observed to occur in different variables (station, depth, and year) for spring, summer and fall seasons. In general, the species composition have remained largely the same as in the past decades; but, some changes have been observed. Changes in the zooplankton populations from 1930 to 1975 were observed to have increased several fold. The detrimental effect of thermal effluent on the zooplankton has been proven reasonably well and to a lesser extent in its beneficial effect. In situations where a sharp temperature increase occurred as in the discharge canal, adverse results were observed through a

decrease in zooplankton. Some growth enhancement in zooplankton populations have been observed to occur in lake stations 4 & 5 and 2 & 3 where a small temperature increment was added to the environment.

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By

Julin D. Lu

A DISSERTATION

Submitted to
Michigan State University
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DOCTOR OF PHILOSOPHY

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DEDICATION

This dissertation is dedicated to
my parents, Mr. and Mrs. Fu-Ning Lu,
my wife, Rita Yang Lu,
and
my daughter, Lavinia Lu

ACKNOWLEDGMENTS

I wish to thank N. R. Kevern, G. W. Mouser, C. R. Humphrys, and M. H. Steinmueller for their guidance, support, and for serving on my committee. This study was supported largely by a grant from the Detroit Edison Company to Michigan State University.

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INTRODUCTION

The objective of this study was to investigate changes in the dynamics of zooplankton populations in western Lake Erie in relation to the effect of thermal effluent from a 3200 megawatt fossil fuel power plant at Monroe,Michigan,on the aquatic ecosystem. The role of thermal effluent on the aquatic ecosystem is controversial largely because of a lack of understanding of this complex subject and the unavailability of data from long term studies. This study was approached both quantitatively and qualitatively by studying both the density and biomass of the dominant species and groups of zooplankton. Studies addressed variations of season and year, horizontal and vertical spatial aspects and temperature. The study period began in 1970 before the operation of the power plant (pre-operational) and continued to 1975 (post-operational). The power plant began its operation in 1971 intermittently. Plankton in Lake Erie has been studied quite extensively. However, most of these studies were limited to short term and qualitative studies. Because of the variability inherent in the dynamics of populations of an aquatic ecosystem, a long term study is imperative before one could draw any quantitative interpretations. This study was part of an ecological investigation of the effect of thermal effluent on the aquatic ecosystem (Parkhurst, 1971; Marcus, 1972; Nalepa, 1972; Edwards, 1973; Kreh, 1973). Some of the more important studies on western Lake Erie include: Wright (1955), Fish (1929), Chandler (1940), Jahoda (1948), Davis (1954, 1958, 1962, 1969), Humschman (1960), Bradshaw (1964), Britt et al. (1973), and Watson (1976).

Study Area

Lake Erie is a relatively shallow lake. Wright (1955) has observed that the average depth in the western basin is about 8 m. Along the western shore, a 6.4 m contour line extends 8-11 km from the shoreline (Figure 1).

Though the western basin only comprises about five percent of the total Lake Erie volume, it receives about 95 percent of the total drainage entering into the lake. The two major waterways, the Detroit River and Maumee River, supply 95 percent and 3 percent, respectively, of the inflow to the western basin. The current movement along the western shore tends to circulate clockwise (Andrews, 1948) as a result of the prevailing south-westerly winds together with the interactions of the Detroit and Maumee Rivers.

Lake stations (1-6) were positioned in a straight line and parallel to the prevailing north-easterly current (Figure 2). The lake basin sediment in stations 1 and 2 were composed mainly of silt, sand, and gravel; in stations 3-5 it was mainly composed of sand. Station 6 sediment was mostly silt.

Plum Creek (station 7) is a broad embayment of about 1 km in length and 1-2 m in depth. Its bottom sediment consisted mainly of silt, clay, and detritus. It flows into the discharge canal at about 1 m^3/sec.

The discharge canal was constructed during 1969 and 1970 for the purpose of discharging the cooling water from the electric power plant. The canal is about 2 km long, 100 m wide, and 6-7 m deep. Its bottom constituents are similar to that in Plum Creek.

The Raisin River was a severely polluted waterway receiving a heavy load of pollutants from Monroe, Michigan, including municipal waste, heavy

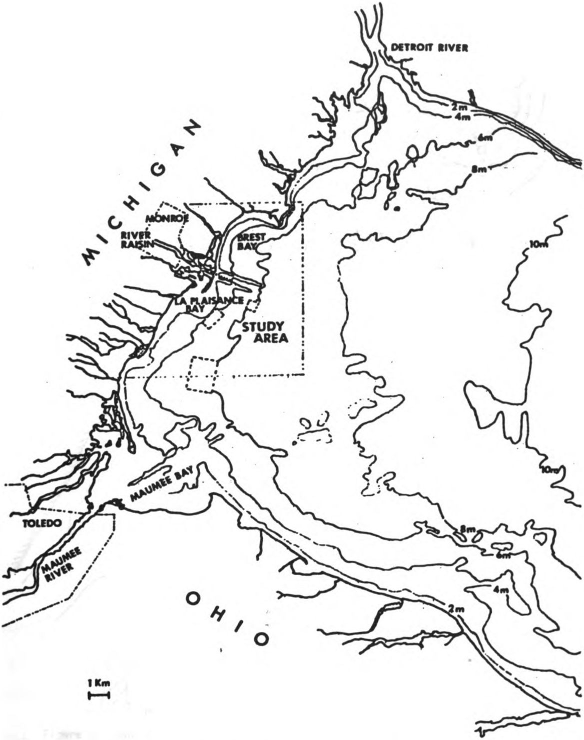


Figure 1. Map of western Lake Erie and specific study area.

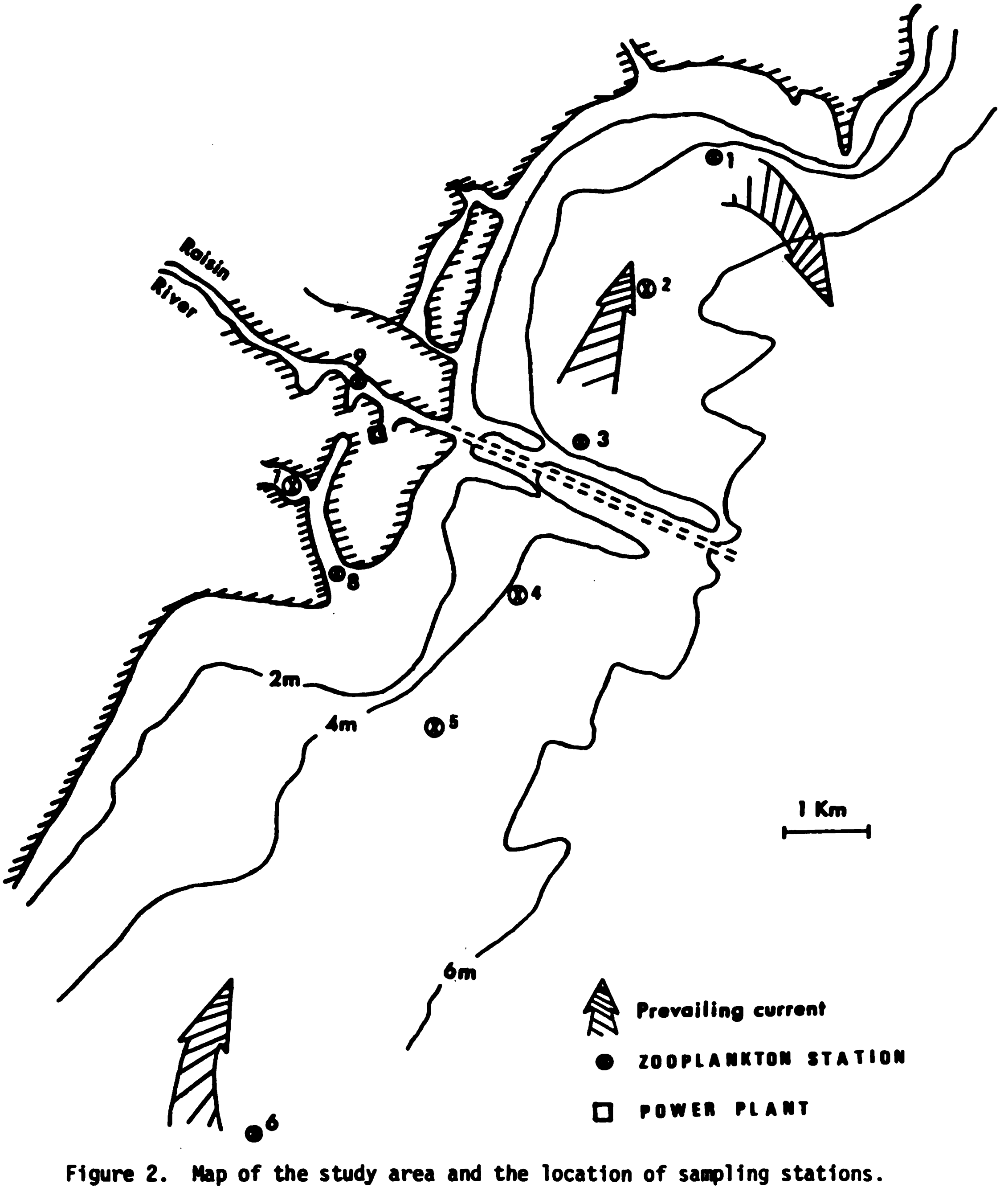


Figure 2. Map of the study area and the location of sampling stations.

metals, and paper mill discharge. The river is about 6-7 m deep. Its bottom sediment consisted of mainly putty-like silt, oily ooze, and paper fibers. It had a discharge rate of 17 m^3/sec.

Experimental Design

Water samples were taken from four different habitats, the lake area (stations 1-6), Plum Creek (station 7), the discharge canal (station 8), and the Raisin River (station 9) (see Figure 2). At each station, each of the three replications were sampled at two different depths (0.5 m and 2.5 m) except for Plum Creek where samples were taken only at 0.5 m due to its shallowness. The sampling period began in May 1970 and ended in June 1975. Samples were taken at 2-3 week intervals from spring to late fall except in 1975 when samples were taken monthly and without those of stations 5 and 7.

Significant changes in zooplankton for different variables (station, depth, and year) were tested for the three dominant orders, Rotifera, Cladocera, and Copepoda (density and biomass) for each season separately (spring, summer, and fall). Significant changes in a variable for a particular season were determined by comparing the mean data from four sampling dates of the same chronological months in different years. Spring, summer, and fall seasons were analyzed for changes from 1970 to 1974. Data from Plum Creek were not included as part of the analysis of variance due to its unequal number of samples, i.e., only one depth. The values for those variables determined to be statistically significant ($p \leq 0.10$) were arranged in increasing order of abundance in accordance with Tukey's multiple range test.

Field and Laboratory Techniques

Samples were collected in an 8-liter Van-Dorn bottle. Four liters were filtered through a No. 25 mesh plankton net. The filtrate was preserved immediately with 5% formalin solution and contained in a volume between 20 and 60 mls depending upon the zooplankton abundance. The zooplankton were measured quantitatively and qualitatively to species in most cases by placing 1 ml aliquot from each sample on a Sedgewick-Rafter counting cell under a microscope. Immature copepods were not identified beyond nauplii or copepodite.

The zooplankton biomass was calculated by the sum of the product of number and size in each species. The value for size was determined by placing an organism into its closest size-category in a biomass-table. The biomass-table was contributed by randomly choosing 60 individuals in each species from different stations and dates of collection. The length and width were measured by a Whipple micrometer. The third dimension assumed the zooplankter to be a particular geometric shape including cone, sphere, ellipsoid, and cylinder. In rotifers, one mean value was calculated for each species. In the Cladocera, Daphnia, Ceriodaphnia, and Diaphanosoma species were seperated in 0.25 mm intervals. The Bosmina and Chydorus species were separated in 0.1 mm intervals. Leptodora Kindtii was excluded from the biomass determination to avoid bias because of its relatively huge size and its rare occurrence. For copepods, species were separated into 0.15 mm. All sample data were converted to number per liter for density and micrograms per liter for biomass.

RESULTS AND DISCUSSION

The mean density and mean biomass from 1970 to 1975 with vertical bars denoting 90% confidence intervals at each sampling date are presented in Figures 3-10. All populations of zooplankton started to increase steadily in early May and decrease in November.

Zooplankton Density

In the lake habitat, the yearly variation in the density of zooplankton was relatively small. Except for the pulse in mid-May 1971, with a mean density of 1,200 organisms/liter, all other major pulses ranged between 800-1,000/liter. The yearly mean density ranged from a low of 310/liter in 1973 to a high of 610/liter in 1971. Values for 1970, 1972, and 1974 were 490, 350, and 480/liter, respectively. The minimum and maximum percent variations were -32 percent in 1973 and +36 percent in 1971, deviating from the 5-year mean. The number of major pulses in a given year varied from one to three. In 1970, 1972, and 1974, two major pulses occurred. In 1971 and 1973, three and one pulses occurred, respectively. The chronological occurrence of pulses also varied from year to year. The primary pulse occurred during late August in 1970, mid-May in 1971, mid-July in 1972, mid-June in 1973, and early August in 1974.

In Plum Creek and the discharge canal, the variation in density was similar including the pattern of yearly variation, the number of pulses, and the chronological occurrence of pulses. The order of density abundance decreased from 1970 to 1973; but in 1974, it rose close to that in 1972. The yearly mean ranged from the low of 170/liter in the creek and 136/liter in the canal during 1973, to the high of 945/liter in the creek and 1,080/liter in the canal during 1970. The minimum percent variations deviating from the 5-year mean were -64 percent and -73 percent for the creek and the canal, respectively, in 1973; the maximum percent variations were +100 percent for the creek and +113 percent for the canal in 1970. In 1970 and 1971, three pulses occurred. In 1972, two occurred in Plum Creek and three occurred in the canal. In 1973, the density in both habitats were low, under 300/liter. In 1974, two pulses occurred. The chronological occurrence of primary and secondary pulses in both habitats coincided closely. The primary and secondary pulses occurred during late August and late May, respectively in 1970; during mid-May and mid-July, respectively, in 1971; during early July and mid-May, respectively in 1972; and during mid-August and mid-October, respectively in 1974. In 1973, one major pulse was observed during mid-June.

In the Raisin River, the yearly variation in the density fluctuated widely. The yearly mean ranged from the low of 103/liter in 1973 to the high of 540/liter in 1974. The minimum and maximum percent variations were -68 percent in 1973 and +70 percent in 1974, deviating from the 5-year mean. A low density was observed in 1970 and 1973. Three pulses occurred in 1971 and 1972. Two occurred in 1974. The chronological occurrence of pulses and their relative size were similar between the creek and the river in 1971 and between the canal and the river in 1972.

Zooplankton Biomass

In the lake habitat, the yearly variation in the biomass was relatively small. Except for the pulse in late June 1970, with a mean of 8,000 μg/liter,

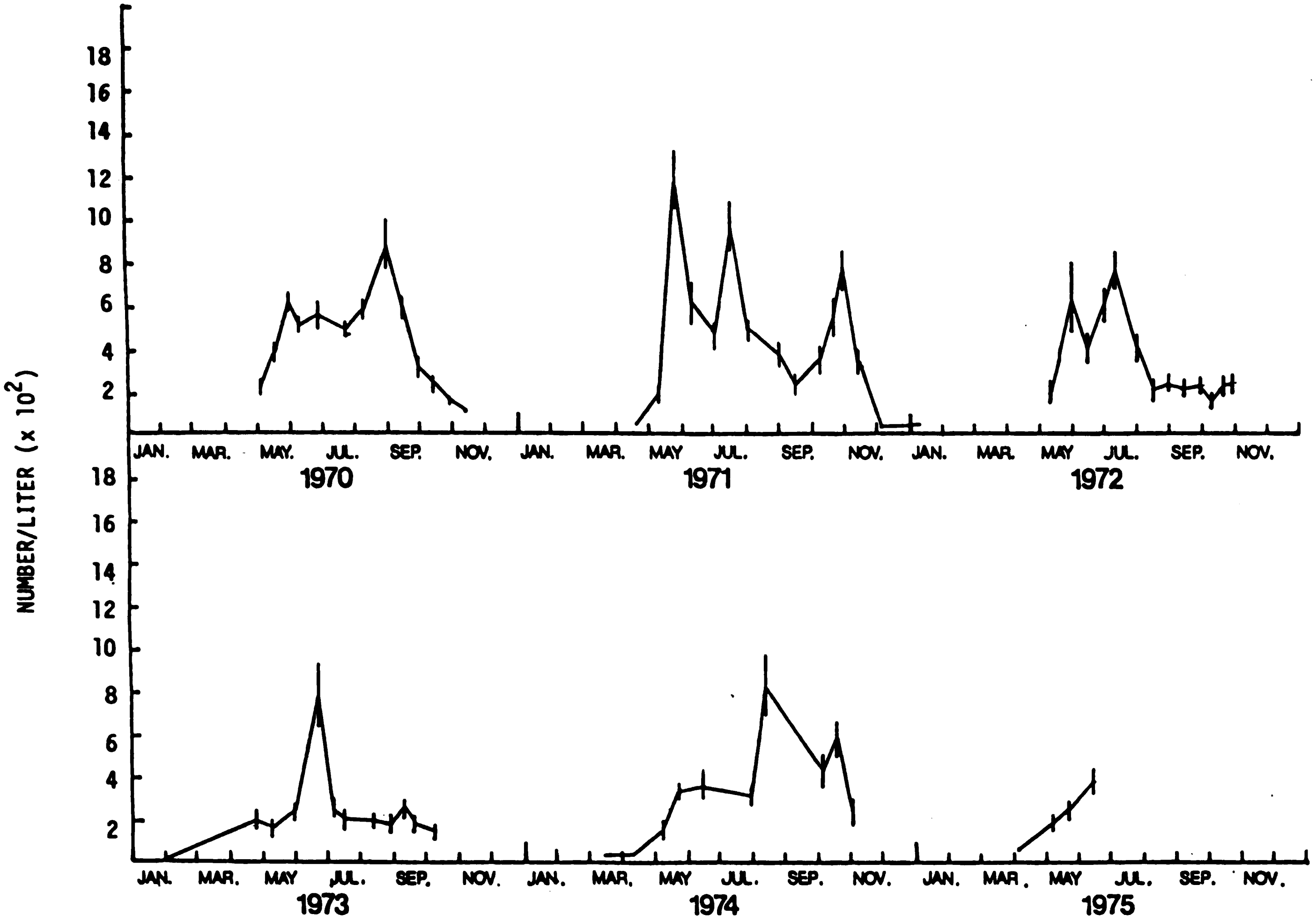


Figure 3. Changes in the mean zooplankton density (number/liter) from 1970 to 1975 in the lake. The vertical bars denote 90% confidence intervals.

