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ENTRAINMENT OF ZOOPLANKTON BY A ONCE
THROUGH COOLING SYSTEM ON WESTERN LAKE ERIE

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ENTRAINMENT OF ZOOPLANKTON BY A ONCE THROUGH COOLING SYSTEM ON WESTERN LAKE ERIE

By

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ABSTRACT

ENTRAINMENT OF ZOOPLANKTON BY A ONCE THROUGH COOLING SYSTEM ON WESTERN LAKE ERIE

By

Mark Andrew Simons

The entrainment of the zooplankton passing through the once-through cooling system of the Monroe Power Plant on western Lake Erie was studied from November, 1972 to October, 1973. The plankton were sampled in the intake region, discharge canal, thermal plume and lake at a total of 7 stations. They were sampled at bimonthly intervals in the morning, afternoon and evening. An 8.1 liter Van Dorn water sampler was used to collect the animals which were concentrated using a 75-μ plankton net and preserved in 5% formalin. One-way analysis of variance and Tukey's test of paired comparisons were conducted for each sampling date on the density and biomass of the major taxa including 3 categories: Cladocera, Copepoda, and Rotifera. Linear regression analysis was used to assess the relation between depth and distribution of the major taxa. Zooplankton diversity was also determined. Entrainment rates were greatest during summer months but time of day appeared not to effect the entrainment rate. Patchy spatial distributions confounded spatial comparisons of density on any particular date but annual mean density and biomass were depressed 35 to 50% regardless of the time of day.

Neither chlorine application nor temperature (as it relates to power plant operation) appeared to be important causative factors. Zooplankters, which were uniformly mixed from top to bottom by condenser passage, appeared to recover vertical distribution similar to that in

the intake as cooling water passed down the discharge canal. Diversity appeared not to be affected by passage. There was no evidence that entrainment effects on zooplankton persisted beyond the thermal plume.

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INTRODUCTION

Prodigious quantities of zooplankton can be transported through once-through cooling systems of steam-electric stations. The demand for cooling water has been doubling every ten years in densely populated areas, like that around the western end of Lake Erie. As energy demanding trends continue, increasing numbers of zooplankton will be transported through cooling systems. Such passage through cooling systems could affect the health and survival of the entrained animals (McNaught, 1972; Coutant, 1970). Zooplankton serve as a trophic linkage between algae and fish populations; therefore changes in zooplankton abundance may be reflected in altered fish population abundances. The purpose of this research was to quantify the passage of zooplankton through a once-through cooling system on western Lake Erie and assess the impact of the passage on zooplankton abundance in the receiving waters of western Lake Erie.

Concern about the effects of entrainment mostly arise from the rapid elevation of temperatures, usually from 5 to 15 C, as water passes through the cooling system, and the length of time the animals remain exposed to elevated temperatures (Coutant, 1970). This problem seems most pressing in the summer when lethal temperatures are most likely to be reached in cooling systems. However, the impact of elevated temperature also may be compounded by other environmental stresses including mechanical damage (McNaught, 1972; Coutant, 1970), the application of chlorine as a biocide (U.S.A.E.C., 1972) and increased vulnerability to predatory fishes concentrated in the thermal discharge (Neill and Magnuson, 1974).

I examined this problem at the Monroe Power plant by measuring (1) the numbers and biomass of important taxa, (2) their size distribution, (3) their capacity to orient to normal vertical distributions and (4) their species diversity. Sampling was conducted at several points in the cooling water source, the cooling system and the thermal plume that mixed with the receiving water of western Lake Erie.

METHODS

Study Area

The study was conducted at the Monroe Power Plant, which is located on the western shore of Lake Erie at the mouth of the Raisin River. The plant has the potential to discharge 85 m^3/sec of cooling water. The plant began operating in June, 1971 with the first of four, 800 megawatt units. The fourth unit began operating in May, 1974. At the time of this study in 1972-73, two to three units operated sporadically. Because of start-up operational difficulties, power generation and heated water output were less stable than expected for the completed power plant. The magnitude of power generation and thermal discharge varied with the number of functioning units and the output of each unit.

Figure 1 shows the cooling system, lake environs around the Monroe Power Plant and the sampling stations used in this study. The cooling water is drawn from two sources: the lake and the Raisin River. The proportion of water coming from both sources is important because the Raisin River water quality differed from that of the lake, partly because it was loaded with municipal and industrial waste. The western basin of Lake Erie is usually very turbid from suspended matter produced by wave action, runoff, and dense algal growths.

The intake is located about 650 m upstream from the mouth of the Raisin River and is designed to take most of the river flow before

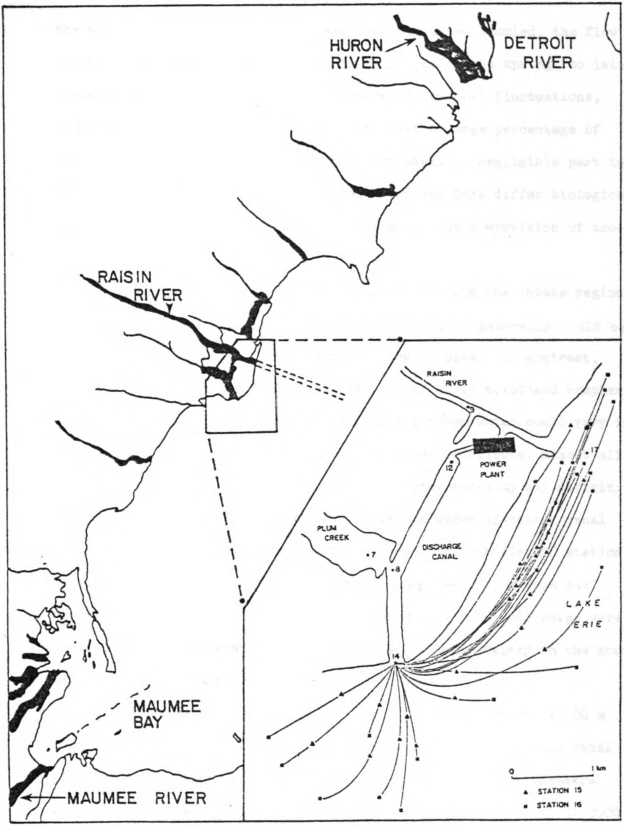

Figure 1. Map of the study area.

the balance is made up from the lake. On the dates sampled, the flow in the river varied from 38 m^3/sec to 63 m^3/sec in the spring, to late summer discharges near 4 m^3/sec. Because of seasonal fluctuations, the river may comprise nearly all or at least a large percentage of the pumped volume in the spring and a very small to negligible part in the late summer and fall. Because the river and lake differ biologically, this variation in flow contribution influences the composition of zooplankton in the cooling system.

Stations 17 and 9 were chosen for sampling from the intake region (Figure 1) because the water at those two locations generally could be representatively sampled with relatively few samples. In contrast, the water in the short intake canal was incompletely mixed and complexly distributed; discrete proportions of lake and river water could vary in position and amount from day to day. The river contributes almost all of its flow to the cooling system and lake water makes up any deficit. In order to compare water at station 12 in the upper discharge canal to the mixture of waters from the two sources, an "artificial" station was calculated for the intake by proportioning water flow from the river and lake (Table 1). Daily USGS measures of river discharge were used along with information from the Detroit Edison Company on the known amounts of water pumped into the discharge canal.

