J. A. WOJCIK

M. S.

J. A. WOJCIK

M. S.

J. A. WOJCIK

M. S.

This is to certify that the

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A Once-Through Cooling System on Western Lake Erie:
Impact Upon Phytoplankton and Productivity

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James Andrew Wojcik

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[signature]

Major professor

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MASS TRANSPORT OF BIOLOGICAL MATERIALS THROUGH A ONCE-THROUGH COOLING SYSTEM ON WESTERN LAKE ERIE: IMPACT UPON PHYTOPLANKTON AND PRODUCTIVITY

By

James Andrew Wojcik

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ABSTRACT

MASS TRANSPORT OF BIOLOGICAL MATERIALS THROUGH A ONCE-THROUGH COOLING SYSTEM ON WESTERN LAKE ERIE: IMPACT UPON PHYTOPLANKTON AND PRODUCTIVITY

By

James Andrew Wojcik

This one year study commenced in November, 1972 at the 3200-megawatt fossil fuel Monroe Power Plant near Monroe, Michigan. Water for cooling was from a river and Lake Erie and discharged via a discharge canal into Lake Erie. Five sampling stations were placed along the discharge and two at the intake for comparison of samples before and during entrainment. Phytoplankton abundance, volume, and biomass changes were assessed along with gross primary productivity (GPP) and community respiration. Three diel (morning, afternoon, and evening) samplings were made at two month intervals.

Results of most samplings indicated no significant change in phytoplankton populations for any algal class or species that could be attributed to entrainment. Some increases noted at plume stations in November and January of some algae were seen as a mixing effect of the discharge with a more productive open lake. Half the summer daylight

measurements of GPP showed reduced photosynthesis in the discharge canal with a recovery in the plume without a clear explanation although chlorination was not totally ruled out.

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INTRODUCTION

The ecological effects of large scale entrainment of biota by water diversion in once-through cooling systems are under intensive study in the Great Lakes. As part of this effort, a comprehensive investigation of impact upon major trophic levels at a large electric power plant on the western shore of Lake Erie was undertaken in late 1972. This thesis concentrates on phytoplankton and addresses possible changes having taken place in the algal assemblage and their metabolism as a result of the power plant's operation.

Phytoplankton are the principal autotrophs in Lake Erie. With the highly enriched state of the lake, especially in the western basin, nuisance growth of phytoplankton is common. Entrainment of substantial numbers of this group could conceivably alter their growth and thus lead to further deterioration of the lake. Of particular concern is a further shift of dominant species from diatoms to less desirable forms, such as blue-green algae, thus altering the food source for the primary consumers and affecting the entire food web. Beside influencing the structure of the algal assemblage, more direct effects of entrainment might be seen in their metabolism. A change in photosynthetic and respiration rates would affect the amount of carbon fixed in the lake ecosystem.

Entrainment Stress

Entrainment in a cooling system will expose phytoplankton to several environmental changes which, depending on the magnitude of the changes and the types of algae, may affect their ability to function. These environmental changes may be categorized as mechanical, thermal, and chemical stresses (Morgan and Stross, 1969).

Mechanical: This stress arises from the excessive water turbulence within pumps and condenser tubes. This turbulence produces sheering forces that could destroy or fragment fragile algae. Starr (1974) attributed a 25.5% mortality of entrained motile algae largely to mechanical factors at two nuclear power plants on Lake Ontario. In contrast, Gurtz and Weiss (1974) studied a power plant near Charlotte, North Carlina, on Lake Wylie where they could control the heat output while maintaining constant pumping rates in the cooling system. By examining pre- and post-condenser algal productivity under controlled conditions when no heat shock was allowed, they found C^{14} primary productivity was stimulated after passage through the condensers. Turbulence of the water was thought to improve the availability of nutrients to the algae and thus increase their productivity.

Thermal: A second entrainment factor is the temperature increase. Its effect varies with the types of algae present, the magnitude of the increase, and the initial environmental conditions. Patrick (1969; 1974) provides a good discussion and literature review on this topic. Each algal species usually possess a wide range of temperature tolerance and a narrower optimum range for maximal growth (e.g., Eppley, 1972). A considerable amount of laboratory work has been done to determine these ranges (Altman and Dittmer, 1973; Hoogenhout and Amesz, 1965). At best these results are approximate for natural populations since the ranges obtained by laboratory experiments are usually from controlled "ideal growth" environments. There have been field studies such as on thermal streams (Castenholz, 1967) which have led to the conclusion that blue-green algae "prefer" temperatures above 35°C while green algae do best below this. Diatom species are reported to grow best usually under 30°C (Patrick, 1969). Of course, such broad generalizations can be hazardous due to the many exceptional species and new strains that can adapt to atypical temperatures (Sorokin, 1960; 1971). Nevertheless, cases have been reported where increasing temperatures have coincided with shifts in dominant forms from diatoms to green and blue-green algae above 30°C (Cairns, 1956; Patrick *et al.*, 1969; Rankin *et al.*, 1974).

Theoretically, lethal temperatures need not be exceeded for some species to out compete other less favored forms if the new temperature is maintained long enough (Goldman and Carpenter, 1974). However, there are limits above which irreversible damage to cells can occur. Apparently, the magnitude of an abrupt temperature change, such as experienced in power plant condensers, is not as important to algal survival as the maximum temperature reached. Beyond the upper limit, destruction of pigments (cartenoids, chlorophyll) and extrusion of lipids have been observed for diatoms (Lanza and Cairns, 1972). Furthermore, Lund (1964) pointed out that an increase in temperature may kill algae before the theoretical upper limit is reached. This would be a consequence of nutrient deficiencies which could be aggravated by an increased metabolic rate with a rise in temperature, and this might eventually "starve" the organism to death. Since different species have varied nutrient requirements, certain forms may be eliminated while those more tolerant of low nutrients survive.

Perhaps, a more definitive way to assess thermal stress on algae would be to measure their metabolism. From laboratory studies results have firmly established that the photosynthetic rate is independent of temperature at sublethal levels when light intensity is low (Aruga, 1965; Nielson and Jorgensen, 1968). Under low light the photochemical portion (light reaction) of photosynthesis is limited by the light intensity. At light saturation such as sunny days, however, the enzymatic portion (dark reaction) controls the rate and is limited by temperature. On the other hand, respiration of algae is directly dependent on temperature since it is usually an enzymatic process (Nielsen and Jorgensen, 1968; Phinney and McIntire, 1965).

Numerous studies have considered primary productivity in evaluating impacts of power plant thermal discharges. The net primary productivity (NPP) measurements of artificially incubated algae in a thermal discharge in Chesapeake Bay (Morgan and Stross, 1969) and the York River, Virginia (Warinner and Brehmer, 1966) showed an affect related to the ambient temperature. When intake temperatures exceeded 15 to 16°C, an increase in temperature (Δt) of 3 to 8°C depressed the NPP (using C^{14}). Below these ambient temperatures and with a similar Δt, the NPP was stimulated. However, at Charlotte, North Carolina (Gurtz and Weiss, 1974) under similar conditions, only depression of the NPP was observed at an ambient temperature as low as 9.5°C and at Δt of 5.6°C. No stimulatory response was seen. This discrepancy in the point at which the NPP depressions occurred was attributed to different species. These results indicate the amount of fixed carbon available to the rest of the rest of the ecosystem would be, perhaps, increased in winter and decreased in summer due to entrainment.

Chemical: Entrainment of algae can also impose chemical stresses. The most important of these is due to the use of chlorine in power plants to destroy attached organisms accumulating in the condensers. Residual chlorine concentrations as low as 1.5 ppm have resulted in severe and perhaps irreversible damage to some algal species (Hirayma and Hirano, 1970). Gross primary productivity and community respiration were reduced by 50% from controls at a chlorine concentration of 0.32 ppm and by 100% at 2.7 ppm or less in experiments of Brook and Baker (1972).

Study Approach and Hypotheses

Few workers have tried to assess the effects of entrainment using natural phytoplankton populations and *in situ* primary productivity measurements. Much of the data available are from river environments using periphyton as indicators of change (e.g., Cairns, 1956; Patrick *et al*., 1969) rather than phytoplankton of lakes. One, therefore, encounters difficulty in predicting the impact of phytoplankton entrainment in the case of Lake Erie. Consequently, this study sought to measure structural and functional changes in the phytoplankton attributable to entrainment. Afterward, the results were placed in the perspective of assessing their impact upon the receiving waters--western Lake Erie.

Based on the literature just cited, several hypotheses were explored with regard to phytoplankton entrainment which include:

1. Entrainment with maximum temperatures <30°C will create an overall stimulation in the growth of the total algal community as reflected by increased abundance and algal volume.
2. At temperatures >30°C some types such as diatoms will display reduced growth.
3. Entrainment will result in an increase in species diversity at temperatures less than 30°C and decreased diversity above this.
4. The average size (specimen volume) of fragile algal species will decrease after entrainment.
5. Entrainment will stimulate the gross primary productivity at an ambient temperature below 16°C and depress it above this point.
6. Entrainment will stimulate community respiration.
7. Primary productivity and respiration will be depressed during condenser chlorination.

METHODS

Description of the Study Area

The cooling system under study was the Monroe, Michigan, Power Plant, a 3200-megawatt fossil fuel facility operated by the Detroit-Edison Company. The intake for cooling water is located on the Raisin River about 1 km from the river mouth (Figure 1). Water is pumped through the condensers and released into a 2600 m discharge canal that was dredged to 7 m depth in its first 1500 m length and to 3 m in the remaining portion. The heated effluent forms a plume in Lake Erie over a sandy shoal generally less than 2 m deep.

During this investigation from late 1972 through to October, 1973, one to three of the four generating units at the power plant were operational but on a sporadic schedule. Pumping rates for the cooling water ranged from 42 m^3/sec to 63 m^3/sec (Appendix A1). Over the study period the intake pumps consumed nearly all the Raisin River flow at all times. At low river flows any pumping deficit was augmented by Lake Erie water which moves upstream to the intake of the plant. Thus, the composition of the cooling water varied from nearly 100% river water to 90% lake water (Figure 2).

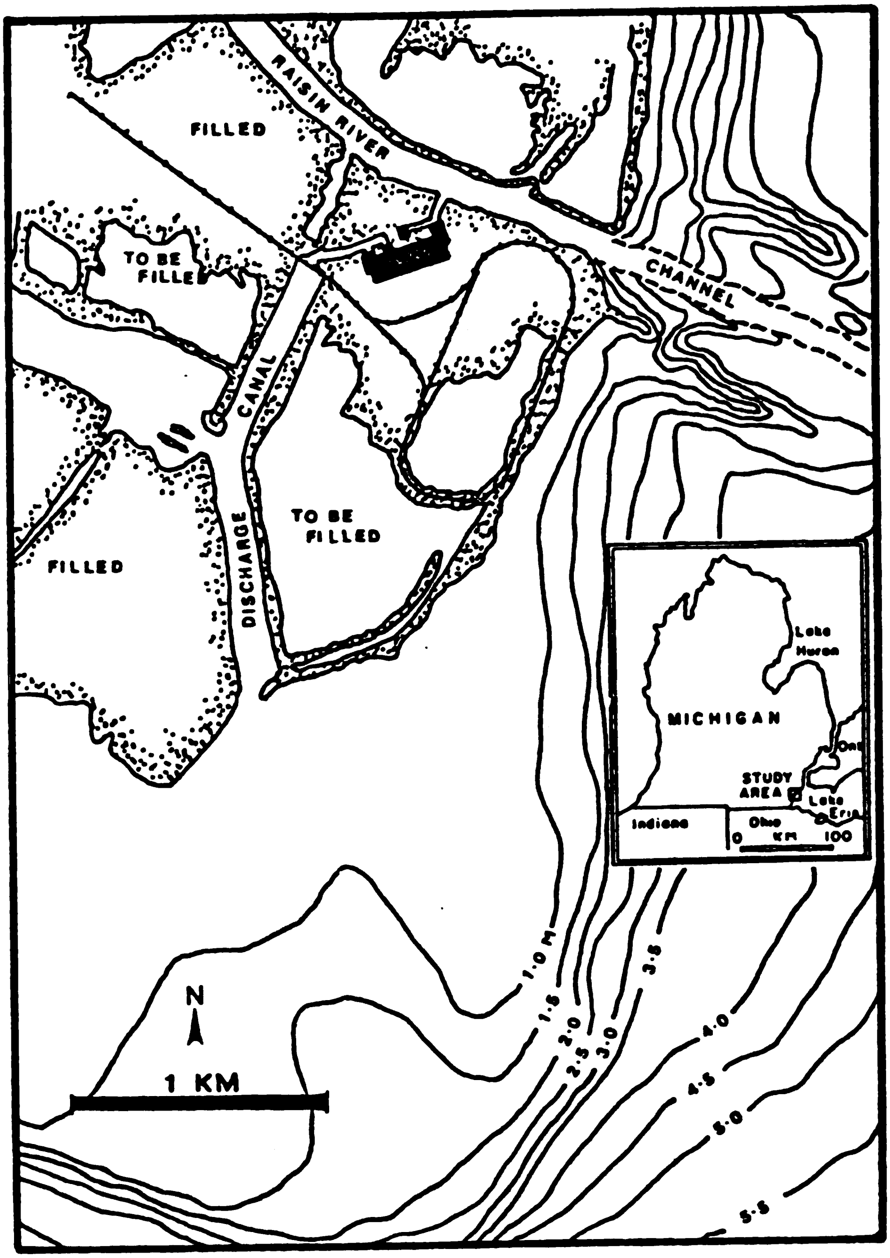


Figure 1. The Monroe Power Plant study area.

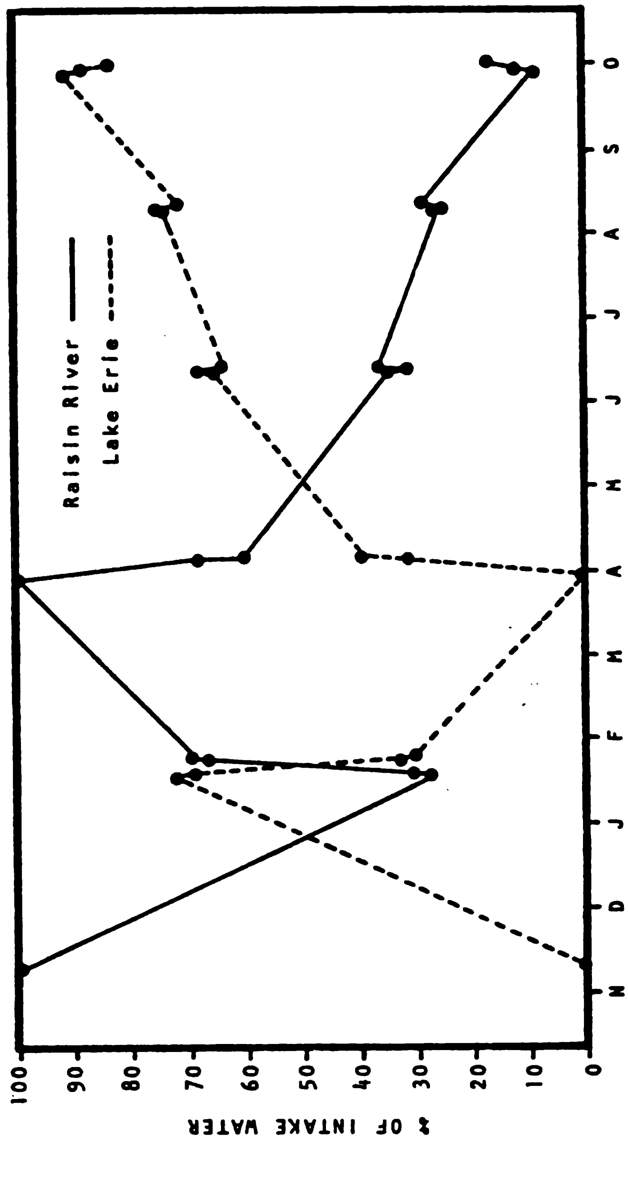


Figure 2. Estimated percent Raisin River and Lake Erie water entering the Monroe Power Plant intake during 1972-73.

Flow rates through the condensers are about 2 m/sec with a passage time of about 7 seconds. The mean velocity through the upper discharge canal ranged from 3.9 to 5.8 cm/sec. At this rate from 11.5 to 7.5 hours was needed for the cooling water to pass through the discharge canal. Due to eddies along the canal, the actual exposure time of some entrained algae to the heated effluent within the canal could be longer. Exposure time is also increased because of recirculation of much of the heated discharge back through the intake during the winter to keep it free of ice. No data were available on the proportion of the discharge recirculated at that time of the year.

Ambient temperatures in the intake area ranged from 3.0 to 27.5°C with the river water usually 1 to 2°C higher than the lake. The Δt's observed never exceeded 15°C. The temperature in the discharge canal ranged from 8.0 to 31.5°C with less than a 10% difference throughout its length. The plume was estimated to cool to ambient temperature in 1 to 2 days.

The chemical quality of the cooling water depends on the relative amount of lake or river water entering the plant. The Raisin River was the recipient of secondary treated municipal wastes and industrial effluents within about 2 km upstream of the intake. Generally speaking, the quality of Lake Erie water is somewhat less enriched with algal nutrients than the river as shown in Table 1.

Table 1. Summary of chemical water quality (in units of mg/liter except for pH) for the Raisin River and Lake Erie near the cooling system intake (data from M.S.U., 1974).

Date and Location	Total Phosphorus as P	Soluble Phosphorus as P	Nitrate Nitrogen as N	Total Inorganic Carbon as C	Total Alkalinity as $CaCo_3$	pH	Free CO_2
11-10-72							
Lake	0.16	0.07	4.54	24.2			
River	0.22	0.14	8.22	35.0			
01-25-73							
Lake	0.21	0.10	4.17	27.6			
River	0.20	0.11	3.90	26.6			
04-04-73							
Lake	0.09	0.04	1.11	18.2			
River	0.11	0.06	3.70	34.4			
06-13-73							
Lake	0.12	0.07	1.25	26.2			
River	0.20	0.12	1.35	34.0			
07-06&07-73							
Lake					120	7.2	14.8
River					184	7.3	16.2
08-01&02-73							
Lake					105	8.6	0.51
River					184	8.1	3.13

Table 1 (cont'd.).

Date and Location	Total Phosphorus as P	Soluble Phosphorus as P	Nitrate Nitrogen as N	Total Inorganic Carbon as C	Total Alkalinity as $CaCo_3$	pH	Free CO_2
08-10-73							
Lake	0.18	0.07	0.58	22.6			
River	0.25	0.16	1.63	38.8			
10-01-73							
Lake	0.11	0.02	0.37	21.6			
River	0.13	0.06	0.48	30.2			

Differences in nutrient concentrations in the power plant's discharge from those listed in Table 1 were small (M.S.U., 1976) and probably insignificant. Therefore, adequate nutrients were assumed to exist throughout the study area at all times for algal growth with the possible exception of low CO_2 in near-shore Lake Erie in the summer.

Chlorination of the condensers as reported in plant records commenced daily at 0800 (local time) and was continued for 30 minutes. During summer, an additional evening application was added. Concentrations of chlorine discharged were not measured but computed to range from 0.83 to 1.63 mg/l as residual chlorine.

Light penetration in the area was nearly always limited by high amounts of suspended matter. Secchi disc transparencies were usually less than 1 meter throughout the study area. Annual dredging of the river channel during late summer and early fall creates an additional sediment load increasing turbidity during this period. Only slightly greater transparencies were found in lake water compared to water from the river or discharge canal.

Sampling Design and Field Procedures

Seven stations were established to sample phytoplankton composition and measure primary productivity (Figure 3). Due to turbulence and possibly incomplete mixing of river and lake water in the short intake canal, intake water was indirectly measured by sampling at lake station

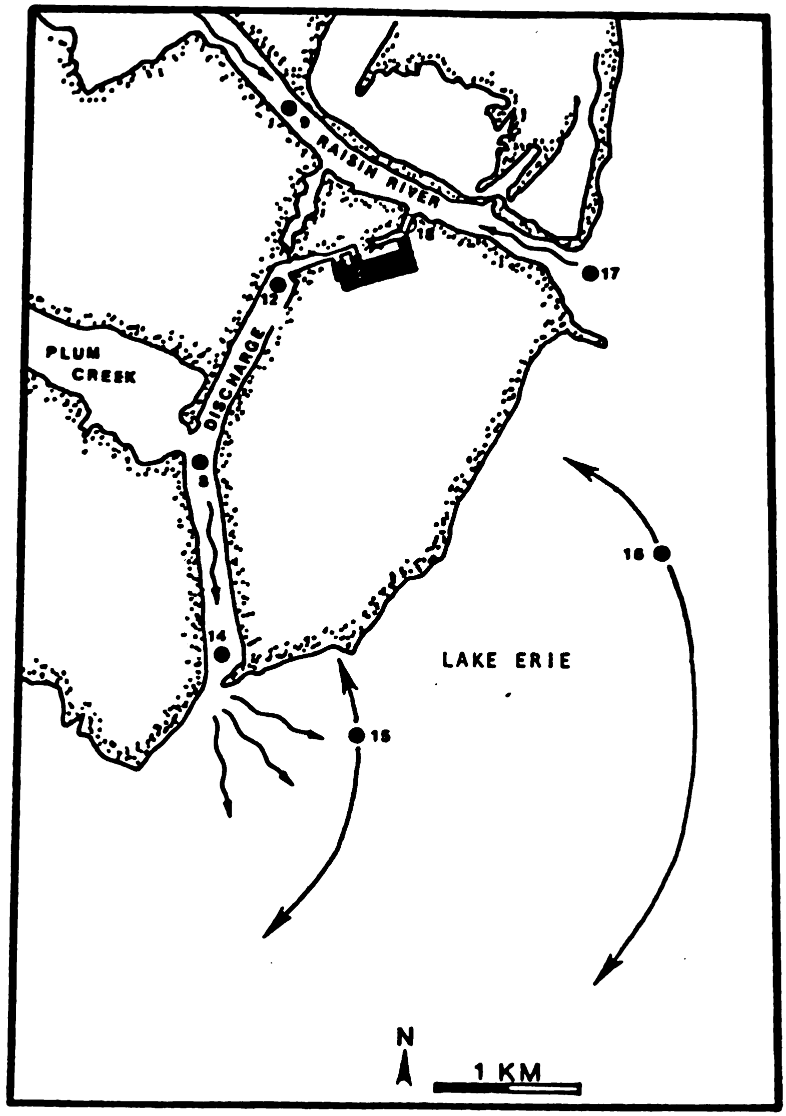


Figure 3. Map of the sampling stations within the study area.