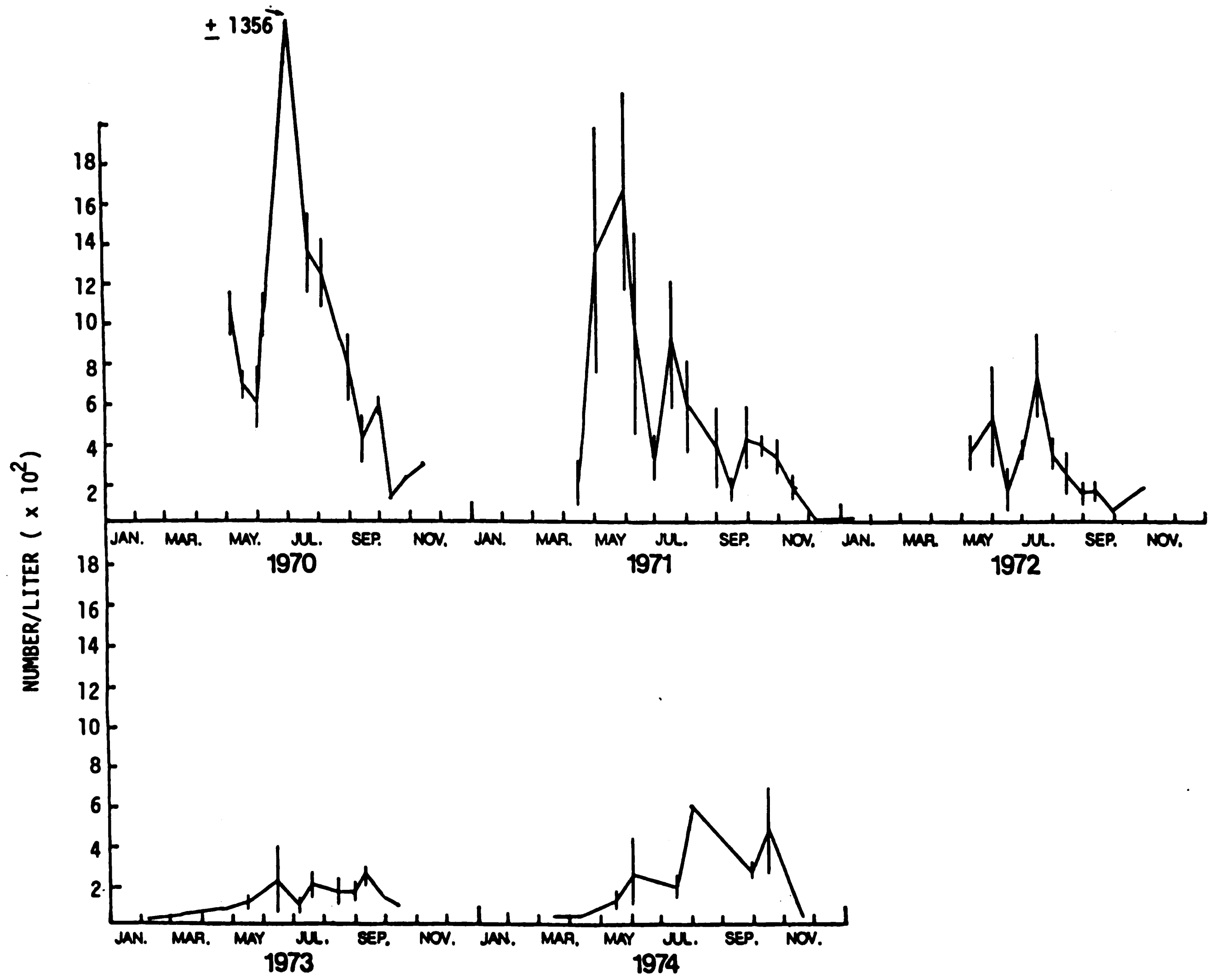


Figure 4. Changes in the mean zooplankton density (number/liter) from 1970 to 1974 in Plum Creek. The vertical bars denote 90% confidence intervals.

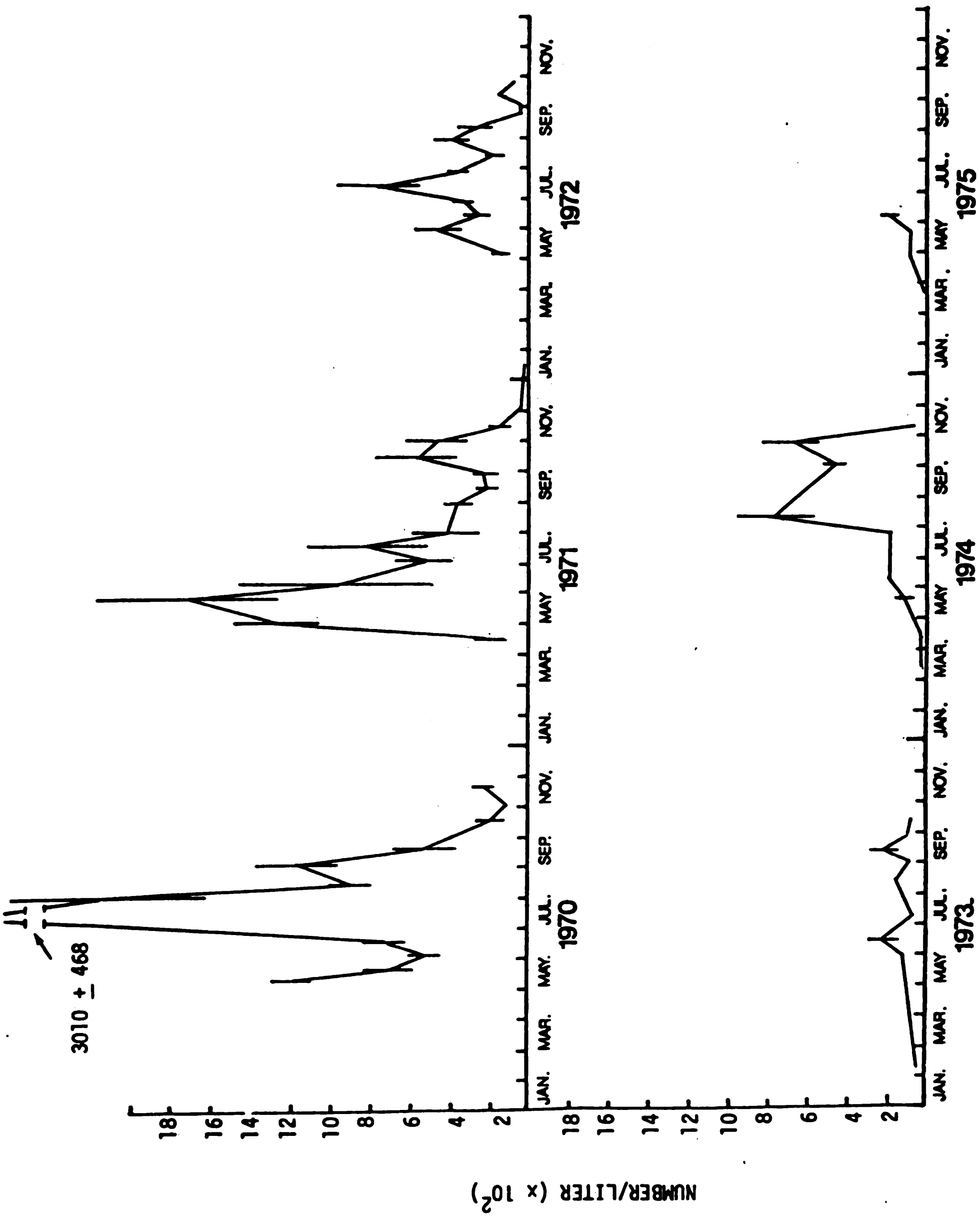


Figure 5. Changes in the mean zooplankton density (number/liter) from 1970 to 1975 in the discharge canal. The vertical bars denote 90% confidence intervals.

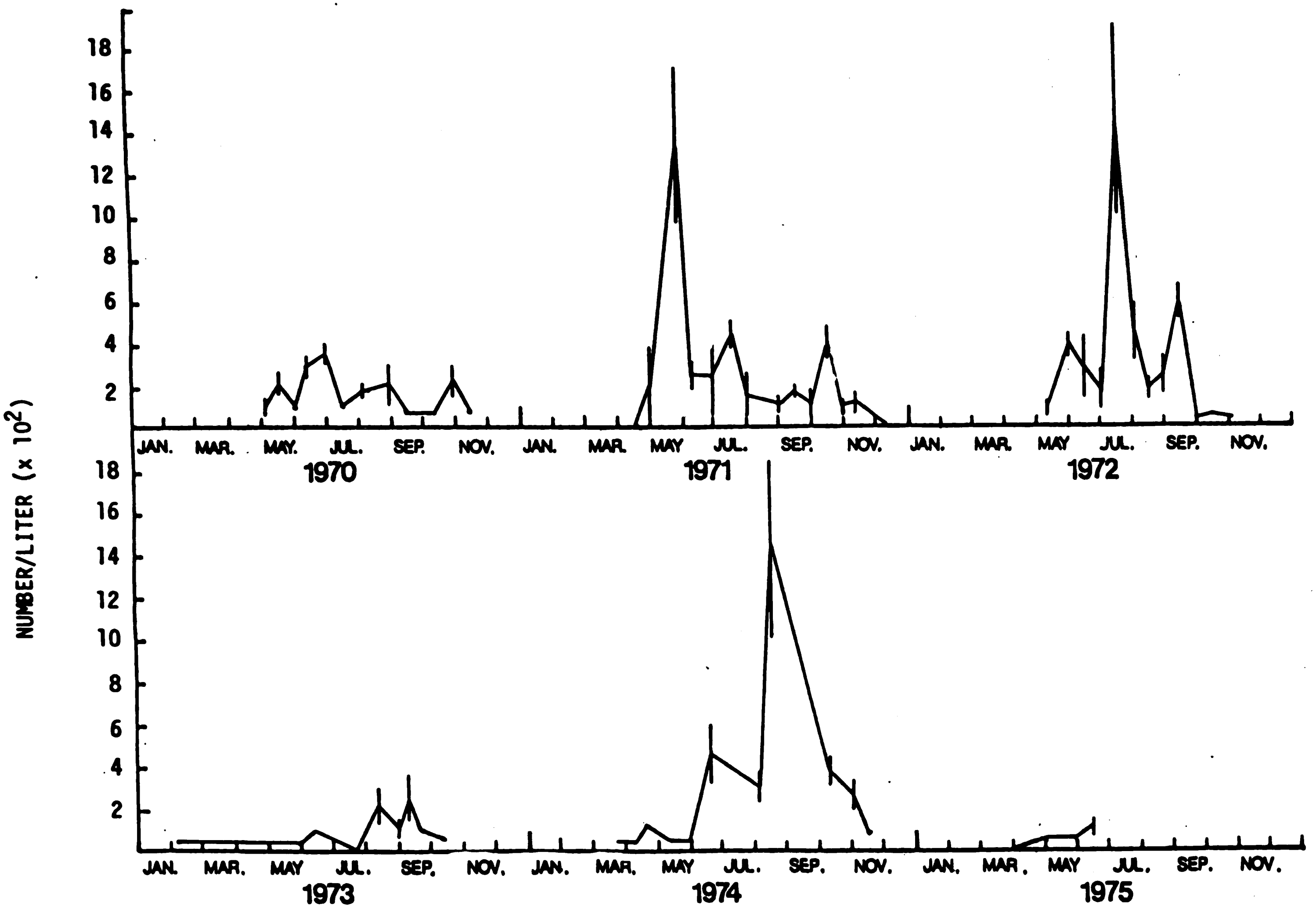


Figure 6. **Changes in the mean zooplankton density (number/liter) from 1970 to 1975 in Raisin River. The vertical bars denote 90% confidence intervals.**

all other major pulses ranged between 9,000 μg/liter to 13,000 μg/liter. The yearly mean biomass ranged from a low of 3,650 μg/liter in 1974 to a high of 5,000 μg/liter in 1971. Values for 1970, 1972, and 1973 were 4,750, 4,300, and 4,350 μg/liter, respectively. The yearly minimum and maximum variations deviating from the 5-year mean were -17 percent in 1974 and +14 percent in 1971, respectively. The low yearly mean biomass occurred in 1974 instead of 1973 as with its corresponding density. Between 1973 and 1974, there was a percentage difference of 39 percent of yearly mean in density and 15 percent in biomass. The number of major pulses in a given year varied from one to two. In 1970 and 1972, two pulses occurred. In 1971, 1973, and 1974, one pulse occurred. The major pulse occurring in October 1971 in density did not have a corresponding pulse in biomass. The chronological occurrence of the primary pulse in density were similar to those in biomass from 1970 to 1974 except for 1971. In 1971, the primary and secondary pulses in density merged into one pulse in biomass. Biomass in the lake habitat area were not similar as those in other habitats.

In general the variation in biomass was similar to those in density between the creek and the canal including the pattern of yearly variation, the number of pulses, and the chronological occurrence of pulses. As in density, the order of biomass abundance decreased from 1970 to 1974 except for those in the canal during 1974 which rose to 2,400 μg/liter. The yearly mean ranged from the low of 700 μg/liter during 1974 in the creek and 1,600 μg/liter during 1973 in the canal to the high of 4,800 μg/liter in the creek during 1970 and 6,800 μg/liter in the canal in 1970. The minimum percentage variations deviating from the 5-year mean were -68 percent in 1974 and -52 percent in 1973 in the creek and the canal, respectively; the maximum percentage variations were +118 percent and +86 percent for the creek and the canal, respectively, in 1970. Two pulses occurred in 1970 and 1972. In 1971, one pulse occurred. The mean biomass in the creek during 1973 and 1974 did not exceed 2,000 μg/liter. Biomass in the canal had three small pulses in 1973 and one major pulse in 1974. The chronological occurrence of primary and secondary pulses in both habitats coincided closely in some years but not in others. In 1970 the secondary and primary pulses occurred during mid-June and mid-September, respectively. The only major pulse in 1971 occurred during mid-June in the creek and mid-July in the canal. The primary pulse in 1972 occurred during mid-July. The primary and secondary pulses occurred during 1973 in the canal in mid-July and mid-June, respectively. The major pulse occurred during 1974 in the canal in mid-June. The chronological occurrence of the major pulses between density and biomass did not coincide closely; most of the primary pulses in density preceded those in biomass.

In the Raisin River, the yearly variation in biomass fluctuated widely as occurred with the density. The yearly mean ranged from the low of 300 μg/liter in 1973 to the high of 4,160 μg/liter in 1970. The minimum and maximum percentage variations deviating from the 5-year mean were -88 percent in 1973 and +63 percent in 1970. The number of major pulses was two in 1970 and 1972, and one in 1971 and 1974. The chronological occurrence of pulses and their relative sizes were similar to those in the creek with the exception of the primary pulse in 1970 and the unusually low mean biomass during 1973 in the river. The pulse pattern between density and biomass in the river were dissimilar.

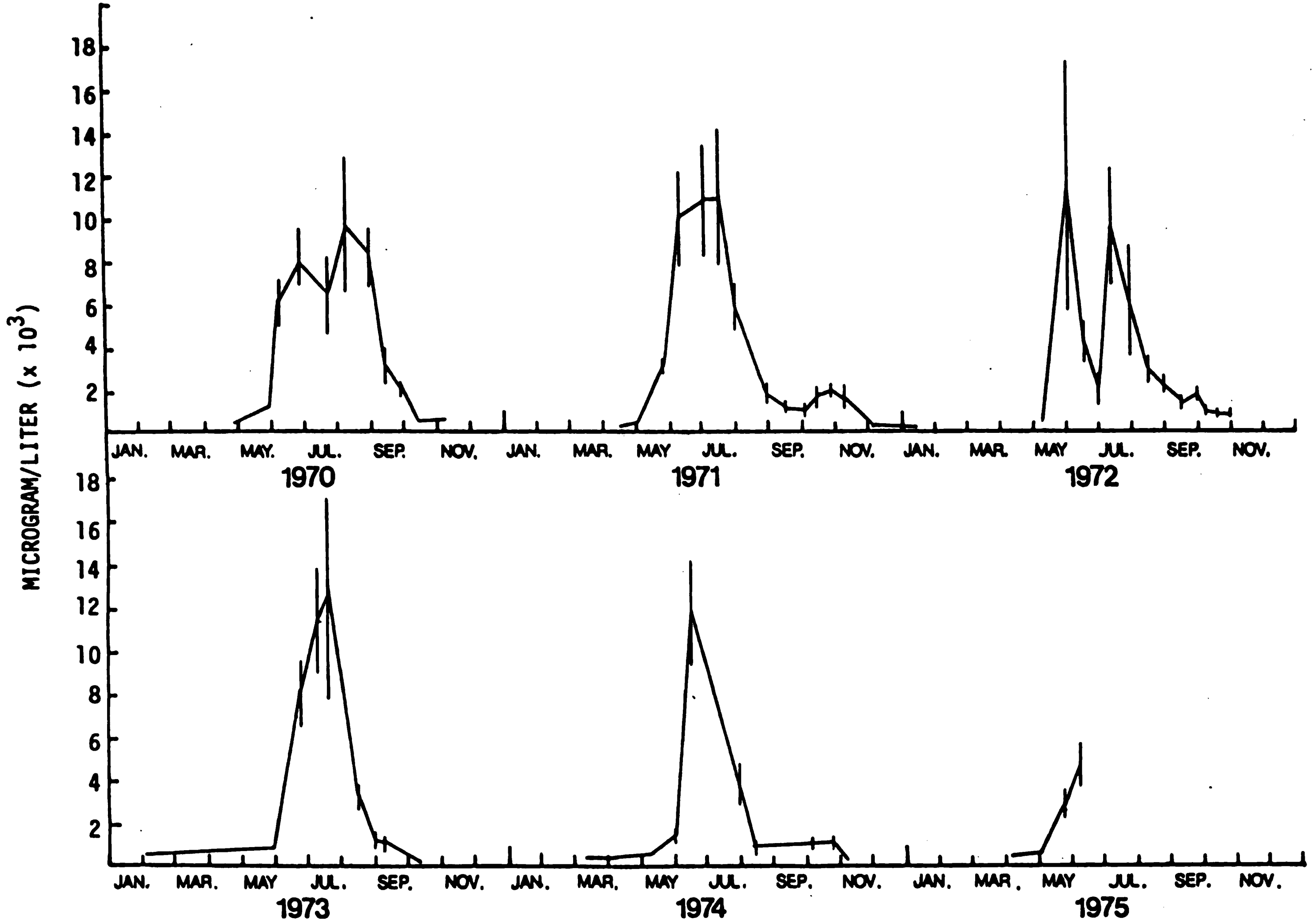


Figure 7. Changes in the mean zooplankton biomass (microgram/liter) from 1970 to 1975 in the lake. The vertical bars denote 90% confidence intervals.