After the water passes through the intake canal (which is 100 m long), it goes through the condensers, then on to the discharge canal via a concrete overflow canal. Water passes through the condensers in 7 seconds at a rate of nearly 2 m/sec. The discharge canal is 2000 m long and averages 175 m in width and 5 to 6 m deep.

TABLE 1. AMOUNTS OF RIVER AND LAKE WATER USED TO DETERMINE THE CONTRIBUTION OF ZOOPLANKTON AT STATION 18 IN THE INTAKE CANAL, WATER PASSAGE TIMES THROUGH THE DISCHARGE CANAL.

Date	River* Water (m^3/sec)	Lake Water (m^3/sec)	Total Discharge (m^3/sec)	Mean Velocity (cm/sec) Upper Discharge	Number of Pumps	Passage Time (hrs)
Nov. 9, 1972 (eve)	57.4	0	42	3.9	6	11.4
Nov. 10, 1972 (aft)	52.0	0	42	3.9	6	11.4
Nov. 10, 1972 (morn)	49.0	0	42	3.9	6	11.4
Jan. 18, 1973 (eve)	17.4	45.6	63	3.9	9	7.5
Jan. 24, 1973 (aft)	42.2	20.8	63	5.8	9	7.5
Jan. 25, 1973 (morn)	44.0	19.0	63	5.8	9	7.5
March 30, 1973 (eve)	63.0	0	63	5.8	9	7.5
April 5, 1973 (aft)	43.0	20.0	63	5.8	9	7.5
April 6, 1973 (morn)	38.0	25.0	63	5.8	9	7.5
June 11, 1973 (eve)	22.0	41.0	63	5.8	9	7.5
June 12, 1973 (aft)	20.0	43.0	63	5.8	9	7.5
June 13, 1973 (morn)	23.0	40.0	63	5.8	9	7.5
Aug. 8, 1973 (eve)	11.0	31.0	42	3.9	6	11.4
Aug. 9, 1973 (aft)	10.5	31.5	42	3.9	6	11.4
Aug. 10, 1973 (morn)	12.0	30.0	42	3.9	9	7.5
Sept. 2, 1973 (eve)	3.7	38.3	42	3.9	6	11.4
Sept. 29, 1973 (aft)	5.0	37.0	42	3.9	6	11.4
Oct. 1, 1973 (morn)	7.0	35.0	42	3.9	6	11.4

* From U.S.G.S. measurements corrected for 1.5 m/sec added by Monroe, Michigan.

Since the upstream half of the discharge canal is dredged to 6 m and the downstream half is dredged only to 3 m, the mean velocity of the downstream end is almost twice that of the upstream end. On the dates sampled, the average rate of flow reached as high as 58 cm/sec near the upper end of the discharge canal (Table 1). However, the velocity is not uniform because high velocity (1 m/sec) water from the overflow canal enters the discharge canal on the west side and forms an eddy of slower water on the east side. This creates wide variation in the exposure time of zooplankton to the heated effluent. During passage through the 2000 m discharge canal to the lake (about 7.5 to 11.4 hours on the average) less than 10% of the heat is lost (Table 1).

Temperatures have been elevated as high as 16 C above ambient during condenser passage, but 10 C is expected to be closer to the normal operational elevation. Temperature elevations varied from date to date during this study but the maximum rise encountered on the dates sampled was 11 C above ambient (Figure 2).

The plume from the thermal discharge extended from the mouth of the canal over an extensive (as indicated by a 1°C elevation above adjacent waters), shallow, sandy shoal. The location of the plume varied with the direction and velocity of the wind (Figure 1). It drifted from about 4 km south of the mouth of the discharge canal to about 1 km north of the mouth of the Raisin River.

Station 15 was located in the plume at a point along the central axis where the temperature was about one-half the difference between the lake temperature and the temperature in the upper discharge canal. For example, when Lake Erie was 10 C, and the upper discharge canal

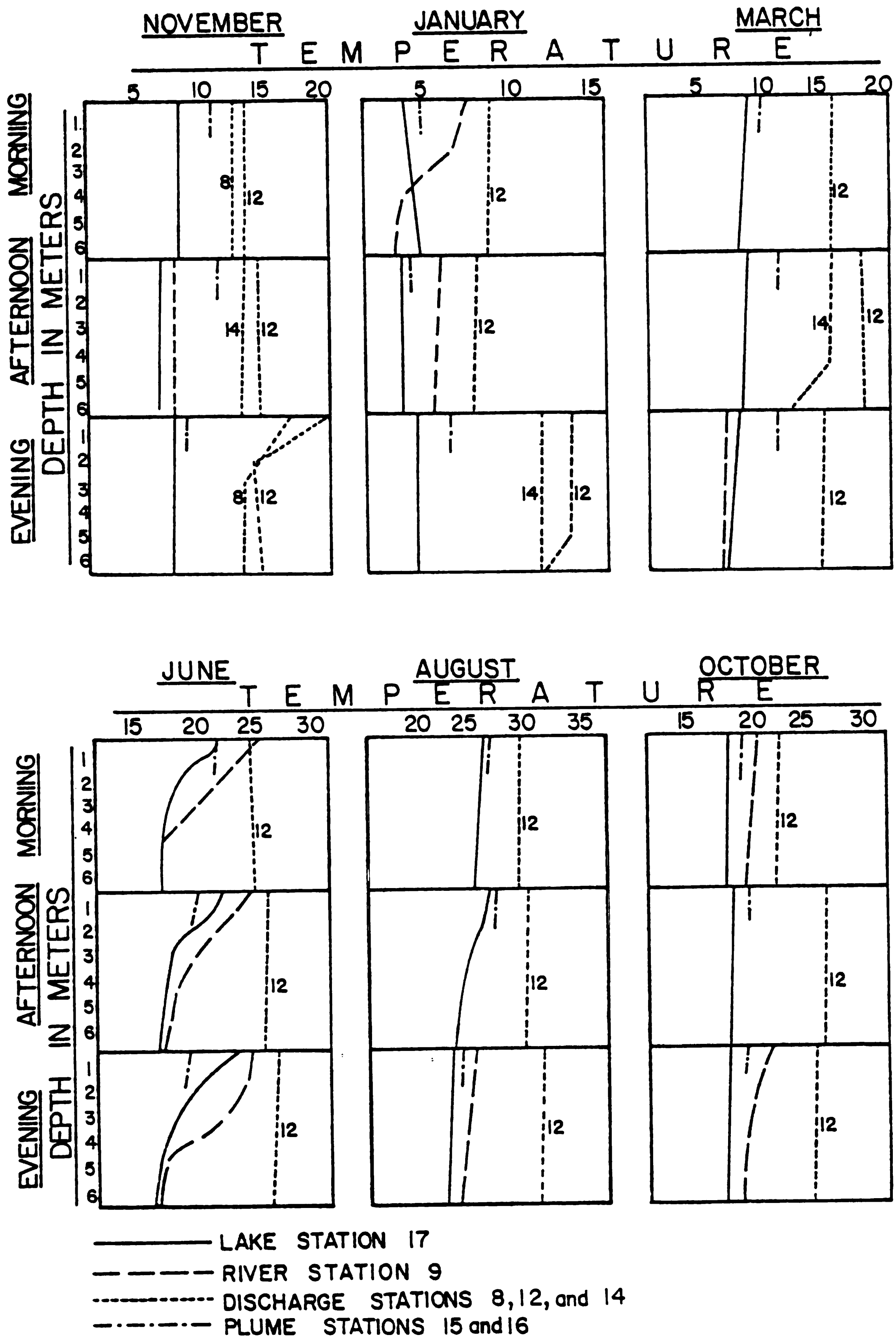

Figure 2. Temperature (C) profile in the study area from November, 1972 through October, 1973.

was 18 C, station 15 was about 14 C. Station 16 was located along the central axis near the plume edge at temperatures about 1 C above ambient.