17 and river station 9. Data from these two locations were proportioned according to the relative contribution of river and lake water used for the intake and being entrained. Values for this calculation are given in Appendix A1. The proportioned results were combined to produce a theoretical intake station designated as station 18.

The heated effluent was sampled in the discharge canal at stations 12, 8, and 14 which represent the upper, middle, and lower discharge canal, respectively. The plume was sampled near the discharge canal mouth (inner plume) at station 15 and farther out in the lake (outer plume) at station 16. These last two stations were variable in location due to the shifting plume direction. The inner plume station was positioned midway in the plume at a point where the temperature had decreased to about half the difference between that in the discharge canal and the lake ambient temperature. The outer plume station was at a point along the plume midline near its outer edge where a 1 to 2°C temperature elevation was still detectable.

The detailed sampling scheme for the various stations is shown in Appendix A2. In general, sampling was conducted once every two months (a seasonal set). During each seasonal set, three separate samplings were made at all stations representing various times of the day--morning, afternoon, and evening. The time of day samplings (hereafter referred to as diel periods) were usually made on separate days within a span of one week. Thus, both long term seasonal and short term diel variations were considered. A summary of the sampling dates for phytoplankton composition and primary productivity are listed in Appendix A3.

Five "replicate" water samples were taken at each station to census the phytoplankton community. Early in the study these samples were collected at the water surface. For dates after January 18, 1973, samples were collected from randomly determined depths (1 to 5 m) along a transect acrosss the river or discharge canal. This was done to obtain a better spatial and vertical profile of conditions at the lake and river stations and the upper, middle, and lower discharge canal stations. Samples from the plume were all taken from the surface due to the shallow area and to insure that the buoyant heated effluent was being sampled.

Samples were obtained with either a 4.1 or 8.1 liter Van Dorn water bottle at the prescribed depth. Aliquots of 480 ml were drawn off and immediately preserved with 20 ml of 37% formaldehyde solution.

Sample Processing and Algal Enumeration

Processing and enumeration of phytoplankton generally followed the membrane filter technique described in "Standard Methods" (American Public Health Association,

1971) which had been tentatively adopted from McNabb (1960). Filtration of predetermined aliquots of sample was done using 0.45 μm "Millipore" filters (Millipore, Inc., Bedford, Mass.). These were subsequently "cleared" with microscope immersion oil and placed under a phase-contrast microscope for identification and enumeration. A "count" constituted a natural algal structural unit (i.e., a unicell, filament, or colony). Conversion of a taxon's frequency in 30 microscopic fields to their sample abundance was determined by the following equation modified from A.P.H.A. (1971):

$$\text{Specimens/ml} = \frac{d \times 10^9}{(\text{quadrat area in um}^2) \times (\text{ml filtered})}$$

where "d" is the theoretical density corresponding to a given frequency.

To facilitate sample analysis, species identifications were limited to afternoon collections except for November when all diel period samples were examined to species. For morning and evening samples of other seasonal sets, phytoplankton were identified only to class.

Except for diatoms, algal species were enumerated directly on the membrane filters. Diatoms were first identified and enumerated only to order (Centrales or Pennales) on the filters. Species identifications required permanent mount slides prepared according to

Weber (1971) using a muffle furnace at 540°C to combust organic material and hyrax as a mounting medium. By determining the percentage of each centric or pennate species on the permanent mounts, these results were related back to the filter densities of the respective diatom orders to produce estimates of diatom species abundance for each sample.

Only one permanent mount slide for diatom species identifications was prepared for each station using combined concentrations of a station's water samples. The relative species abundances obtained from a single permanent mount for a station were applied to the densities of diatom orders of each of the station's five samples. Thus, diatom species densities varied between station samples only in response to the variability of the centrics or pennates. Although this facilitated diatom processing, this practice automatically introduced a bias into the data by artificially reducing the variability between the "replicates" of a station on the species level--a factor that becomes apparent in the statistical analysis.

Species identifications were based upon a number of literature sources. Principally, these included Hustedt (1930a, 1930b), Patrick and Reimer (1966), Prescott (1970), Smith (1920), Taft (1945), Taft and Taft (1971), Thienemann (1942), and Weber (1971). The identification of coccoid Cyanophyceae are based on the revisions of Drouet and Daily (1956). Some questionable forms were referred to Dr. D. C. Jackson and Dr. F. Begres of Eastern Michigan University, Ypsilanti, Michigan.

The volume ($\mu m^3/ml$) of a taxon in a sample was calculated by multiplying its abundance with its estimated mean specimen volume (MSV). The MSV for a taxon was usually approximated based on a modified formula for volume of common geometric shapes applied to sizes of enumerated specimens and averaged for the stations of a diel period. A weighted grand mean annual MSV value was used for a species' volume calculation of a given diel period if fewer than 10 specimens were observed on the membrane filters or permanent mount diatom slides during regular enumerations. Otherwise, a different MSV was determined for volume calculations for each diel period. Unless otherwise noted, individual station estimates of volume were not used. Algal class MSV's for morning and evening periods (except November) were not obtained by direct observations of specimens from their samples. Rather, estimates were based on computed class volume of the corresponding afternoon data.

Phytoplankton biomass (carbon content) was theoretically derived using the formula of Strathmann (1967) with the taxon's MSV used as its "cell volume". Units are expressed as micrograms of carbon per milliliter of sample.

Primary Productivity Methods

Gross primary productivity (GPP) and community respiration (R) were determined *in situ* using the change in oxygen light-dark bottle technique (A.P.H.A., 1971). Chemical fixation and titration followed the azide modification of the Winkler method (Environmental Protection Agency, 1974) with phenylarsine oxide as the titrant. Three light and three dark bottles plus two initials (300 ml) were filled at each station with water collected at a depth of 1/2 m (1/4 m for August, 1973, and later measurements) and immediately resuspended at the same depth.

Morning, afternoon, and evening measurements were made from 0800 to 1230 hours, 1200 to 1800 hours, and after sunset, respectively, with 2 to 4 1/2 hour incubations. Morning primary productivity measurements were timed to approximately coincide with chlorine application at the power plant in order to assess this impact upon GPP.

Weather information was obtained from the National Weather Service at Toledo, Ohio, 40 km to the south of the study area. Weather data are summarized for sampling and primary productivity measurement dates in Appendix A4. These data were also supplemented by direct observation of general weather and light conditions in the study area.

Water transparency was measured with a Secchi disc on most sampling dates. Beginning in August, 1973, a model LMD-BA submarine photometer (Whitney Underwater Instruments, San Luis Opispo, Calif.) was employed to measure light at depths of 0.5 m, 1.0 m and 1 m intervals below that. Water temperature was measured with a YSI model 51A combination oxygen-thermistor meter (Yellow Springs Instruments Co., Yellow Springs, Ohio).

Data Analysis

For comparative purposes between all diel periods, species data were also pooled into class and total algae density, volume, and biomass to give results on three taxonomic levels. Arithmetic means were computed for each station from the replicate data. However, due to expected heterogeneity of the variances as measured by the F-max test (Sokal and Rohlf, 1969), abundance and volume data were transformed to $\log_{10}(x + 1)$ for most statistical analyses. A three-way analysis of variance (AOV) was performed on the transformed density and volume results for total algae and the major classes. The sources of error (main effects) for these AOV's were season, diel period, and station for the purpose of determining where statistically significant variance for the data lay.

Density and volume estimates for selected species and centric-pennate diatoms were statistically analysed for afternoon results using a two-way AOV with season and station as main effects. This was a preliminary step to ascertain whether significant station differences for species or orders of diatoms existed. Since results were available for all diel periods of the November seasonal set for centrics and pennates, an additional two-way AOV was made on those transformed density and volume data using diel period and station as main effects.

Means of transformed station results of abundance and volume were compared with one another using the Bonferroni-t statistic procedure (Miller, 1966). This little recognized method was especially useful here in that it permitted non-orthogonal contrasts among station means. Thus, a set of comparisons could involve the intake station mean compared to pooled discharge canal means and to each discharge canal or plume station result separately. Significant station variance from the AOV was not a prerequisite of the Bonferroni-t procedure. This method was used with transformed data only. Untransformed mean comparisons, such as in the case of biomass data, utilized 95% confidence intervals.

Diversity indices were computed at each station using species density, volume, and biomass data. Two indices were used for comparative purposes: Margalef's index (Margalef, 1968) and the Shannon-Wiener index (Pielou, 1969). Equitability among species ($E = H'/\log_{10}s$ where H' is the Shannon-Wiener index and "s" is the number of species) was calculated for each station's replicates and averaged.

GPP and R estimates were expressed in units of mg O_2/liter/hour of incubation. Analyses (using 95% confidence intervals of station means) were made directly on these values rather than on extrapolated daily production or on carbon estimates. These practices reduced the loss of information through rounding errors. For comparison with literature values, GPP and R means could be converted to carbon production using a multiplication factor of 0.312 (Westlake, 1969).

RESULTS

Water Temperatures in the Study Area

The average Δt at the water's surface of the discharge relative to the intake was about 5°C (6°C at the bottom). A maximum Δt of 13.5°C occurred at the surface in November when the ambient temperature was 9°C. In general, the largest Δt's were observed during the cold weather months. The maximum temperatures recorded for the discharge was 31.5°C (31.0°C at the bottom) on August 9, 1973, when the ambient water tempeature averaged 26°C. Large variations between diel periods of a seasonal set, particularly common during the winter, are explained by fluctuations in the number of generators operating, by variable pumping rates, and by the proportion of discharge water recirculated through the intake.

Annual Mean Algal Abundance, Volume, and Biomass

Eight algal classes were recognized during the enumeration process: the Bacillariophyceae (diatoms), Chlorobacteriae, Chlorophyceae (green algae), Chrysophyceae, Cryptophyceae, Cyanophyceae (blue-green algae), Dinophyceae, and Euglenophyceae. Annual mean daily density of the classes at each station calculated for morning, afternoon, and evening samplings are shown in Table 2. Clearly, the phytoplankton community was dominated by three classes which constituted over 95% of all algae observed--diatoms, green algae, and blue-green algae. Diatoms were most abundant with green and blue-green algae being of roughly equal densities. The Euglenophyceae also exceeded 1% of the total abundance but was a relatively rate class.

From Table 2 it can also be observed that total algae, green algae, and, in particular, blue-green algae were substantially less abundant in the afternoon than either morning or evening periods. Densities of diatoms and other classes did not differ greatly between these diel periods. Further analysis of this observation indicated these differences were probably artifacts of the enumeration technique. However, analysis of the results was not greatly affected by this problem.

Differences in algal densities between sampling stations in Table 2 were not very great. No profound changes can be seen for algal densities at the discharge stations compared to the intake. Although total abundance was generally higher in the discharge, this was an abrupt increase immediately apparent at the upper discharge canal station (12) with little or no further increase at downstream discharge stations (8, 14, 15, and 16). A consistent increase in numbers would have been expected if growth of algae was stimulated.

Table 2. Annual mean daily abundance (specimens/ml) of all algae averaged for the diel periods and stations.

	Abundance							
	Stations							
Taxonomic Class	Lake 17	River 9[1]	Intake 18[1]	Upper Discharge 12	Middle Discharge 8	Lower Discharge 14	Inner Plume 15[1]	Outer Plume 16[1]
MORNING								
Bacillariophyceae	5126	4667	4968	4938	4981	5026	5068	4693
Chlorobacteriae	1	0	0	0	0	0	0	0
Chlorophycease	2971	2688	2861	2757	.3001	2940	3226	2924
Chrysophyceae	1	0	0	0	0	0	0	0
Cryotophyceae	11	5	10	6	11	11	33	17
Cyanophyceae	2256	1914	2106	2243	3341	2910	2828	3296
Dinophyceae	0	4	2	0	0	6	0	2
Euglenophyceae	134	98	109	120	119	111	134	87
TOTAL	10500	9376	10055	10064	11453	11004	11289	11018
AFTERNOON								
Bacillariophyceae	4373	5611	4543	4688	4832	5274	4845	4617
Chlorobacteriae	0	0	0	0	6	19	0	0
Chlorophyceae	1456	932	1394	1454	1648	1460	1877	1649
Chrysophyceae	0	6	2	0	10	8	0	0
Cryptophyceae	11	2	8	22	41	13	10	10
Cyanophyceae	826	552	785	1001	1065	864	998	1037
Dinophyceae	0	0	0	3	3	0	0	3
Euglenophyceae	25	105	77	80	102	64	68	53
TOTAL	6691	7206	6807	7249	7707	7705	7774	7367

Table 2 (cont'd.).

Taxonomic Class	Lake 17	River 9[1]	Intake 18[1]	Upper Discharge 12	Middle Discharge 8	Lower Discharge 14	Inner Plume 15[1]	Outer Plume 16[1]
	Abundance Stations							
	EVENING							
Bacillariophyceae	3606	4611	3762	4940	4558	5311	3799	3983
Chlorobacteriae	0	0	0	0	0	0	0	0
Chlorophyceae	1827	2309	1894	2179	2048	2625	3255	2291
Chrysophyceae	0	0	0	3	0	3	0	0
Cryptophyceae	11	16	15	0	16	22	23	8
Cyanophyceae	2288	2103	2175	2461	2910	2807	3025	3483
Dinophyceae	0	0	0	0	0	0	0	0
Euglenophyceae	61	91	93	58	112	80	85	77
TOTAL	7791	9127	7940	9641	9644	10848	10187	9843

[1]Includes estimates because of missing data.

No obvious shifts in the relative dominance of any class were observed between station annual means. Variability was consistently less than 10% and no patterns were seen.

Table 3 lists the mean daily abundance, volume, and biomass of the study year for the major classes (exceeding 1% of the total density) and total algae for the afternoon period at each station. Diatoms were dominant when expressed volumetrically (86% of the total). Their biomass (about 69% of the total) was slightly greater than their density (65% of the total). The large sized green algae exceeded blue-green in the overall proportion of the total volume and biomass. The Euglenophyceae were relatively insignificant.

For most groups listed in Table 3, considerably higher abundnace, volume, and biomass were observed in the discharge relative to the intake. The differences are more easily seen in Table 4 which shows the percent deviation for various stations compared to the intake station. For most algae the largest increases were at the plume stations. However, results at the lake station (17) were as large as these at the plume stations. Thus, the plume increases observed may be merely a reflection of mixing of discharge water with that in the lake receiving water. Therefore, the results presented in Tables 3 and 4 do not demonstrate a clear trend of steadily increasing abundance, volume, or biomass.

Table 3. Abundance (specimens/ml), volume ($\mu m^3/ml \times 10^6$), and biomass (μg C/ml) of the major algal classes and total algae averaged across the study year's afternoon samplings.

	Stations							
	Lake 17	River 9	Intake 18	Upper Discharge 12	Middle Discharge 8	Lower Discharge 14	Inner Plume 15[1]	Outer Plume 16[1]
CLASS BACILLARIOPHYCEAE (DIATOMS)								
Abundance	4373	5611	4543	4688	4832	5274	4845	4617
Volume	17.85	9.22	13.97	15.89	13.94	15.89	15.58	18.57
Biomass	0.804	0.521	0.670	0.742	0.677	0.756	0.768	0.867
CLASS CHLOROPHYCEAE (GREEN ALGAE)								
Abundance	1456	932	1394	1454	1648	1460	1877	1649
Volume	1.39	0.37	1.12	1.02	1.22	0.87	1.48	1.44
Biomass	0.159	0.048	0.132	0.121	0.147	0.106	0.202	0.192
CLASS CYANOPHYCEAE (BLUE-GREEN ALGAE)								
Abundance	826	552	785	1008	1065	864	998	1037
Volume	0.35	0.09	0.26	0.25	0.22	0.27	0.57	0.37
Biomass	0.047	0.013	0.040	0.036	0.031	0.036	0.051	0.055
CLASS EUGLENOPHYCEAE								
Abundance	25	105	77	80	102	64	68	53
Volume	0.02	0.05	0.04	0.06	0.04	0.01	0.02	0.03
Biomass	0.002	0.006	0.005	0.005	0.007	0.002	0.004	0.004
TOTAL ALGAE								
Abundance	6691	7206	6807	7249	7707	7705	7774	7367
Volume	19.62	9.73	15.40	17.21	15.48	17.10	18.16	20.42
Biomass	1.014	0.590	0.848	0.917	0.869	0.906	1.111	1.122

[1]Missing data on some dates was estimated.

Table 4. Percent increase (+%) or decrease (-%) of each station's afternoon abundance, volume, and biomass as compared to the intake station for the major classes and total algae.

	Stations							
	Lake 17	River 9	Intake 18	Upper Discharge 12	Middle Discharge 8	Lower Discharge 14	Inner Plume 15	Outer Plume 16
CLASS BACILLARIOPHYCEAE (DIATOMS)								
Abundance	-3.7	+23.5	0.0	+3.2	+6.4	+16.1	+6.6	+1.6
Volume	+27.8	-34.0	0.0	+13.7	-0.2	+13.7	+11.5	+32.9
Biomass	+20.0	-22.2	0.0	+10.7	1.0	+12.8	+14.6	+29.4
CLASS CHLOROPHYCEAE (GREEN ALGAE)								
Abundance	+4.4	-33.1	0.0	+4.3	+18.2	+4.7	+34.6	+18.3
Volume	+24.1	-67.0	0.0	-8.9	+8.9	-22.3	+32.1	+28.6
Biomass	+20.5	-63.6	0.0	-8.3	+11.4	-19.7	+53.0	+45.5
CLASS CYANOPHYCEAE (BLUE-GREEN ALGAE)								
Abundance	+5.2	-29.7	0.0	+28.4	+35.7	+10.1	+27.1	+32.1
Volume	+34.6	-65.4	0.0	-4.8	-15.4	+.8	+119.2	+42.3
Biomass	+17.5	+32.5	0.0	-10.0	-22.5	-1.0	+27.5	37.5
CLASS EUGLENOPHYCEAE								
Abundance	-67.5	+36.4	0.0	+3.9	+32.5	-16.9	-11.7	-31.2
Volume	-50.0	+20.0	0.0	+50.0	0.0	-75.0	-50.0	-25.0
Biomass	-60.0	+20.0	0.0	0.0	+40.0	-60.0	-20.0	-20.0
TOTAL ALGAE								
Abundance	-1.7	+5.9	0.0	+6.5	+13.2	+13.2	+14.2	+8.2
Volume	+27.4	-36.8	0.0	+11.8	+0.5	+11.0	+17.9	+32.6
Biomass	+19.6	-30.4	0.0	+8.1	+2.5	+6.8	+31.0	+32.3

Another interesting observation from Table 4 is that the densities of blue-green algae from the discharge canal were greater than at the intake, but volume and biomass were not. This indicates that although this class was more abundant in the discharge, the sizes of the organisms were much smaller.

Seasonal Comparisons of Algal Abundance and Volume

Since much useful information is lost by averaging the highly seasonal nature of most algae, emphasis will now be placed on seasonal station differences in abundance and volume. For brevity biomass data is not considered in this analysis since it closely paralleled the volume results.

Total Algae: Total algae abundance and volume data were obtained for all three diel periods of the six seasonal sets thus allowing a three-way AOV to be performed upon transformed results. The purpose of this or, indeed, any other AOV was to partition the data variance to one or more sources. In this case, the sources of variance considered were season, diel period, and station. Strongly significant interactions ($\alpha \leq 0.001$) among these main effects prevented simple interpretation of the sources of variance. However, most of the variance was, as expected, attributed to the seasonal factor with the diel period and station main effects sharing equally a much smaller portion of the variability of the data.

Total algal results are shown in Figures 4, 5, and 6 for morning, afternoon, and evening periods, respectively. The majority of the station mean differences that were statistically significant ($\alpha \leq 0.05$) with the Bonferroni-t procedure occurred in the November, January, and March-April seasonal sets. Differences of a smaller magnitude, yet still significant, were found in June (evening) and September-October (evening).

Several examples existed of a trend of increasing density and/or volume at successive stations down the discharge's flow. Such trends might represent stimulated growth of algae as exposure time to the elevated temperatures increased. Specifically, November 9 and 10, 1972, had significant ($\alpha \leq 0.05$) increases in only algal volume for all three diel periods by up to 88% at the lower discharge canal and plume stations when compared to the intake. Although density results for November had no ($\alpha > 0.05$) such significant increases, algal abundance appeared to be larger in the discharge canal than the intake. January also had trends of both increasing abundance and volume at the lower discharge canal and plume stations for afternoon and, perhaps, the evening periods. The January evening changes were more questionable due to a lack of intake station results.

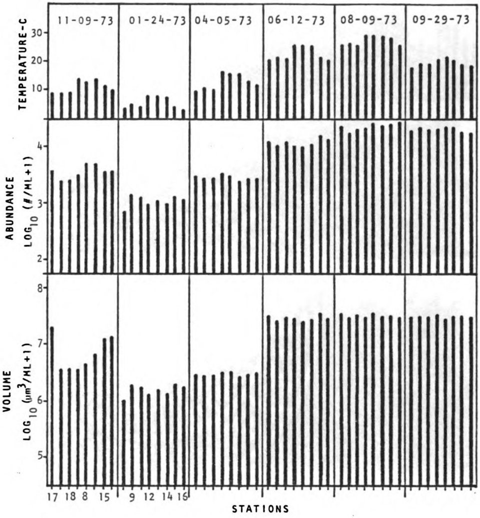


Figure 4. Algal abundance and volume (means of five replicates) and water temperatures for morning samplings of 1972-73.