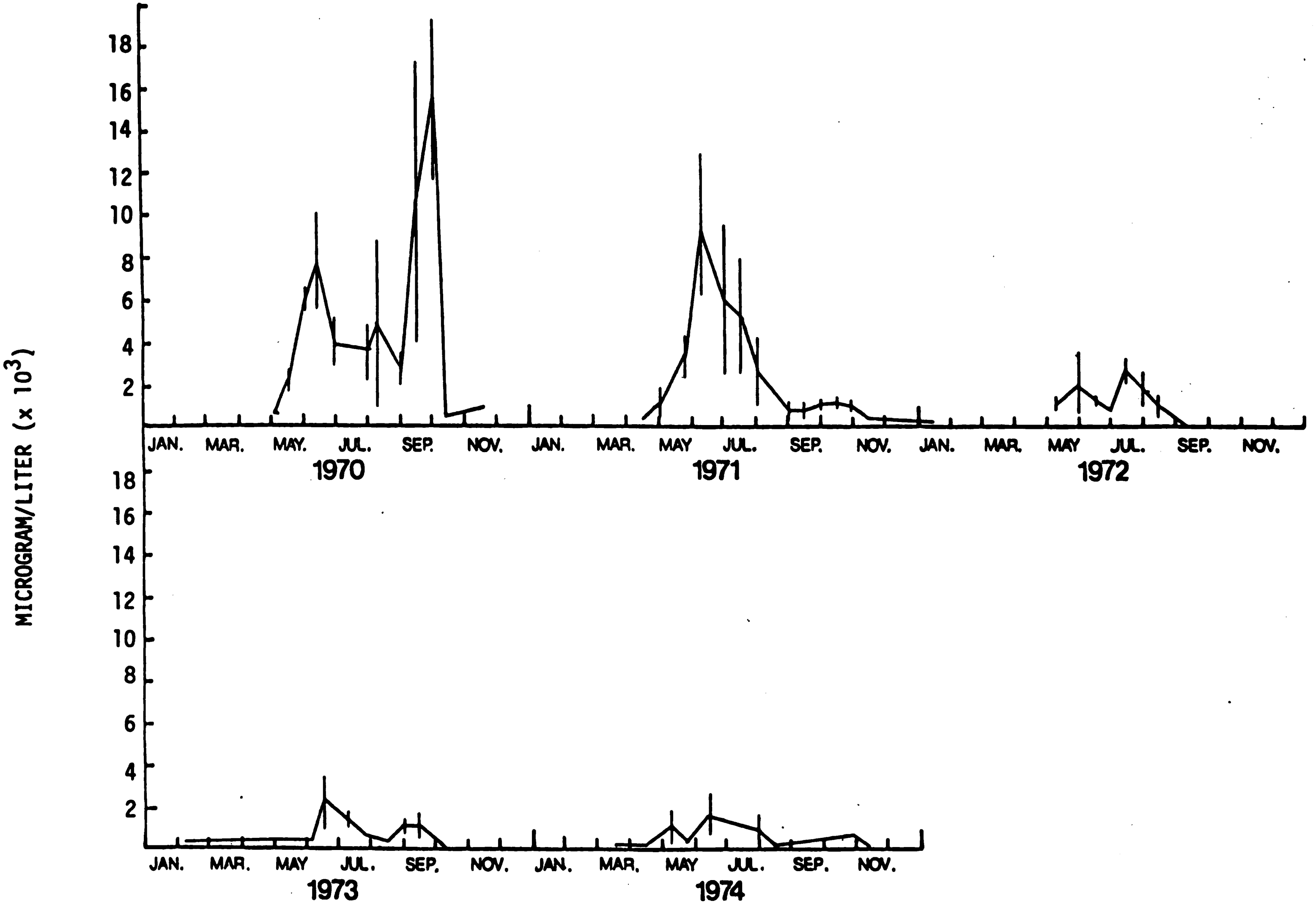


Figure 8. Changes in the mean zooplankton biomass (microgram/liter) from 1970 to 1974 in Plum Creek. The vertical bars denote 90% confidence intervals.

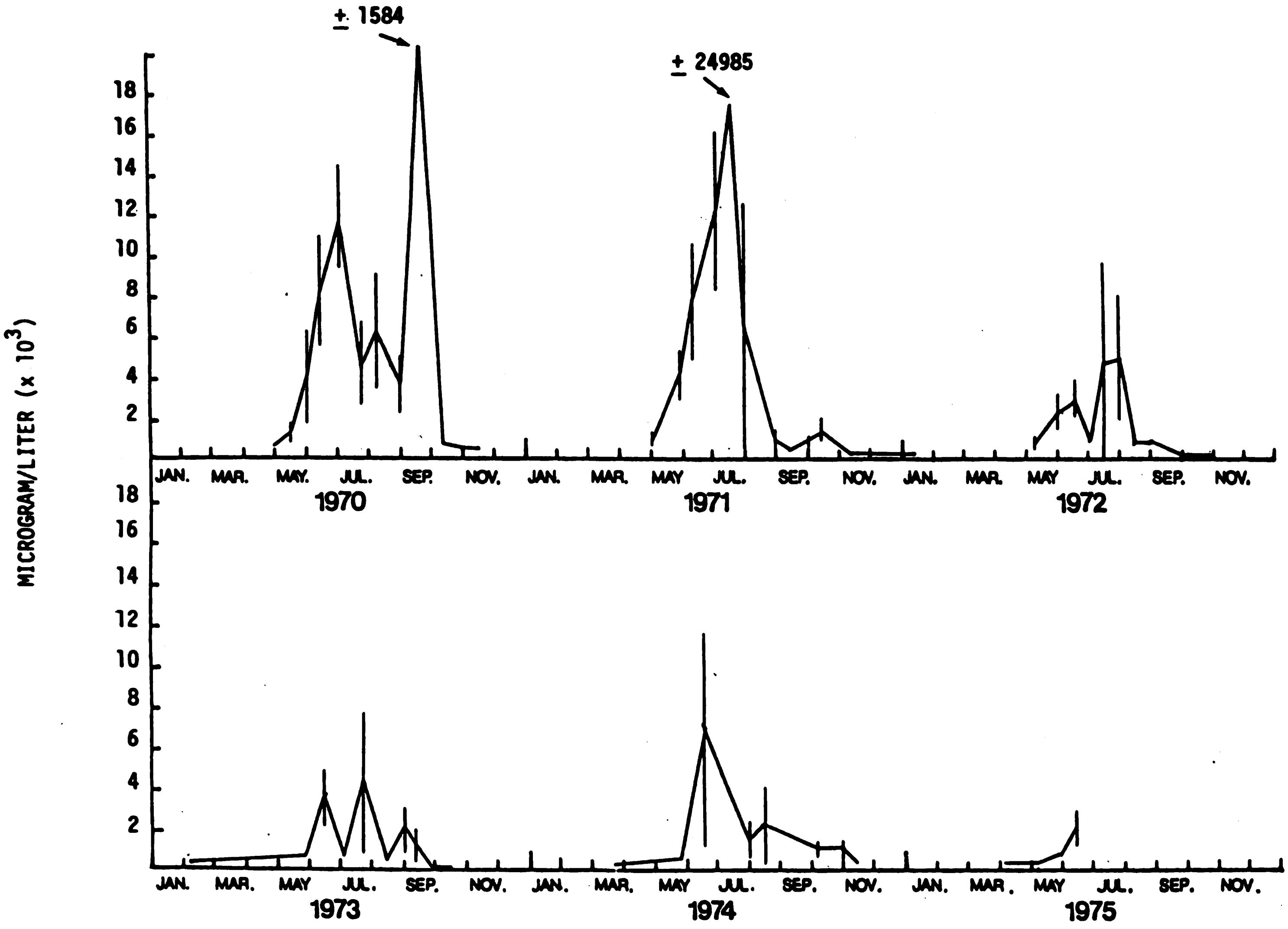


Figure 9. Changes in the mean zooplankton biomass (microgram/liter) from 1970 to 1975 in the discharge canal. The vertical bars denote 90% confidence intervals.

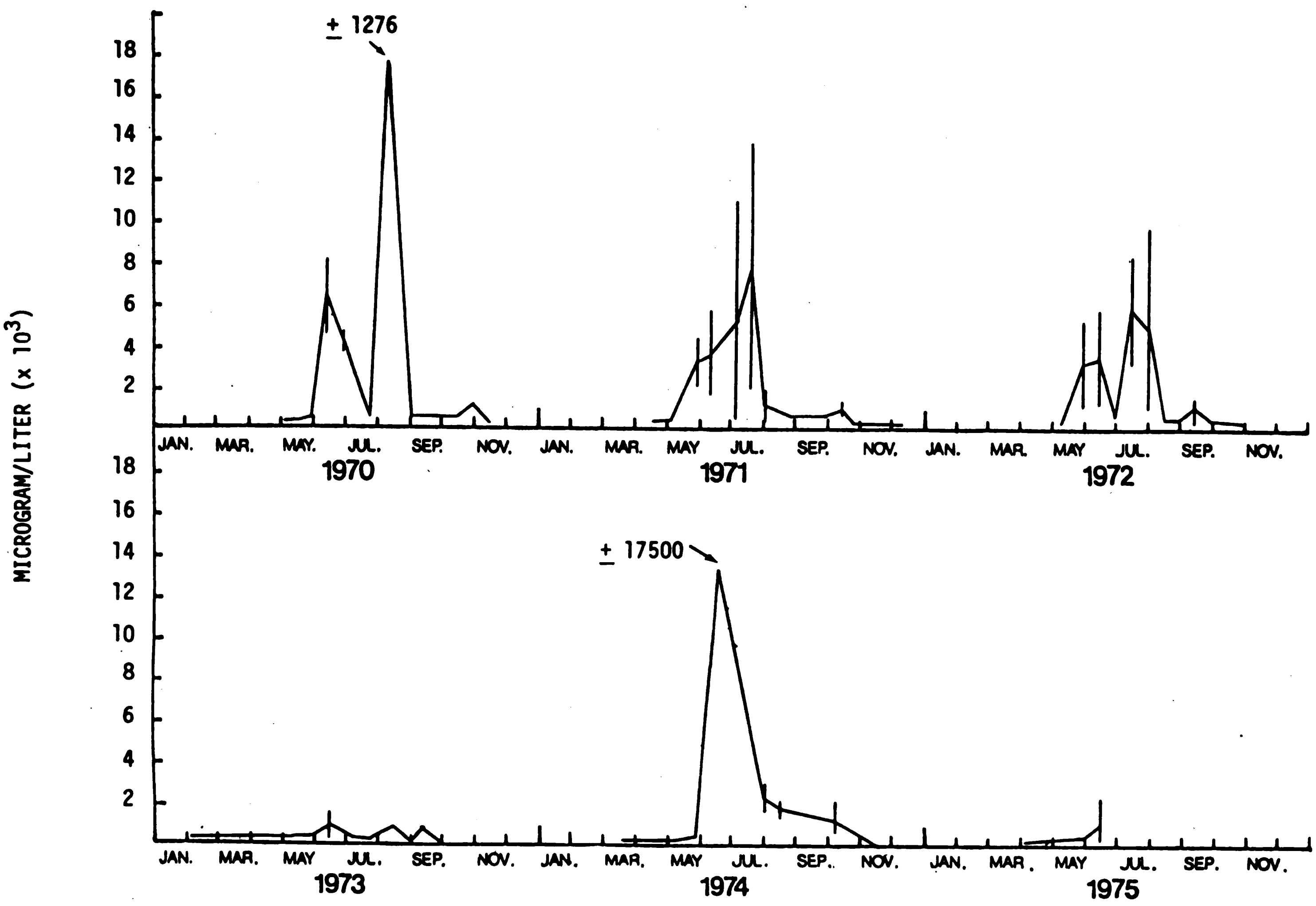


Figure 10. Changes in the mean zooplankton biomass (microgram/liter) from 1970 to 1975 in Raisin River. The vertical bars denote 90% confidence intervals.

Percent Composition of Density of Three Major Groups

Generally, the percentage of relative abundance of density of the three major zooplankton groups was highest in rotifers, followed somewhat closely by copepods with cladoceran being the least, from 1970 to 1975 in all four habitats (Figures 11-14). Little similarities in the pattern of yearly changes were observed among different years and habitats. The total mean of the primary pulse for the four habitats from 1970 to 1974 was 56 percent, 18 percent and 26 percent for rotifers, cladoceran, and copepods,respectively. The secondary pulse was 52 percent, 11 percent, and 37 percent for rotifers, cladocerans, and copepods,respectively. Few cladoceran pulses were observed. The percentage of cladoceran was mostly under 30 percent, except for those in 1970 whose relatively higher abundance occurred mostly from May to July with the exception of the lake habitat which extended into August. The percentage of relative abundance during their primary and secondary pulses showed similar patterns as in their mean yearly distribution. At the time of primary and secondary pulses, the percentage of the three major groups was found to fluctuate widely among different habitats and years.

Percent Composition of Biomass of Three Major Groups

The percentage of relative abundance of biomass in the three major groups of zooplankton was dissimilar as in their corresponding density and fluctuated widely in all four habitats from 1970 to 1975 (Figures 11-14). As in density, the percent biomass of cladoceran were highest in value in 1970, and little similarities in the pattern of yearly changes were observed. Little or no correlations were found among different habitats and years. The total mean in percentage for the four habitats during the time of primary pulses from 1970 to 1974 was 10 percent, 54 percent, and 36 percent for rotifers, cladocerans, and copepods, respectively. The total mean in percentage of the secondary pulse was generally similar to those of primary pulse.

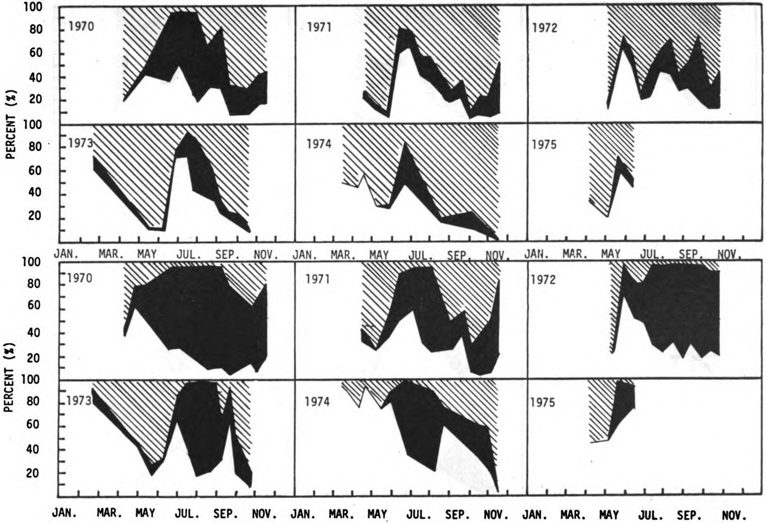


Figure 11. The percent (%) changes in density (top) and biomass (bottom) of the major zooplankton groups in the lake from 1970-1975. Top stipling -- rotifers; middle shaded area -- cladocerans; bottom blank -- copepods.

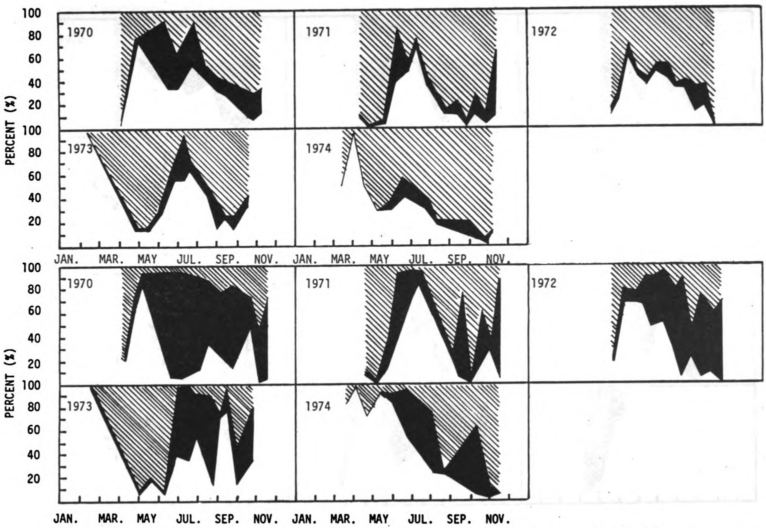


Figure 12. The percent (%) changes in density (top) and biomass (bottom) of the major zooplankton groups in Plum Creek from 1970-1974. Top stipling -- rotifers; middle shaded area -- cladocerans; bottom blank -- copepods.