Hydrology

Chloride was measured in order to confirm mixing ratios in the intake and estimate what portion of the water at station 16 was indeed discharge water. Most of the time, station 16 was composed almost entirely of lake water according to the chloride index (Table 2). The discharge water was partially diluted by lake water by the time it had reached station 15, and at station 16 the chloride in the discharge water was mixed back to ambient concentrations in the lake water. Since station 16 and station 17 have similar chloride values, both were considered to be lake water which should behave similarly in terms of zooplankton abundances. Variation between the two were expected to be a measure of spatial variation of zooplankton in the lake.

Zooplankton Sampling

Three sets of zooplankton samples were collected over a two to three day period in the morning, afternoon and evening every two months from November, 1972 through October, 1973. The morning sampling began at approximately 0800 hrs., to match the time that the plant chlorinated its condensers (0730 hrs.). The afternoon sampling began when the sun approached its peak at about 1300 hrs. The evening sampling was initiated promptly after sunset. During the summer months, the cooling system was also chlorinated during this evening period. Sampling consisted of 5 replicates from 7 stations at randomly located depths,

Table 2. The distribution of mean total chloride (mg/liter) and mean temperature (^{o}C) at all stations, June 11 through October 1, 1973.[1]

	Station															
	17		9		18		12		8		14		15		16	
Date	Cl	T^{o}C	Cl	T^{o}C	Cl	T^{o}C	Cl	T^{o}C	Cl	T^{o}C	Cl	T^{o}C	Cl	T^{o}C	Cl	T^{o}C
6/11/73 Eve	18.7[2]	21.0	22.0	21.5	19.9	22.0	19.4	27.0	20.2	27.0	21.0	26.5	19.3	21.0	18.1	19.5
6/12/73 Aft	19.3	20.5	25.3	22.0	21.2	21.0	19.3	26.0	21.3	26.0	20.7	25.5	17.7	20.0	16.4	20.0
6/13/73 Morn	20.7	20.5	24.8	22.0	22.2	21.0	21.6	25.5	21.3	26.0	21.6	25.5	18.5	21.5	17.4	21.0
8/8/73 Eve	17.1	24.5	31.7	26.0	20.9	25.0	21.9	31.0	20.2	31.0	20.0	31.0	19.0	26.0	18.1	26.0
8/9/73 Aft	17.4	25.5	28.2	26.0	20.1	26.0	19.9	30.0	20.1	30.5	21.0	31.0	20.1	30.0	17.5	27.0
8/10/73 Morn	17.7	25.5	29.3	26.0	21.0	26.0	22.9	29.0	21.4	29.0	20.1	29.0	20.3	28.0	14.2	25.5
9/28/73 Eve	13.2	18.5	33.6	21.0	15.0	19.0	13.7	25.5	15.7	25.5	16.6	25.5	16.1	20.0	14.3	19.0
9/29/73 Aft	14.1	18.5	30.1	21.0	15.0	19.0	16.3	27.0	17.1	26.0	17.4	26.0	14.7	22.0	13.4	20.0
10/1/73	14.1	18.0	25.1	19.5	15.9	18.0	22.5	21.0	23.1	21.5	22.5	20.5	17.9	19.0	15.2	18.5
Grand Mean	16.9		27.8		19.1		19.7		20.0		20.1		18.2		16.1	

[1]Dates selected for inclusion in this table were at times when zooplankton were abundant. The average concentration over the whole year at station 17 in the lake and station 16 in the plume edge were, respectively, 20.6 and 21.4 mg/liter.

[2]Each value is the mean of 5 samples.

except for samples obtained in November, 1972 and January, 1973. At those times, all replicates were taken from the surface (Table A1). One incomplete set of samples was taken on January 25, when stations 1 and 2 were omitted because of inclement weather

By sampling during different times of the day, we incorporated diurnal variability into estimates of the entrainment and mass movement of organisms through the cooling system. Sampling every two months included seasonal changes in the relative river and lake contributions to the system and seasonal changes of ambient temperatures.

Laboratory and Statistical Analysis

Zooplankton samples were obtained using an 8.1 liter Van Dorn water sampler. The samples were concentrated using a #25 Wisconsin plankton bucket and preserved in 5% formalin. In the laboratory they were diluted to a known concentration, and a 1-ml aliquot was placed in a Sedgewick-rafter counting cell. Using a binocular zoom scope, I counted organisms, measured (using a Whipple micrometer), identified them to species when possible, and then calculated population density, biomass, and indices of species diversity.

Individual zooplankter volumes were estimated by using linear measurements of length and width to calculate the volume of a common geometric figure which best approximated the shape of the animal. Dry weights were calculated from the volume by assuming that the organism's specific gravity was 1.0 and it was 90% water (Cummins and Waycheck, 1971).

Analysis of variance among stations (combining depth) was conducted for each sampling date on the density and biomass of the major taxa including three categories: Cladocera, Copepoda, and Rotifera. This was followed by Tukey's test of paired comparisons (Sokal and Rohlf, 1969). The data were corrected for heterogeneity in variance by $\log_{10}$ transformation. Linear regression analyses were also used to assess the relation between depth and distribution of the major taxa. Differences in coefficients measured at different stations were used to indicate the relative ability of zooplankters to redistribute in relation to depth as they passed through the cooling system. The zooplankton diversity was determined using the species diversity index as described by Pielou (1969):

$$H = \sum_{j=1}^{S} (N_j/N)\log_{10}(N_j/N)$$

where N = total number or total weight of all species together, N_j = the number or weight of the jth species and S = species.

RESULTS

Zooplankton Abundance and Size

The Intake and Discharge Canals

Zooplankton abundance varied from nearly negligible quantities of copepods, cladocerans and rotifers in winter to greatest concentrations in late summer and early fall (Table 3; Figure 3). Biomass varied over the year more than density because the small rotifers were relatively numerous in winter. The three most abundant species were *Bosmina* sp., *Cyclops vernalis* and *Daphnia retrocurva* (Table 4; Figure 3). *Bosmina* sp. was abundant in June, August, and September while *C. vernalis* and *D. retrocurva* were abundant only in June and August. Based on these sampling results, nearly all zooplankton entrainment occurs between April and November.

Abundances varied less dramatically over the short-term periods when the cooling system was sampled morning, afternoon, and evening (Figures 3), Even so, the abundances found at different times of the day commonly varied up to 100% or more of the mean. However, there was no consistant relationship between abundance and the time of the day sampled. Mean densities for morning, afternoon, and evening samples reveal no important differences that are related to the time of the day (Table 5). The greatest mean density, in the afternoon, was only 35% more than the lowest mean density, in the evening. The taxa varied

Table 3. Mean annual density (numbers/liter) at all stations throughout the water column and near the surface (in parentheses).