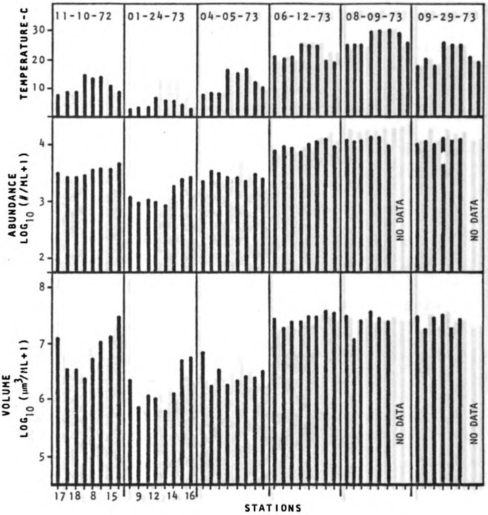


Figure 5. Algal abundance and volume (means of five replicates) and water temperatures for afternoon samplings of 1972-73.

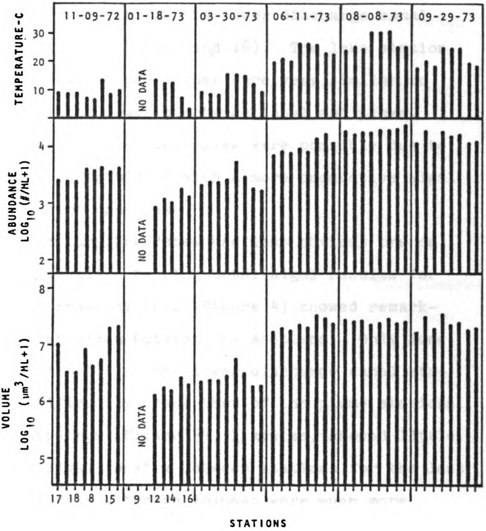


Figure 6. Algal abundance and volume (means of five replicates) and water temperatures for evening samples of 1972-73.

Although the increases in November and January would support the hypothesis of stimulated growth of the algae due to a rise in temperature, these changes tended to be restricted to the lower discharge canal and plume stations (14, 15, and 16). The lake station (17) algal abundance and volume were very similar to the results at the lower discharge canal and plume. Therefore, the observed increases were possibly due to the discharge water mixing with a more productive algal assemblage in the open lake.

The other sampling dates had less obvious trends or no trends at all. Morning total algal results for the last four seasonal sets (Figure 4) showed remarkably little variation between the stations. Only June 13th's algal density at the lower discharge canal station was significantly below that of the plume stations. Afternoon samplings (Figure 5), likewise, showed little variation in algal density between stations for the last four seasonal sets although volumes were much more erratic but without any consistent trends. Corresponding evening sampling results were more interesting. A significant ($\alpha \leq 0.05$) peak in the density and volume was observed for algae at the middle discharge canal station (8) on March 30th. No analagous pattern was seen for the other diel periods of the March-April seasonal set. For the evening of June 11th, the algal abundance at the lower discharge canal and two plume stations was up to

55% above that at the intake which was significant ($\alpha \leq 0.05$). The algal volume at the lower discharge canal station at this time was 43% above the intake volume. Beyond the June seasonal set no other significant trends were evident for the evening period although on August 8th an insignificant increase in density along the discharge occurred.

Diatoms: Diatoms constituted over 75% of the total algal volume at all times of the study year. Their proportion of the total abundance was also very high (65% to 90%) for the first three seasonal sets but dropped to as little as 20% of the algal density in August. Thus, overall phytoplankton dynamics in the study area were often largely a reflection of the diatom fluctions.

As with total algae, a three-way AOV was performed on the transformed diatom abundance and volume data. However, using the F-max test of variance homogeneity, the transformed data had significant ($\alpha \leq 0.05$) heterogeneity. Nevertheless, sufficient rigor was assumed for the AOV to minimize the consequences of this upon the parametric analysis. Results of the AOV were inconclusive due to strong interactions among the main effects.

Figure 7 presents the afternoon data of density and volume for diatoms. Major deviations for the morning and evening diel periods from the afternoon results shown

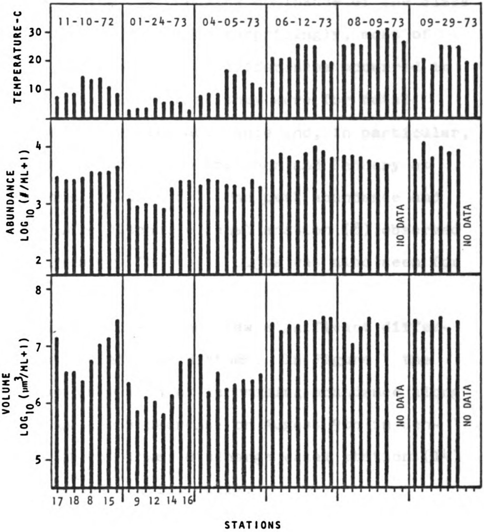


Figure 7. Diatom abundance and volume (means of five replicates) and water temperatures for afternoon samplings in 1972-73.

will be mentioned. For at least the first four seasonal sets (i.e., November, January, March-April, and June), the diatom results closely resembled those described for total algae due to the overwhelming dominance of the class at these times of the year. Not surprisingly, most of the significant ($\alpha \leq 0.05$) station differences occurred in the first three seasonal sets as they were for total algae. Trends of increasing abundance and, in particular, volume were most pronounced in November and January at the plume stations (15 and 16). The peak abundance and volume at the middle discharge canal station (8) observed on March 30th (evening) for total algae was also seen for diatoms.

The other seasonal sets had few significant differences among station data for diatoms. In Figure 7 the visible trends on June 12th of increasing abundance along the discharge flow and a decrease on August 9th in density and volume at the lower discharge canal station (14) could not be defended statistically.

Green Algae: The problem of excessive heterogeneity of variance for transformed abundance and volume was greater for green algae than for diatoms. Nevertheless, the same three-way AOV was used for this transformed data. As before, results of the AOV for green algae showed strongly significant ($\alpha \leq 0.001$) interactions among the sources of variance. This complex nature of the variance meant, as with earlier algal analyses, that station mean comparisons had to be made for each sample date separately.

Figure 8 portrays the afternoon green algal results. The data from the afternoon samplings along with that of the morning and evening periods were highly variable between stations making distinguishing unusual station dfiferences difficult. Virtually all significant ($\alpha \leq 0.05$) station differences, regardless of diel period, were found in November. The pattern for that seasonal set was one of higher density and volume at the lower discharge canal and plume stations (14, 15, and 16) for green algae. However, no ($\alpha > 0.05$) significant difference existed between the plume results and those for the lake station (17). Therefore, mixing of the discharge which had more production of green algae could explain these plume increases in density and volume.

Changes seen at the discharge stations in Figure 8 after November were mostly insignificant with only a few minor exceptions. However, insignificant evidence of declines in abundance and volume were observed in the discharge in January and, perhaps, April. Possible increases in density were indicated in June and August.

Blue-green Algae: The logarithmic transformation for blue-green algal abundance and volume results produced insignificant ($\alpha > 0.05$) heterogeneity of the

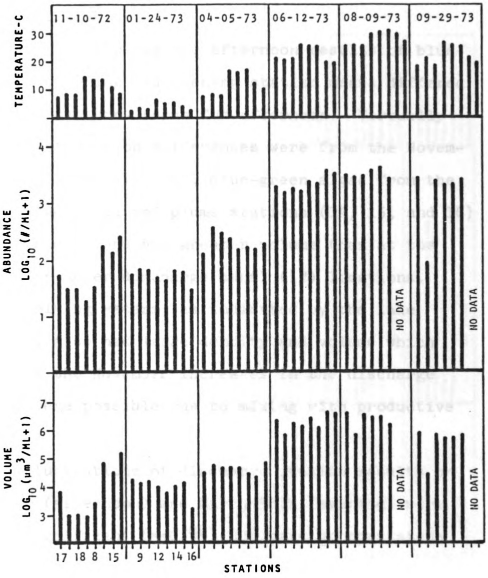


Figure 8. Green algae abundance and volume (means of five replicates) and water temperatures for afternoon samplings of 1972-73.

variances. However, the three-way AOV of this data was, again, complicated by significant interactions of the sources of variance.

Figure 9 illustrates the afternoon results of blue-green algae. Morning and evening station means differed little in the patterns shown for afternoon. Virtually all significant station differences were from the November samplings. At this time, blue-green algae from the lower discharge canal and plume stations (14, 15, and 16) were more abundant and had greater volume than at the intake (18) or upper discharge canal (12) locations. The lake receiving waters, as indicated by the lake station (17), also had large density and volume which suggests that the November increases in the discharge noted above were possible due to mixing with productive Lake Erie.

Large fluctuations of discharge station results on January 24th (afternoon) and March 30th (evening) were also found significant ($\alpha \leq 0.05$) but gave no consistent trends. On other sampling dates the results were much too variable to identify any trends and none of the station differences were statistically significant.

<u>Euglenophyceae</u>: The euglenoids represented the only other class to become an important component of the phytoplankton. This class was evident principally in the March-April seasonal set. The three-way AOV showed

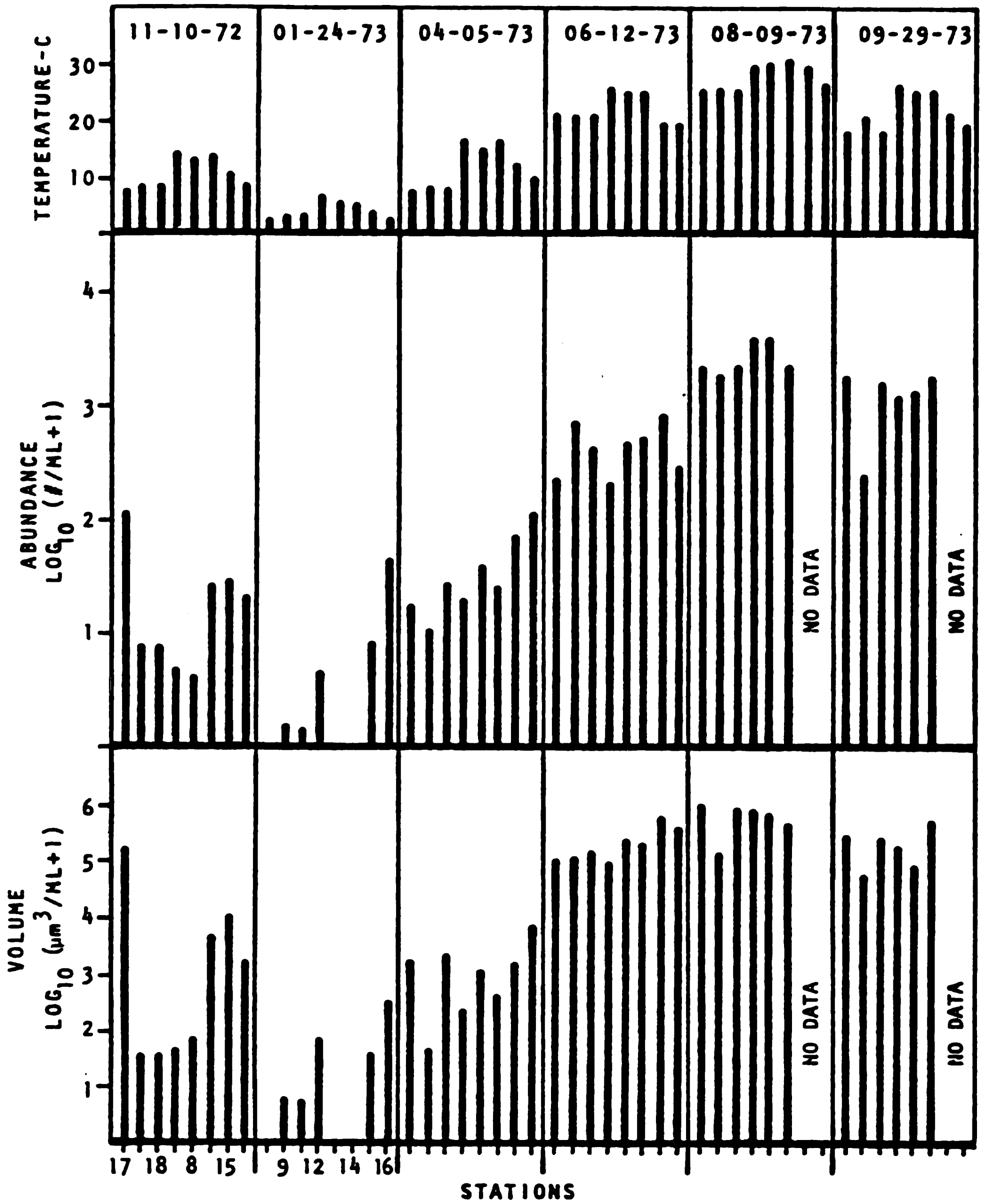


Figure 9. Blue-green algae abundance and volume (means of five replicates) and water temperatures for afternoon samplings of 1972-73.

significant interaction among the main effects. Bonferroni-t mean comparisons indicated only a few significant ($\alpha \leq 0.05$) station mean differences in the June and September-October sets when the class was relatively rare. Due to the low densities at these times, the significant differences probably represented a patchy distribution of individuals.

Centric and Pennate Diatoms: Up to this point, results presented have dealt only with the algal classes. However, the two orders of diatoms, Centrales and Pennales, are often recognized as ecologically as well as morphologically distinct groups. Since data were available for most of the seasonal sets for the afternoon period only, a two-way AOV was performed on transformed abundances and volumes using season and station as the sources of variance. Results were also obtained for all three November diel periods for centrics and pennates which required a separate AOV with diel period and station sources of variance. Heterogeneity of variances and main effect interactions remained major problems for these analyses.

Results for the afternoon period samplings for centrics and pennates are shown in Figures 10 and 11, respectively. The centric diatoms were the largest portion of the class and, not surprisingly, their histogram was very similar to that for the entire class (Figure 7). November and January had most of the

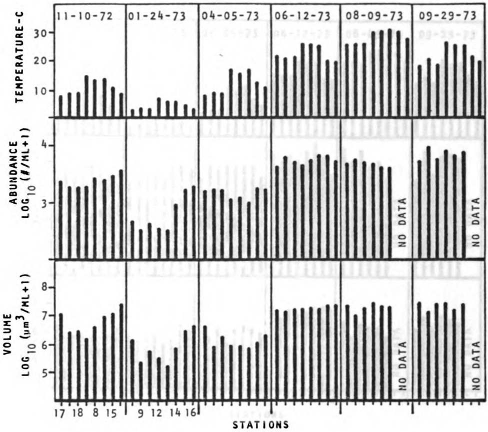


Figure 10. Centric diatom abundance and volume (means of five replicates) and water temperatures for afternoon samplings of 1972-73.

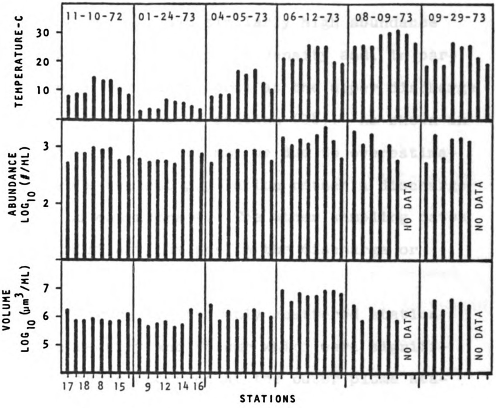


Figure 11. Pennate diatom abundance and volume (means of five replicates) and water temperatures for afternoon samplings of 1972-73.

significant ($\alpha \leq 0.05$) discharge changes with a gradual increase in centric abundance and volume at the lower discharge canal and plume stations (14, 15 and 16). However, Lake Erie also had similarly high abundance and volume. Significant drops in density and, in particular, volume occurred in April at the upper discharge canal compared to the intake station (18). As shown in Figure 10, this April result may be due to overestimating the intake's centric population rather a discharge reduction due to entrainment. The other sampling dates lacked any significant changes in the discharge or trends.

Pennates (Figure 11) had only scattered station differences in density and volume which were significant. Most of these occurred at the outer plume station (16). So, little evidence of change was seen in the discharge that might be related to pennate entrainment.

Shifts in Algal Class Dominance

It is possible that changes in the relative importance of algal classes can be affected by the stesses of entrainment. To assess this, the relative percentage of the total abundance and volume for each station were computed using untransformed station means. No statistical analysis of these values was attempted.

For the first three seasonal sets, changes in the relative importance of any algal class along the discharge canal or plume was usually less than 10%. During this time, the only exception to this statement was in the March-April set from the evening period when the outer plume station (16) diatom percentage of the total abundance rose by almost 15% compared to the intake largely at the expense of green algae and euglenoids. However, no trends of increasing diatom importance along the discharge flow support this outer plume change as being due to entrainment.

Of the last three seasonal sets, only June showed any unusual shifts in class dominance. Diatoms decreased in percent of total abundance by over 10% (6 to 11% by volume) from the upper discharge canal station (12) to the outer plume station (16). At the same time, green algae and, to a lessor degree, blue-green algae assumed proportionally greater dominance.

Species Composition Within the Cooling System

One would anticipate only severe environmental change to seriously alter the relative density or volume of entire algal classes because each is composed of many species each of which has slightly differing environmental requirements for survival and growth. Results pooled or averaged at the class level might conceal subtle but perhaps ecologically important changes in the phytoplankton. Therefore, changes at the species level were examined.

Of nearly 350 distinctive forms of algae recognized during the study, 255 represented identifiable species. Appendix A5 lists all algal forms observed during this study. An abridged list was prepared (Table 5) which roughly indicates the percent of total volume of species which exceeded 1% of this for afternoon samplings of each seasonal set.

Of the species listed in Table 5, clearly diatoms were the most prominent and the most diverse. Of the 70 species and unknowns given, 59 were diatoms. Of course, many of the forms given were relatively rare. Navicula, for example, was a genus with a large number of species, but none of those forms ever had a volume much above 1% of the total. Especially major species (above 10% of the total volume) frequently were Coscinodiscus radiatus and Cyclotella meneghiniana and less frequently Fragilaria spp., Stephanodiscus astrae, and Stephanodiscus niagarae.

A detailed analysis of the changes in species' abundance and volume like that done for the major classes was practical for only a few species which had sufficiently large numbers to make statistical analysis useful. Therefore, seven species were chosen for detailed study. Representative species from each of three three major classes were selected taking adequate

Table 5. Major algal species (1% or more of the total volume during any sampling) enumerated for the 1972-73 study year and their relative afternoon percentage of the total volume at each station.[1]

Species Name	Stations: Lake 17	River 9	Intake 18	Upper Discharge 12	Mid Discharge 8	Lower Discharge 14	Inner Plume 15	Outer Plume 16
Class Bacillariophyceae								
Asterionella formosa	-b----	a-C---	abc---	-bC---	--C---	a-c---	abc-**	abc-**
Cocconeis placentula	------	------	------	-b----	-b----	------	----**	----**
Coscinodiscus radiatus	ABCDEF	a--DEF	aBcDEF	-b-DEF	A-CDE-	AbcDEF	ABcD**	ABcD**
Cyclotella glomerata	------	-bc---	-b----	-bc---	-b----	-b----	--c-**	----**
C. kutzingiana	------	------	------	a-----	------	------	----**	----**
C. meneghiniana	aBcdef	ABCDEF	ABcdEf	AbCdeF	ABCde-	aBcdeF	abCd**	abcd**
C. stelligera	------	----e-	------	------	------	------	----**	----**
Cymatopleura solea	-b----	a-----	a-----	ab----	------	--c---	----**	--c-**
Cymbella spp.	------	------	------	------	------	------	-b--**	----**
Diatoma elongatum	---d--	---d--	---d--	---d--	---d--	---d--	---d**	----**
D. sp.	------	-b----	-b----	--c---	------	------	----**	----**
D. vulgare	------	-----f	------	------	------	-b----	----**	----**
Diploneis oblongella	------	------	------	--c---	------	------	----**	----**
Fragilaria crotonensis	-bc---	--c---	-bc---	--c---	a-c---	------	-b--**	-bc-**
F. spp.	--CDef	---d-F	--CDef	aB-De-	--CDef	--CDef	-BCD**	-bCD**
Gomphonema angustatum	------	------	------	------	-b----	------	----**	----**
G. olivaceum	-b----	abc--f	abc---	abc---	-b----	-bc---	--c-**	--c-**
G. parvulum	------	------	------	------	------	-b----	----**	----**
Gyrosigma acuminatum	------	------	------	------	--c---	------	----**	----**
G. spencerii	------	a-c---	a-----	abc---	-bc---	--c---	----**	----**
Melosira ambigua	--c---	--cd--	--c---	-bc---	-b----	-bc---	-bc-**	--c-**
M. arenaria	------	abc---	abc---	abc---	abc---	abc---	a-c-**	-bc-**
M. granulata	---def	a--DeF	a--def	a--d-f	---de-	---d-f	a-cd**	--cd**
M. islandica	ab----	------	------	a-----	a-----	------	----**	--C-**

Table 5 (cont'd.).