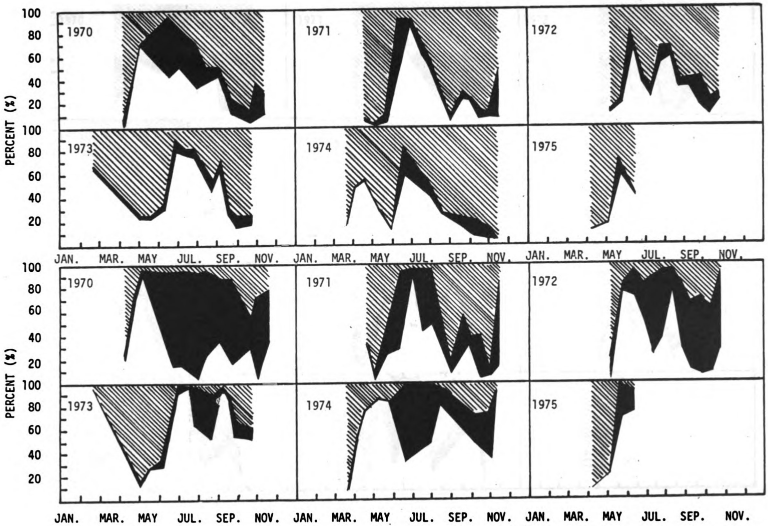


Figure 13. The percent (%) changes in density (top) and biomass (bottom) of the major zooplankton groups in the discharge canal from 1970-1975. Top stipling -- rotifers; middle shaded area -- cladocerans; bottom blank -- copepods.

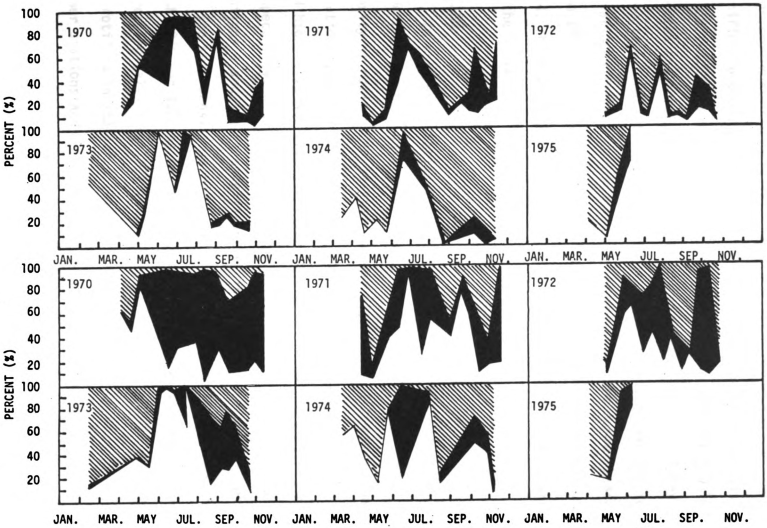


Figure 14. The percent (%) changes in density (top) and biomass (bottom) of the major zooplankton groups in Raisin River from 1970-1975. Top stipling -- rotifers; middle shaded area -- cladocerans; bottom blank -- copepods.

Significant Changes in Seasons

Significant changes of variables, station, depth, and year in the three major zooplankton groups for each of the three seasons are presented. The significance probability of F-statistics of all variables are listed in Tables 1-3. Only those variables whose mean value showed $p \leq 0.10$ are reported and arranged in increasing order of abundance with Tukey's multiple range test. Data from 1970 to 1974 were available and examined for analysis of variance for the spring and fall seasons. For the summer season, data from 1970 to 1973 were used owing to the lack of certain sampling dates in 1974. Data from Plum Creek were excluded from the analysis of variance, due to the unavailable samples at 2.5 m in depth.

Spring

In rotifers, station and year in both mean density and mean biomass were found to be highly significant, $p \leq 0.10$ (Table 4A and 4B). The mean density of rotifers in stations showed significant differences among lake (stations 1-6), canal (station 8), and the river (station 9). The lowest and highest values were 128/liter in station 9 and 301/liter in station 8, respectively, with the lake station values being intermediate. Values of stations 1 and 5 were significantly higher than those of stations 2, 4, and 3. The mean density in years was significantly different among four periods with 1970 and 1972 as one period. Excluding 1970, the mean density decreased chronologically from 1971 (403/liter) to 1974 (80/liter). The mean biomass of rotifers in station 1 (616 μg/liter) was significantly higher than all other stations and was twice that of the next highest, station 6 (292 μg/liter). Station 9 was the lowest with 157 μg/liter. The highest station in density (8) was the third highest in biomass and was half that of the highest, station (1). Significant differences in years were found to occur among three time periods, 1974 and 1970, 1972 and 1973, and 1971. Unlike mean density in years, the order of abundance biomass did not follow any similar or consistent chronological trends.

In cladocerans, the mean density of station and year and the mean biomass of depth and year were found to have significant differences (Tables 5A and 5B). The mean density in station 8 (40.6/liter) was significantly higher than all other stations. Station 9 (18.7/liter) was only slightly higher than the lowest, station 3 (17.8/liter). Significant differences in years occurred among four periods with 1972 and 1970 as one period. A chronological increase was observed from 1974 to 1970-1971. The highest mean density in 1971 (55/liter) was twice that of the next highest year, 1970 (27.6/liter). 1974 was lowest with only 1.35/liter. The mean biomass of cladocerans at depth 2.5 m with 958 μg/liter was significantly higher than 542 μg/liter at 0.5 m. The years were all significantly different from each other. The lowest and highest were 45.7 μg/liter (1974) and 1,390 μg/liter (1971), respectively. In cladocerans, the chronological pattern in the order of abundance was the same for both density and biomass.

In copepods, variables of significance were the same as those in cladocerans (Tables 6A and 6B). The mean density in station 9 (45.8/liter) was significantly lower than all other stations. The mean density of station 8 (128/liter) was next lowest and was unlike those in rotifers and cladocerans which showed the highest value. The highest copepod mean density in stations was station 3 with 165/liter. The years were significantly different among the four periods with 1973 and 1971 as one period. The lowest two years, 1974 (35.2/liter) and 1973 (125/liter) were the same as in the mean density of rotifers and cladocerans. The highest mean density of copepods occurred in 1970 with 204/liter. The mean biomass of copepods at 2.5 m depth

(1,553 μg/liter) was significantly higher than 1,089 μg/liter at 0.5 m. With 2,755 μg/liter, 1972 was significantly higher than all other years. The lowest occurred in 1974 with 370 μg/liter. The chronological pattern in their order of abundance for years was not similar to that in rotifers and cladocerans.

Table 1. The significance probability of F-statistics of station, depth, and year for spring season 1970-1974.

	Rotifers		Cladocerans		Copepods	
	Density	Biomass	Density	Biomass	Density	Biomass
Station	0.001	0.001	0.016	0.323	0.001	0.157
Depth	0.502	0.255	0.275	0.001	0.648	0.108
Year	0.001	0.001	0.001	0.001	0.001	0.001

Table 2. The significance probability of F-statistics of station, depth, and year for summer season 1970-1973.

	Rotifers		Cladocerans		Copepods	
	Density	Biomass	Density	Biomass	Density	Biomass
Station	0.001	0.001	0.001	0.001	0.001	0.001
Depth	0.061	0.021	0.001	0.001	0.142	0.001
Year	0.001	0.001	0.001	0.026	0.001	0.001

Table 3. The significance probability of F-statistics of station, depth, and year for fall season 1970-1974.

	Rotifers		Cladocerans		Copepods	
	Density	Biomass	Density	Biomass	Density	Biomass
Station	0.001	0.001	0.001	0.001	0.001	0.003
Depth	0.001	0.001	0.001	0.001	0.002	0.158
Year	0.001	0.001	0.001	0.001	0.001	0.001

Table 4A. The mean density of rotifers (number/liter) arranged in increasing order of abundance in station and year for spring 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	9	3	4	2	6	5	1	8
Mean	128	174	184	193	204	228	264	301
Multiple range	———	———	———	———	———			
					———	———		
						———	———	———

Year	1974	1973	1970	1972	1971
Mean	80	151	207	207	403
Multiple range	———	———	———	———	———

Table 4B. The mean biomass of rotifers (microgram/liter) arranged in increasing order of abundance in station and year for spring 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	9	4	3	2	5	8	6	1
Mean	157	163	177	226	226	278	292	616
Multiple range	———	———	———	———	———			
					———	———	———	———

Year	1974	1970	1972	1973	1971
Mean	42.8	104	311	371	506
Multiple range	———	———	———	———	———

Table 5A. The mean density of cladocerans (number/liter) arranged in increasing order of abundance in station and year for spring 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

<table>
<tr><th>Station Number</th><th>3</th><th>5</th><th>9</th><th>4</th><th>6</th><th>2</th><th>1</th><th>8</th></tr>
<tr><td>Mean</td><td>17.8</td><td>18.1</td><td>18.7</td><td>21.2</td><td>23.6</td><td>25.8</td><td>26.4</td><td>40.6</td></tr>
<tr><td>Multiple range</td><td colspan="7">————————————————</td><td>——</td></tr>
</table>

<table>
<tr><th>Year</th><th>1974</th><th>1973</th><th>1972</th><th>1970</th><th>1971</th></tr>
<tr><td>Mean</td><td>1.35</td><td>12.3</td><td>24.0</td><td>27.6</td><td>55.0</td></tr>
<tr><td>Multiple range</td><td>——</td><td>——</td><td colspan="2">——————</td><td>——</td></tr>
</table>

Table 5B. The mean biomass of cladocerans (microgram/liter) arranged in increasing order of abundance in depth and year for spring 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Depth (meter)	0.5	2.5
Mean	542	958
Multiple range	___	___

Year	1974	1973	1972	1970	1971
Mean	45.7	341	871	1,102	1,390
Multiple range	____	____	____	_____	_____

Table 6A. The mean density of copepods (number/liter) arranged in increasing order of abundance in station and year for spring 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	9	8	6	4	1	5	2	3
Mean	45.8	128	134	137	142	158	160	165
Multiple range	____	____	____	____				
			____	____	____			
				____	____	____	____	
					____	____	____	____

Year	1974	1973	1971	1972	1970
Mean	35.2	125	132	173	204
Multiple range	____	____	____	____	____

Table 6B. The mean biomass of copepods (microgram/liter) arranged in increasing order of abundance in depth and year for spring 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Depth (meter)	0.5	2.5
Mean	1,089	1,553
Multiple range	———	———

Year	1974	1970	1973	1971	1972
Mean	370	929	1,158	1,392	2,755
Multiple range	———	———			
		———	———	———	———

Summer

Variables of station, depth, and year in all three groups of zooplankton, rotifers, cladocerans, and copepods were all observed to be highly significant in both density and biomass except for the mean density of depth in copepods (Table 2).

The mean density of rotifers in station 8 (304/liter) was significantly higher than all other stations (Table 7A). Station 9 was second highest with 180/liter and was unlike those in the spring season where station 9 was lowest. The mean density at 2.5 m (183/liter) was significantly higher than 166/liter at 0.5 m. The mean density in 1970 and 1972 was significantly higher than 1971 and 1973. The highest value in 1970 (225/liter) was about four times as great as the lowest in 1973 (51/liter). As in the mean density of rotifers, the two highest mean biomass stations were station 8 (241 μg/liter) and station 9 (163 μg/liter) (Table 7B). However, the order of abundance within the six lake stations varied between those in density and those in biomass. In depth, the mean biomass at 2.5 m (137 μg/liter) was significantly higher than 114 μg/liter at 0.5 m. The chronological pattern in the order of abundance of biomass was the same as in density, with the minimum value of 87 μg/liter in 1973 to the maximum value of 152 μg/liter in 1970.

The mean density of cladocerans in station 5 (135/liter) was significantly higher than all other stations (Table 8A). Just opposite to those in rotifers, the two lowest stations were station 9 (16/liter) and station 8 (41/liter). Depth at 2.5 m (122/liter) was about twice as high as at 0.5 m (64/liter). The mean density in 1970 (179/liter) was significantly higher than all other years. The lowest occurred during 1973 with 47/liter. The order of abundance of mean biomass in stations was somewhat similar to that in density (Table 8B). The two lowest were station 9 (1,041 μg/liter) and station 8 (2,246 μg/liter). The two highest were station 5 (5,803 μg/liter) and station 4 (6,836 μg/liter). Depth at 2.5 m (6,520 μg/liter) was about 3.5 times higher than that at 0.5 m (1,821 μg/liter). The mean biomass in 1970 (5,218 μg/liter) was significantly higher than all others. The lowest year occurred during 1972 (3,508 μg/liter) instead of 1973 as in density.

In copepods, the mean density of lowest and highest stations was station 9 with 92/liter and station 8 with 359/liter, respectively (Table 9A). In the mean density of years, all four years were significantly different from each other and decreased chronologically from 1970 with 325/liter to 1973 with 85/liter. The order of abundance of mean biomass in stations was generally similar to that in density (Table 9B). Station 9 with 938 μg/liter was significantly lower than all other stations. Station 8 was the highest with 2,727 μg/liter. The mean biomass at 2.5 m (2,372 μg/liter) was significantly higher than 1,529 μg/liter at 0.5 m. The mean biomass of the lowest and highest year was 1972 (1,212 μg/liter) and 1971 (3,197 μg/liter), respectively.

Table 7A. The mean density of rotifers (number/liter) arranged in increasing order of abundance in station, depth, and year for summer 1970-1973 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	6	2	3	4	1	5	9	8
Mean	137	138	143	163	164	167	180	304
Multiple range	———	———	———	———	———	———		
				———	———	———	———	———

Depth (meter)	0.5	2.5
Mean	166	183
Multiple range	———	———

Year	1973	1971	1972	1970
Mean	51	198	222	225
Multiple range	———	———	———	———

Table 7B. The mean biomass of rotifers (microgram/liter) arranged in increasing order of abundance in station, depth, and year for summer 1970-1973 with Tukey's multiple range test ($p \leq 0.10$).

<table>
<tr><th>Station Number</th><th>5</th><th>4</th><th>6</th><th>1</th><th>2</th><th>3</th><th>9</th><th>8</th></tr>
<tr><td>Mean</td><td>59</td><td>88</td><td>97</td><td>103</td><td>105</td><td>150</td><td>163</td><td>241</td></tr>
<tr><td>Multiple range</td><td>___</td><td colspan="4">______________________</td><td colspan="2">___________</td><td>___</td></tr>
</table>

<table>
<tr><th>Depth (meter)</th><th>0.5</th><th>2.5</th></tr>
<tr><td>Mean</td><td>114</td><td>137</td></tr>
<tr><td>Multiple range</td><td>___</td><td>___</td></tr>
</table>

<table>
<tr><th>Year</th><th>1973</th><th>1971</th><th>1972</th><th>1970</th></tr>
<tr><td>Mean</td><td>87</td><td>118</td><td>145</td><td>152</td></tr>
<tr><td>Multiple range</td><td>____</td><td>____</td><td colspan="2">______________</td></tr>
</table>

Table 8A. The mean density of cladocerans (number/liter) arranged in increasing order of abundance in station, depth, and year for summer 1970-1973 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	9	8	6	1	3	2	4	5
Mean	16	41	96	109	113	117	117	135
Multiple range	___	___	___	___				
				___	___	___	___	___

Depth (meter)	0.5	2.5
Mean	64	122
Multiple range	___	___

Year	1973	1971	1972	1970
Mean	47	69	77	179
Multiple range	___	___	___	___

Table 8B. The mean biomass of cladocerans (microgram/liter) arranged in increasing order of abundance in station, depth, and year for summer 1970-1973 with Tukey's multiple range test (p $\leq$ 0.10).

<table>
<tr><th>Station Number</th><th>9</th><th>8</th><th>2</th><th>1</th><th>6</th><th>3</th><th>5</th><th>4</th></tr>
<tr><td>Mean</td><td>1,041</td><td>2,246</td><td>4,225</td><td>4,314</td><td>4,346</td><td>4,551</td><td>5,803</td><td>6,836</td></tr>
<tr><td>Multiple range</td><td colspan="2">____________</td><td colspan="4">________________________</td><td>_____</td><td>_____</td></tr>
</table>

<table>
<tr><th>Depth (meter)</th><th>0.5</th><th>2.5</th></tr>
<tr><td>Mean</td><td>1,821</td><td>6,520</td></tr>
<tr><td>Multiple range</td><td>_____</td><td>_____</td></tr>
</table>

<table>
<tr><th>Year</th><th>1972</th><th>1971</th><th>1973</th><th>1970</th></tr>
<tr><td>Mean</td><td>3,508</td><td>3,868</td><td>4,088</td><td>5,218</td></tr>
<tr><td>Multiple range</td><td colspan="3">______________________</td><td>_____</td></tr>
</table>

Table 9A. The mean density of copepods (number/liter) arranged in increasing order of abundance in station and year for summer 1970-1973 with Tukey's multiple range test ($p \leq 0.10$).

<table>
<tr><th>Station Number</th><th>9</th><th>2</th><th>1</th><th>3</th><th>6</th><th>5</th><th>4</th><th>8</th></tr>
<tr><td>Mean</td><td>92</td><td>158</td><td>163</td><td>191</td><td>194</td><td>224</td><td>239</td><td>359</td></tr>
<tr><td>Multiple range</td><td>___</td><td colspan="2">__________</td><td colspan="2">__________</td><td colspan="2">__________</td><td>___</td></tr>
</table>

<table>
<tr><th>Year</th><th>1973</th><th>1972</th><th>1971</th><th>1970</th></tr>
<tr><td>Mean</td><td>85</td><td>143</td><td>257</td><td>325</td></tr>
<tr><td>Multiple range</td><td>____</td><td>____</td><td>____</td><td>____</td></tr>
</table>

Table 9B. The mean biomass of copepods (microgram/liter) arranged in increasing order of abundance in station, depth, and year for summer 1970-1973 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	9	2	6	1	3	5	4	8
Mean	938	1,557	1,881	1,899	2,098	2,128	2,380	2,727
Multiple range	—	—	—	—	—			
			—	—	—	—	—	
							—	—

Depth (meter)	0.5	2.5
Mean	1,529	2,372
Multiple range	—	—

Year	1972	1973	1970	1971
Mean	1,212	1,622	1,772	3,197
Multiple range	—	—	—	—

Fall

Significant variables in the fall season were the same as those in the summer season except the mean copepod density for depth is replaced by the mean copepod biomass for depth (Table 3).