	Station							
Taxa	17	9	18	12	8	14	15	16
Rotifera	76.6(54.4)	45.4(40.7)	66.5(50.3)	43.0(46.5)	54.2(50.2)	56.0(55.4)	(46.9)	(52.6)
Cladocera	35.2(16.8)	9.1(15.1)	26.8(15.0)	12.9(10.7)	16.2(7.1)	16.2(10.9)	(16.0)	(27.3)
D. retrocurva	13.7(6.4)	3.0(.9)	10.5(5.8)	5.0(2.8)	6.8(2.2)	5.5(4.5)	(2.9)	(5.0)
Bosmina sp.	13.0(5.4)	5.2(6.8)	10.6(5.1)	6.3(5.5)	7.7(4.5)	7.8(5.9)	(8.7)	(15.1)
Adult Copepoda	80.9(69.6)	31.3(9.7)	66.4(67.1)	52.2(41.7)	51.2(46.6)	52.1(50.6)	(54.4)	(47.8)
Adult *C. vernalis*	59.1(33.6)	29.3(16.0)	49.7(31.9)	37.6(36.0)	37.6(27.9)	42.2(28.8)	(36.8)	(32.6)
Nauplii	21.3(26.9)	13.5(6.5)	27.5(20.5)	11.9(9.3)	17.7(15.5)	22.0(25.7)	(19.9)	(27.3)
Total Copepoda	102.3(96.5)	44.9(16.2)	93.8(87.9)	64.0(51.0)	68.9(62.1)	74.1(76.2)	(74.2)	(75.0)
Total	214.3(167.7)	99.4(72.0)	187.1(154.9)	119.9(108.2)	139.3(119.3)	146.3(142.5)	(137.1)	(154.9)

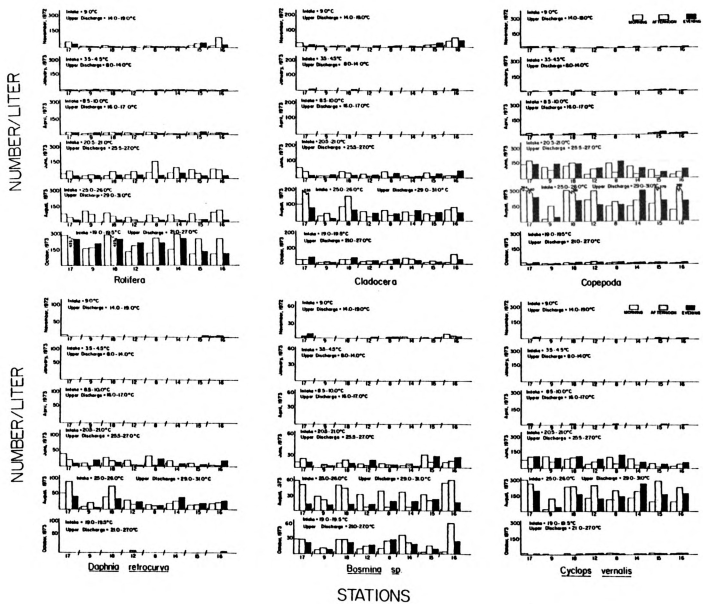

Figure 3. Mean annual density of major taxa throughout the sampling period (numbers/liter).

Table 4. Mean annual biomass (μg/liter) at all stations throughout the water column and near the surface (in parentheses).

	Station							
Taxa	17	9	18	12	8	14	15	16
Rotifera	9.4(5.9)	6.5(6.3)	8.0(5.5)	5.5(5.3)	7.8(6.7)	5.5(5.5)	(5.8)	(5.7)
Cladocera	183.0(57.4)	47.1(9.5)	139.4(49.5)	73.4(48.6)	78.0(18.3)	48.2(39.7)	(34.9)	(52.8)
D. retrocurva	156.7(52.6)	42.9(4.6)	124.0(46.4)	57.4(41.1)	66.3(13.7)	38.8(24.4)	(22.7)	(38.2)
Bosmina sp.	17.3(2.6)	3.6(9.8)	13.8(2.6)	6.9(5.7)	6.4(4.5)	4.9(3.2)	(8.1)	(13.7)
Adult Copepoda	252.8(136.7)	114.3(40.7)	212.5(127.5)	169.4(164.1)	152.1(128.7)	162.1(112.7)	(175.6)	(143.5)
Adult *C. vernalis*	186.8(89.4)	90.7(34.7)	159.0(86.1)	123.4(121.4)	106.0(90.7)	128.7(86.0)	(93.9)	(86.2)
Nauplii	2.3(2.5)	1.2(.64)	2.75(2.05)	1.0(.68)	1.3(1.1)	1.5(1.7)	(1.7)	(2.4)
Total Copepoda	255.5(139.4)	115.4(41.4)	234.5(131.9)	170.8(164.7)	153.4(130.1)	163.4(114.7)	(177.4)	(145.9)
Total	447.9(202.7)	169.0(57.2)	381.9(186.9)	249.7(218.6)	239.2(155.1)	217.1(159.9)	(218.1)	(204.4)

Table 5. Mean density (numbers/liter) for the major taxa at the three daily sampling periods.

Taxa	Morning	Afternoon	Evening
Rotifera	342.9	486.0	289.3
Cladocera	136.0	132.2	126.7
D. retrocurva	46.3	37.5	40.7
Bosmina sp.	72.7	66.7	55.7
Adult Copepoda	311.3	426.7	371.7
Adult *C. vernalis*	212.3	315.5	308.9
Nauplii	169.5	141.3	90.4
Total Copepoda	480.9	567.8	462.1
Total Mean	959.8	1186.0	878.1

independently from each other from one time of day to the next without any indication of trends. The total zooplankton biomass estimates also show only minor, short-term temporal differences, although in this instance, evening samples had the highest biomass (Table 6). Accordingly, the mean individual size was greatest in evening samples, particularly in *C. vernalis* and *D. retrocurva* (Table 7).

The short-term variation in density and biomass indicated no consistant effects from chlorine application in the morning and evening. If chlorine had been an important factor, the morning and evening zooplankton concentrations in the upper discharge canal at station 12 should have been consistantly lower than afternoon concentrations (Table 8). Because mean water velocities would carry water to station 8 in 4 to 6 hours, afternoon samples would tend to be lower than morning and evening samples if chlorine were an important factor.

The subtle spatial differences that appear in the comparisons of annual means (Table 3) rarely show up as significant ($\alpha = 0.05$) differences on the individual dates sampled; probably because of the relatively low sampling intensity for the spatial variability that exists. Lake concentrations at intake station 17 averaged about twice as great as river concentrations at station 9 (Table 3) and the differences were significant ($\alpha = 0.05$) on several dates for most of the taxa (Table A3). The statistically identified differences among stations in the intake and discharge canals may have been caused by naturally patchy distributions in the study area rather than by entrainment effects. However, significant ($\alpha = 0.05$) differences for total zooplankton density and biomass were determined 3 out of 9 times when animals were common and intake abundances always ranked higher. This indicates that although

Table 6. Mean biomass (µg/liter) for the major taxa at the three daily time periods.