Species Name	Lake 17	River 9	Intake 18	Upper Discharge 12	Mid Discharge 8	Lower Discharge 14	Inner Plume 15	Outer Plume 16
				Stations				
M. italica	---d-F	---de-	---d-F	---D-f	---d--	----ef	----**	----**
M. sp.	------	----e-	----e-	---d-f	a--D--	---D--	-b--**	-b--**
V. varians	-b-d--	Ab----	Ab-d--	ABcd--	Abcd--	a-cd--	-b--**	-b--**
Navicula canalis	------	------	------	------	-b----	------	----**	----**
N. cryptocephala	------	-bc---	-b----	abc---	-bc---	-b----	--c-**	----**
N. cuspidata	------	------	------	------	-b----	------	----**	----**
N. gastrum	------	-b----	-b----	------	------	-b----	----**	----**
N. mutica	------	------	------	------	------	-b----	----**	----**
Navicula rhynchocephala	------	ab----	a-----	abc---	ab----	-b----	----**	----**
N. tripuncta	------	-b---f	-b----	-b----	-b----	-bc---	-bc-**	----**
N. virdula	------	------	------	------	-b----	-b----	----**	----**
Nitzschia acicularis	------	--c---	--c---	--c---	--c---	-bc---	--c-**	----**
N. angustata	------	------	------	------	-b----	------	----**	----**
N. filiformis	------	ab----	ab----	abc---	------	-bc---	----**	----**
N. gracilis	-b----	-bc---	-b----	-bc---	-bc---	-bc---	--c-**	----**
N. palea	------	------	------	------	------	--c---	----**	----**
N. sigma	------	-b----	-b----	------	-b----	------	----**	----**
N. sp. #1	------	------	------	------	a-----	------	----**	----**
N. sp. #3	------	------	------	------	ab----	------	----**	----**
N. spp.	----e-	a---e-	a---e-	a-----	------	------	----**	----**
Pinnularia gibba	------	-b----	-b----	-b----	------	------	----**	----**
Rhizolenia eriensis	--c---	---d--	------	------	------	--c---	-bc-**	-bc-**
Rhoicosphenia curvata	------	-b----	-b----	------	------	-b----	----**	----**
Stephanodiscus astraea	AbCdef	abcd--	abcdef	abCdef	a-cdef	ab-def	Abcd**	ABC-**
S. niagarae	ABCdEF	---dE-	-BCdEF	--C-Ef	A--dE-	AB--E-	AB--**	ABC-**
S. sp.	---d--	--cd--	--cd--	--cd--	a-c---	a-cd--	a-cd**	abcd**
Surirella angusta	------	-b----	------	--c---	------	------	--c---	------

Table 5 (cont'd.).

Species Name	Lake 17	River 9	Intake 18	Upper Discharge 12	Mid Discharge 8	Lower Discharge 14	Inner Plume 15	Outer Plume 16
				Stations				
Surirella ovata	------	abc---	ab----	a-c---	-bc---	------	----**	----**
S. robusta var. splendida	a-----	------	------	------	------	------	----**	----**
Synedra acus	------	------	------	------	------	-b----	----**	----**
S. ulna	ab-d--	aB-d-f	ab-d--	aBcd--	aB-de-	abcd--	-bcd**	-b--**
S. vaucheriae	------	------	------	------	------	-b----	----**	----**
Tabellaria fenestrata	-bcd--	------	-b-d--	--cd--	------	------	-bc-**	-bc-**
Unknown centric filament	---d--	---D-F	---d-f	---d-f	------	-----f	----**	----**
Unknown pennate #4	------	------	------	------	------	------	-b--**	----**
Class Chlorophyceae								
Binuclearia eriensis	a--de-	----E-	----E-	----e-	----e-	----e-	----**	----**
Chlamydomonas sp. #3	------	------	------	------	------	------	----**	--c-**
Cosmarium formulosum	----e-	----e-	----e-	------	------	------	----**	----**
Dictyosphaerium pulchellum	---d--	------	------	------	------	------	----**	----**
Mougeatia elegantula	---D-f	---d--	---d-f	---d--	---d--	---d-f	---d**	---d**
Pandorina morum	------	------	------	--c---	------	------	----**	----**
Ulothrix subtillissima	---d--	---d--	---d--	---d--	---d--	---d--	---d**	---d**
Class Cyanophyceae								
Aphanizomenon gracile?	a--de-	------	----e-	----e-	------	------	---d**	---d**
Oscillatoria spp.	---d--	------	------	------	------	------	----**	----**
Class Euglenophyceae								
Euglena gracilis	------	--c---	------	------	------	------	----**	----**
Trachelomonas volvocina	------	--c---	------	--c---	--c---	--c---	--c-**	--c-**

Table 5 (cont'd.).

[1]Table symbols: letters indicate the different sampling dates -

A, a = November 10, 1972
B, b = January 24, 1973
C, c = April 5, 1973
D, d = June 12, 1973
E, e = August 9, 1973
F, f = September 29, 1973

Upper case letters indicate the species was $\geq$10% of the total volume.
Lower case indicates the species was $\geq$1% but $<$10% of the total volume.
A dash (-) indicates a volume <10%. An asterick (*) indicates no data.

abundance or volume and morphology (i.e., unicell, colony, or filament) of the species into consideration. Thus, two unicellular diatoms were chosen: Coscinodiscus radiatus and Cyclotella meneghiniana. Three green algal species were selected: the colonial Dictyosphaerium pulchellum, the coenobial Scenedesmus quadricauda var. longispina, and the filamentous Ulothrix subtillissima. Two blue-green algal species were included: the colonial Anacystis incerta and the filamentous Aphanizomenon gracile. Collectively, these species constituted about 34% of the average total station abundance.

Species Annual Mean Abundance, Volume, and Biomass

Table 6 presents the annual afternoon station means of untransformed abundance, volume, and biomass for the selected algal species. No statistical analysis was attempted for these results, so the significance of changes discussed below must be considered tentative.

As mentioned, C. radiatus was a very important species in the study area. It accounted for 15% of the diatom abundance and 33% of the class volume. Results for it in Table 6 indicated an increase of abundance, volume, and biomass occurred at the lower discharge canal station (14), and even larger values were evident at the plume stations (15 and 16). The outer plume station's abundance, volume, and biomass were all 75% above those at the intake station. However, data of the lake station (17) suggests at least some of the

Table 6. Mean daily abundance (specimens/ml), volume ($\mu m^3/ml \times 10^3$), and biomass (μg C/ml $\times 10^{-3}$) of selected species averaged across afternoon samplings for an annual average at each station.

	Stations							
Species Name	Lake 17	River 9	Intake 18	Upper Discharge 12	Mid Discharge 8	Lower Discharge 14	Inner Plume 15[1]	Outer Plume 16[1]
<u>Coscinodiscus</u> <u>radiatus</u>								
Abundance	808	146	611	634	544	680	834	957
Volume	6344.5	1157.0	4817.8	4923.7	4221.0	5344.7	6652.6	7583.1
Biomass	273.8	49.9	207.8	213.2	182.7	230.7	286.3	327.0
<u>Cyclotella</u> <u>meneghiniana</u>								
Abundance	966	2197	1307	1176	1506	1504	1031	909
Volume	1122.8	2458.3	1440.0	1200.6	1512.0	1563.0	1170.1	1017.5
Biomass	76.2	169.5	98.3	84.1	106.4	109.2	145.2	163.1
<u>Dictyosphaerium</u> <u>pulchellum</u>								
Abundance	54	11	45	60	83	43	77	53
Volume	19.1	4.4	15.5	21.7	28.1	14.1	29.2	18.0
Biomass	3.0	0.7	2.2	3.6	4.4	2.2	4.6	2.8
<u>Scenedesmus</u> <u>quadricauda</u> var. <u>logispina</u>								
Abundance	41	42	44	48	38	96	54	36
Volume	5.8	7.0	6.4	7.1	5.3	13.3	7.9	4.9
Biomass	1.0	1.2	1.1	1.3	0.9	2.4	1.4	0.9
<u>Ulothrix</u> <u>subtillissima</u>								
Abundance	240	55	187	130	212	128	396	391
Volume	232.0	54.9	178.9	125.4	195.6	118.3	388.9	399.4
Biomass	32.0	7.5	24.7	17.3	27.1	16.4	53.5	53.8

Table 6 (cont'd.).

	Stations							
Species Name	Lake 17	River 9	Intake 18	Upper Discharge 12	Mid Discharge 8	Lower Discharge 14	Inner Plume 15[1]	Outer Plume 16[1]
Anacystis incerta								
Abundance	94	32	81	151	106	60	106	115
Volume	28.6	9.1	24.7	40.2	29.6	17.7	31.9	34.7
Biomass	4.6	1.5	4.0	6.6	4.8	2.9	5.1	5.6
Aphanizomenon gracile								
Abundance	105	18	70	80	50	53	124	137
Volume	182.7	34.5	123.0	134.7	90.8	95.2	223.9	245.6
Biomass	22.3	4.3	15.7	17.2	11.5	12.1	28.4	31.2

[1]Missing data was estimated.

increase was due to mixing of discharge and more productive receiving water.

C. meneghiniana constituted 38% of the diatom density and 11% of the class volume across all stations. The station means in Table 6 were quite variable although there was some indication of decreasing abundance and volume but not biomass.

The three green algal species, *D. pulchellum*, *S. quadricauda* var. *longispina*, and *Ulothrix subtillissima* were, respectively, 3.4%, 3.5%, and 13.9% of the class density averaged for the year. They all tended to be prominent only during the summer. In Table 6 no unusual differences between the discharge and the intake were evident. However, *U. subtillissima* did have substantially larger plume density, volume, and biomass.

The two blue-green algal species, *A. incerta* and *A. gracile*, were common summer forms. The former species was 12% and 10% of its class' abundance and volume, respectively. The second species was 11% and 52% of the abundance and volume, respectively, of the class. Only *A. gracile* had substantially larger density, volume, and biomass in the discharge plume stations (15 and 16) over those at the intake. However, its abundance was so low that this increase is questionable.

Seasonal Comparison of Species Abundance and Volume

Due to the seasonality of many of the selected species, only an analysis of the station means on that basis will properly describe the results. For each of the selected species, a two-way AOV was made on logarithmically transformed abundances and volumes from the afternoon samplings using season and station as the sources of variance.

Coscinodiscus radiatus: Substantial heterogeneity remained for transformed data of *C. radiatus* based on the F-max test. Despite this, the AOV indicated highly significant ($\alpha \leq 0.001$) interactions existed between the main effects. Therefore, station results were not pooled across the seasonal sets for evaluation of their mean differences.

Figure 12 illustrates the station means of abundance and volume for *C. radiatus*. Obviously, large fluctuations to zero abundance and volume occurred at some stations during the first three seasonal sets. Although the Bonferroni-t mean comparisons indicated these erratic variations were significant ($\alpha \leq 0.05$), they were most likely artifacts of the enumeration procedure for diatoms which could easily give zeros especially when densities were low. Nevertheless, trends were evident for abundance and volume of the species in November and January when these values steadily increased in magnitude along the discharge

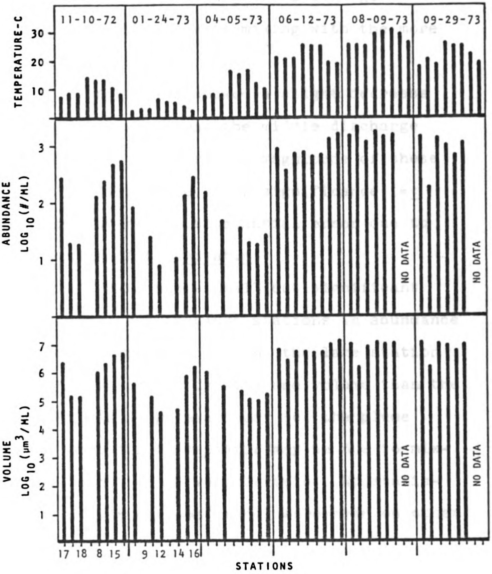


Figure 12. Coscinodiscus radiatus abundance and volume (means of five replicates) and water temperatures for afternoon samplings of 1972-73.

flow. However, again the lake station (17) had similar density and volume to those of the plume stations (15 and 16) indicating the discharge increases were probably due to mixing with the more productive open lake.

Results of April 5th showed a slight decrease in density and volume beyond the middle discharge canal station (8). However, the magnitude of these changes were small despite their significance ($\alpha \leq 0.01$) and were subject to substantial error due to the low densities of C. radiatus.

June 12th's data had a small but significant ($\alpha \leq 0.01$) increase at both plume stations in abundance and volume of the species. Again, the lake station also had higher values of density and volume than the intake or most discahrge stations; so, the plume increases of June for C. radiatus may be due to mixing with the more productive Lake Erie. No statistically or visually obvious trends were seen on other sampling dates.

Cyclotella meneghiniana: The log transformation for density and volume data for C. menghiniana was not very successful in reducing heterogeneity of variances. Therefore, the parametric statistical analyses with this transformed data must be viewed with some skepticism.

The AOV for this species was plagued by strong ($\alpha \leq 0.01$) interactions of the main effects. Station mean comparisons were, therefore, limited to unpooled results.

Results for this species, as shown in Figure 13, produced an opposite trend than seen previously in November. Significantly decreasing density and volume values were observed at the lower discharge canal and plume stations (14, 15, and 16). Nevertheless, the reason for the decreases seemed to be the same. The lake station (17) also had low density and volume which indicates the open lake was less productive of C. meneghiniana than the discharge. Thus, as the plume dispersed into the open lake, the abundance and volume for this species understandably declined.

The more typical trend appeared in Janaury with significantly ($\alpha \leq 0.01$) higher density at the plume although volume increases were not significant to the $\alpha = 0.05$ level. Mixing of discharge and receiving water did not seem as likely an explanation here since the lake station results were not similar to the final plume levels.

Other sampling dates had some significant fluctuations of C. meneghiniana's abundance and, to a lessor degree, volume in the discharge, but these were erratic variations without obvious trends.

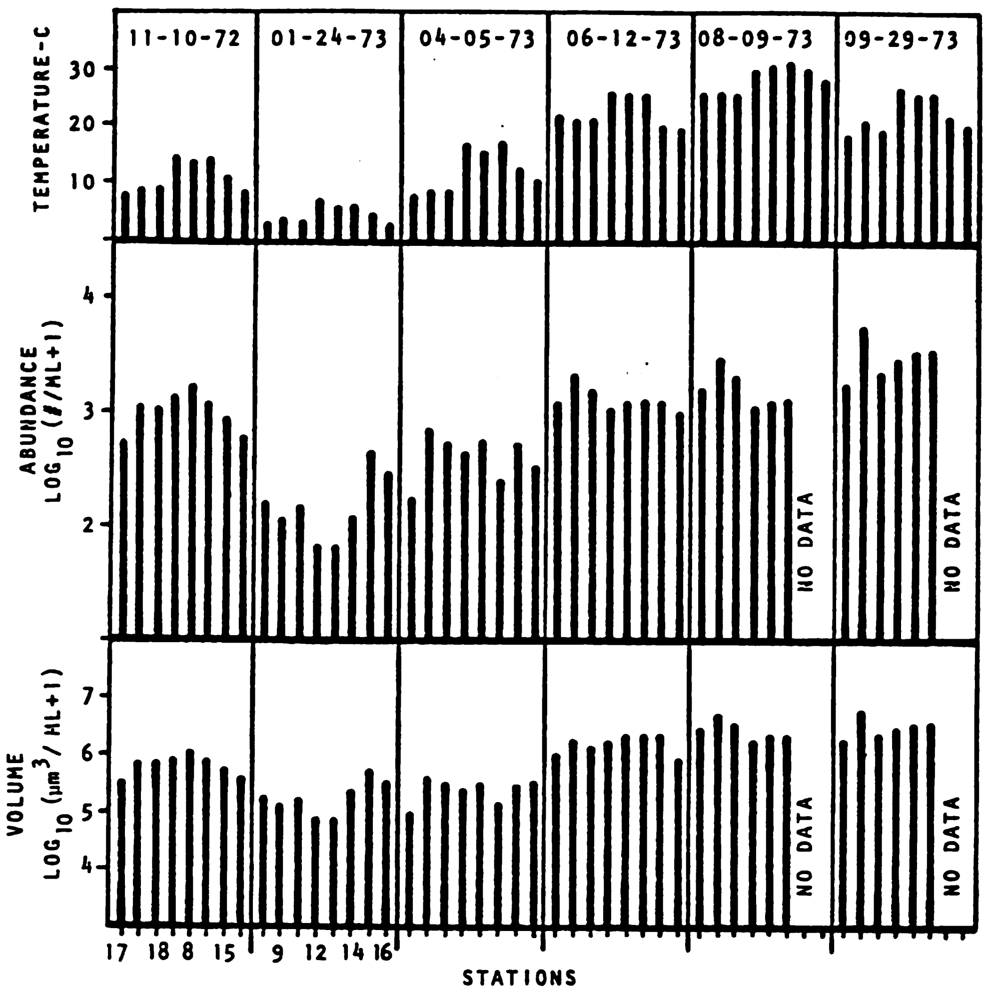


Figure 13. Cyclotella meneghiniana abundance and volume (means of five replicates) and water temperatures for afternoon samplings of 1972-73.

Dictyosphaerium pulchellum, Scenedesmus quadricauda var. longispina, and Ulothrix subtillissima: Of the three green algae species examined, heterogeneity of transformed density and volume variances for D. pulchellum and U. subtillissima remained significant ($\alpha \leq 0.01$). The AOV results showed almost no interactions between season and station main effects for all three species. Both D. pulchellum and U. subtillissima had significant ($\alpha \leq 0.05$) variability attributed to each of the main effects with, of course, season assuming the greater share. However, S. quadricauda var. longispina had significant variance of both abundance and volume attributed to only the season component. So, presumably no significant station differences existed over any of the seasonal sets for this one species. Therefore, no station mean comparisons were deemed necessary for S. quadricauda var. longispina.

Figures 14, 15, and 16 illustrate abundance and volume results for D. pulchellum, S. quadricauda var. longispina, and U. subtillissima, respecitvely. These all were common only during the warmer months. Their results indicated high variability and so almost no significant abundance or volume station differences could be demonstrated for any species. No significant trends in the data appeared, and simple inspection of the Figures 14, 15, and 16 supported this. A possible exception was U. subtillissima which had a small

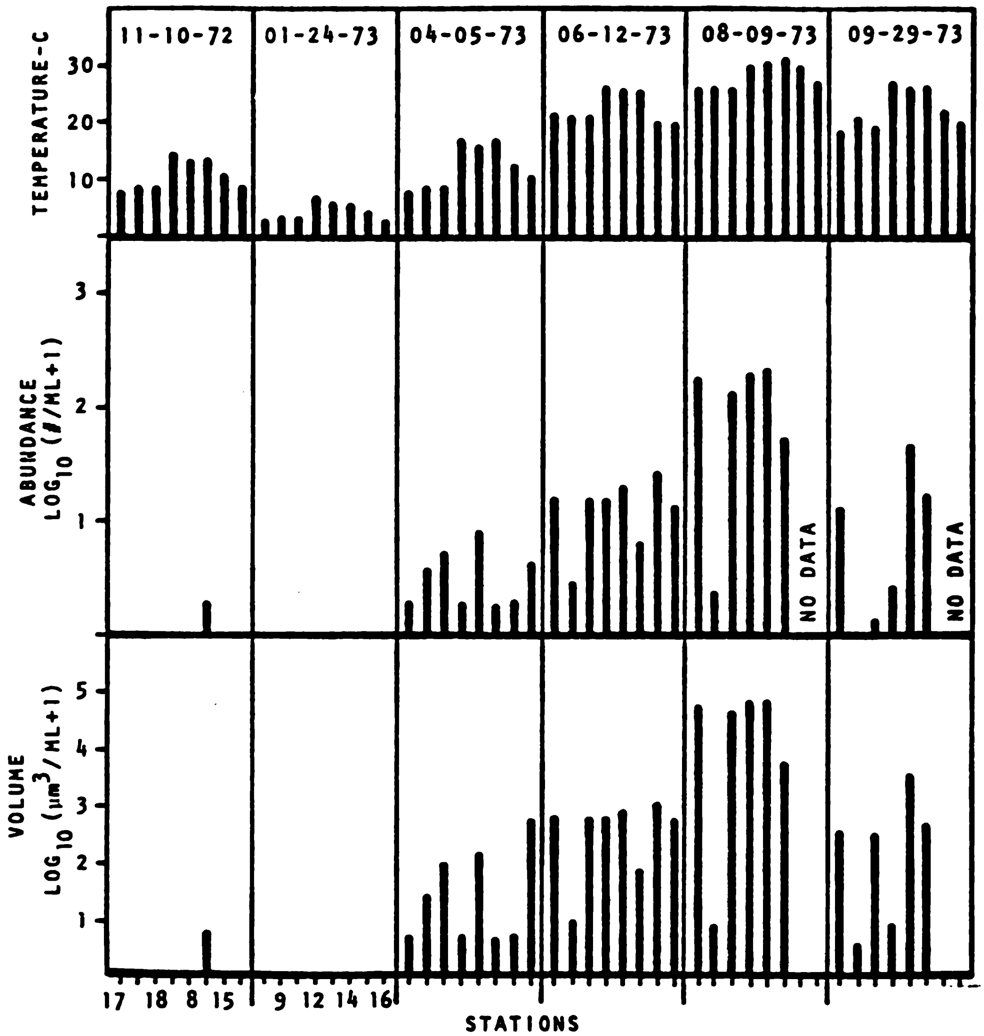


Figure 14. Dictyosphaerium pulchellum abundance and volume (means of five replicates) and water temperatures for afternoon samplings of 1972-73.