The mean density of rotifers in stations was lowest in station 9 with 110/liter and highest in station 1 with 236/liter (Table 10A). The mean density at 2.5 m with 202/liter was significantly higher than 163/ liter at 0.5 m. The mean density in years was significantly different among four periods with 1972 and 1973 as one period. No particular chronological trend in the order of abundance in the mean density was observed. The mean biomass in station 9 was lowest with 146 μg/liter and was highest in station 2 with 308 μg/liter (Table 10B). The mean biomass at 2.5 m with 271 μg/liter was significantly higher than 165 μg/liter at 0.5 m. The chronological pattern in the mean biomass of year was the same as in density. The highest year, 1971, with 551 μg/liter was about nine times as much as the lowest year, 1972, with 59 μg/liter.

The mean density of cladocerans in station 9 with 14.6/liter and station 8 with 22.5/liter were the two lowest stations (Table 11A). Station 5 with 64.8/liter was significantly higher than all other stations. Depth at 2.5 m with 45.7/liter was significantly higher than 29.7/liter at 0.5 m. The mean density in years was significantly different among four periods with 1970 and 1971 as one period. The lowest mean density occurred during 1973 with 8.5/liter and the highest occurred during 1972 with 57.6/liter. The pattern in the increasing order of abundance in the mean biomass of stations was the same as in density; however, the pattern in the multiple range test among stations was not similar for density and biomass (Table 11B). The lowest, station 9, and the highest, station 5, were 151 μg/liter and

698 µg/liter, respectively. The mean density at 2.5 m with 506 µg/liter was significantly higher than 293/liter at 0.5 m. The highest mean biomass in 1970 with 687 µg/liter was about six times as much as the lowest in 1973 with 107 µg/liter.

The mean density of copepods in station 6 with 42.4/liter was significantly higher than all other stations (Table 12A). Station 9 with 14.1/liter was significantly lower than all other stations. Depth at 2.5 m (32.1/liter) was signficiantly higher than 26.5/liter at 0.5 m. The mean density in years was significantly different among four periods with 1973 and 1970 as one period. 1974 and 1972 were the lowest (16.3/liter) and the highest (42.5/liter), respectively. The mean biomass of copepods in the lowest and highest stations were station 2 with 77.9 µg/liter and station 6 with 225.7 µg/liter, respectively (Table 12B). Excluding 1974, the mean biomass in years increased chronologically from 1970 (60.5 µg/liter) to 1973 (223.6 µg/liter).

Species Composition

The dominant zooplanktons were mainly Rotifera, Cladocera, and Copepoda. Other groups such as Amphipoda and Ostracoda were minor as reported by Hubschman (1960) and minimal in the present study. Protozoa were reported to have comprised 10 percent of total zooplankton in 1939 (Chandler, 1940) at all three levels of depths but were rarely seen in the present study. Since protozoans were observed throughout the entire column of water in Chandler's study, explanation of the virtual absence of protozoan in the present study is puzzling. Even if the protozoan were mostly bottom sediment dwellers, the turbulent actions of the waves should have distributed at least some of the specimen near the upper layer of water unless the populations had either actually decreased substantially since Chandler's study or the species had adapted to live in the deeper sediment away from turbulence.

In general, the species composition of zooplankton in western Lake Erie was similar to that found in previous studies (Wright, 1955; Chandler, 1940; Davis, 1969; Hubschman, 1960; Watson, 1976). However, some qualitative and quantitative changes were observed.

In the present study, the *Rotifera* is represented mainly by a few species. They are *Brachionus calciflorus*, *Keratella cochlearis*, *Keratella quadrata*, and *Polyarthra*. These occurrences concurred well with those of Davis (1969) who reported *K. cochlearis*, *K. quadrata*, *B. calciflorus*, and *Polyarthra* species to be the most abundant species. Compared with the findings of Davis (1940), certain species appear to have vanished while others have appeared. Davis (1940) reported only one species of *Brachionus*, *B. angularis*, whereas in the present study several other species of *Brachionus* including *B. calciflorus* (one of the most abundant species), *B. caudatus*, *B. havanaensis*, *B. plicatilis*, and *B. angularis* were observed. Species such as *Synchaeta*, *Nothocla*, *Collotheca mutalilis*, and *Euchlanis* were relatively more abundant during 1938 and 1939 have become relatively rare in the present study. For example, *Synchaeta stylata* reached a maximum of 70/liter in September, 1939. On the other hand, species such as *K. quadrata* have become more abundant in the present study as compared to the late thirties.

The cladocerans have been reported to be dominated by a few genera including *Daphnia*, *Diaphanosoma*, and *Bosmina* from 1930 to the present study. Wright (1955) reported in 1930 the dominant species of cladocerans were

Table 10A. The mean density of rotifers (number/liter) arranged in increasing order of abundance in station, depth, and year for fall 1970-1974 with Tukey's mulitple range test ($p \leq 0.10$).

Station Number	9	6	8	4	3	5	2	1
Mean	110	144	160	185	187	214	224	236
Multiple range	———	———————	———————	———————	———————	———————	———————	
							———————	———————

Depth (meter)	0.5	2.5
Mean	163	202
Multiple range	———	———

Year	1972	1973	1970	1974	1971
Mean	105	106	150	256	295
Multiple range	———————	———————	———	———	———

Table 10B. The mean biomass of rotifers (microgram/liter) arranged in increasing order of abundance in station, depth, and year for fall 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	9	3	8	6	4	5	1	2
Mean	146	173	178	206	209	250	276	308
Multiple range	———	———	———					
		———	———	———	———			
				———	———	———		
						———	———	
							———	———

Depth (meter)	0.5	2.5
Mean	165	271
Multiple range	———	———

Year	1972	1973	1970	1974	1971
Mean	59	110	128	244	551
Multiple range	———	———	———		
			———	———	———

Table 11A. The mean density of cladocerans (number/liter) arranged in increasing order of abundance in station, depth, and year for fall 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

<table>
<tr><th>Station Number</th><th>9</th><th>8</th><th>2</th><th>3</th><th>4</th><th>1</th><th>6</th><th>5</th></tr>
<tr><td>Mean</td><td>14.6</td><td>22.5</td><td>25.8</td><td>36.5</td><td>38.1</td><td>43.6</td><td>56.0</td><td>64.8</td></tr>
<tr><td>Multiple range</td><td>____</td><td colspan="2">____________</td><td colspan="2">____________</td><td>____</td><td>____</td><td>____</td></tr>
</table>

<table>
<tr><th>Depth (meter)</th><th>0.5</th><th>2.5</th></tr>
<tr><td>Mean</td><td>29.7</td><td>45.7</td></tr>
<tr><td>Multiple range</td><td>____</td><td>____</td></tr>
</table>

<table>
<tr><th>Year</th><th>1973</th><th>1974</th><th>1970</th><th>1971</th><th>1972</th></tr>
<tr><td>Mean</td><td>8.5</td><td>23.8</td><td>47.4</td><td>51.4</td><td>57.6</td></tr>
<tr><td>Multiple range</td><td>____</td><td>____</td><td colspan="2">______________</td><td>____</td></tr>
</table>

Table 11B. The mean biomass of cladocerans (microgram/liter) arranged in increasing order of abundance in station, depth, and year for fall 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	9	8	2	3	4	1	6	5
Mean	151	220	241	324	401	472	685	698
Multiple range	___	___	___					
		___	___	___				
				___	___			
					___	___	___	___

Depth (meter)	0.5	2.5
Mean	293	506
Multiple range	___	___

Year	1973	1974	1971	1972	1970
Mean	107	162	387	652	687
Multiple range	___	___	___	___	___

Table 12A. The mean density of copepods (number/liter) arranged in increasing order of abundance in station, depth, and year for fall 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	9	4	8	2	1	3	5	6
Mean	14.1	25.8	26.8	29.0	30.0	31.2	35.0	42.4
Multiple range	———	———	———	———				
			———	———	———	———		
					———	———	———	———

Depth (meter)	0.5	2.5
Mean	26.5	32.1
Multiple range	———	———

Year	1974	1973	1970	1971	1972
Mean	16.3	25.0	26.6	36.0	42.5
Multiple range	———	———	———	———	———

Table 12B. The mean biomass of copepods (microgram/liter) arranged in increasing order of abundance in station and year for fall 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	2	9	1	3	5	8	4	6
Mean	77.9	98.2	113.1	148.9	155.8	164.0	190.9	225.7
Multiple range	———	———	———					
		———	———	———				
			———	———	———	———		
				———	———	———	———	
							———	———

Year	1970	1971	1974	1972	1973
Mean	60.5	69.6	175.8	204.3	223.6
Multiple range	———	———	———	———	
				———	———

Diaphanosoma and Daphnia; other species such as Bosmina were present in insignificant numbers. Species composition was reported more thoroughly by Chandler (1940) who observed that the dominant species were Bosmina longirostris, Daphnia, and Diaphanosoma. The species D. longispina, D. pulex, and Sida crystallina were reported only during 1939 by Chandler (1940). Similar to the present study, Hubschman (1960) and Davis (1969) reported in 1959 and 1968, respectively, cladocerans to be dominated by Daphnia followed by Bosmina, Chydorus, and Diaphanosoma. The presence of Holopedium giberum was reported in 1968 (Davis, 1969) and 1970 (Watson, 1976). Leptodora kindtii has been found since the earlier report (Wright, 1955) to the present, but its number has remained small. As Watson reported in 1970 (1976), D. ambigua and D. pulex were not observed in the present study. In addition, Watson reported the presence of Alona affinis, Eurycerus lamellatus, and Latoma setifer at many stations, but these were not found in the present study. Although it is possible that these species were misidentified, perhaps as a result of cyclomorphosis. Other possible explanations include their minimal occurrences.

The species composition of Copepoda has remained largely the same. Reports from 1930 to the present by various investigators have enumerated the presence of more or less the same species (Wright, 1955; Chandler, 1940; Hubschman, 1960; Davis, 1969; Watson, 1976). Wright (1955) reported that during 1930, the copepods were dominated by Cyclops, Diaptomus, and nauplii, with a few insignificant number of Epischura and Limnocalanus. The important species from the earlier reports in 1930 to the seventies (including the present study) have remained to be Cyclops, Diaptomus, and nauplii. Cyclopoid species included Tropocyclops prasinus, Cyclops vernalis, and Cyclops bicuspidatus. Diaptomus species included D. ashlandi, *D. minutus*, *D. oregonensis*, *D. sicilis*, and *D. siciloides*. However, the present study did not observe *Limnocalanus*, *Epischura*, and *Mexocyclops edax* as found in other studies (Chandler, 1940; Wright, 1955; Watson, 1976). Some of the minimal number of species observed included *Canthocamptus robertcokeri* and *Eurytremora affinia*.

Vertical Distribution

The phenomenon of vertical distribution in zooplankton has been well documented. Distribution at a particular depth may be due to a single or multiple factors such as temperature, dissolved oxygen predation, food availability, and physiological adaptation. In the present study, the pattern of vertical distribution of different groups at different depths was not at all consistent. Tables 1, 2, and 3 show that the F-statistics of different variables at different depths during spring season, exhibited a much smaller significant difference than those of summer and fall seasons. Possible explanation for this occurrence could be the presence of any vertical distribution having been largely destroyed by the more turbulent conditions in the water during spring season. The relatively less turbulent conditions in the summer and fall should then exhibit a more significant difference between depths, and indeed this is the case. When Chandler's data in 1939 (1940) were recalculated by dividing the 1939 data into three seasons -- spring, summer, and fall at different depths and major groups of zooplankton -- no consistent trend in the vertical distribution was observed. The relatively more significant difference in depths found in the present study was probably due to the longer periods of time involved, i.e., a less obvious condition could accumulate into a more distinct condition by virtue of its longer period of time.

Changes from 1930 to 1975

Changes in the dynamics of zooplankton populations in western Lake Erie from 1930 to 1975 are examined through the densities of three major groups; rotifers, cladocerans, and copepods (Figures 15, 16, and 17). In order to arrive at a reasonably realistic comparison of zooplankton changes between the present study and others, studies only in relatively close proximity are used (Wright, 1955; Chandler, 1940; Hubschman, 1960). Since the sampling methods and sampling locations are reasonably similar and close, comparison of studies among the different investigators are assumed to be valid. Data reported by others were recalculated to obtain better comparison. In Chandler's report (1940), the density was recalculated by taking the mean value of 0 m and 5 m in depth. The copepod group in Wright's 1930 data (1955) included Diaptomus and Cyclops; the cladoceran group included Daphnia and Diaphanosoma. In Hubschman's study (1960) the copepod group included Cyclopoida and Calanoida. Some zooplankton studies in Lake Erie are not used because their sampling locations were not close enough to that of the present study to offer meaningful comparison (Davis; 1954, 1962), as Lake Erie has been demonstrated to differ biologically in the three basins (Davis, 1969). For example, the two pulses of rotifers occurring in mid-May with 1,450/liter and mid-October with 1,300/liter in the Cleveland harbor area greatly exceeds all known rotifer population inclusive of the present study (Davis, 1962). In addition, studies of short duration (Davis, 1969) were also deleted for comparative purposes since spot or scanty results offer little of value in the analysis of seasonal or yearly changes as the time of pulse varies chronologically from year to year. No attempt is made to convert density, as reported by other investigators, to biomass for comparison since error would undoubtedly arise from inaccurate assumptions as to the designation of biomass value to the specimen. Consequently, any possible significant changes could be masked by error induced in the data manipulation. This could render any interpretation meaningless.

Significant changes in the density of rotifers have been observed beginning with a steady increase since 1930 (Figure 15). In 1930 (Wright, 1955) the rotifers were lowest of all years with a maximum density of 25/liter in June. But in 1938 and 1939 (Chandler, 1940), significant changes were observed. A primary pulse occurred September 19, 1939 with 240/liter and a secondary pulse occurred May 23, 1939 with 90/liter. The highest occurred on September 23, 1938 with 48/liter. Since the chronological occurrence of pulses is known to vary from year to year and the fact that sampling was available only in September to December in 1938, the dynamics of rotifer population is then difficult to assess for that year. Rotifer density in 1939 might then be compared with some of the leaner years reported in the present study, such as 1973.

Cladocerans density in 1930 and 1938-1939 was lowest of all three groups and were also relatively unchanged (Figure 16). But in the summer of 1959, two pulses were observed, and its density could be compared with some of those years in the present study such as 1971 and 1973. Cladoceran in 1959 included only Daphnia and Diaphanosoma. In the present study, 1970 showed the highest value. However, the graph may be deceiving. If sampling on September 1, 1970 is deleted for the moment, then the graph of 1970 would resemble more the rest of the years in the nineteen-seventies. Thus, the deletion of just one important sampling date would alter the increase in density from six-fold to possibly two-fold between 1959 and the present study. In addition, knowing that the reported densities could easily fluctuate by several-fold (e.g., data manipulation and experimental error), the significant increase in the cladoceran population could have appeared before 1970.

Changes in copepod density from 1930 to 1959 appeared to be relatively little (Figure 17). But beginning in 1970, a significant increase of about five-fold was observed. Except for 1974, which lacked a distinct pulse, the other years in the present study are relatively close in abundance. Copepod density in Hubschman's study (1960) included _Calanoid_ and _Cyclopoid_, and would probably be higher had it included _nauplii_ which are known to have occurred at almost all times.

The Effect of Thermal Effluent

The effect of thermal effluent from electric power plants on the aquatic ecosystem is controversial mainly due to the lack of understanding of a complex subject and the unavailability of data from long term studies. Short term studies often provide only qualitative information at best and would not be likely to offer any meaningful quantitative information due to the wide fluctuation inherent in the dynamics of aquatic populations. Both detrimental and beneficial effects have been documented in the discharge of thermal effluent into its aquatic ecosystem (Krenkel and Parker, 1969). While enormous fish-kills have been reported by some, others have reported growth enhancement of aquatic organisms. Enhancement in the proliferation of aquatic organisms could be induced by gradual rise in temperature which would increase the organism's metabolism, thereby resulting in a higher growth rate, assuming all other factors considered remained constant. On the other hand, a detrimental effect could result if the temperature changes are relatively abrupt and exceed the organism's physiological

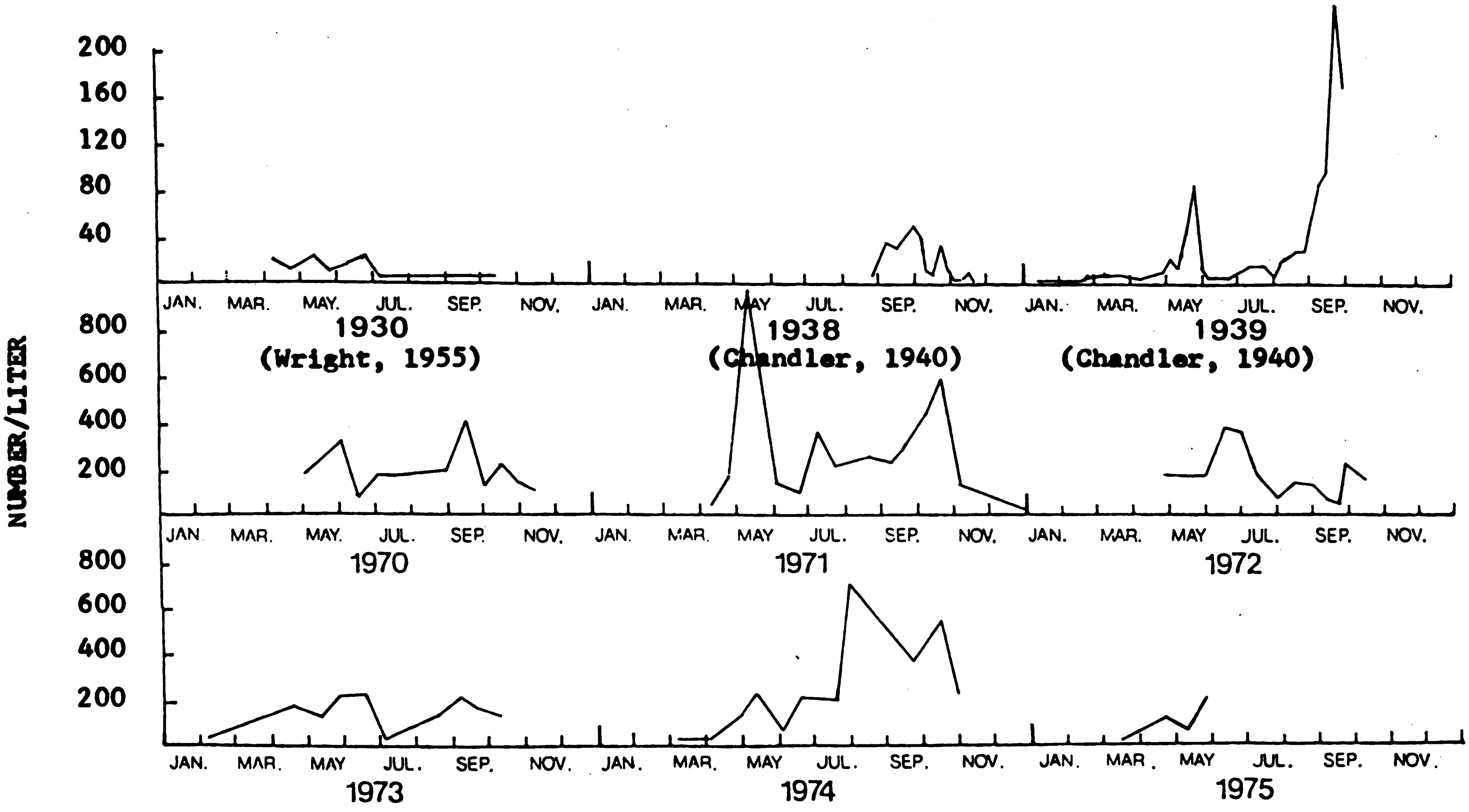


Figure 15. Changes in the mean rotifers density (number/liter) in western Lake Erie from 1930 to 1975.