Taxa	Morning	Afternoon	Evening
Rotifera	42.5	57.3	37.7
Cladocera	553.9	437.6	556.7
D. retrocurva	459.2	369.3	456.7
Bosmina sp.	71.2	61.7	45.5
Adult Copepoda	993.9	1224.3	1315.9
Adult *C. vernalis*	639.9	830.7	1004.7
Nauplii	16.0	12.0	7.2
Total Copepoda	1009.9	1236.2	1323.1
Total	1606.3	1731.1	1917.5

Table 7. Mean size/individual for the major taxa at the three daily time periods.

Taxa	Morning	Afternoon	Evening
Rotifera	0.12	0.12	0.13
Cladocera	4.1	3.3	4.4
D. retrocurva	9.9	9.8	11.3
Bosmina sp.	0.98	0.93	0.82
Adult Copepoda	3.2	2.9	3.5
Adult *C. vernalis*	3.0	2.6	3.3
Nauplii	0.09	0.08	0.08
Total Copepoda	2.1	2.2	2.9
Total	2.1	1.9	2.5

Table 8. Comparison in mean annual density (numbers/liter) between the intake station (18) and the upper discharge station (12) at the three daily time periods.

	Morning		Afternoon		Evening	
	Station 18	Station 12	Station 18	Station 12	Station 18	Station 12
Rotifers	70.7	35.8	90.2	49.7	47.8	40.4
Cladocerans	26.6	15.6	36.2	8.4	21.5	14.7
Daphnia retrocurva	11.0	7.5	15.1	3.3	7.0	4.0
Bosmina sp.	13.4	7.8	13.8	3.6	6.6	7.1
Adult Copepoda	107.9	62.9	114.2	89.4	72.3	57.5
Adult *Cyclops vernalis*	55.2	25.6	55.8	51.5	45.4	35.5
Nauplii	37.0	20.5	34.8	22.5	15.9	10.4
Total Copepoda	144.9	83.4	149.0	111.9	88.2	67.9
Total	242.2	134.8	275.4	170.0	157.5	123.0

patchy distributions increased the variability, there were consistant depressions in abundances as a consequence of passage through the cooling system. Among the most abundant species, significant differences ($\alpha = 0.05$) were about equally represented by higher and lower concentrations in the discharge canal compared to the intake. The incidence of statistical difference seemed not to be related to absolute water temperature or the elevation at the condenser.

The mean annual density of all taxa appeared to decrease from 27 to 55% in passage from the intake to the upper discharge canal (Table 3). Biomass also seemed to decrease similarly (Table 4) so that the mean size of animals remained about the same. In passage from the upper to the lower discharge canal the mean annual density of most taxa increased slightly while mean annual biomass changed very little. Therefore, mean annual sizes of zooplankters seemed to decrease at least slightly among most zooplankter groups as water passed through the discharge canal (Table 9).Apparent changes in mean size were most pronounced in the cladocera which decreased 40% in mean size during the passage.

Although there was no indication that obvious vertical migration occurred within any of the taxa investigated, based on day and night comparisons, both cladocerans and copepods exhibited depth related distributions (Figure 4). Both groups were more abundant near the bottom than near the surface at three of the four stations (17, 9, 12 and 8) where depths were randomly sampled over 5 m from top to bottom. Other stations were too shallow to sample similarly. The time of day did not seem to influence this distribution (Figure 4). No depth-related distribution was observed in the upper discharge canal (station 12). Whatever disrupted the distributional pattern in the upstream

Table 9. Mean annual size/individual (μg) throughout the water column and near the surface (in parentheses).

	Station							
Taxa	17	9	18	12	8	14	15	16
Rotifera	.12(.11)	.14(.16)	.12(.11)	.13(.11)	.14(.13)	.10(.10)	(.12)	(.11)
Cladocera	5.2(3.4)	5.2(1.2)	5.2(3.3)	5.7(4.6)	4.8(2.6)	3.0(3.6)	(2.2)	(1.9)
D. retrocurva	11.5(8.2)	14.3(5.3)	11.7(8.0)	11.7(14.7)	9.9(6.2)	7.1(5.5)	(7.8)	(7.6)
Bosmina sp.	1.3(.5)	0.7(.7)	1.3(.5)	1.1(1.0)	0.8(1.0)	0.6(.5)	(.9)	(.9)
Adult Copepoda	3.1(2.0)	3.6(4.2)	3.2(1.9)	3.2(3.9)	3.0(2.8)	3.1(2.2)	(3.2)	(3.0)
Adult *C. vernalis*	3.2(2.7)	3.1(3.7)	3.2(2.7)	3.3(3.4)	2.8(3.3)	3.1(3.0)	(2.6)	(2.6)
Nauplii	.11(.09)	.09(.10)	.10(.10)	.09(.07)	.08(.07)	.07(.07)	(.09)	(.09)
Total Copepoda	2.5(1.4)	2.6(2.5)	2.5(1.5)	2.2(2.1)	2.2(2.1)	2.2(1.5)	(2.4)	(1.9)
Total	2.6(1.6)	2.6(1.3)	2.6(1.6)	2.8(2.3)	2.4(1.6)	1.8(1.7)	(1.6)	(1.3)

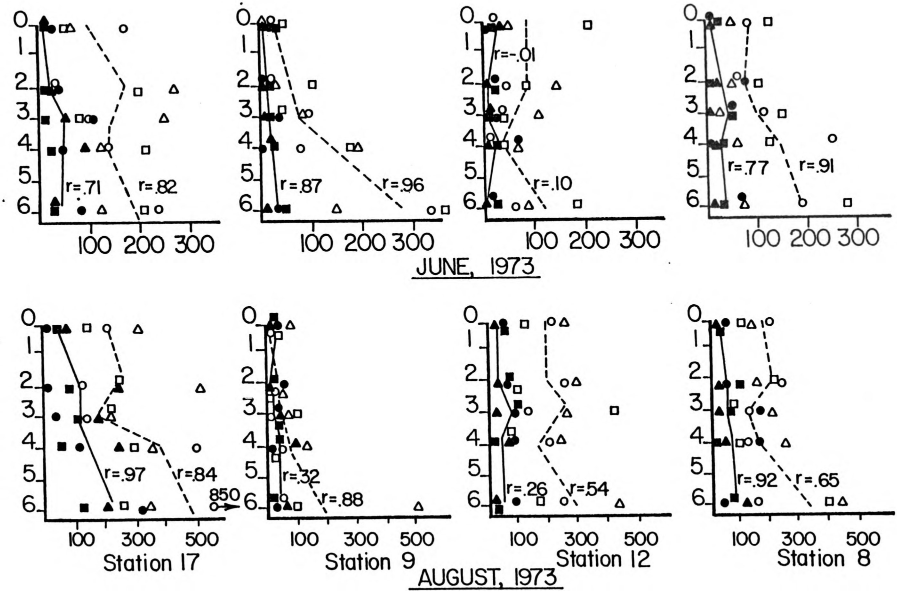

Figure 4. Density at all depths for the three time periods showing a plot of the mean densities and r values. Regression values are calculated from samples taken from all time periods in a particular data set.

portion of the canal did not persist in effect after the water mass approached the middle of the discharge canal at station 8.