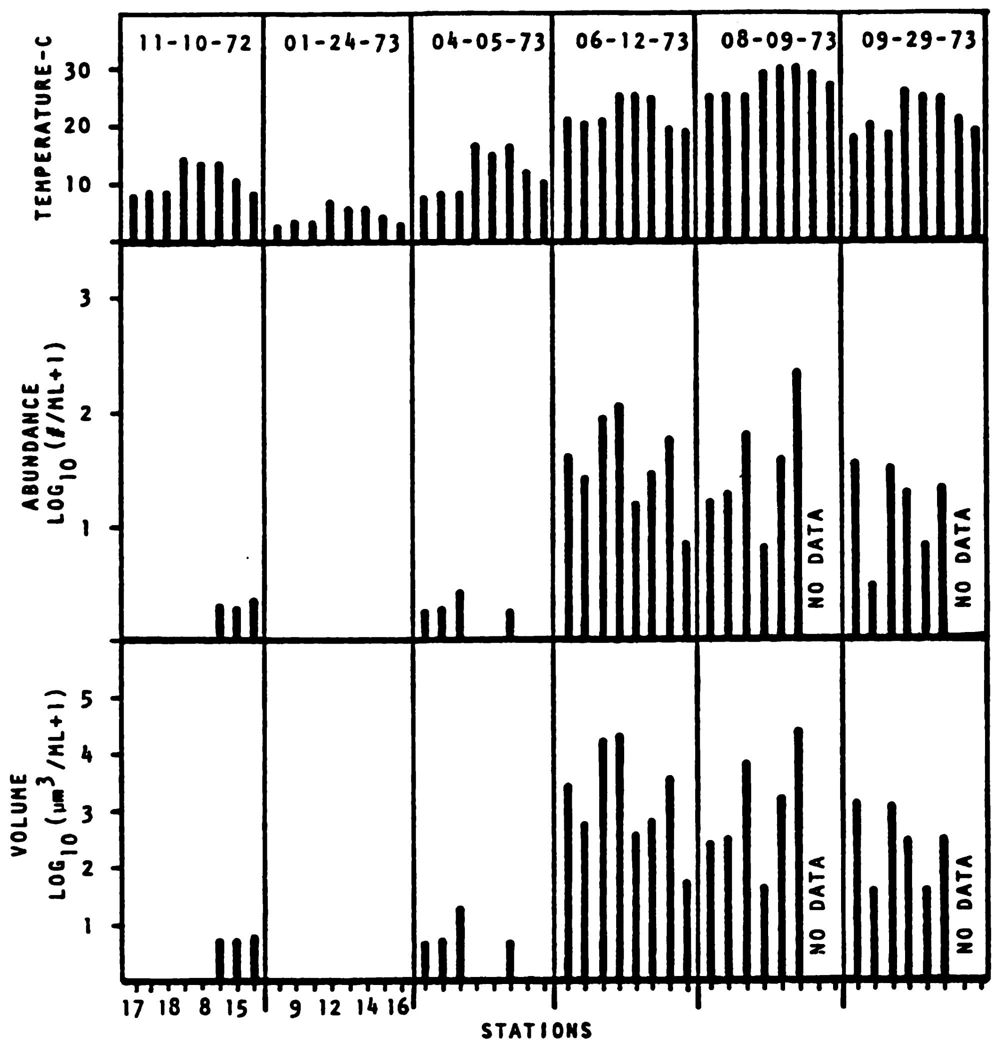


Figure 15. Scenedesmus quadricauda var. longispina abundance and volume (means of five replicates) and water temperatures for afternoon samplings of 1972-73.

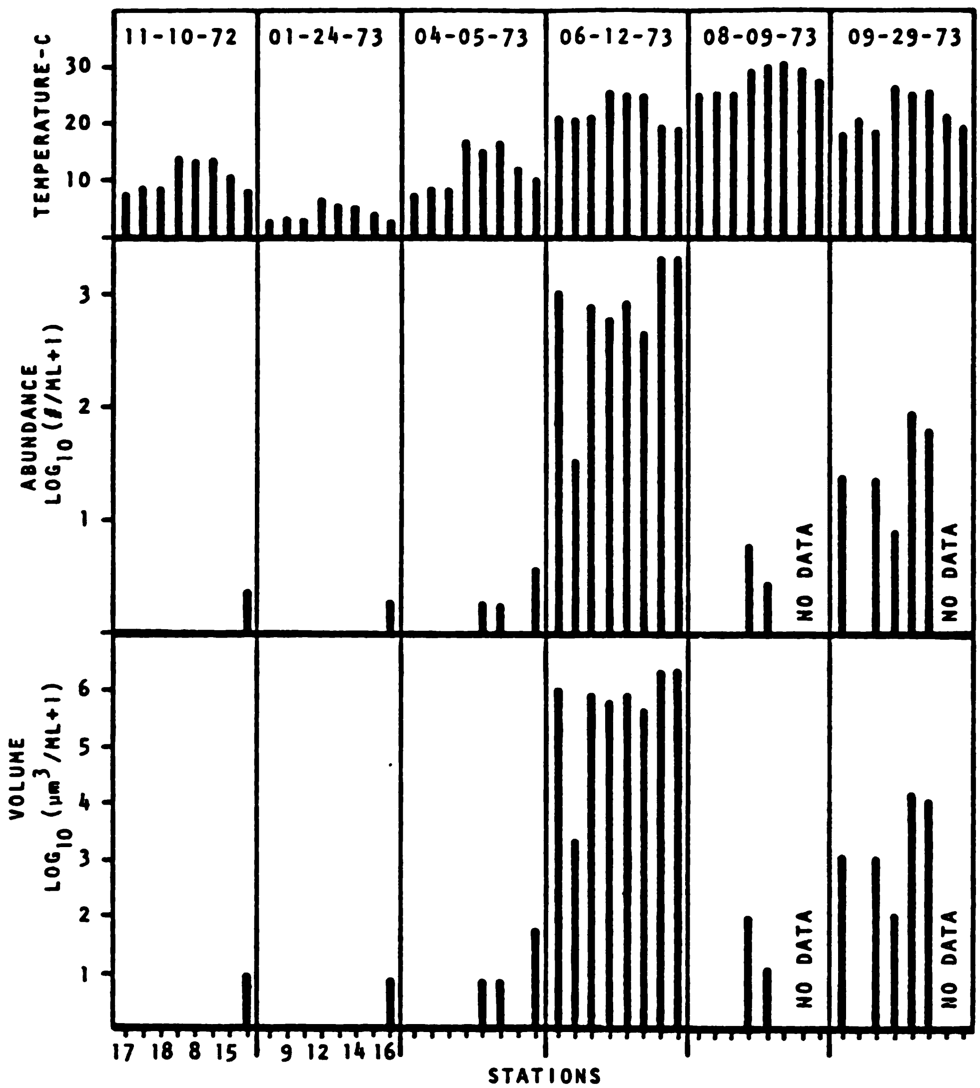


Figure 16. Ulothrix subtillissima abundance and volume (means of five replicates) and water temperatures for afternoon samplings of 1972-73.

increase in density and volume at the plume stations (15 and 16) in June, but since the lake station (17) also had somewhat high values, the plume increase may be due to mixing of the discharge with a more productive Lake Erie.

Anacystis incerta and Aphanizomenon gracile: Despite some heterogeneity of variances of abundance and volume for A. incerta and A. gracile, the two-way AOV's were performed. For both species the AOV's had significant ($\alpha \leq 0.05$) interactions appear between the main effects.

The coccoid blue-green alga, A. incerta, showed little, if any, significant entrainment effects as seen in Figure 17. Only the June and September results had significant ($\alpha \leq 0.01$) station mean differences which were usually seen as decreases in density and volume in the discharge canal relative to the intake, but abundance was so low that those results may not be considered reliable. Statistically insignificant ($\alpha > 0.05$) decreases in abundance and volume were seen on August 9th, but the upper discharge canal station (12) values were so much above the intake's that a patchy distribution of the species could explain this.

A. gracile's results in Figure 18 were even more variable between stations than those of A. incerta. Despite high summer volumes, almost no station means for A. gracile were statistically ($\alpha \leq 0.05$) different

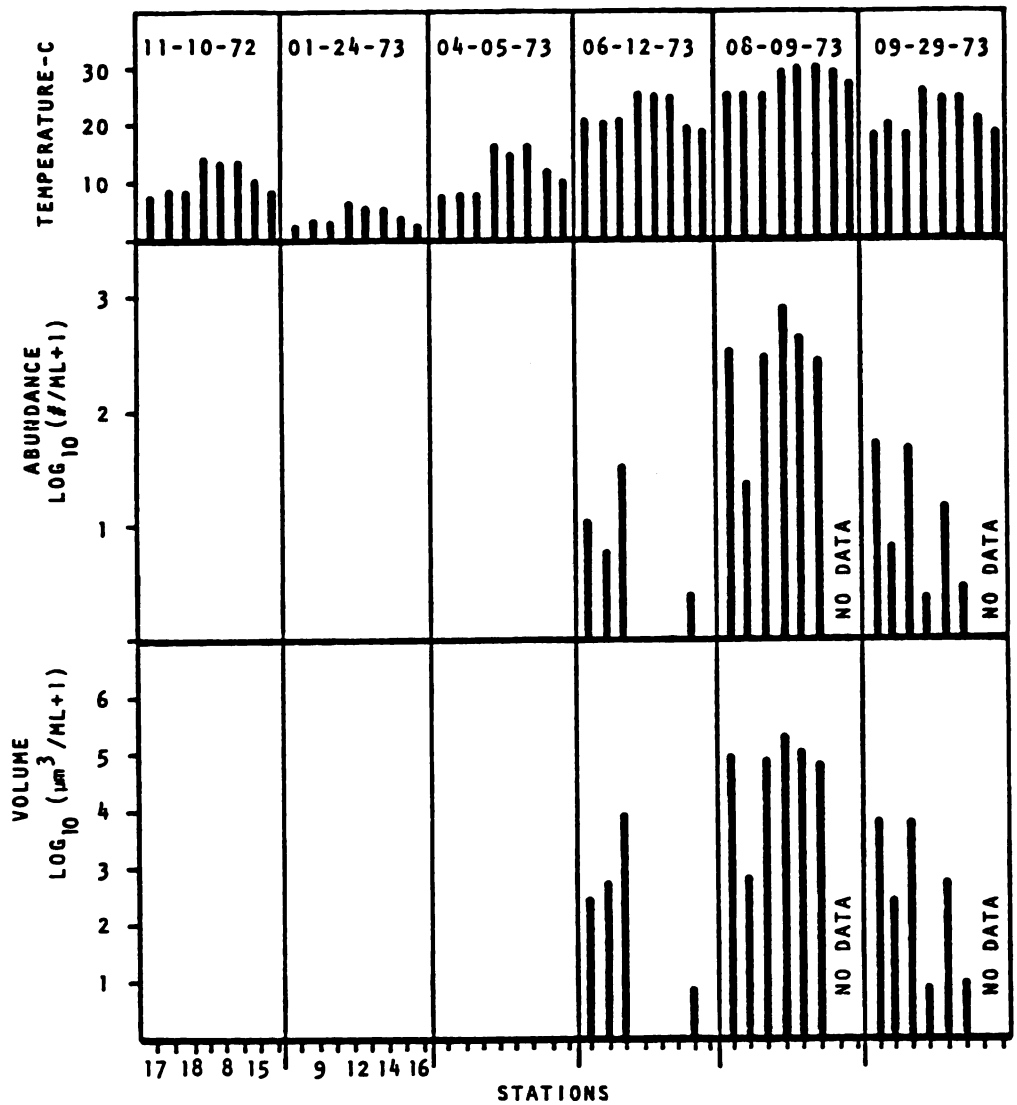


Figure 17. Anacystis incerta abundance and volume (means of five replicates) and water temperatures for afternoon samplings of 1972-73.

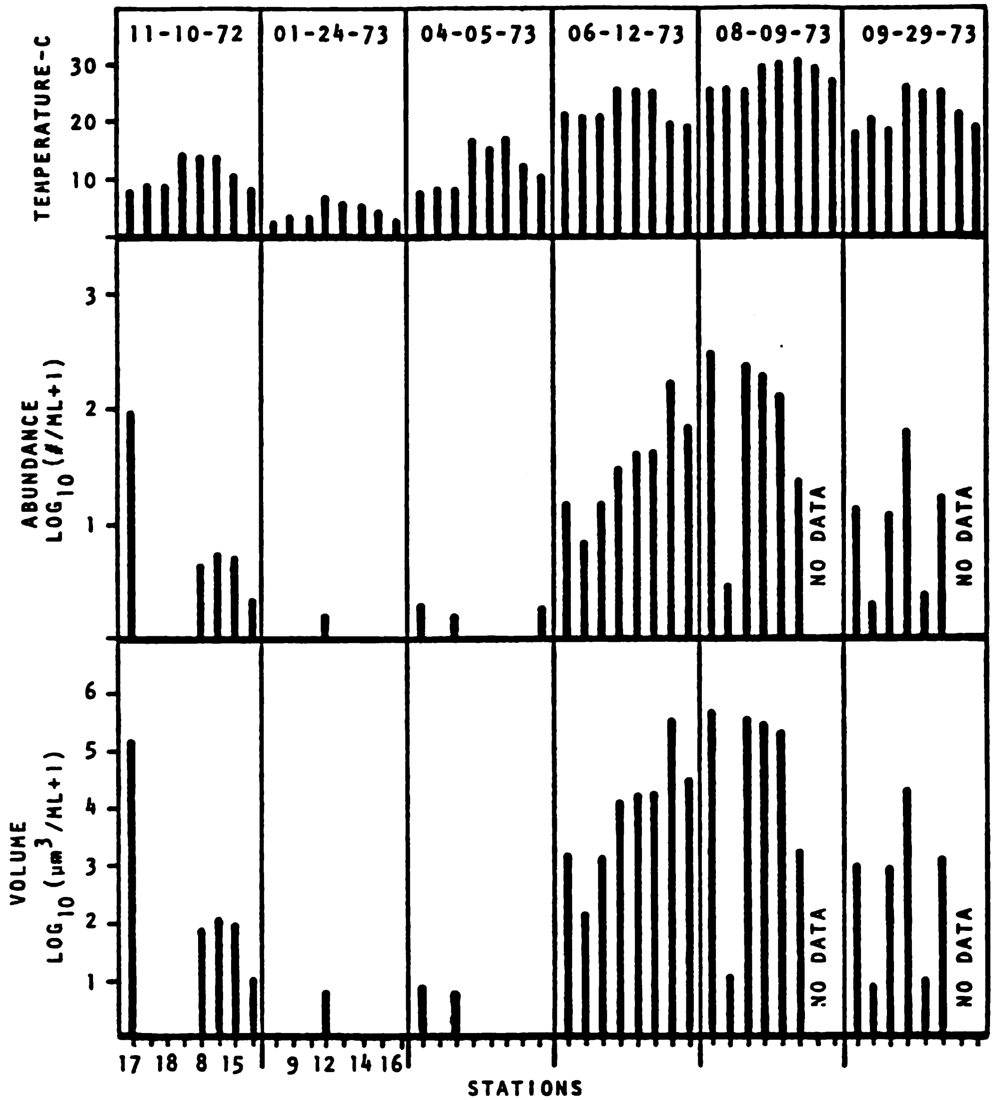


Figure 18. Aphanizomenon gracile abundance and volume (means of five replicates) and water temperatures for afternoon samplings of 1972-73.

from one another. Yet, June's sampling results offered some indication of greater abundance and volume at some discharge canal and the inner plume stations (8, 14, and 15).

Mean Specimen Volume Changes for Selected Species

So far, results have been presented to address the question of whether entrainment influenced the relative growth or mortality rates of the algal classes and species. Another consideration was the change in cell size or mean specimen volume (MSV) of a species in response to the stresses of entrainment. Limited evidence (e.g., Margalef, 1954) indicated that a reduction in cell size might occur after a rise in temperature for some species. Furthermore, the specimen size of a colony or filament might be reduced by fragmentation due to turbulence with passage through the power plant condensers.

These new questions were examined by considering the seven selected species just discussed (Table 7). To insure reasonably accurate estimates of the MSV, only annual means of afternoon sampling stations are given. The intake station, 18, was a theoretical station and had no MSV's estimated for it.

Of the seven species, only *U. subtillissima*, a filament, showed a sizable decrease in its MSV in the discharge canal. However, these changes for this

Table 7. Mean cell volumes (±S.E.) at each station for 1972-73 afternoon samplings of seven selcted algal species.

Species Name	Lake 17	River 9	Upper Discharge 12	Middle Discharge 8	Lower Discharge 14	Inner Plume 15	Outer Plume 16
Coscinodiscus radiatus (cell)	7233 ± 603.9	10034 ± 1022.6	9284 ± 605.4	7623 ± 924.3	8026 ± 771.7	8559 ± 847.4	8504 ± 943.6
Cyclotella meneghiniana (cell)	1270 ± 158.5	1119 ± 154.8	1358 ± 187.0	1236 ± 167.8	1330 ± 223.8	1491 ± 212.8	1265 ± 224.3
Distyosphaerium pulchellum (colony)	336 ± 140.0	138 ± 41.0	307 ± 82.4	370 ± 122.8	244 ± 53.6	430 ± 233.0	504 ± 350.7
Scenedesmus quadricauda var. longispina (coenobial)	139 ± 17.4	130 ± 16.9	158 ± 21.9	169 ± 3.6	157 ± 24.1	199 ± 36.7	210 ± 30.5
Ulothrix subtillissima (filament)	1099 ± 118.1	897 ± 137.6	887 ± 127.2	756 ± 94.3	794 ± 188.0	1034 ± 200.4	1504 ± 187.7
Anacystis incerta (colony)	299 ± 88.8	318 ± 186.3	215 ± 50.7	397 ± 158.5	254 ± 63.3	--	170 ± 119.6
Aphanizomenon gracile (filament)	1773 ± 243.9	1485 ± 562.8	1830 ± 444.7	2469 ± 401.8	1382 ± 320.9	1891 ± 339.7	2313 ± 390.1

species were still within one or two standard errors of the means for the intake region (i.e., stations 17 and 9).

<u>Seasonal Changes in Species Diversity</u>

As a last consideration of the phytoplankton community structure in this study, species diversity indices were evaluated as a means of determining changes in the relative dominance of some species due to entrainment. Margalef's index, the Shannon-Wiener or simply Shannon's index, and equitability were computed from species data for each station's replicates. Indices for abundance, volume, and biomass were obtained. Density and volume versions of Shannon's index and corresponding equitability are illustrated in Figure 19. The 95% confidence intervals are indicated about each station mean.

Margalef's index did not prove too useful for comparing intake-discharge differences due to the index's high dependence upon the number of species in a sample. The intake station was always inflated, as a result, since it was a theoretical combination of species at the lake and river stations. Shannon's index was not so sensitive to the number species factor and seemed to be the more conservative measure of species diversity.

For November, Shannon's index for abundances increased slightly at the lower discharge and two

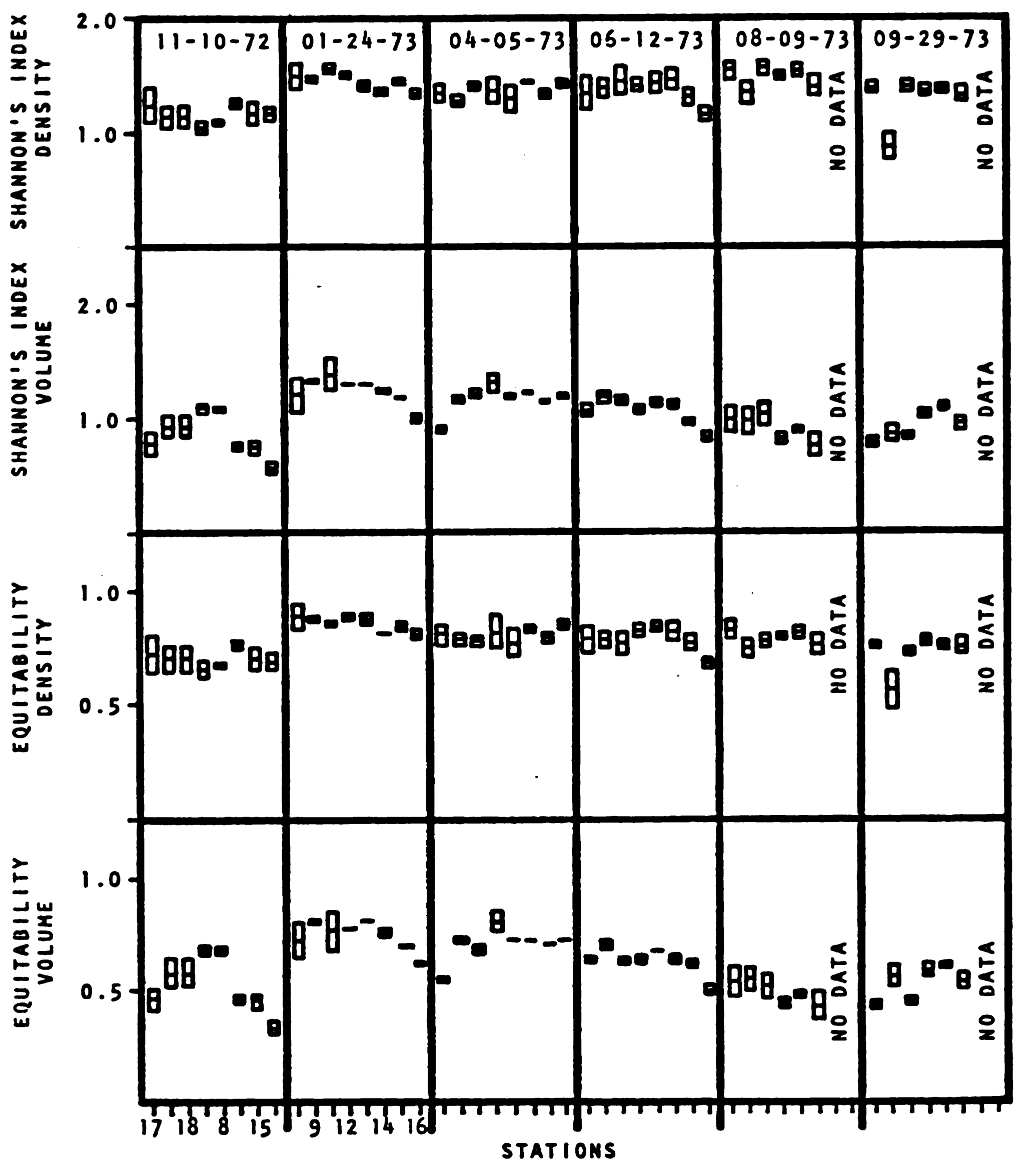


Figure 19. Shannon's species diversity and equitability indices for algal density and volume for afternoon samplings of 1972-73.

plume stations (14, 15, and 16) compared to the intake (18) but decreased there over 25% using the volume index. Equitability density and volume results were similarly affected. Since the species volume diversity decreased to a great extent while the number of species did not change at the lower discharge and plume, apparently dominance in volume of a few large-sized species was greater here. As was seen earlier in the section of seasonal species results, Coscinodiscus radiatus, a very large-sized species, increased volumetrically while the smaller sized Cyclotella meneghiniana decreased at these same stations which supports the conclusion of a change in dominance. Similar station changes in the diversity indices were observed for the morning and evening periods of November. However, since the lake station (17) species volume diversity index was also low in November, the decline at the lower discharge canal and plume may still be attributed to mixing with the open lake.