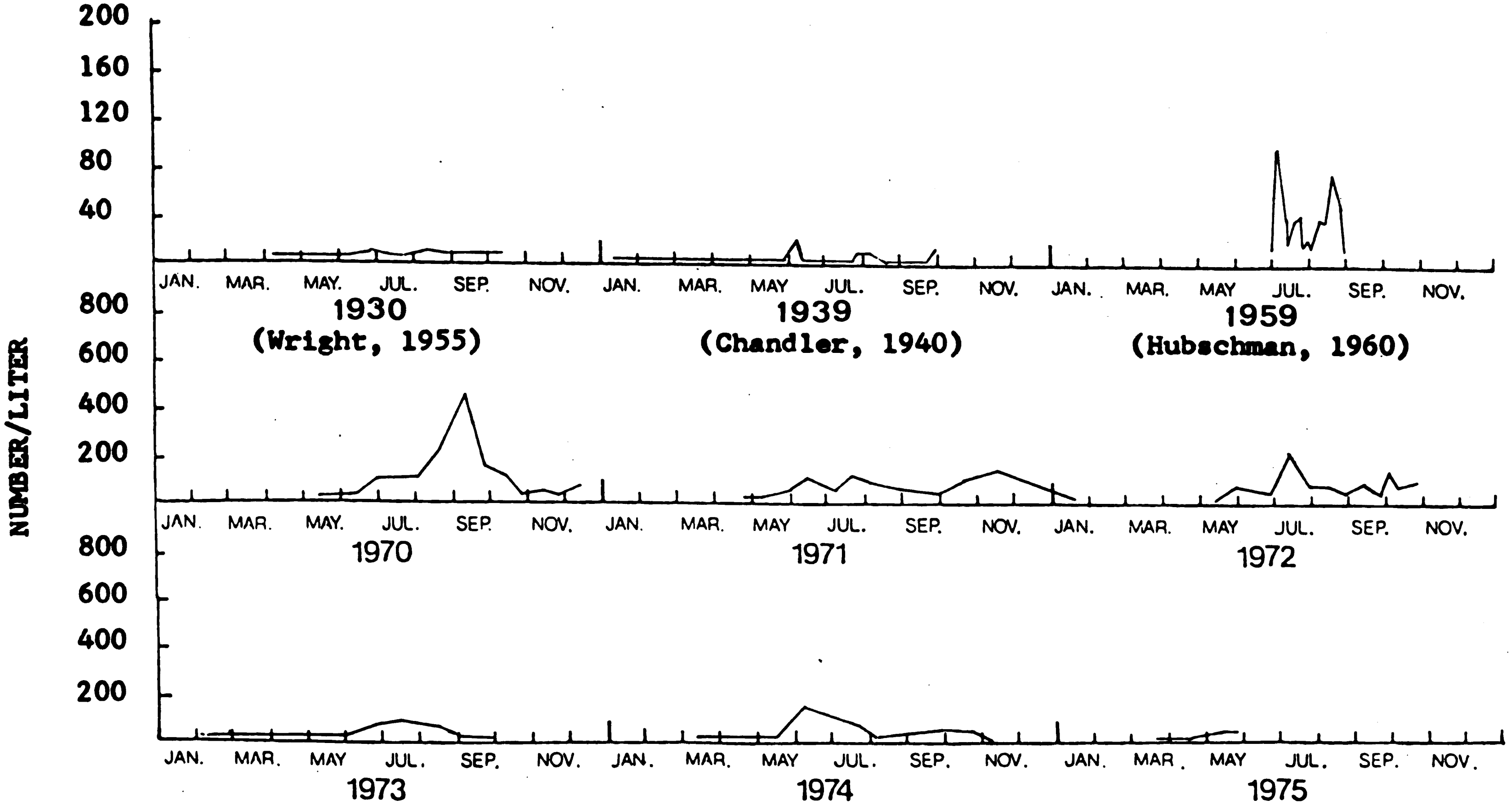


Figure 16. Changes in the mean cladocerans density (number/liter) in western Lake Erie from 1930 to 1975.

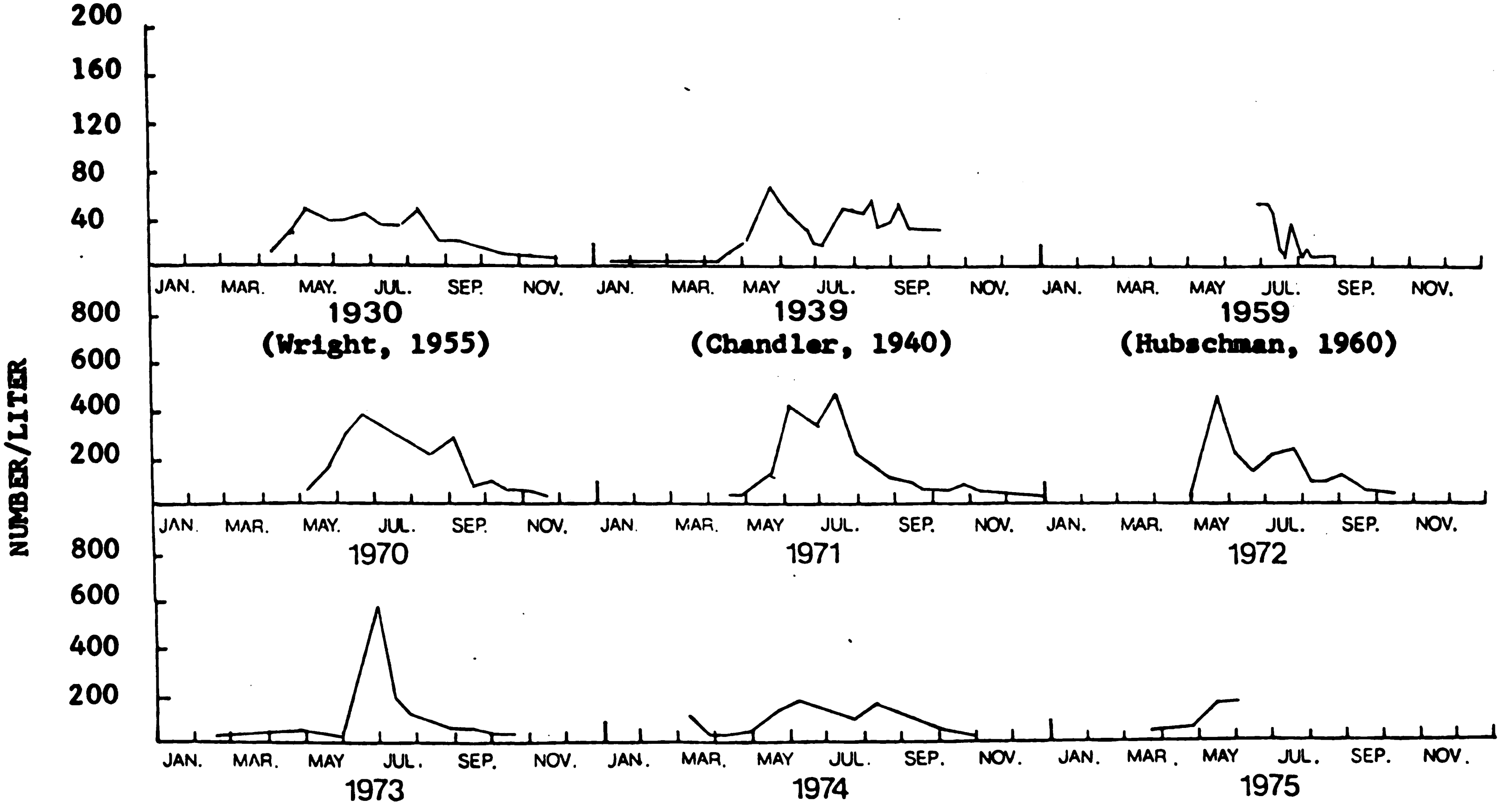


Figure 17. Changes in the mean copepods density (number/liter) in western Lake Erie from 1930 to 1975.

limitations. The controversy or confusion about the effect of thermal effluent may have arisen partially from the poor integration of science and the state of art, somewhat analogous to the earlier stages in the statistical application to applied biology. Since the oscillation in the dynamics of aquatic ecosystems is governed by the instantaneous sum of all interactions of different factors, the effect of the thermal effluent could, thus, fluctuate back and forth between being detrimental and beneficial.

In assessing the effect of thermal effluent, it is hypothesized that if the temperature differential in the canal and lake stations rose relatively slowly and within the tolerance level of the plankton's physiological limitations, an enhancement in the growth of aquatic organisms could be expected; but if the temperature differential rose abruptly and exceeded the organism's tolerance level, a detrimental effect is expected.

In testing this hypothesis, significant changes in zooplankton populations between two chronological periods, pre-operational (1970) and post-operational (1971-1974), are compared by assigning the discharge canal station and the six lake stations into four groups in accordance with the extent of the thermal effect in three separate seasons for both density and biomass. The discharge canal (station 8) would have the highest temperature differential. Lake stations would have about half of the temperature differential as the canal due to dilution, followed by stations 2 & 3. Stations 1 & 6 would be least affected owing to their greater distances from the thermal plume and could serve as control stations in the lake. The extent of protrusion of the thermal plume from the shoreline mouth of the discharge canal is largely determined by the magnitude of discharge and the existing current. Based on the discharge rate and the prevailing current in the lake, the thermal plume is estimated to be about 2-3 km long, projecting outward into the lake and bent towards the northeast with the current and halved in temperature differential at each successive 2 km. The total heat loss through evaporation is relatively unimportant as reported by Hoops et al. (1968) to be 5 percent.

These estimates agree reasonably well with the findings from the Davis-Besse Nuclear Power Station at Toledo, Ohio, where the excess temperature isotherms of 7.8, 6.7, 5.5, 4.4, and 3.3 (^{o}C) had a distance of 0.08, 0.15, 0.32, 0.37, and 2.35 km, respectively (Great Lakes Fishery Laboratory, Bureau of Commercial Fisheries at Ann Arbor, Michigan, 1970). Temperature fluctuations from surface to bottom in western Lake Erie have been known to be minor. For the most part, the present study observed a temperature change of about two degrees (C) from surface to bottom. This concurs with Chandler's finding (1940) also of two degrees (C). Brett (1969, 1960) has reported that adult fish could endure temperature fluctuations of up to seven degrees (C). Zooplankton, being much smaller than fish, would have a lower temperature fluctuation level. Knowing that zooplankton have a two degree (C) fluctuation in the natural surface-bottom environment, two additional degrees are assumed to be within the tolerance level.

The detrimental effect of the thermal effluent on the lake could come from two sources. One is the abrupt temperature fluctuations. The other comes from the damaged plankton that had been in contact with the turbine in the power plant. Since an enormous amount of water is needed for cooling, in the order of about 50 m^{3}/sec (Table 13), the quantity of possibly damaged zooplankton could play an important role in the well-being of its lake populations. Because the absolute seasonal temperature varies among the years, a same temperature differential could not be regarded as possessing the same effect as in another year. Instead, importance would

Table 13. The mean pumping rate (m^3/sec) of the electric power plant at Monroe, Michigan, from 1971 to 1974.

Year	1971	1972	1973	1974
Spring	42.00	47.25	60.75	63.00
Summer	45.00	42.75	74.25	101.25
Fall	51.00	40.50	83.25	69.75

be better attached to the relative population changes among different affected areas within each year. The mean temperature differential for three seasons (spring, summer, and fall from 1970 to 1974) are calculated except for the summer season which did not include 1974 (Figure 18).

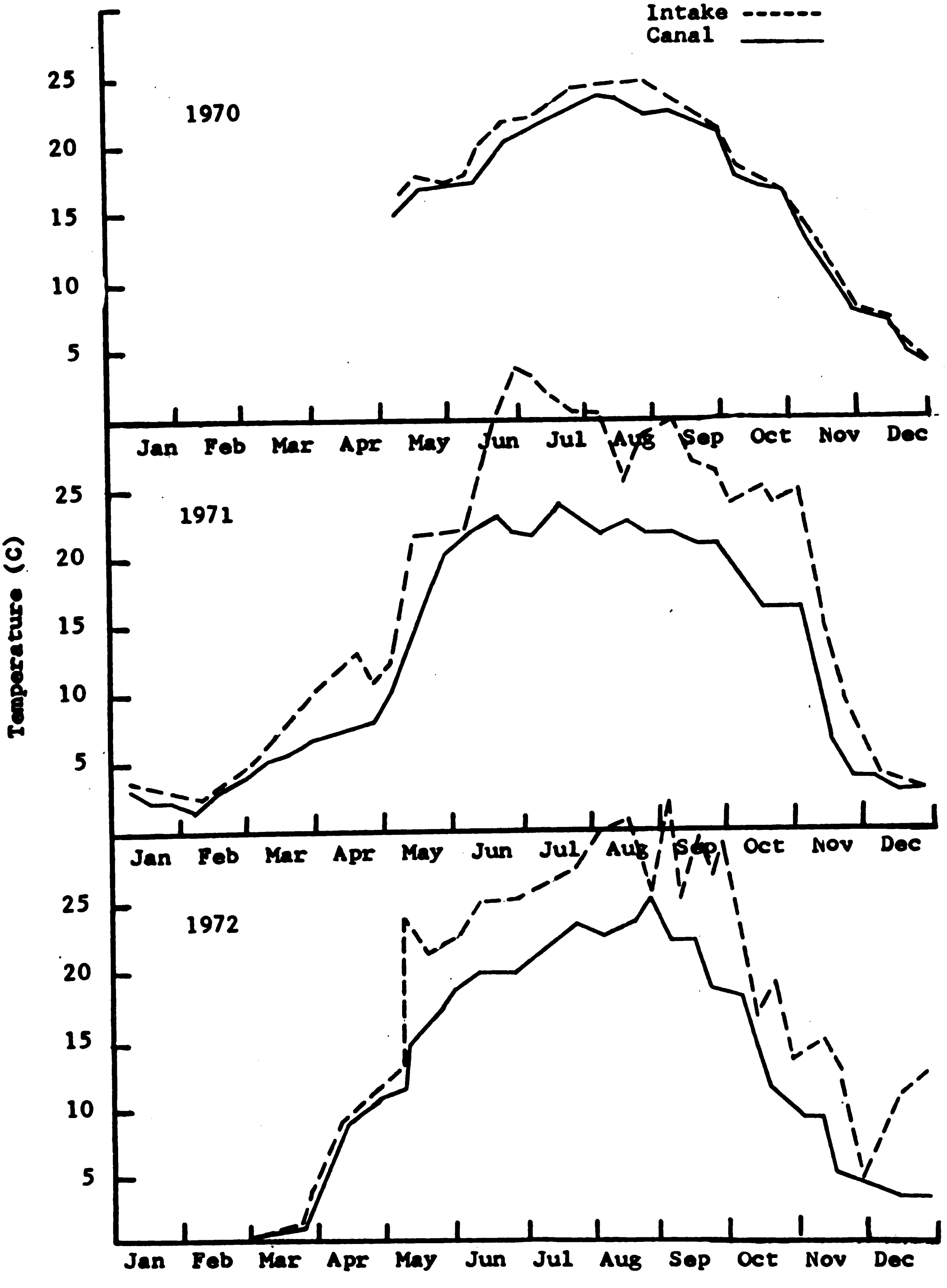
The zooplankton populations during the pre-operational period in 1970 would be used as a reference to compare with those during the post-operational period from 1971 to 1974. Extensive zooplankton population fluctuations were observed in 1970. The mean density in the discharge canal in spring and summer were twice and three times that of the lake mean (Table 14). The mean density in fall between the discharge canal and the lake stations was similar. The mean biomass in the discharge canal was 1.7 times that of the lake during spring, and similar during summer and fall seasons; however, stations 4 & 5 had the highest mean biomass with 11,221 μg/liter, almost twice that of the discharge canal during the summer. During fall, the highest mean biomass occurred in stations 1 & 6, with 1,664 μg/liter and was slightly more than twice as much as the discharge canal. Thus, it is observed that a fluctuation of up to 2.5 times among different stations could be expected in the natural environment. The occurrence of somewhat higher abundance of zooplankton in the discharge canal than in the lake may be explained by the more sheltered environment in the canal. If a more sheltered environment is offered in the canal, it is then reasonable to suggest the occurrence of a higher reproduction rate yielding a smaller individual size. A calculation in 1970 showed that the individual biomass in the lake mean exceeded all those in the canal in all three seasons, especially during the summer (a ratio of 12.6 to 3.8 μg/individual organism).