In summary, only subtle trends in the mean zooplankton concentration and sizes may have occurred as the organisms passed through the cooling system from the intake to the mouth of the discharge canal. Apparently, power plants effects, at least on the dates sampled, had far less effect on abundance than did the other environmental factors operating on the populations in the river and lake cooling water sources. However, there was some indication that concentrations of animals in the water column were somehow depressed in the upper discharge canal by an average of about one third to one half. As they passed through the discharge canal over a period of 8 to 11 hrs there appeared to be a slight net effect which increased the density and depressed the mean size. Although passage through the plant appeared to disrupt depth oriented vertical distributions in the upper discharge canal, they seem to have recovered their capacity to orient by the time they reached the middle station in the discharge canal.

The Discharge Plume

Chloride concentrations and temperatures measured in the plume indicate that most of the heat is mixed into the receiving waters of the lake rather than into the atmosphere. If there had been a substantial loss of heat to the atmosphere, chloride concentrations at station 16, near the plume-edge, would have averaged higher than ambient concentrations in the lake. But concentrations in the plume and the lake were similar (Table 2). This observation indicates that the concentration of zooplankton in the plume is a mixture of lakes, receiving water populations and populations that have passed through the once-through cooling system at least once.

By the time that water masses from the cooling system and the lake have mixed back to ambient chloride concentrations and temperatures, zooplankton concentrations also were expected to have mixed back to concentrations like those found in the lake dilution water at the same depth. The data presented in Table 10 support this view. The plume-edge concentrations of zooplankton fall into the range of concentrations observed at the reference stations in the lake.

Station 15 was located about midway between the mouth of the discharge canal and the plume edge at a point where temperature and chloride concentration averaged close to midway between the conditions in the discharge canal and the lake. As at station 16, sampling was conducted only at the surface (0.5 m) because the thermal plume tended to float and the water depth averaged only 1 to 1.5 m. Based on mixing ratios defined by chloride concentration and temperature, I expected zooplankton concentrations in the plume at station 15 to average midway between those at stations 14 and 16. Sampling variability obscured any possibility of differentiating the concentrations estimated at station 15 from population estimates for other locations in the study area.

Diversity in the Cooling System

There are no indications of consistent changes in diversity anywhere in the cooling system at times of year when the diversity was high enough to contrast (Table 11). Differences in diversity over a three

Table 10. Comparison of mean density, biomass, an d size among the lake stations and lower discharge station 14 at 0.5 m below the surface. Samples included in the comparison were collected from April to November because no winter samples were taken at stations 3, 4, and 5.

	Station						
	Discharge Canal	Plume		Adjacent Lake Area			
Taxa	14	15	16	17	3	4	5
				DENSITY			
Rotifera	83.0	70.3	78.8	81.5	107.0	109.0	90.0
Cladocera	16.4	24.0	41.0	25.2	30.2	27.6	18.8
Total Copepoda	114.3	111.2	112.6	144.7	106.7	70.6	101.8
Total	213.7	205.6	232.4	251.4	243.9	207.2	210.6
				BIOMASS			
Rotifera	8.2	8.7	8.5	8.9	9.8	10.9	12.8
Cladocera	59.5	52.3	79.1	86.1	162.8	110.6	59.7
Total Copepoda	172.0	265.9	218.7	209.0	115.5	141.4	92.7
Total	239.7	326.9	306.3	304.0	288.1	262.9	165.2
				MEAN SIZE/INDIVIDUAL			
Rotifera	0.10	0.12	0.11	0.11	0.09	0.10	0.14
Cladocera	3.6	2.2	1.9	3.4	5.4	4.0	3.2
Total Copepoda	2.1	2.4	1.9	1.4	1.1	2.0	0.9
Total	1.1	1.6	1.3	1.2	1.2	1.3	0.8

Table 11. Diversity index values for zooplankton taxa captured in the cooling system.

	Station							
	17	9	18	12	8	14	15	16
6/11	0.53	0.59	0.53	0.57	0.59	0.59	0.66	0.65
6/12	0.70	0.51	0.59	0.73	0.78	0.69	0.48	0.64
6/13	0.68	0.35	0.51	0.57	0.72	0.65	0.61	0.51
8/9	0.48	0.69	0.64	0.40	0.45	0.41	0.29	0.46
8/10	0.57	0.85	0.78	0.53	0.83	0.59	0.71	0.76
8/8	0.42	0.49	0.45	0.50	0.43	0.35	0.37	0.41
9/30	0.89	0.76	0.89	0.76	0.80	0.77	0.83	0.79
9/29	0.81	0.83	0.83	0.93	0.96	0.96	0.92	0.89
9/28	0.84	0.76	0.92	0.87	0.95	0.89	0.80	0.85

day period at specific stations were often as great as differences observed among stations at any particular time. There were no consistant trends in diversity related to the time of sampling. Short-term vairations appear to be caused primarily by spatial variability among samples at each station and may secondarily be effected by patchy distributions associated with different water masses. There is no indication that entrainment had any effect on diversity.

DISCUSSION

There are a number of ways in which zooplankton abundance and size distributions could be altered by power plant operation at the Monroe site. They could respond to (1) water quality in the river water as river and lake water mixed, (2) the toxic effect of chlorine application at the condenser, (3) mechanical damage during condenser passage, (4) thermal "shock" caused by rapid temperature change and prolonged exposure to elevated temperature, and (5) increased vulnerability to predation caused by thermal shock or increased concentrations of predators in the discharge canal.

Trends were recognizable in the mean annual averages of all the major taxonomic groups investigated but limited statistical confidence can be placed on what may have been a subtle net decrease in density as zooplankton passed from the intake to the upper discharge canal. A mean annual average of about 40% of all zooplankton seemed to disappear from the water column sampled somewhere between the intake and the upper discharge canal. The effect was not size related. This loss, if it is real, probably has a negligible affect on the lake ecosystem. However, explanations for any loss may be pertinent to future power plant design or observations at other sites.

A possible explanation for the apparent loss is that the chloride tracing technique for evaluating mixing in the intake inaccurately estimates the proportions of river and lake water drawn by the power plant. If the river impact has been underestimated, then the observed 40% depression is an artifact of the sampling design. However, such a sampling artifact should be reflected in the abundance ratios of specific taxa. For example, rotifers were relatively more abundant than copepods in the river water compared to lake water. If the underestimation of river water contribution to the mix were the only factor, then rotifer densities should decrease less than copepod densities. Just the opposite appeared in the data.

Whatever may have caused the decreased zooplankton density in the discharge canal did so before the water reached the upstream station in the discharge canal. The plankton pass through condensers at about 2 m/sec and then into a concrete overflow canal which carries them at about 0.75 m/sec to the upper discharge canal only minutes after condenser passage. Potential predators, the fish populations, have never been sampled in the overflow canal but velocities seem too high to maintain very high fish densities. Chlorine was not applied in the afternoon but density differences between that time and chlorination times are not enough to implicate chlorine as the cause. Even if chlorine were involved it would not destroy the bodies of individual zooplankters.

Settling of dead, dying or "shocked" animals could have decreased densities in the sampled water column, although this probably would not happen in the rapidly flowing water of the overflow canal. Settling may have occurred in the upper discharge canal soon after water emptied into it from the overflow canal. Velocities in the discharge canal averaged less than 0.15 m/sec and may have been much less than that near the bottom. Perhaps some of the animals actively swam toward the bottom as soon as they passed into the upper discharge canal. McLaren (1963) and Gehrs (1974) found that certain zooplanktonic species swam toward bottom when they were exposed to higher temperatures. Passage through to the upper discharge canal appeared to uniformly mix any remaining zooplankton evenly throughout the water column.