January's results were overall higher in magnitude than November's, but the volume results showed a similar pattern in the discharge. The plume stations again had lower diversity than the intake or all discharge canal stations. In this case, however, the lake station volume diversity was not similarly low which indicates open lake mixing might not have been the cause of the plume diversity decreases.

The species diversity of April varied little between the discharge and intake stations. Then, however, the lake station had a very low species volume diversity which did not reduce the plume values through mixing as suggested for November's samplings.

On June 12th another decline at the plume stations in both species density and volume indices was observed. Equitability was similarly affected. These declines may be only partially attributed to mixing with the open lake since somewhat low volume indices were also indicated for the lake.

Results of August and September were more complex. For the August 9th data, Shannon's volume diversity index and volume equitability for all discharge canal stations were considerably below the intake's levels. This was not observed for abundance diversity or equitability. The opposite situation occurred on September 29th when the discharge canal stations had substantially higher species volume diversity and volume equitability. For both of these seasonal sets, the diversity changes were seen immediately at the upper discharge canal station (12) with little further change beyond that point.

Entrainment Impact Upon Primary Productivity

One problem with examining possible growth responses to a change in environment is that the algae may require hours or days to react. However, a more immediate response of algae to environmental perturbations might be seen in their metabolic processes, in particular the photosynthetic rate. The gross primary productivity (GPP) and community respiration (R) were, therefore, examined.

Annual Mean Changes in the GPP and R

Table 8 summarizes the station GPP and R results averaged for each diel period over the study year and also averaged for those sampling dates with an ambient water temperature below 16°C (winter) and for those dates above 16°C (summer). The 16°C figure is used since some studies indicated depressions of net primary productivity occurs with algal entrainment when the ambient temperature is above this value. The winter averages include data from November, January, and March-April seasonal sets while the summer means are from measurements during the remaining sets.

Table 8 gives evidence of sharp declines in GPP at the discharge canal stations (12, 8, and 14) during morning and afternoon periods. These are restricted to the "summer" averages, however. In addition, a recovery of the GPP occurred to a level similar to that

Table 8. Mean station gross primary productivity and community respiration for the cooling system stations averaged for winter (Nov., Jan., and March-April) and summer (June, Aug., and Sept.-Oct.) seasonal sets of 1972-73 (all values in mg O_2/liter/hour).

PERIOD Pooled Seasonal Sets (Range of Ambient °C)	Lake 17	River 9	Intake 18	Upper Discharge 12	Mid Discharge 8	Lower Discharge 14	Inner Plume 15	Outer Plume 16
				GROSS PRIMARY PRODUCTIVITY				
MORNING								
Winter Average (3-11)	0.03	0.06	0.06	0.03	0.00[1]	0.03	0.05	0.01
Summer Average (18-26)	0.76	0.39	0.66	0.34	0.36	0.42	0.62	0.79
Morning Average	0.40	0.22	0.36	0.18	0.22[1]	0.22	0.33	0.40
AFTERNOON								
Winter Average (3-10)	-0.04	0.01	0.00	0.01	0.03	0.05	0.07	0.00[2]
Summer Average (18-28)	0.26	0.13	0.22	0.21	0.12	0.16	0.31	0.30
Afternoon Average	0.11	0.07	0.11	0.11	0.08	0.10	0.19	0.18[2]
EVENING								
Winter Average (4-10)	0.02[3]	-0.02[3]	-0.01[3]	0.00	0.00	0.00	0.01[3]	0.00[3]
Summer Average (18-27)	0.02	0.02	0.04	-0.03	0.00	0.01	-0.06	-0.01
Evening Average	0.02[3]	0.00[3]	0.02[3]	-0.02	0.00	0.00	-0.04[3]	-0.01[3]

Table 8 (cont'd.).

PERIOD Pooled Seasonal Sets (Range of Ambient °C)	Lake 17	River 9	Intake 18	Stations Upper Discharge 12	Mid Discharge 8	Lower Discharge 14	Inner Plume 15	Outer Plume 16
				COMMUNITY RESPIRATION				
MORNING								
Winter Average (3-11)	0.00	0.05	0.04	0.01	0.02[1]	0.05	0.02	-0.01
Summer Average (18-26)	0.08	0.07	0.08	0.05	0.08	0.08	0.09	0.10
Morning Average	0.04	0.06	0.06	0.03	0.06[1]	0.06	0.06	0.04
AFTERNOON								
Winter Average (3-10)	0.10	0.05	0.01	0.07	0.11	0.12	-0.02	0.00[2]
Summer Average (18-28)	0.09	0.16	0.11	0.12	0.05	0.08	0.11	0.08
Afternoon Average	0.10	0.10	0.06	0.10	0.08	0.10	0.04	0.05[2]
EVENING								
Winter Average (4-10)	-0.02[3]	-0.05[3]	-0.05[3]	0.03	0.03	0.06	0.02[3]	0.00[3]
Summer Average (18-27)	0.03	0.09	0.05	0.09	0.07	0.04	0.04	-0.04
Evening Average	0.01[3]	0.04[3]	0.01[3]	0.06	0.05	0.05	0.04[3]	-0.03[3]

[1]Does not include data of 04-06-73.

[2]Does not include data of 11-10-72.

[3]Stations 17, 9, 18, 15, and 16 lack data from 03-30-73 while 15 and 16 also lack data from 11-09-72.

expected for the open lake based on the lake station (17) means. Evening GPP's displayed no measurable photosynthesis, as expected. The "winter" GPP's were very low in magnitude. At this time of the year GPP changes in the discharge were not well defined.

The R was very low throughout the year and, surprisingly, had only slightly different averages for winter or summer. Although the morning winter R results were inconclusive, the afternoon and evening averages indicated a slight stimulation of R in the discharge canal. In contrast, morning and afternoon periods of summer showed modest depressions of R at some discharge canal stations. In nearly all measurements, the plume R results were similar to that of the lake station (17) and probably the open lake too.

Annual Mean Changes in the P/R Ratio

When the GPP/R or, more simply, P/R ratios were computed at each station for the morning and afternoon periods, the resulting values were quite variable and of questionable reliability due to the presence of zeros. To minimize this the ratios were averaged into winter and summer means as shown earlier for Table 8. The winter mean ratios were still too erratic to show changes in the discharge. The summer mean P/R ratios, however, did have interesting results. Intake values averaged highest at 8.25 in the morning period of summer while the afternoon intake mean value was only 2.00. Substantially lower P/R values occurred at all discharge canal stations for morning which ranged from 4.50 to 6.80. For the same period the plume stations showed a recovery to 6.89 and 7.90. No such changes in P/R appeared in the discharge for the afternoon summer means.

Seasonal Changes in the GPP and R

Gross Primary Productivity: To better visualize the more significant data, Figures 20, 21, and 22 portray the summer GPP's of June, August, and September-October, respectively, for the morning and evening periods. The water temperature, phytoplankton biomass, and the GPP are indicated for each station. The 95% confidence intervals are given about biomass and GPP means. A brief note of sky conditions on each date of GPP measurements is included although more complete weather data is given in Appendix A4.

For the first three seasonal sets of measurements, GPP was usually negligibly different from zero at most stations based on 95% confidence intervals of station means. Relatively high sampling variability, low algal biomass, poor light conditions, and perhaps too deep an incubation depth (1/2 m) for GPP measurements contributed to the lack of significant winter results.

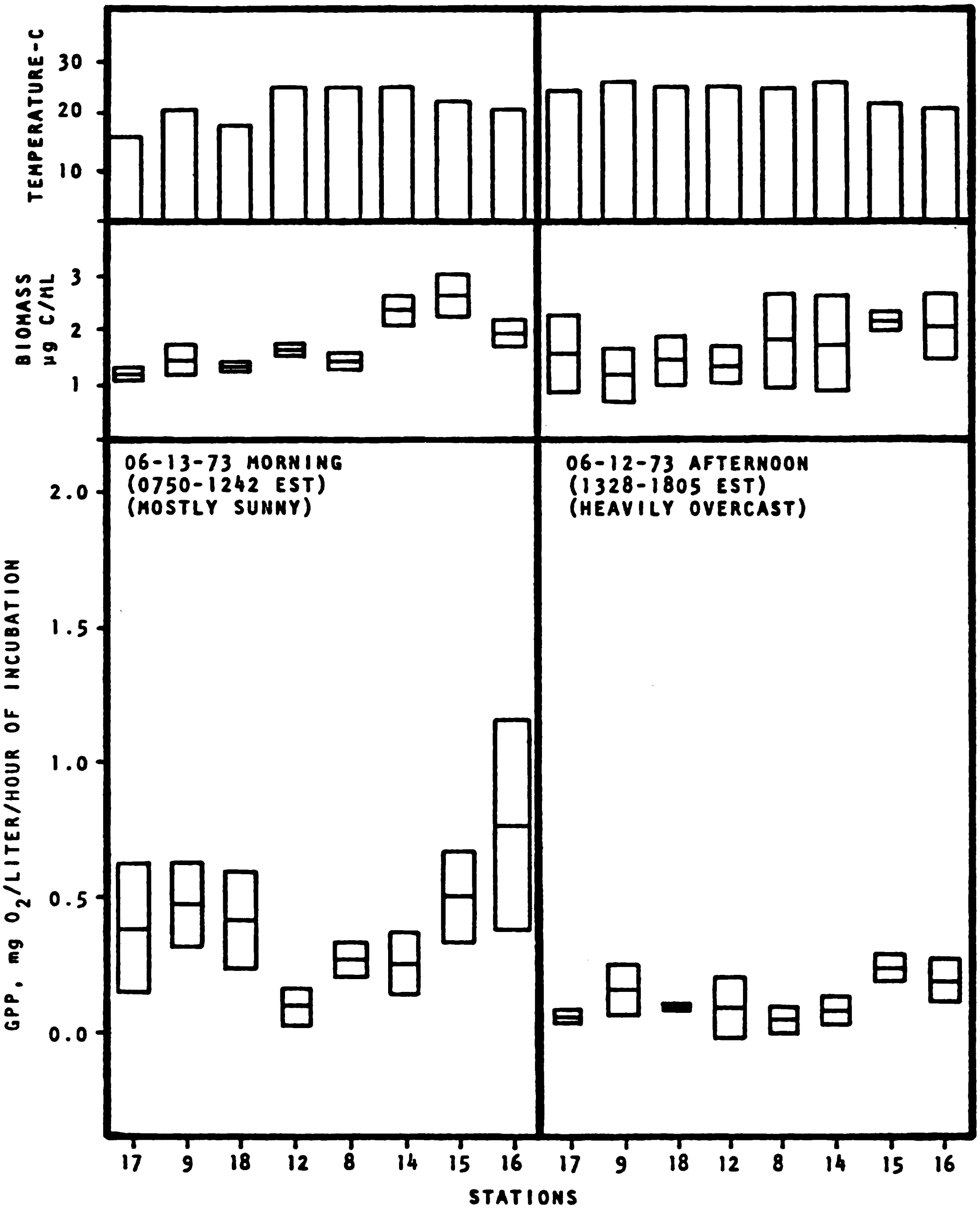


Figure 20. Station water temperatures, algal biomass, and GPP for June, 1973 measurements.

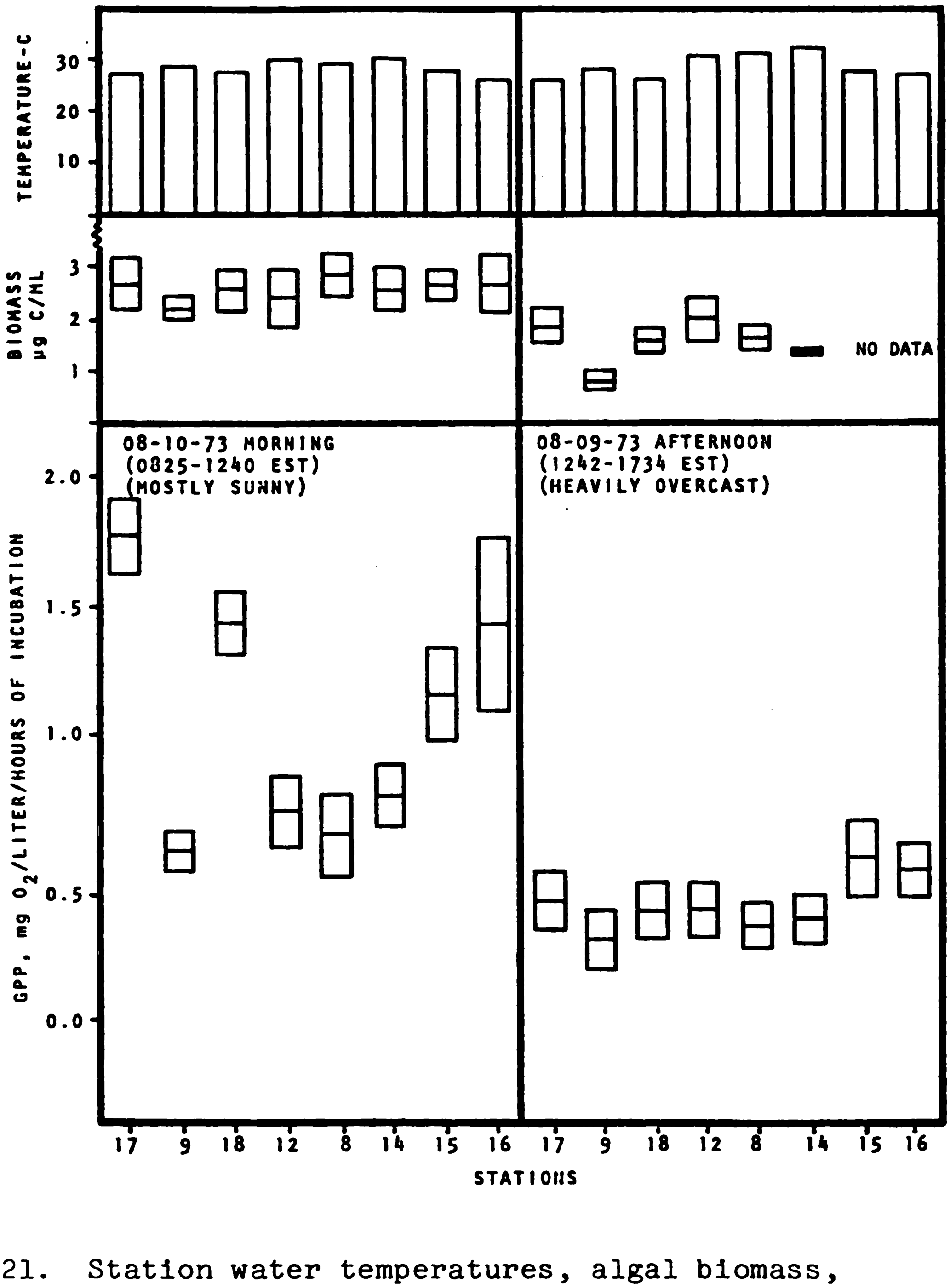


Figure 21. Station water temperatures, algal biomass, and GPP for August, 1972 measurements.

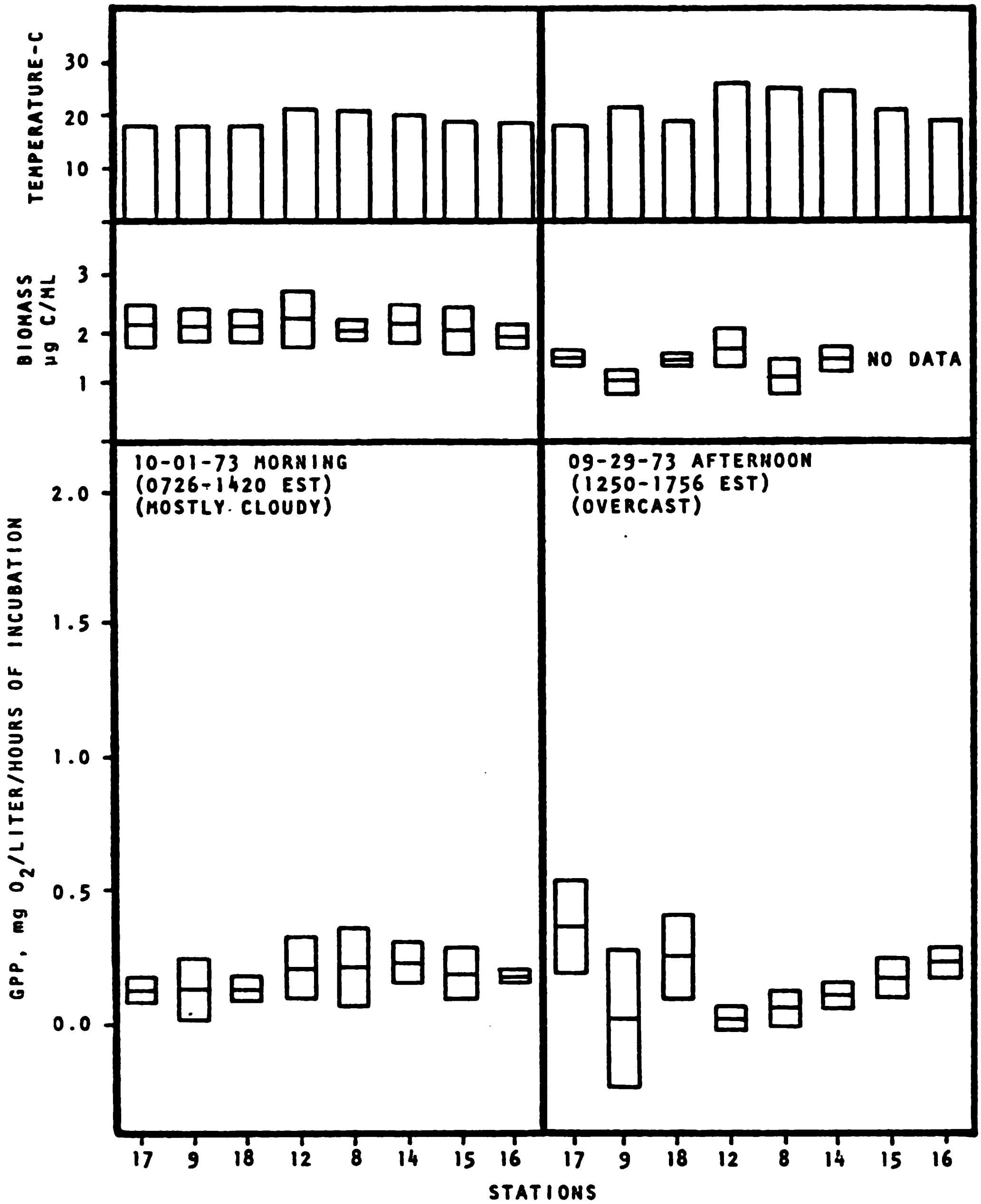


Figure 22. Station water temperatures, algal biomass, and GPP for September-October measurements of 1973.

No obvious changes or trends in the GPP were seen in the discharge during this time period.

In contrast, inspection of Figures 20, 21, and 22 show not only significant GPP's above zero but also substantial reductions in the primary productivity at the discharge canal stations (12, 8, and 14) compared to the intake (18). The depressions of GPP occurred on at least two or, perhaps, three occasions--June 13th (morning), August 10th (morning), and September 29th (afternoon). In each case an immediate drop in th GPP was observed at the upper discharge canal station (12). The relatively low productivity was more or less sustained in the discharge canal followed by an apparent recovery in the plume. The recovery, however, may be more related to mixing with open lake water and the plume than to a return of the entrained algal productivity to pre-entrainment levels.

The largest absolute decrease in GPP was about 0.7 mg O_2/liter/hour which occurred on August 10th while the largest percentage drop was on June 13th where a 75% drop in the rate was found in the discharge as compared to the intake. The depressions showed no relationship to the temperature increases experienced by the phytoplankton since the other diel period of the same seasonal set had no depressions despite similar ambient temperatures and Δt's. A poor correlation was also seen for the observed GPP and the corresponding station biomass in Figures 20, 21, and 22 although it may be related to low river (9) and high plume station (15 and 16) GPP's. The depressed discharge canal GPP's were not associated with unusually low biomass.

Light may have been a significant factor in controlling when the GPP depressions took place. The largest decreases of June and August occurred on sunny days. Most cloudy and overcast days which had productivity measurements had no depressions except September 29th when it was cloudy and raining. However, due to substantial variability in the intake GPP estimate and the small size of the discharge decrease in the rate, September 29th's results are certain.

Community Respiration: As for primary productivity the R data of November, January, and March-April indicated that respiration was negligible and without trend in the discharge. R during the summer was still barely measurable by the oxygen change method. Variability was such that June's measurements were negligibly different from zero. For that seasonal set there was a substantial but insignificant (based on 95% confidence intervals) drop in R of up to 0.07 mg O_2/liter/hour at the lower discharge canal station (14) for morning and afternoon. In contrast, August sampling dates had R values that increased in the discharge above the intake levels. This was most evident on August 8th (evening) when the intake station had virtually no R while the upper discharge canal station (12) rate was 0.19 mg O_2/liter/hour. The September-October measurements had rather large but probably still insignificant declines in R within the discharge for afternoon and evening periods while morning results showed no such change.