Since the temperature in spring and fall is relatively colder than in summer, a temperature change is expected to have greater significance during the cooler seasons than the warmer summer season.

During spring, 1971, the mean density of zooplankton in the discharge canal was twice that of the lake mean. This may be interpreted that the higher temperature in the canal (a temperature differential of 4.8 degrees) could induce higher growth rate. If stations 4 & 5 showed a mean density value that is intermediate of the canal and the other lake stations, the concept of growth enhancement due to the temperature increase in the canal could be strengthened; but as the mean density in lake stations was similar, no such affirmation could be expressed. In the summer of 1971 with a temperature differential of 7.5 degrees, the mean density in the canal was somewhat lower than the lake stations including the control stations, 1 & 6. The higher mean density in stations 4 & 5 could be interpreted as being induced by the temperature increase. At stations 4 & 5, the temperature differentials of 7.5 degrees would have been lowered to somewhere between 3.0 and 4.0 degrees, a range within the estimated tolerance level of zooplankton. The somewhat higher mean density in the control stations 1 & 6 than in that of the canal would indicate a slightly detrimental effect of temperature fluctuation. Similar patterns resulted in fall 1971, but with slightly more distinction in the effect of temperature increase; however, the temperature differential in this case is 6.6 degrees, one degree less than summer, 1971. The abundance pattern of biomass in spring, 1971, was similar to its density. The biomass pattern in summer, 1971, was somewhat different than its density. Although the mean biomass in stations 4 & 5 were again highest, they are only slightly higher than those in the canal, the next highest. The canal is also about one-third higher than those in

Table 14. The mean temperature differential, T. D. (C) between the intake area and the discharge canal area in three separate seasons from 1970 to 1974, and the mean density (number/liter) and mean biomass (microgram/liter) of total zooplankton of the discharge canal and lake stations 4 & 5, 2 & 3, and 1 & 6.

				Station Number				
Season	Year	T. D.		8	4 & 5	2 & 3	1 & 6	$\bar{X}$ (1-6)
Spring	1970	1.0	Density	799	441	419	608	422
			Biomass	3489	2363	1890	1645	1966
	1971	4.8	Density	1071	512	542	546	533
			Biomass	4794	3439	3304	3048	3264
	1972	6.0	Density	302	439	345	558	447
			Biomass	1651	3609	3169	7236	4671
	1973	5.2	Density	124	286	445	335	355
			Biomass	929	1983	2590	2323	2300
	1974	9.3	Density	52	178	95	144	139
			Biomass	178	609	330	782	574
Summer	1970	1.4	Density	1796	740	594	592	642
			Biomass	6800	11221	7175	5971	8122
	1971	7.5	Density	500	701	461	562	575
			Biomass	9311	9872	6363	6087	7441
	1972	5.3	Density	419	451	445	370	422
			Biomass	2866	6109	4787	5600	5500
	1973	6.1	Density	104	203	223	208	211
			Biomass	1881	7393	7049	7625	7356
Fall	1970	0.5	Density	207	247	199	305	250
			Biomass	732	789	540	1664	998
	1971	6.6	Density	319	446	416	427	430
			Biomass	700	1189	909	1352	1150
	1972	6.2	Density	114	241	226	224	230
			Biomass	242	1552	837	934	1108
	1973	8.5	Density	109	135	132	148	138
			Biomass	466	574	324	462	453
	1974	7.2	Density	300	310	361	278	316
			Biomass	537	662	574	536	591


Intake
Canal
1970
1971
1972
Temperature (C)
25
20
15
10
5
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

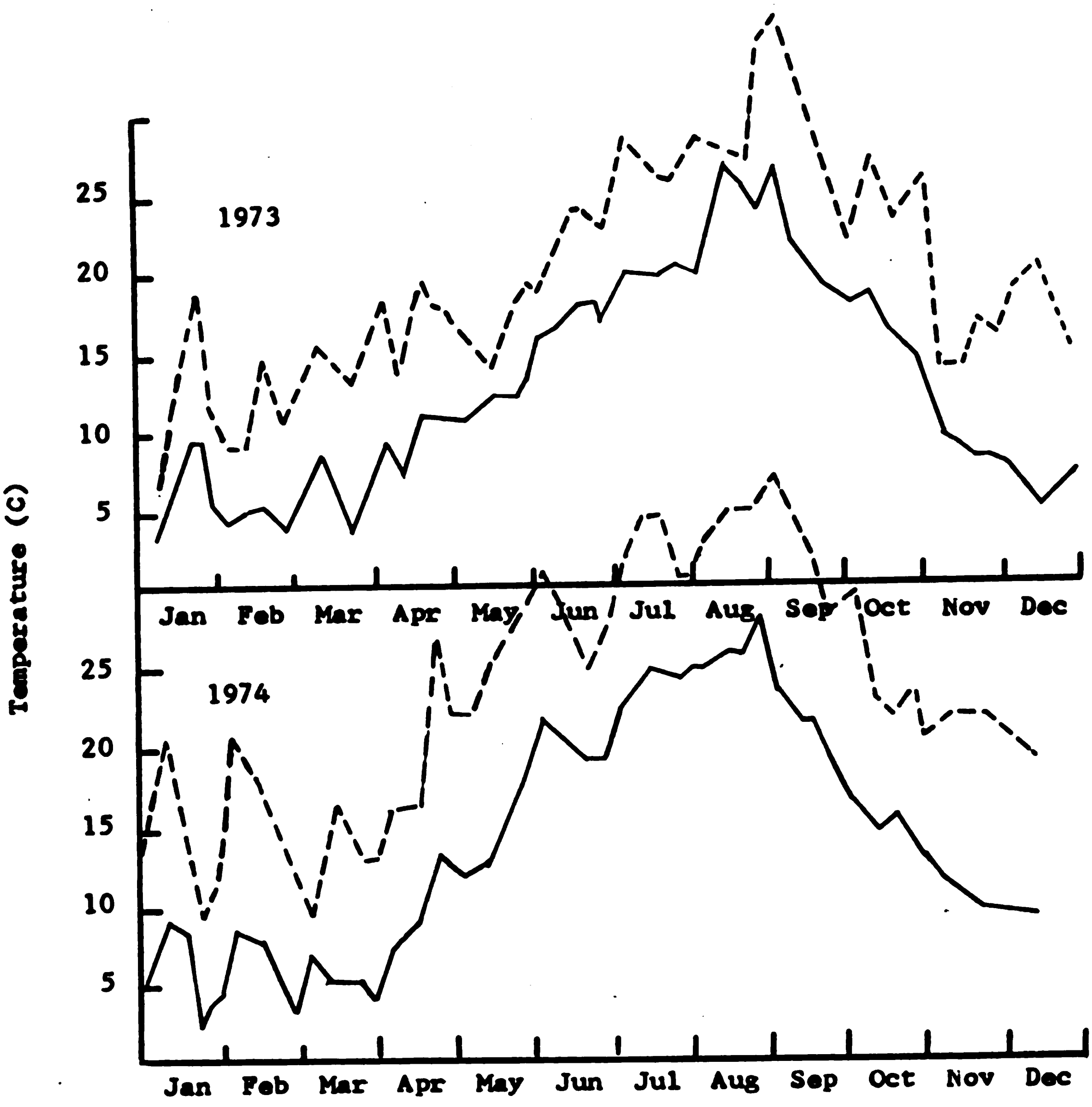


Figure 18. Temperatures in the discharge canal and the intake from 1970 to 1974.

the control stations 1 & 6. A calculation of the individual biomass of the plankter showed that zooplankton in the discharge canal is largest in size, with a ratio of 18.6 (canal) to 13.1 μg/organism (lake mean). The mean biomass in fall, 1971, followed a similar pattern as in its density.

In spring, 1972, with a temperature differential fo 6.0 degrees, the temperature increase in the discharge canal seemed to have a depressing effect as the mean density in the canal was lowest of all lake stations. The higher mean density in stations 4 & 5 than that in the canal would appear to demonstrate a lessening of the depressing effect of the temperature differential than the canal, as the control stations 1 & 6 showed the highest value of all stations. The mean density in the summer of 1972 with a temperature differential of 5.3 degrees was similar among the discharge canal and the lake stations. In this case, a temperature differential of 5.3 degrees did not seem to have any effect either way. In fall, 1972, with a temperature differential of 6.2 degrees, the mean density in the discharge canal was about half that of the lake stations. As the values in the lake stations were very close, it may be said that while the temperature differential of 6.2 degrees had a depressing effect in the canal, it really did not enhance growth as control stations 1 & 6 did not differ much from the other lake stations. The mean biomass in spring, 1972, followed the same pattern as in its density, but showed somewhat more distinct differences between the discharge canal and the lake stations, e.g., the mean biomass of the lake mean was almost three times that of the discharge canal. Unlike its density, the mean biomass in summer, 1972, was dissimilar among canal and lake stations. As the mean biomass in the discharge canal increased from 2,866 μg/liter to 6,109 μg/liter in stations 4 & 5 with the control stations 1 & 6 having 5,600 μg/liter, the temperature differential may be viewed as an enhancement to the growth of biomass or as the larger individual having a greater tolerance for temperature fluctuations. The individual size in the canal was greater than those in the lake stations. But as one examined the mean biomass in the fall of 1972, some contradictions to the idea that the larger organism could endure greater temperature change than smaller ones were observed. Here, the individual organism in the lake stations was 4.7 g/individual as compared with 2.1 g/individual in the canal. Nevertheless, the abundance pattern of mean biomass in the canal and the lake stations was similar to its respective density.

In spring, 1973, with a temperature differential of 5.2 degrees, the mean density of the discharge canal was about half that of the lowest lake stations, 4 & 5. The highest value found in stations 2 & 3 may possibly be interpreted as good growth enhancement and could have resulted at a temperature increment of 1.3 degrees during spring season. The 1.3 degree figure was calculated by halving the 5.2 degrees twice successively. In summer, 1973, with a temperature differential of 6.1 degrees, the mean density of the discharge canal was almost exactly half that of the lake stations. In view of the similar values among all the lake stations, the low value in the discharge canal was probably due to the depressing effect of temperature increase. In fall, 1973, with a temperature differential of 8.5 degrees, the mean density in all seven stations was low and similar, with the value in the discharge canal being slightly lower. The low mean density observed in fall, 1973, and spring, 1974, might be due to other unknown factors besides the relatively high temperature differential and natural seasonal fluctuations. The mean biomass of discharge canal during spring, 1973, were half that of the lake mean as in its density; however, the values among the different lake stations were much more uniform than in density. In summer, 1973, the mean biomass of lake stations were similar and about four times as much as in the discharge canal instead of twice, as in density. The mean biomass in fall, 1973, were similar between discharge canal and lake mean.

In spring, 1974, with a 9.3 degree temperature differential, the mean density in all stations was lowest of all years. The relatively low value in the canal might again be viewed as resulting from the depressing effect of high temperature increase. In fall, 1974, with a temperature differential of 7.2 degrees, the mean density in the discharge canal and lake stations was similar. As the temperature differential in stations 4 & 5 decreased to 3.6 degrees by dilution, some enhancement of growth could have occurred, especially during the fall season when the water temperature cooled. Possibly, one beneficial factor could be negated by another. The mean biomass in spring, 1974, and fall, 1974, were similar in the abundance pattern as in respective density.

CONCLUSION

The hypothesis on the detrimental effect of thermal effluent on the aquatic organisms has been proven reasonably well and to a lesser extent in its beneficial effect, based on the present study. The estimated tolerance level of two additional degrees appear to agree reasonably well with the calculated temperature differential occurring in the lake stations 2-5, having a range of 2.5 to 4.5 degrees. An abrupt temperature increase of five degrees or higher has been shown to be able to initiate an adverse effect on aquatic organisms. But because of the wide fluctuations inherent in the dynamics of populations, it is difficult to conclude definitively in the cause and effect relationship without a long term study.

In situations where a sharp temperature increase occurred, as in the discharge canal, adverse results were observed through a decrease in zooplankton populations. Counting 24 instances of both density and biomass from 1971 to 1974 in all three seasons (Table 14), 67 percent showed canal population to be the lowest, 12 percent highest, and 21 percent showed little or no differences among discharge canal and lake stations. The spring season revealed the greatest detrimental effect of temperature increase in the discharge canal with 73 percent of all instances; both summer and fall seasons showed 50 percent. If the 12 percent of the instances (density and biomass of spring, 1971, biomass of summer, 1971) that showed the higher population abundance in the discharge canal than those in the lake could be explained by the discharge canal's better sheltered environment and the intermittent operation of the power plant during the first half of 1971, the adverse effect of the sudden temperature increase in the aquatic environment could be more strongly affirmed.

Some growth enhancement, due to the small temperature increment, have been observed in stations 4 & 5 and 2 & 3. If populations at stations 4 & 5 were highest with control stations 1 & 6 being higher than discharge canal, a growth enhancement may be suggested, such as in the instance in the density of summer, 1971, and biomass of summer, 1972. When stations 2 & 3 having the highest values with stations 4 & 5 being higher than control stations 1 & 6 and with discharge canal being the lowest, it could be interpreted that greater growth enhancement might be derived with an even smaller temperature increment than those occurring in stations 4 & 5, such as observed in the density and biomass of spring, 1973.

Instances where population abundance in the discharge canal were lowest with the lake stations values being similar, several possibilities exist. While the temperature increase depressed populations in the discharge canal, the additional heat increment had no effect in the lake stations because of the existing high ambient temperature which might nullify any relatively small temperature change, thereby resulting in a similar abundance among the lake stations as in the density and biomass of summer, 1973. But if the existing ambient temperature were cooler as in spring and fall seasons making the temperature increment relatively larger, an enhancing value could be observed through a higher population in stations 4 & 5 as in the density of spring, 1974, and biomass of fall, 1972. However, the limited data in the present study does not allow any conclusive statement about the role that different ambient temperatures at different seasons could play, although theoretically, a difference in the seasonal ambient temperature would likely to be an important factor.

Changes in populations have been observed to occur in both polluted and unpolluted water. Roach (1932) has reported that little or no difference in the quality of plankton exists between clean and polluted water. Fluctuations of the zooplankton populations have been observed to occur within days, depths, seasons, and years. The assumption of being able to obtain representative samples might deserve additional review as possible gross errors inherent in the scheme of sampling period have been reported to be large (Hubschman, 1960). The question in defining pollution and its detrimental effect, arises and asks what are considered to be good or bad changes or if any changes at all. The problem of pollution may be analogous to the factor that breaks the camel's back. One could almost always add a little more or less so called pollutant to an ecosystem or to accept a little more change in fauna composition without seemingly damaging the parameter in question. One point that should be recognized is the change in the inherent quality or behavior in each factor and its overall interactions with others. The so called "quality of life" that is being applied to man is equally applicable to all other things. An organism or a condition could probably endure for quite a long while under different unfavorable stress. Logically, the more healthy and vigorous environment would likely yield a higher quality of products. The problem of detecting the effect of pollution may not always correlate with changes in populations. Under this premise, all of the so called significant changes could easily become meaningless.

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LITERATURE CITED

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APPENDIX

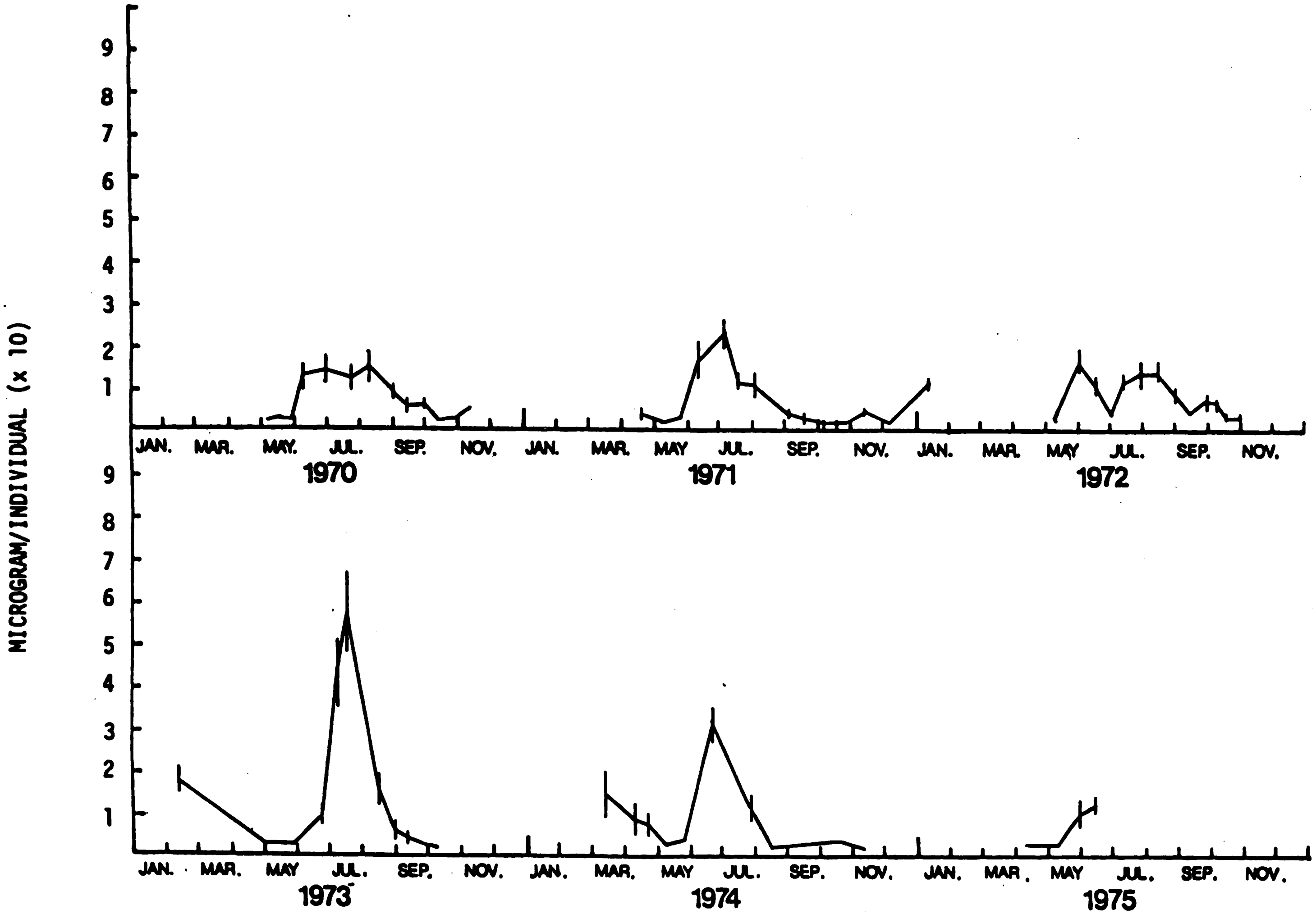

Figure A. Changes in the mean individual zooplankton biomass (microgram/individual) from 1970 to 1975 in the lake. The vertical bars denote 90% confidence intervals.