Changes in the abundance and size distribution of zooplankton may have occurred after the plankton drifted beyond station 12 in the upper discharge canal. Although the density changed slightly as the plankton passed down the discharge canal, the mean size of zooplankton appeared to decrease consistantly among the taxa. These changes could have resulted because (1) larger animals, more than smaller ones, were eaten, settled out, or emigrated from the water column, (2) small animals immigrated or were born into the populations, or (3) there was some combination of size-related mortality and recruitment. Among copepods, the mean size of adults remained fairly constant and apparent average increases in the density of nauplii caused a decrease in copepod mean size. However, it seems unlikely that the number of nauplii would increase as much as indicated by birth alone. Assuming life expectancies of 2 weeks and a mean fecundity per individual of about 10 young, (Geiling and Cambell, 1972; Eckstein, 1964; and Munro, 1974) I would expect only a 2 to 3% increase from birth during the 8 to 11 hr passage. Either nauplii are moving up from the bottom or the distribution is a chance consequence of patchiness. Nauplii were particularly abundant at the mouth of the discharge canal on one date.

Among the Cladocera and the Rotifera, regeneration rates also are likely to cause little change in density over a few hours, but densities seem to increase 20 to 25% as the water passes through the cooling system. This could be caused by animals moving up from the bottom after they have recovered from the impact of condenser passage. Apparently these taxa are capable of recovering their ability to orient to depth related differences within their environment within a few hours of the time that they passed through the condenser. But, because mean sizes of cladocerans, in particular, seemed to decrease as the plankter passed down the canal, either larger animals settled or moved out of the water column or they were consumed by predators. Kenaga and Cole (1975) indicated that certain fish species caught in the vicinity of the power plant tend to be size-selective feeders. Kelly and Cole (1976) also found parallel size changes in benthic organisms inhabiting the discharge canal. Although apparent size changes may be the chance outcome of variability, it is also possible they reflect the effect of predation in the discharge canal.

If a size related selection process is operating in the cooling system it was too subtle to have any impact on the measured diversity. Diversity indices have been promoted as a means of identifying community-wide influences of man-caused perturbations (Wilhm and Dorris, 1968). None of the diversity estimates made during this study indicate that passage through the cooling system had any consistent impact on community structure.

There was no indication from the chloride data that substantial quantities of lake water were being recycled by power plant operation even though measurements of plume temperatures indicated that wind frequently forced the plume waters northward toward the intake. Neither samples of zooplankton or chloride taken over three day periods revealed any trends in changing concentration that would imply cumulative effects from recycling. Apparently the mixing of discharge waters and the receiving waters in Lake Erie effectively diluted any subtle impact from entrainment.

In summary, although there were some subtle indications that plant operation caused transitory disorientation and may have slightly altered distributions or susceptibility to predators, there was no indication of consequential or persistent effects beyond the thermal plume.

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Table A1. Depth in meters at the various stations.

Station	Depth				
17	0	3	6	4	2
9	3	6	4	2	0
12	2	0	6	4	3
8	0	3	4	6	2
14	S	B	S	B	S*
15	S	S	S	S	S
16	S	S	S	S	S

*S = surface; B = bottom

Table A2. Percent composition of the taxa encountered in the study.

Taxa	Percent
ROTIFERA	
Keratella cochlearis	6.3
Keratella quadrata	<1.0
Brachionus sp.	
Brachionus calyciflorus	5.3
Brachionus havanensis	<1.0
Brachionus budapestensis	1.2
Brachionus plicatilis	<1.0
Brachionus angularis	<1.0
Brachionus quadridentata	<1.0
Brachionus urceolaris	<1.0
Brachionus caudatus	<1.0
Asplanchna sp.	1.9
Kellicottia longispina	<1.0
Tricochera cylindracea	1.5
Tricochera multicrinis	<1.0
Tricochera longiseta	<1.0
Polyarthra sp.	4.7
Filinia longiseta	<1.0
Ploesoma sp.	<1.0
Rotaria neptunia	<1.0
Synchaeta sp.	1.0
Euchlanis dilatata	<1.0
Cephalodella sp.	<1.0
Epiphanes sp.	<1.0
Monostyla sp.	<1.0
Eosphora sp.	<1.0
Ascomorpha sp.	<1.0
Chromogaster sp.	<1.0
Gastropus sp.	<1.0
Asplanchnopus sp.	<1.0
Notholca acuminata	<1.0
Trichotria sp.	<1.0
Lecane sp.	<1.0
Pompholyx sp.	<1.0
Lepadella sp.	<1.0
Conochilus unicornis	<1.0
Philodina sp.	<1.0
Unknown rotifera #1	<1.0
Unknown rotifera #2	<1.0

Table A2 (cont'd)

Taxa	Percent
CLADOCERA	
Leptodora kindtii	<1.0
Daphnia retrocurva	4.4
Daphnia pulex	<1.0
Daphnia galeata mendotae	<1.0
Diaphanosoma leuchtenbergianum	<1.0
Ceriodaphnia lacustris	<1.0
Alona sp.	<1.0
Chydorus sphaericus	<1.0
Bosmina sp.	6.8
Immature *Daphnia* sp.	<1.0
COPEPODA	
Diaptomus ashlandi	<1.0
Diaptomus sicilis	<1.0
Diaptomus minutus	<1.0
Diaptomus oregonensis	<1.0
Diaptomus siciloides	2.3
Immature calanoid	<1.0
Immature cyclopoid	1.8
Cyclops vernalis	29.2
Cyclops bicuspidatus	1.2
Eurytremora affinis	<1.0
Limnocalanus macrurus	<1.0
Canthocamptus robertcokeri	<1.0
Tropocyclops prasinus	<1.0
Nauplii	14.1

Table A3. Tukey's multiple range test for zooplankton density. Stations identified with the same letter were not differentiated at $\alpha = 0.05$; a is greatest and e least. Only those dates with differences are included in the table.

		Station							
Variable	Date	17	9	18	12	8	14	15	16
Total Zooplankton	6/12/73	a	b	a	a b	a	a b	b	a b
	8/8/73	a	b	a	a	a	a	a	a
	8/9/73	a	b	a	a b	a b	b	a b	a
	8/10/73	a	b	a	a b	a b	a b	a b	a b
	9/28/73	a	b	a	a b	a b	a	b	b
	9/29/73	a	c	a	b c	a b	a b	b c	a b
	10/1/73	a	b	a	b	b	b	b	b
Copepoda	6/12/73	a	a b	a	a b	a b	a b	b	a b
	8/8/73	a	b	a	a	a	a	a	a
	8/9/73	a	b	a	a	a b	a b	a	a
	8/10/73	a	b	a	a	a	a	a	a

Table A3 (cont'd)

Variable	Date	Station							
		17	9	18	12	8	14	15	16
	8/9/73	a		a					a
		b	b	b				b	
			c		c	c	c		
	9/29/73	a			a	a	a		a
		b		b	b	b	b	b	b
			c	c				c	
	10/1/73	a		a			a		
			b	b	b	b			
			c			c		c	c
Daphnia retrocurva	6/11/73	a	a			a			a
		b		b		b			
		c		c			c		
				d			d	d	
					e		e	e	
	6/12/73	a		a					
				b	b				
			c		c	c	c	c	c
	6/13/73	a		a		a			
				b		b		b	
			c		c		c	c	c