DISCUSSION

Community Structural Changes

In the introduction, several hypotheses were introduced pertaining to predicted effects of entrainment upon the phytoplankton structure. In essence, four questions were asked about the impact of entrainment. First, does it stimulate the growht of phytoplankton in general? Second, can entrainment affect the survival and growth of certain types of algae differently than for others leading to shifts in dominating forms? Third, is the species diversity affected? Finally, does entrainment alter the sizes of algal individuals? The following will attempt to consolidate and interpret the results in light of these hypotheses.

Algal Growth: The results of extensive measurements of density and volume of algae to the species level often showed statistically significant changes in the discharge canal. These were most pronounced for the total algae, the three major classes (diatoms, green algae, and blue-green algae), and two of the seven algal species examined, *C. radiatus* and *C. meneghiniana*.

Some of the differences between stations in abundance and volume could be attributed to phytoplankton patchiness since no attempt was made to sample the same water mass as it passed through the cooling system. Indeed, samples of the upper discharge canal station were usually taken prior to the samplings of the intake region. Thus, for example, the sharp increase in density and volume observed for diatoms for the evening period of the March-April seasonal set was probably due to algal patchiness. Similarly, abrupt increases or decreases in numbers observed immediately at the upper discharge canal station are suspected to be from patchiness. Such abrupt changes were observed in the annual means of total algae and the August abundance of _A. incerta_.

Therefore, emphasis was necessarily placed on trends along the discharge of gradually increasing or decreasing abundance and volume in relation to increased exposure time of entrained biota within the effluent. Presumably, stimulation or inhibition of algal growth would lead to increasing or decreasing values with longer exposure to the environmental change. Since the discharge stations were set at points to reflect this exposure time factor, a typical trend might be increasing abundance along the flow of the discharge with the least change at the upper discharge station and the greatest difference at the lower discharge station or plume.

The trends in November and January, at first glance, indicated a strong proliferation of the algae for most taxon's examined. This rise in abundance and/or volume of algae was observed at the lower discharge and plume stations for total algae and diatoms but only in November for green algae and blue-green algae. However, as pointed out earlier, density and volume at the lake station, which was not affected by the discharge, were usually quite similar to those values at the plume. Although the one lake station was not necessarily an accurate representation of true open lake conditions, the values obtained at that station indicated the increases noted above were largely a product of mixing discharge water with a more productive Lake Erie.

Such a large difference between the discharge's algal assemblage and that in the open lake is understandable since the Raisin River, with a river-type of algal flora, made up a large proportion of the water entering the power plant's intake in November and January. An examination of the major species found at some stations for November and January could clarify this question. Table 9 lists the relative percentage of major species at selected stations. The intake station (18) in Table 9 represented mostly river water

Table 9. Major algal species (exceeding 1% of the total volume of algae) in November and January (afternoon samplings) with their relative percentage of the total phytoplankton volume at selected stations.

Species	11-10-72 Lake 17	11-10-72 Intake 18	11-10-72 Upper Discharge 12	11-10-72 Lower Discharge 14	11-10-72 Outer Plume 16	01-24-73 Lake 17	01-24-73 Intake 18	01-24-73 Upper Discharge 12	01-24-73 Lower Discharge 14	01-24-73 Outer Plume 16
Asterionella formosa	--	1.4	--	--	2.2	2.7	1.7	1.3	--	1.8
Cocconeis placentula	--	--	--	--	--	--	--	1.7	--	--
Coscinodiscus radiatus	17.6	4.5	--	20.3	17.6	25.9	16.3	4.0	5.4	31.4
Cyclotella glomerata	--	--	--	--	--	--	1.1	1.7	5.5	--
C. kutzingiana	--	--	2.0	--	--	--	--	--	--	--
C. meneghiniana	2.5	21.3	37.6	7.2	1.4	10.0	12.9	7.3	23.0	5.7
Cymatopleura solea	--	1.4	2.6	--	--	1.5	--	3.6	--	--
Diatoma sp.	--	--	--	--	--	--	2.3	--	--	--
D. vulgare	--	--	--	--	--	--	--	--	3.6	--
Fragilaria crotonensis	--	--	--	--	--	4.1	2.6	--	--	8.9
F. spp.	--	--	1.0	--	--	--	--	17.8	--	1.8
Gomphonema olivaceum	--	1.6	1.7	--	--	2.7	4.3	4.9	3.0	--
G. parvulum	--	--	--	--	--	--	--	--	2.1	--
Gyrosigma spencerii	--	1.3	2.4	--	--	--	--	1.7	--	--
Melosira ambigua	--	--	--	--	--	--	--	1.5	1.8	--
M. areraria	--	1.7	--	1.1	--	--	--	--	--	--
M. granulata	--	1.3	2.1	--	--	--	--	--	--	--
M. islandica	2.2	--	2.7	--	--	1.4	--	--	--	--
M. varians	--	44.6	12.5	5.4	--	3.8	5.6	11.2	--	6.1
Navicula cryptocephala	--	--	--	--	--	--	1.3	1.3	2.3	--
N. cuspidata	--	--	--	--	--	--	--	1.6	--	--
N. gastrum	--	--	--	--	--	--	1.2	--	--	--
N. hungarica	--	--	--	--	--	--	--	--	1.1	--

Table 9 (cont'd.).

Species	11-10-72 Lake 17	Intake 18	Upper Discharge 12	Lower Discharge 14	Outer Plume 16	01-24-73 Lake 17	Intake 18	Upper Discharge 12	Lower Discharge 14	Outer Plume 16
N. rhynchocephala	--	1.6	3.3	--	--	--	--	2.1	1.9	--
N. mutica	--	--	--	--	--	--	1.9	3.4	3.4	--
Navicula tripuncta	--	--	--	--	--	--	1.9	3.4	3.4	--
N. viridula	--	--	--	--	--	--	--	--	3.8	--
Nitzschia acicularis	--	--	--	--	--	--	--	--	1.0	--
N. filiformis	--	1.0	--	--	--	--	2.4	1.3	8.0	--
N. gracilis	--	--	--	--	--	1.9	2.4	3.0	6.2	--
N. sigma	--	--	--	--	--	--	1.4	--	--	--
N. spp.	--	2.2	6.5	--	--	--	--	--	--	--
Pinnularia gibba	--	--	--	--	--	--	1.3	2.4	--	--
Rhizolenia eriensis	--	--	--	--	--	--	--	--	--	1.2
Rhoicosphenia curvata	--	--	--	--	--	--	1.2	--	2.6	--
Stephanodiscus astraea	11.2	2.2	--	4.0	5.8	3.9	3.0	1.0	2.8	16.1
S. niagarae	47.8	--	--	50.9	64.8	20.9	13.2	--	29.6	10.8
S. sp.	--	--	--	1.2	2.2	--	--	--	--	3.5
Surirella ovata	--	1.5	1.1	--	--	--	1.1	--	--	--
S. robusta var. splendida	8.6	--	--	--	--	--	--	--	--	--
S. acus	--	--	--	--	--	--	--	--	1.4	--
S. ulna	1.3	3.3	8.0	1.4	--	5.3	7.3	14.9	3.8	2.0
S. vaucheriae	--	--	--	--	--	--	--	--	2.1	--
Tabellaria fenestrata	--	--	--	--	--	2.4	1.5	--	--	3.9
Aphanizomenon flos-aquae	1.2	--	--	--	--	--	--	--	--	--

algae as an estimate of the initial algal assemblage being entrained. Since the discharge water was mostly river water, one would expect a similar group of algae between the intake station and the upper discharge canal station (12). In contrast, if the terminal discharge stations were similar to the open lake in algal content, one would expect for the plume stations to have a similar assemblage to that at the lake station (17). Indeed, Table 9 showed this to be the case. For November 10th a key species was C. radiatus which was highly productive at the lake station and the lower discharge canal and plume stations (14 and 16). C. meneghiniana was rare at those locations but common at the intake and upper discharge canal stations (18 and 12). Another species, Melosira varians, was a river species seen at the intake and upper discharge canal but rare elsewhere in the study area.

On January 24th and most other sampling dates, these distinctions are less clear because a greater proportion of lake water entered the cooling system. Nevertheless, C. radiatus was common at the lake station and the outer plume on that date but relatively scarce at the other stations. Also, more rare species were observed at the intake, upper discharge canal, and lower discharge canal than at the lake or outer plume stations.

To expand on this further for all sampling dates, chloride distribution at the various stations was used to indicate the degree of mixing of discharge water in the plume with the open lake (M.S.U., 1976). Typically, the discharge canal chloride levels were higher due to a high river input and lower in the open lake. The plume waters were always intermediate to these extremes which indicates mixing was common.

Although the arguments presented above do not prove that all changes in algal abundance in the plume were due solely to mixing with Lake Erie, certainly the largest increases of November and January were mostly a product of this phenomenon. This suggests that the plume was an unreliable place to find evidence of an entrainment effect on algal growth or survival. By ruling out the plume stations as indicators of changed abundance or volume, virtually all of the significant differences producing recognizable trends of population growth are eliminated. June, in particular, was the other sampling seasonal set showing such trends of increased density and volume for total algae, perhaps green algae, *C. radiatus*, and *U. subtillissima*. However, these trends were largely confined in the plume and, therefore, are questionable indications of stimulated growth. Other seasonal sets lacked significant trends of any kind largely due to erratic variability of algal station results.

For the most part, evidence for stimulated growth of phytoplankton or any single algal group was not apparent. Increases were common beyond the confines of the discharge canal, but these were likely a consequence of plume mixing with the receiving waters. Within the canal itself, almost no significant trends were indicated.

Why was stimulation of the algal growth not observed more conclusively? The responses of algae to temperature changes, such as they experience in the discharge, has been discussed by Eppley (1972) and, more recently, by Goldman and Carpenter (1974). At sublethal temperatures, a fairly predictable increase in growth follows a temperature increase. The change in growth rate may vary for different species or groups and under different environmental conditions.

To explain the lack of evidence of increased growth at the Monroe Plant, keep in mind that the maximum passage time of cooling water through the discharge canal was estimated to be only 11.4 hours. This is not sufficient time for most algae to develop detectable changes in abundance or volume. To illustrate, consider a fast growing species having 2 doublings per day at the intake, a Q_{10} of 2 for its growth-temperature relationship, and no lag time in the growth response. An increase in temperature of 10°C with entrainment would mean its growth rate would reach 4 doublings per day. Thus, if 100 entrained individuals entered the intake, by the time they reached the lower discharge stations there would be somewhat less than 400 individuals. However, the normal growth rate would have produced 200 individuals by the end of the discharge canal. So the increase in abundance was actually 100%. Of course, this is a highly simplistic model but for many species a 100% increase in abundance was not statistically significant! Even in the case of total algae, an increase in abundance from that at the intake of 50% or more was needed to show a significant change at a discharge station. Such would be rare, indeed, over a period of eleven hours or less. In addition, most algae display a lag phase in responding to changing environments which may last hours or even days for some slow growing species. Furthermore, conditions for growth in the study area were far from idea, primarily due to a poor light environment, which would hinder algal growth.

Shifts in Algal Dominance: Entrainment could create shifts in the relative importance of various phytoplankton forms. In extreme cases some species might be killed by a temperature beyond its upper tolerance limit. Although there was no attempt during this study to assess the death of algae, some effort was made to determine whether there were major shifts in dominating classes. Cases of blue-green algae and green algae replacing dominant diatoms when temperatures exceeded 30°C have been reported (Cairns, 1956; Patrick et al., 1969; Rankin et al., 1974). Such temperatures were encountered at the Monroe Power Plant discharge canal in August samplings.

The only evidence of a major shift in relative proportions of the algal classes occurred in June when green and blue-green algae increased 10% at the expense of diatoms. The maximum temperature at this time in the discharge was 27°C. This change was primarily a plume response and not a spatial trend along the discharge. Mixing of the plume with the open lake having different proportions of algae might also serve to explain this shift.

Changes in Species Diversity: Results of species diversity indices calculations showed the plume to be the principal region of reduced species diversity for November, January, and June. For November and January, the lake station also displayed low species diversity, indicating that mixing with the open lake might explain reduced species diversity in the plume.

For June, however, results were not related to mixing since there was apparently little similarity between the lake station and plume diversity estimates. To explain the plume results, it is important to bear in mind that species diversity is weighted by both equitability between species and the species richness (i.e., the number of species in a sample). A sharp change in either component of diversity may change the species diversity index obtained. During June, equitability decreased in the plume but not as much as the species richness. At the lower discharge canal between station volume equitability was 0.63, and the number of species there was found to be 59. However, at the inner plume station these values became 0.58 and 47, respectively. Obviously, the number of species lost between these two stations was the major reason for the drop in the species diversity. The loss in species richness was primarily limited to the diatoms which may also explain the decreased importance of diatoms in the plume discussed for June in the previous section. However, since these observations were restricted to the plume with no evidence of trends earlier in the discharge, it is impossible to be certain how the above changes are related to entrainment without more data to support it.

April, August, and September afternoon species diversity results showed no clear entrainment impact. The latter two months had sizable variations in volume species diversity and equitability at the discharge canal stations, but these were abrupt changes most likely due to patchiness of algae.

Changes in the Sizes of Algae: A limited amount of data was examined for possible changes in the sizes or mean specimen volumes of algae. Of seven species considered with different morphologies, none showed unusual changes beyond natural variability. This indicates that turbulence in the power plant condensers had a minimal effect on fragmentation of certain colonial or filamentous algal forms.

Algal Metabolic Changes

Among the stated hypotheses three dealt with effects upon algal metabolism. First, stimulation of the GPP would be expected in the discharge when the ambient temperature was below 16°C, but a depression of the GPP would occur above this ambient temperature. This hypothesis was largely based upon the conclusions of Morgan and Stross (1969) and Warinner and Brehmer (1966) discussed earlier. The second hypothesis was that respiration of phytoplankton would increase during entrainment. This follows from the fact that respiration is largely a temperature dependent enzymatic reaction. The last hypothesis was that the GPP should decline in the discharge in response to chlorination activities at the power plant. Morning GPP measurements were intended to test this aspect of entrainment impact.

Evidence of GPP Simulation or Depression: The GPP measurements taken when ambient temperatures were below 16°C (November, January, and March-April sets) showed no increases anywhere in the discharge compared to the intake. However, almost all the GPP's observed at these times were also negligibly different from zero. The method used to measure primary productivity may have lacked the sensitivity to detect an increase in the rate.

An explanation of the low GPP during these months was that biomass at this time of the year was very low--averaging only 17% of the algal biomass for the warmer months. Furthermore, the light conditions for photosynthesis were poor on the days the measurements took place. Only January 18th (afternoon), during the winter GPP measurements, had a sunny day, but even then the primary productivity was negligible.

In contrast, the GPP was high in June, August, and September-October when ambient temperatures exceeded 16°C. Half the daylight GPP measurements showed no significant change in the GPP at the discharge stations compared to the intake stations. However, the morning measurements of June and August and the afternoon measurements of the September-October set displayed sharp reductions in the GPP at all the discharge canal stations. In each case of GPP depressions, the plume stations showed recovery of the primary productivity.

The reasons for the GPP depressions on some days and not others was difficult to understand. Biomass and temperature differences were small between the two daylight diel periods of a given seasonal set. Light conditions may have been related to the differing GPP results since on two of the three days when depressions were observed, the skies were sunny. All other summer daylight GPP measurements were on days of poor light conditions due to overcast skies. The depressions of GPP for the afternoon in the September-October set were observed on an overcast day, but these were also the smallest GPP reductions compared to other dates.

The reductions in GPP at the Monroe plant were generally consistent with the declines in net primary productivity (using C^{14}) observed for artifically illuminated samples of several different power plant effluents (Morgan and Stross, 1969; Warinner and Brehmer, 1966; Gurtz and Weiss, 1974). However, in all of these published studies no recovery followed the depressions. At the Monroe plant site, GPP recovery in the plume was seen although there was evidence that this was more a response to mixing with the open lake water which already had a high GPP than to actual improvement of the discharge rate.

Kreh (1973), in an earlier study on phytoplankton in the vicinity of the Monroe Power Plant, observed depressions in 1971 for *in situ* GPP. Furthermore, he experimented by transferring sampled water from the discharge canal to the open lake and *vica versa* along with similar exchanges between the intake and discharge canal and then measured the GPP of these samples *in situ*. At the time these were done, ambient temperatures were 25°C at the intake, 33°C in the discharge, and 22°C in Lake Erie. His results showed GPP depressions for all samples incubated in the discharge canal but which had been collected elsewhere. In contrast, discharge canal samples that were incubated at the intake or Lake Erie showed no GPP depressions. Samples collected in the discharge canal and also incubated there did show lower primary productivity. Apparently, there was nothing inherently different in the photosynthetic capacity of algae in the discharge canal, intake, or open lake.

One could interpret Kreh's observations of depressed GPP in the above experiments as temperature related since it was the only environmental parameter that differed between the intake, discharge, and Lake Erie. Effects of chlorination and mechanical stress were eliminated. The ability of discharge canal samples moved elsewhere for incubation at the ambient temperatures to have GPP's as high as that expected of the open lake or intake indicated recovery of the depressed primary productivity was possible.

None of the published power plant studies mentioned nor Kreh's (1973) work were designed to offer a mechanistic explanation for the depressions of net or gross primary productivity. Likewise, the data presented in this thesis on GPP depressions say nothing about the physiological changes in the incubated phytoplankton that might explain their lowered productivity.

Since the depressions were observed at temperatures as low as 25°C in June and even lower in other published investigations, outright death of algae in sufficient numbers to reduce the photosynthetic capacity seems a remote possibility. The evidence of a recovery of the GPP both in this study and Kreh's indicates the capacity for photosynthesis was not impaired. However, apparently no literature has dealt with possible shock of algae due to an abrupt rise in temperature which might temporarily impair photosynthesis. This might be a factor particularly due to the acclimation of the entrained algae to an ambient temperature. However, Δt's on days when the GPP decreases occurred were 3.0 for June 13th and August 10th and 8.2 for September 29th at the surface. Since other summer dates with no depressions had similar Δt's, the explanation must be more complicated.

Since light was a factor for two of the three days when GPP was depressed and since water samples were incubated near the surface, perhaps increased susceptibility of algae to photoinhibition followed an abrupt rise in temperature. For example, photoinhibition at high light levels was more common for <u>Thalassiosira nordenskioldii</u>, a marine diatom, when its photosynthetic temperature optimum was exceeded (Durbin, 1974). However, little is known about the effect upon photo-inhibition with abrupt temperature changes.

Photorespiration can also lead to reduced primary productivity. This process is light dependent consumption of O_2 and release of CO_2 with production of glycolic acid (Tolbert, 1974). It is promoted by saturated O_2 concentrations, low CO_2 and a pH between 8 and 9. However, these conditions existed to a significant degree only in the open lake. Highest 0 concentrations were found there, and after the primary productivity incubations, supersaturation was most pronounced for Lake Erie measurements. The pH in summer was between 8 and 9 and CO_2 was near zero in Lake Erie. The discharge had lower O_2 concentrations, lower pH, and relatively high CO_2 during the summer (M.S.U., 1976). Therefore, photorespiration should have been more common in the open lake than in the discharge canal where the depressions of GPP were actually observed.

Although the effect of chlorination has yet to be discussed, the cause of the GPP depressions cannot be answered with the data made available in this study. Regardless of why decreases in GPP were seen, the impact was a reduction in the rate of carbon fixation. P/R ratios in the discharge were reduced but still exceeded 1.00 over the incubation periods. So, the net effect of entrainment upon primary productivity was a loss in net production during possibly half the summer days but not to the point of being heterotrophic during daylight.

Change in the Community Respiration: Community respiration estimates were so low at all times of the year that typical results were negligibly different from zero even during summer. Based strictly on 95% confidence intervals of station mean community respiration, no significant difference in respiration could be demonstrated between the discharge and the intake.

Chlorination Impact Upon GPP: The use of chlorine by power plants can also sharply reduce algal productivity in the cooling water effluent (Hirayma and Hirano, 1970; Brook and Baker, 1972). The depressions in GPP observed at the Monroe plant discharge canal may be partially explained by this. There is, however, uncertainty as to the impact because the exact times when chlorination commenced and finished on a given day were not recorded by plant operators. Also, residual chlorine concentrations were calculated, not measured, from amounts added to the cooling system.

Supposedly chlorination began at 0700 E.S.T. for June, August, and September-October seasonal sets. The application of chlorine was to be of 1/2 hour duration. Residual chlorine concentration during these times were estimated at 0.90 ppm in June samplings and 1.35 ppm for later ones.

Based on the above information, the decrease in GPP on June 13th may have been related to chlorination, especially at the upper and middle discharge canal stations. These stations were sampled at 0750 and 0802 E.S.T., respectively. Assuming a certain amount of delay in the discharge flow reaching these stations, these stations should have been in the chlorinated water mass. On August 10th when the largest decline in GPP occurred, only the middle discharge canal station should have been affected since it was sampled at 0825 E.S.T. when the chlorinated water mass might have reached it. The upper discharge canal station on this date was sampled one hour after chlorination supposedly ceased in which case the affected water mass probably had passed.

However, the depression on September 29th can hardly be related to chlorination since sampling was done 5 to 6 hours after chlorine application ceased. This seems particularly true at the upper discharge canal station which was sampled first but had the strongest depression in GPP in the canal.

Chlorination might explain some but not all the GPP depressions. At best, the evidence given here is tenuous due to the reasons just stated. Further, as mentioned earlier, Kreh (1973) showed depressions can be entirely independent of chlorination.