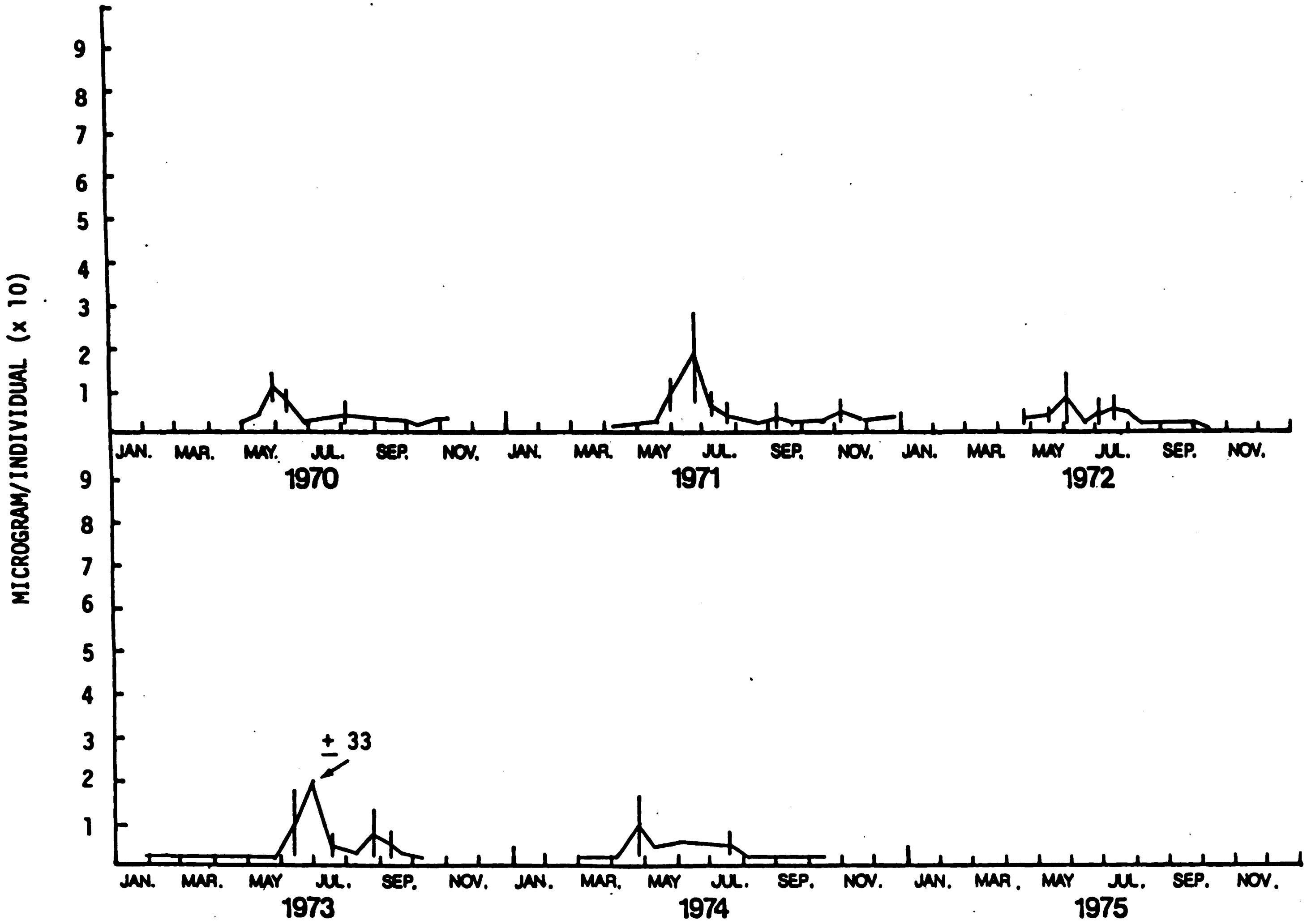

Figure B. Changes in the mean individual zooplankton biomass (microgram/individual) from 1970 to 1974 in Raisin River. The vertical bars denot 90% confidence intervals.

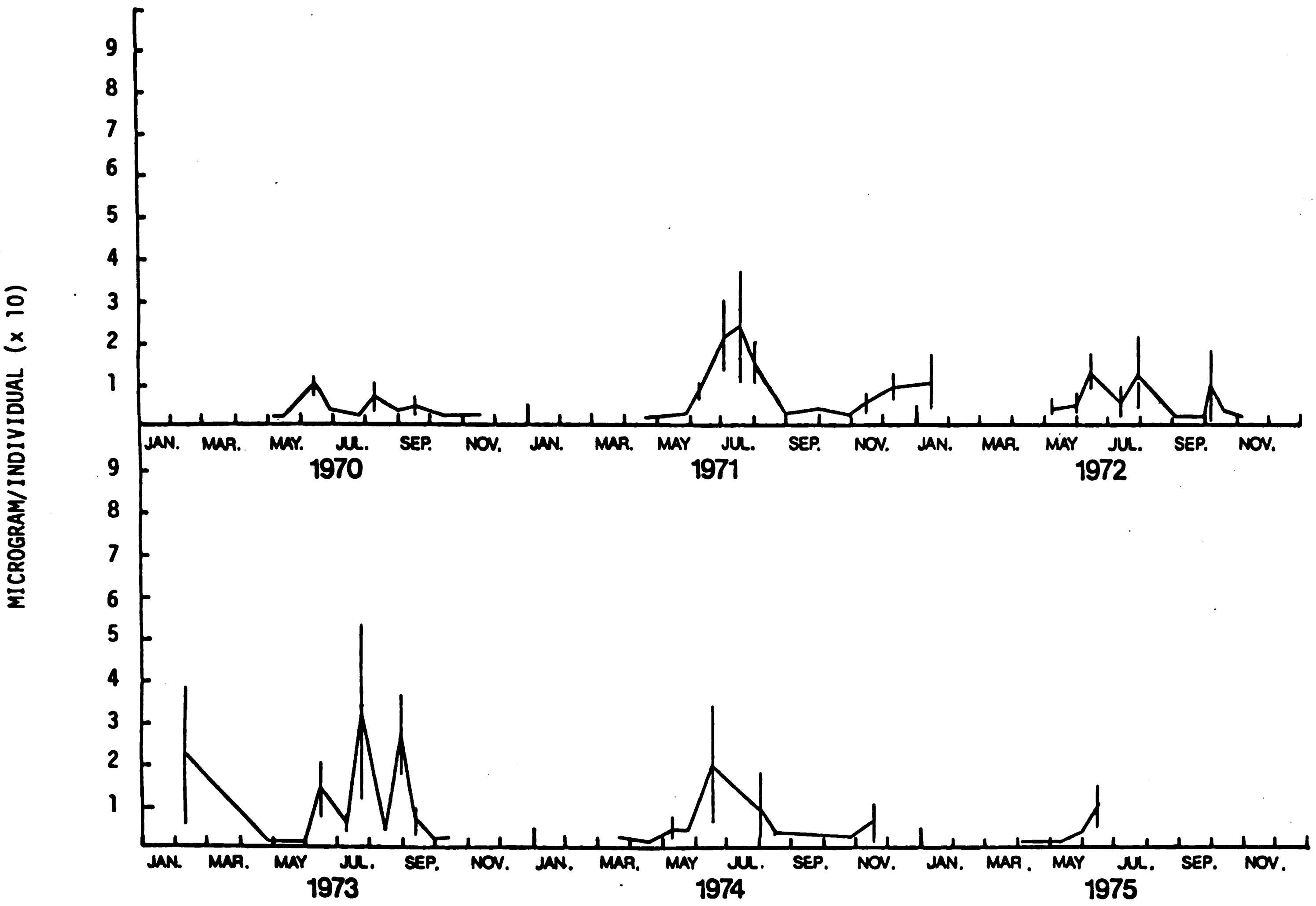

Figure C. Changes in the mean individual zooplankton biomass (microgram/individual) from 1970 to 1975 in the discharge canal. The vertical bars denote 90% confidence intervals.

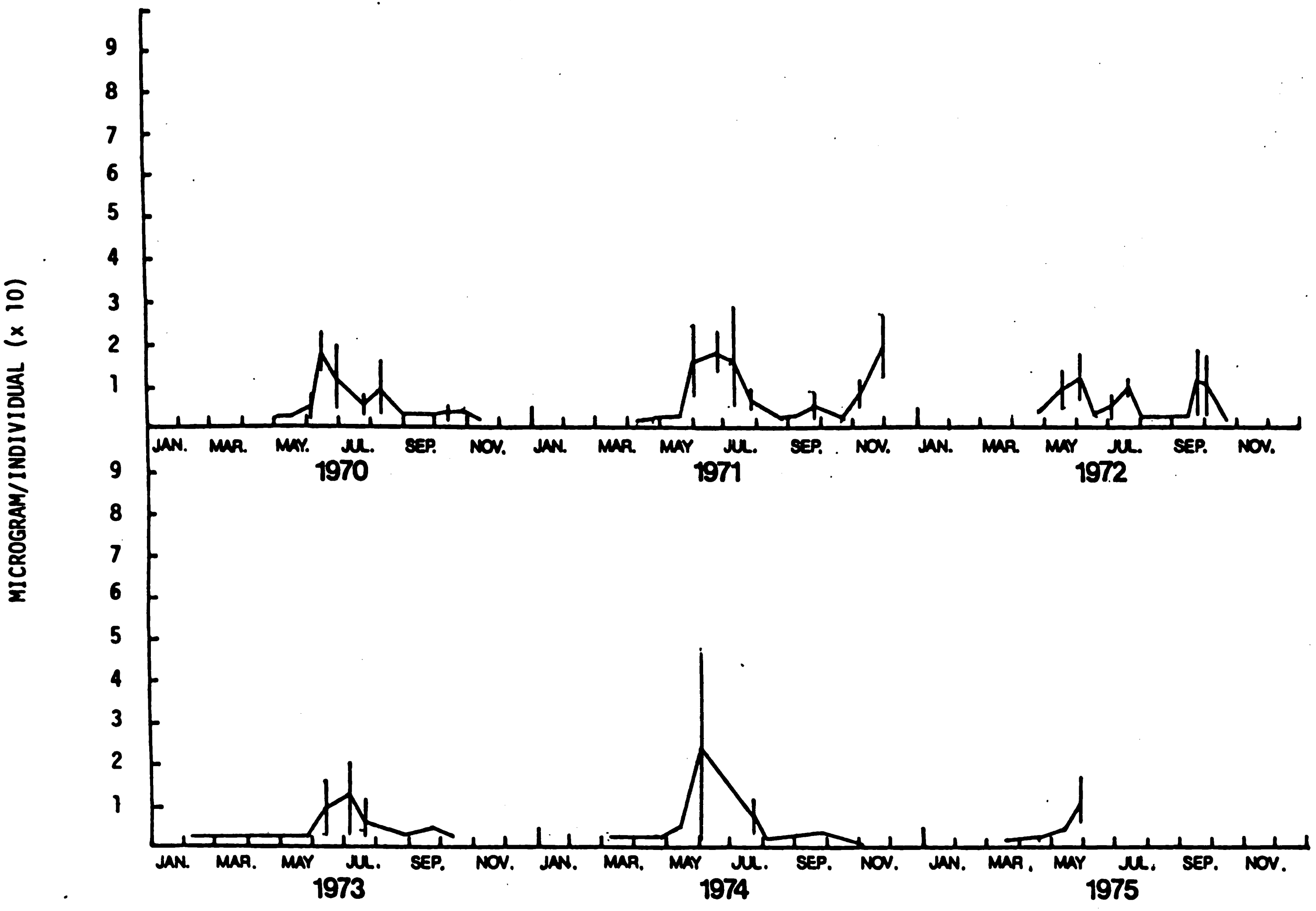

Figure D. Changes in the mean individual zooplankton biomass (microgram/individual) from 1970 to 1975 in Raisin River. The vertical bars denote 90% confidence intervals.

Table A. The individual biomass of rotifers (microgram/individual) arranged in increasing order of abundance in station and year for spring 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	4	3	5	8	9	2	6	1
Mean	0.86	0.89	0.93	0.93	0.94	1.04	1.31	1.70
Multiple range	———	———						
		———	———	———				
			———	———	———	———	———	———

Year	1970	1974	1972	1971	1973
Mean	0.31	0.42	0.92	2.14	4.72
Multiple range	———	———	———	———	———

Table B. The mean individual biomass of cladocerans (microgram/individual) arranged in increasing order of abundance in station, depth, and year for spring 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	8	2	1	9	3	6	5	4
Mean	17.0	23.1	25.3	25.6	28.4	29.6	33.3	37.1
Multiple range	———	———						
		———	———	———	———	———		
					———	———	———	
							———	———

Depth (meter)	0.5	2.5
Mean	24.4	30.5
Multiple range	———	———

Year	1974	1973	1971	1972	1970
Mean	7.31	24.0	34.2	35.0	36.7
Multiple range	———	———	———	———	———

Table C. The mean individual biomass of copepods (microgram/individual) arranged in increasing order of abundance in station, depth, and year for spring 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	2	5	1	8	6	3	9	4
Mean	6.79	8.78	9.26	9.97	9.98	10.4	11.3	12.6
Multiple range	———	———	———					
		———	———	———	———	———	———	
					———	———	———	———

Depth (meter)	0.5	2.5
Mean	8.81	10.9
Multiple range	———	———

Year	1970	1974	1973	1971	1972
Mean	4.96	9.57	10.2	10.9	13.8
Multiple range	———	———	———	———	———

Table D. The mean individual biomass of rotifers (microgram/individual) arranged in increasing order of abundance in station, depth, and year for summer 1970-1973 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	5	4	8	6	9	2	3	1
Mean	0.41	0.55	0.71	0.80	0.88	1.07	1.07	1.20
Multiple range	—	—						
		—	—	—				
			—	—	—			
					—	—	—	
						—	—	—

Depth (meter)	0.5	2.5
Mean	0.77	0.91
Multiple range	—	—

Year	1970	1971	1972	1973
Mean	0.56	0.59	0.59	1.61
Multiple range	—	—	—	
				—

Table E. The mean individual biomass of cladocerans (microgram/individual) arranged in increasing order of abundance in station, depth, and year for summer 1970-1973 with Tukey's multiple range test ($p \leq 0.10$).

<table>
<tr><th>Station Number</th><th>3</th><th>2</th><th>5</th><th>6</th><th>9</th><th>1</th><th>8</th><th>4</th></tr>
<tr><td>Mean</td><td>43.2</td><td>44.7</td><td>44.8</td><td>44.9</td><td>47.4</td><td>49.2</td><td>50.7</td><td>61.2</td></tr>
<tr><td>Multiple range</td><td colspan="7">____</td><td>____</td></tr>
</table>

<table>
<tr><th>Depth (meter)</th><th>0.5</th><th>2.5</th></tr>
<tr><td>Mean</td><td>33.1</td><td>63.4</td></tr>
<tr><td>Multiple range</td><td>____</td><td>____</td></tr>
</table>

<table>
<tr><th>Year</th><th>1970</th><th>1972</th><th>1971</th><th>1973</th></tr>
<tr><td>Mean</td><td>27.8</td><td>42.9</td><td>55.5</td><td>66.8</td></tr>
<tr><td>Multiple range</td><td>____</td><td>____</td><td>____</td><td>____</td></tr>
</table>

Table F. The mean individual biomass of copepods (microgram/individual) arranged in increasing order of abundance in depth and year for summer 1970-1973 with Tukey's multiple range test ($p \leq 0.10$).

Depth (meter)	0.5	2.5
Mean	9.28	12.9
Multiple range	____	____

Year	1970	1972	1971	1973
Mean	6.42	8.93	11.9	17.7
Multiple range	____	____	____	____

Table G. The mean individual biomass of rotifers (microgram/individual) arranged in increasing order of abundance in station, depth, and year for fall 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	1	3	4	8	5	6	2	9
Mean	0.87	0.92	0.96	1.01	1.04	1.08	1.09	1.31
Multiple range	—	—	—	—				
		—	—	—	—	—		
			—	—	—	—	—	—

Depth (meter)	0.5	2.5
Mean	0.95	1.12
Multiple range	—	—

Year	1972	1970	1974	1973	1971
Mean	0.56	0.82	0.99	1.02	1.79
Multiple range	—	—	—		
			—	—	—

Table H. The mean individual biomass of cladocerans (microgram/individual) arranged in increasing order of abundance in station, depth, and year for fall 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	2	8	1	3	4	5	6	9
Mean	8.63	8.70	9.16	9.89	10.2	10.9	11.1	12.6
Multiple range	——	——	——	——	——	——		
		——	——	——	——	——	——	
					——	——	——	——

Depth (meter)	0.5	2.5
Mean	8.88	11.4
Multiple range	——	——

Year	1974	1971	1972	1973	1970
Mean	6.9	7.4	11.8	12.1	12.4
Multiple range	——	——	——	——	——

Table I. The mean individual biomass of copepods (microgram/individual) arranged in increasing order of abundance in station and year for fall 1970-1974 with Tukey's multiple range test ($p \leq 0.10$).

Station Number	2	1	3	5	6	9	8	4
Mean	2.79	4.08	4.97	5.34	5.95	7.24	7.43	7.89
Multiple range	———	———	———					
		———	———	———	———			
			———	———	———	———	———	
				———	———	———	———	———

Year	1971	1970	1972	1973	1974
Mean	2.20	3.01	4.40	9.09	9.85
Multiple range	———	———	———	———	———