Table A3 (cont'd)

Variable	Date	Station 17	9	18	12	8	14	15	16
	9/29/73	a	c	a	b c	a b c	a b	b c	b c
	10/1/73	a	a b	a	b	b	b	b	b
Cyclops vernalis	6/12/73	a	a b c	a b	a	a b	c d	d	b c d
	6/13/73	a	a b	a b	a b	a	a	a	a b
	8/8/73	a b	b	b	a b	a b	a	a b	a b
	8/10/73	a	b	a b	a	a	a	a	a
Bosmina spp.	6/11/73	b c	d	c	a b	c d	d	a	a
	6/12/73	a b	c	a b	c	b c	b c	a b	a
	6/13/73	b	c	b	b c	b	c	a	b
	8/8/73	b	a	a	a	a	a	a	a

Table A3 (cont'd)

		Station							
Variable	Date	17	9	18	12	8	14	15	16
Cladocera	8/8/73	a	a b	a	a b	a b	a	a b	a b
	8/9/73	a	a b c	a b	b c	c	a b c	a b c	a b c
	9/29/73	a	b	a	a b	a b	a b	a b	a
	10/1/73	a b	a b c	a b	a b c	a b c	a	c	b c
Rotifera	11/9/72	a	c	c	c	c	b c	a b	a b
	11/10/72	a	b c	b c	b c	c	b c	a b	a
	4/6/73	a b	b	a b	a b	a	a b	a b	a b
	6/13/73	a b	b	a b	a b	a	a b	a	a
	8/9/73	a	a b	a	b	a b	a b	a b	a
	8/10/73	a b	a	a b	b	a b	a b	a b	b
	9/28/73	a	a b	a	a b	a b	a	b	b

Table A4. Tukey's multiple range test for zooplankton biomass. Stations identified with the same letter were not differentiated at $\alpha = 0.05$; a is greatest and d least. Only those dates with differences are included in the table.

		Station							
Variable	Date	17	9	18	12	8	14	15	16
Copepoda	6/11/73	a	ab	a	ab	ab	ab	b	ab
	8/8/73	a	b	a	a	a	a	a	a
	8/9/73	a	b	a	a	ab	ab	a	a
	8/10/73	a	b	a	a	a	a	a	ab
Cladocera	6/12/73	a	c	ab	abc	c	c	bc	c
	8/8-73	a	b	a	a	ab	a	a	a
	8/9/73	a	ab	ab	ab	b	ab	ab	ab
	9/29/73	ab	c	ab	abc	abc	abc	bc	a
	10/1/73	a	abc	a	abc	bc	ab	bc	c
Rotifera	11/9/73	a	b	b	b	b	b	a	a
	11/10/73	ab	ab	ab	b	b	ab	a	a

Table A4 (cont'd)

Variable	Date	Station 17	9	18	12	8	14	15	16
	4/6/73	a b	b	a b	a b	a b	a b	a	a
	6/12/73	b c	b c	b c	a b	a	a b c	c	c
	8/9/73	a b	a	a b	b	a b	a b	a b	a b
	8/10/73	a b	a	a b	b	a b	a b	a b	b
	9/29/73	a b	a b	a b	a b	a	a b	a b	b
Cyclops vernalis	6/11/73	a	a b	a b	a b	a	a b	b	a b
	6/12/73	a	b	a b	a	a b	c	c	b c
	6/13/73	a	a	a	a	a	a	a	b
	8/8/73	a b	b	b	a b	b	a	a b	a b
	8/10/73	a	b	a	a	a	a	a	a
Bosmina spp.	6/11/73	a b	c d	b c	a b	c d	d	a b	a

Table A4 (cont'd)

Variable	Date	Station 17	9	18	12	8	14	15	16
	6/12/73	a		a				a	
				b			b	b	b
			c		c	c	c	c	c
	6/13/73	a						a	
		b		b		b			b
				c	c	c			c
			d		d	d	d		
	8/9/73	a		a				a	a
				b	b			b	
			c		c	c	c		
	9/29/73	a				a	a		a
		b		b	b	b	b		
			c	c	c	c	c	c	
	10/1/73	a	a	a			a		
			b	b	b	b			
			c		c	c		c	c
Daphnia retrocurva	6/11/73	a	a	a		a			a
				b		b	b		
					c		c	c	
	6/13/73	a		a		a			
			b	b		b		b	
			c		c		c	c	c
	8/8/73	a			a		a	a	
		b		b	b			b	b
			c	c		c			c
	8/9/73	a		a	a		a		a
				b	b	b	b		b
			c		c	c	c		c
			d		d	d	d	d	

Table A5. Percent change in zooplankton numbers (over day 0) in aquaria after transplanting from the cooling system.

	(Day 2) June 28	(Day 5) July 1	(Day 14) July 10	(Day 21) July 17
Copepods (Mature)				
12-a	50.0	990.0	425.0	580.0
12-b	-12.5	274.0	26.0	-29.6
8-a	8.7	348.0	156.0	100.0
8-b	18.0	195.0	32.0	-27.3
14-a	67.0	1033.3	344.4	267.0
14-b	-33.0	555.5	255.5	211.0
Intake-a	126.0	589.7	116.0	89.5
Intake-b	300.0	1060.0	713.0	140.0
Control-a	36.7	93.3	296.7	43.3
Control-b	63.0	136.7	143.3	56.7
Copepods (Nauplii)				
12-a	63.5	511.5	992.3	550.0
12-b	100.0	928.9	1331.1	540.0
8-a	136.9	346.2	195.4	955.4
8-b	425.0	169.6	39.1	189.0
14-a	362.5	737.5	175.0	893.8
14-b	568.8	575.0	537.5	187.5
Intake-a	653.3	916.7	1056.7	1400.0
Intake-b	192.6	403.7	1264.8	359.2
Control-a	100.0	294.6	428.6	8.9
Control-b	708.3	833.3	941.7	191.7
Cladocerans				
12-a	55.5	133.3	177.8	822.2
12-b	-57.9	-31.5	-52.6	21.0
8-a	37.0	11.1	-70.4	-59.3
8-b	55.5	-5.5	-8.0	-83.3
14-a	52.0	8.0	-4.0	8.0
14-b	153.8	53.8	69.2	77.0
Intake-a	83.3	55.5	-50.0	-55.5
Intake-b	28.6	42.9	-14.3	-85.7
Control-a	133.3	-33.3	16.7	-83.3
Control-b	78.6	35.7	100.0	7.0
Rotifers				
12-a	152.2	137.4	15.4	80.2
12-b	80.0	586.7	77.8	-43.9
8-a	137.2	140.3	28.3	-75.6
8-b	185.7	229.5	12.0	-53.9

Table A5 (cont'd)

	(Day 2) June 28	(Day 5) July 1	(Day 14) July 10	(Day 21) July 17
14-a	366.0	322.0	175.2	103.7
14-b	232.9	363.4	89.0	-5.5
Intake-a	124.1	473.0	80.4	7.0
Intake-b	130.4	292.6	380.9	273.5
Control-a	28.8	137.5	284.6	50.0
Control-b	70.8	443.8	802.1	8.3