Entrainment Impact Upon Western Lake Erie

It is important to put some of the changes seen, regardless of their reason, in perspective of the receiving waters, i.e., western Lake Erie. The western basin can be distinguished from the rest of the lake by a line of islands on the basin's eastern side. The basin, including Sandusky Bay and the islands, occupies 3411 km^2 (Wright, 1955). I estimate its volume to be about 25 x 10^{12} liters. It is strongly influenced by the Detroit River which accounts for 97% of the basin's inflow (using the 1936-1971 average for a total Detroit River inflow of 164 x 10^{12} liters/year). Other rivers such as the Raisin, Portage, and Maumee account for most of the remaining input. Outflow is to the east.

If the Monroe Power Plant's discharge were considered to be entirely an inflow into the western basin, it would account for about 1.0% of the total input for the year. Of course, an estimated 41.2% of the plant's discharge during 1972-73 had its source already from the lake, so real input to the lake was that of the Raisin River (0.98 x 10^{12} liters/year for the study period) or less than 1% of the basin's inflow. In terms of the power plant's discharge into the basin, it is of small importance from strictly a hydrological point of view. The discharge's input of entrained phytoplankton should be, likewise, small relative to that of, for example, the Detroit River.

To press the argument further, results of the population data can be used to estimate an impact for the basin. The average biomass, in terms of organic carbon, drawn through the intake station was 1.74×10^6 kg C/year for the study year. Using the lower discharge canal station results rather than the plume data, to avoid the problem of mixing of the discharge with the open lake, the plant's effluent had an increased biomass of 1.89×10^6 kg C/year. Thus, 0.15×10^6 kg C/year was added to the lake above that of no entrainment effect at all. Since the extra biomass would eventually decompose, more oxygen from the water would have to be used. For the entire basin this increase in biomass would consume an additional 0.017 mg/l of dissolved oxygen on a cummulative basis across the entire year.

Of course, the effect of oxygen depletion may be more localized than this. Consider a lake area circle extending from the discharge canal at a 9.4 km radius. This would have a lake area of 166.5 km^2 and a volume of roughly 620×10^9 liters. Such an area was selected by geographic barriers to the discharge effect (for example, the Stony Point penninsula to the north was 0.4 km away). For this volume the biomass increase previously noted would lower the dissolved oxygen only 0.69 mg/l over the entire year. Such a drop, while considerably more than for the entire basin, is still negligible on a daily basis. Furthermore, I assumed no atmospheric exchange and no mixing with the rest of the lake. The impact of simple increased biomass is, thus, extremely small.

Ecological impact need not be simple the quantity of change but can also be a qualitative effect. Other studies have suggested thermal discharges increase blue-green and green algae at the expense of diatoms at temperature extremes. No definitive evidence of such a class shift was demonstrated here. Short exposure to the increased temperature and the slow algal response was the probably reason.

Although the entrainment effects here were minimal, some caution must be added. I have considered this plant's impact without regard to other facilities along the western basin of Lake Erie. Entrainment of phytoplankton at these other locations may have a combined effect on the basin's ecology above that of any one plant alone. Therefore, an effect should be made to assess the total effect of all once-through cooling systems for the entire basin including new facilities contemplated in the future.

SUMMARY

1. Overall increase in abundance and volume of algae were observed only in the plume of the discharge during November, January, and June. However, the November and January increases were primarily a result of mixing of a lower productive discharge with the more productive receiving waters of Lake Erie. The June increase, although still probably caused by mixing, could be evidence of stimulated growth.
2. Diatoms were the most prominent algal class and demonstrated increases in abundance and volume in November and January only in the plume. The reason for this was mixing with productive Lake Erie. Green and blue-green algae had significant increases in November only and then only in the plume for the same reason as diatoms.
3. Shifts in the relative dominance of classes were rare. Only in June was there evidence of increased green and blue-green dominance at the expense of diatoms in the discharge. No statistical significance was found for this shift, however.

4. Diatom species dominated the cooling system over most of the year. Of seven algal species studied in detail representing the major classes, only the diatoms Coscinodiscus radiatus and Cyclotella meneghiniana showed change in the discharge. The former species showed increases in abundance and volume in the plume in November, January, and June with only the change in June not being clearly demonstrated as a mixing effect. For C. meneghiniana there were decreases in November and increases in January of density and volume in the plume due to mixing.
5. Species volume diversity declined in the plume in November, January, and June. For November and January, the decreased values were due to mixing with a volumetrically less diverse open lake. However, decreased diversity during June in the plume was not a mixing effect and appeared to be caused by a loss of diatom species.
6. No observed change in the mean specimen volume of species was observed due to entrainment.
7. No stimulation of gross primary productivity was observed. Decreases were seen in the GPP in mornings of June and August in the discharge canal, possibly due to chlorination. Another depressed GPP in the discharge canal appeared in an afternoon of September. Other measurements showed no

significant change in discharge GPP possibly due to poor light conditions. The depressed GPP's may be explained by abrupt temperature increases, photo-inhibition, or other factors.

8. Community respiration was negligbly different from zero over most of the year. No significant change in respiration in the discharge was demonstrated.
9. The impact of the power plant on algae in the western basin of Lake Erie or in the near-shore area was considered negligible.

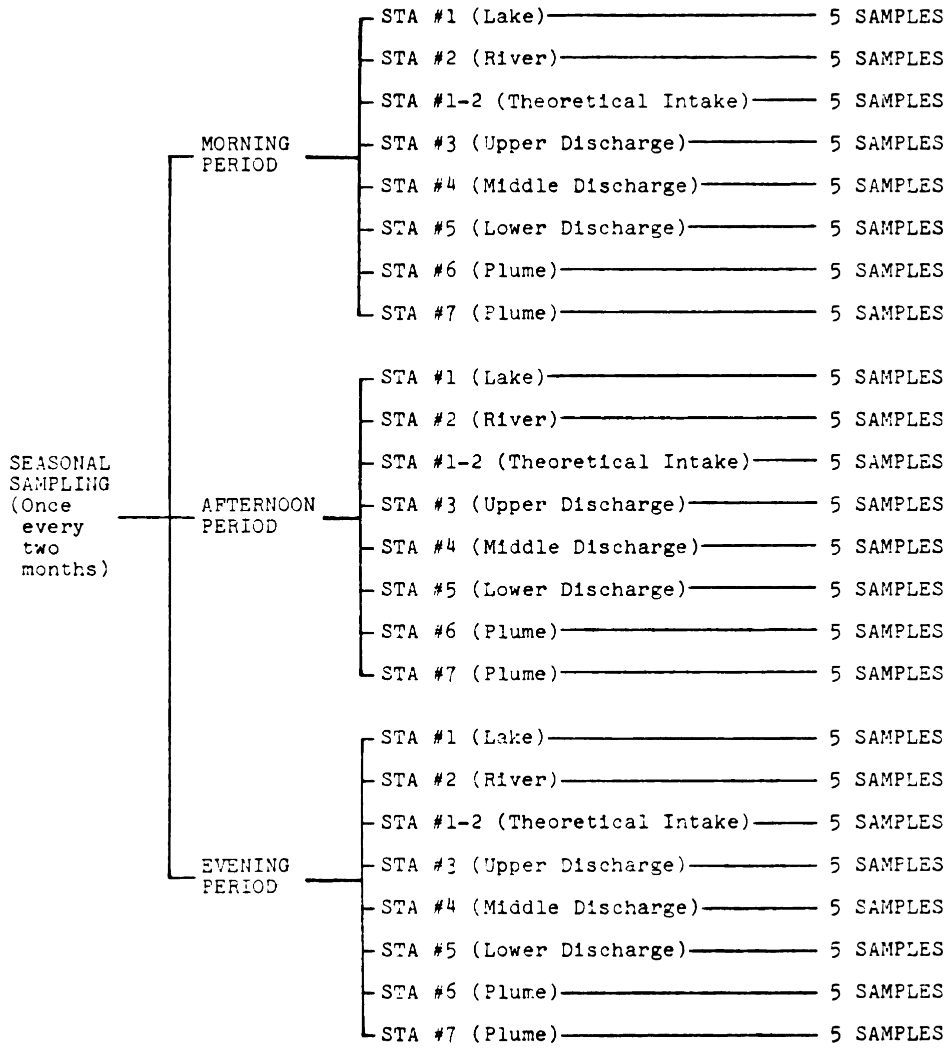
APPENDICES

Appendix A1. Estimated relative amounts of river and lake water contributing to the intake flow along with discharge data and passage times through the discharge canal.

Date	River Water[1] (m^3/sec)	Estimated Percent River Water	Lake Water (m^3/sec)	Estimated Percent Lake Water	Total Discharge (m^3/sec)	Upper Discharge Velocity (cm/sec)	Number Of Pumps	Passage Time (Hours)
11/09/72	57.4	100	0.0	0	42.0	3.9	6	11.4
11/10/72	52.0	100	0.0	0	42.0	3.9	6	11.4
01/18/73	17.4	27.6	45.6	72.4	63.0	5.8	9	7.5
01/19/73	19.4	31.0	43.6	69.0	63.0	5.8	9	7.5
01/24/73	42.2	67.0	20.8	33.0	63.0	5.8	9	7.5
01/25/73	44.0	69.8	19.0	30.2	63.0	5.8	9	7.5
03/30/73	63.0	100	0.0	0	63.0	5.8	9	7.5
04/05/73	43.0	68.3	20.0	31.7	63.0	5.8	9	7.5
04/06/73	38.0	60.3	25.0	39.7	63.0	5.8	9	7.5
06/11/73	22.0	34.9	41.0	65.1	63.0	5.8	9	7.5
06/12/73	20.0	31.7	43.0	68.3	63.0	5.8	9	7.5
06/13/73	23.0	36.5	40.0	63.5	63.0	5.8	9	7.5
08/08/73	11.0	26.2	31.0	73.8	42.0	3.9	6	11.4
08/09/73	10.5	25.0	31.5	75.0	42.0	3.9	6	11.4
08/10/73	12.0	28.6	30.0	71.4	42.0	3.9	6	11.4
09/28/73	3.7	8.8	38.3	91.2	42.0	3.9	6	11.4
09/29/73	5.0	11.9	37.0	88.1	42.0	3.9	6	11.4
10/01/73	7.0	16.7	35.0	83.3	42.0	3.9	6	11.4

[1] River discharge data from U.S.G.S. records for the Raisin River.

Appendix A2. Schematic representation of sampling plan.



Appendix A3. Sampling and primary productivity dates of field collections to be included in this report.

Sampling Number	Period	Date	Type of Data
1	Morning	11/09/72	Algal samples, primary prod.
	Afternoon	11/10/72	Algal samples, primary prod.
	Evening	11/09/72	Algal samples, primary prod.
2	Morning	01/25/73	Algal samples
		01/19/73	Primary productivity
	Afternoon	01/24/73	Algal samples
		01/18/73	Primary productivity
	Evening	01/18/73	Algal samples
		01/25/73	Primary productivity
3	Morning	04/06/73	Algal samples
		04/05/73	Primary productivity
	Afternoon	04/05/73	Algal samples
		03/30/73	Primary productivity
	Evening	03/30/73	Algal samples
		04/05/73	Primary productivity
4	Morning	06/13/73	Algal samples, primary prod.
	Afternoon	06/12/73	Algal samples, primary prod.
	Evening	06/11/73	Algal samples, primary prod.
5	Morning	08/10/73	Algal samples, primary prod.
	Afternoon	08/09/73	Algal samples, primary prod.
	Evening	08/08/73	Algal samples, primary prod.
6	Morning	10/01/73	Algal samples, primary prod.
	Afternoon	09/29/73	Algal samples, primary prod.
	Evening	09/28/73	Algal samples, primary prod.

Appendix A4. Meterological information pertaining to plankton and productivity dates of interest in this study (1972-73).

Date	% Possible Sunshine for Day	% Sky Cover	Average Wind Speed (km/hr.)	Prevailing Wind Direction	Average Air Temperature (°C)
11/09/72	0	100	11.6	NE	5.0
11/10/72	0	100	15.4	E	5.6
01/18/73	54	80	19.6	S	11.1
01/19/73	0	100	27.3	W	5.6
01/24/73	91	40	15.3	SW	-2.2
01/25/73	100	0	20.1	SW	2.8
03/30/73	5	100	13.7	SW	10.6
04/05/73	49	70	20.1	W	6.7
04/06/73	89	40	21.6	SW	11.7
06/11/73	90	20	15.4	SW	27.8
06/12/73	47	90	15.4	SW	25.6
06/13/73	81	30	11.7	N	18.9
08/08/73	82	40	11.4	S	26.1
08/09/73	63	70	15.3	SW	26.7
08/10/73	66	50	15.8	W	22.2
09/28/73	0	100	11.7	E	18.9
09/29/73	0	100	9.0	NE	15.6
10/01/73	16	80	10.6	E	17.2

Appendix A5. List of all phytoplankton species and unknowns enumerated during the 1972-73 study year.[1]

CLASS BACILLARIOPHYCEAE

Achnanthes clevei Grun.

A. flexella (Kütz.) Brun.

A. lanceolata (Bréb.) Grun.

A. minutissima Kütz.

A. sp.

Amphora ovalis Kütz.

A. ovalis var. *pediculus* Kütz.

**Asterionella formosa* Hass.

Caloneis bacillum (Grun.) Cleve.

C. sp.

C. ventricosa (Ehr.) Meist.

Cocconeis diminuta Pant.

C. disculus (Schumann) Cleve.

C. pediculus Ehr.

**C. placentula* Ehr.

**Coscinodiscus radiatus* Ehr.

Cyclotella antiqua W. Smith

C. bodanica Eulenst.

C. comta (Ehr.) Kütz.

**C. glomerata* Bachmann

**C. kutzingiana* Thwaites

**C. meneghiniana* Kütz.

C. michiganiana Skv.

Appendix A5 (cont'd.).

C. ocellata Pant.

C. sp.

**Cyclotella stelligera* Cleve. and Grun.

**Cymatopleura solea* (Bréb.) W. Smith

Cymbella affinis Kütz.

C. microcephala Grun.

C. prostrata (Berk.) Cleve.

C. sinuta Greg.

**C.* spp.

C. ventricosa Kütz.

**Diatoma elongatum* (Lyng.) Agardh

D. hiemale (Lyng.) Heiberg

**D.* sp.

**D. vulgare* Bory.

**Diploneis oblongella* (Naeg. *ex* Kütz.) Ross

D. sp.

Eucocconeis sp.

Eunotia pectinalis (Kütz.) Rabh.

E. sp.

Fragilaria brevistrata Grun.

F. capucina Desm.

**F. crotonensis* Kitton

F. intermedia Grun.

F. leptostauron (Ehr.) Hust.

Appendix A5 (cont'd.).

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*F. spp.

Gomphonema acuminatum var. coronata (Ehr.) W. Smith

*G. angustatus (Kütz.) Rabh.

G. constrictum Ehr.

G. gracile Ehr.

*G. olivaceum (Lyng.) Kütz.

*G. parvulum (Kütz.) Grun.

Gomphonema sp.

*Gyrosigma acuminatum (Kutz.) Rabh.

G. kutzingii (Grun.) Cleve.

*G. sp.

G. spencerii (Quek.) Griff. & Henfr.

Hantzschia amphioxys (Ehr.) Grun.

H. sp.

Mastogloia grevellei W. Smith

M. smithii Thwaites Ex. W. Smith

M. smithii var. amphicephala Grun.

*Melosira ambigua (Grun.) O. Müll.

*M. arenaria Moore

M. binderana Kütz.

*M. granulata (Ehr.) Ralfs

*M. islandica O. Müll.

*M. italica (Ehr.) Kütz.

*M. sp.

Appendix A5 (cont'd.).

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*M. varians Agardh.

Meridion circulare (Grev.) Agardh

Navicula anglica Ralfs

N. bacillum Ehr.

*N. canalis Patrick

N. cari Ehr.

N. cincta (Ehr.) Ralfs

N. contenta Grun.

*N. cryptocephala Kütz.

*N. cuspidata (Kütz.) Kütz

N. decussis Østr.

N. exigua (Greg.) O. Müll.

*Navicula gastrum (Ehr.) Kütz.

N. hungarica Grun.

N. integra (W. Smith) Ralfs

N. krasskei Hust.

N. menisculus Schumann

N. minima Grun.

N. minuscula Grun.

*N. mutica Kütz.

N. muticopsis Van Heurck

N. perigrina (Ehr.) Kütz.

N. placentula (Ehr.) Kütz.

N. pupula Kütz.

Appendix A5 (cont'd.).

N. pygmaea Kütz.

N. radiosa Kütz.

*N. rhynchocephala Kütz.

N. salinarum Grun.

N. scutelloides W. Smith

N. sp.

*N. tripuncta (O. F. Müll.) Bory

*N. virdula Kütz.

Neidium dubium (Ehr.) Cleve.

*Nitzschia acicularis (Kütz.) W. Smith

N. amphibia Grun.

*N. angustata (W. Smith) Grun.

N. commutata Grun.

N. dissipata (Kütz). Grun.

*N. filiformis (W. Smith) Hust.

*N. gracilis Hantz.

Nitzschia hungarica Grun.

N. kutzingiana Hilse

N. lacunarum Hust.

*N. palea (Kütz.) W. Smith

N. sigma (Kütz.) W. Smith

N. sigmoidea (Ehr.) W. Smith

N. sp. #1

N. sp. #2

Appendix A5 (cont'd.).

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*N. sp #3

*N. spp.

N. stagnorum Rabh.

N. tryblionella Hantzsch

N. tryblionella var. victoriae Grun.

Ophephora martyi Herib.

*Pinnularia gibba Ehr.

P. sp.

*Rhizolenia eriensis H. L. Smith

*Rhoicosphenia curvata (Kütz.) Grun.

Rhopalodia gibba (Ehr.) O. Müll.

Stauroneis anceps Ehr.

S. smithii Grun.

S. sp.

*Stephanodiscus astraea (Ehr.) Grun.

*S. niagarae Ehr.

*S. sp.

S. tenuis Hust.

*Surirella angusta Kütz.

*S. ovata Kütz.

*S. robusta var. splendida (Ehr.) Van Heurck

Surirella sp.

Synedra actinastroides Lemm.

*S. acus Kütz.

Appendix A5 (cont'd.).

S. nana Meist.

S. parasitica (W. Smith) Hust.

S. sp.

**S. ulna* (Nitz.) Ehr.

**S. vaucheriae* Kütz.

**Tabellaria fenestrata* (Lyrg.) Kütz.

*Unknown centric filament

Unknown pennate #1

Unknown pennate #2

Unknown pennate #3

*Unknown pennate #4

Unknown pennate #5

Unknown pennate #6

Unknown pennate #7

CLASS CHLOREBACTERIAE

Pelogloea bacillifera Lauterborn

P. chlorina

CLASS CHLOROPHYCEAE

Actinastrum gracillimum G. M. Smith

A. hantzschii var. *fluvitile* Schroeder

Ankistrodesmus convolutus Corda

A. falcatus (Corda) Ralfs

A. falcatus var. *mirabilis* (W. & G. S. West)

**Binuclearia eriensis* Tiffany

Appendix A5 (cont'd.).

Carteria _klebsii_ (Dang.) Dill

Characium _limneticum_ Lemm.

Chlamydomonas sp. #1

_C_. sp. #2

_C_. sp. #3

_C_. spp

Chlorella sp. #1

_C_. sp. #2

*_C_. sp. #3

Closteriopsis _longissima_ Lemm.

Coelastrum _microporum_ Naegeli

Cosmarium _abbreviatum_ Raciborski

*_C_. _formulosum_ Hoffman

_C_. sp.

_C_. _subcrenatum_ Hantzsch

Crucigenia _alternans_ G. M. Smith

_C_. _apiculata_ (Lemm.) Schmidle

_C_. _crucifera_ (Wolle) Collins

_C_. _fenestrata_ Schmidle

_C_. _irregularis_ Wille

_C_. _lauterbornei_ Schmidle

_C_. _quadrata_ Morren

_C_. _rectangularis_ (A. Braun) Gay

_C_. sp.

Appendix A5 (cont'd.).

C. tetrapedia (Kirch.) W. & G. S. West

Dictyosphaerium ehrenbergianum Naegeli

**D. pulchellum* Wood

Elaktothrix gelatinosa Wille

E. viridis (Snow) Printz

Errella bornhemiensis Conrad

Franceia droescheri (Lemm.) G. M. Smith

Geminella minor (Naeg.) Heering

Gloeocystis gigas (Kuetz.) Lagerheim

Golenkinia radiata (Ched.) Wille

G. radiata var. *brevispina* Tiffany and Ahlstrom

Hematococcus lacustris (Girod.) Wittrock

Kirchneriella contorta (Schmidle) Bohlin

K. lunaris (Kirch.) Moebius

K. lunaris var. *dianae* Bohlin

K. obesa (W. West) Schmidle

K. obesa var. *aperta* (Teiling) Brunnthaler

K. obesa var. *major* (Bernard) G. M. Smith

K. sp.

K. subsolitaria G. S. West

Lagerheimia genevensis var. *subglobosa* (Lemm.) Chodat

L. longiseta (Lemm.) Printz

L. quadriseta (Lemm.) G. M. Smith

Appendix A5 (cont'd.).

L. subsalsa Lemm.

L. wratislawiensis Schroeder

Micractinium pusillum Fresenius

M. quadrisetum (Lemm.) G. M. Smith

*Mougeotia elegantula Wittrock

*Pandorina morum (Muell.) Bory

Pediastrum boryanum (Turp.) Meneghini

P. duplex Meyen

P. duplex var. gracillimum W. & G. S. West

P. simplex (Meyen) Lemm.

P. simplex var. duodenarium (Bailey) Rabh.

Pediastrum tetras (Ehr.) Ralfs

Pharotus lenticularis (Ehr.) Stein

Planktosphaeria gelatinosa G. M. Smith

Polydriopsis spinulosa Schmidle

Quadrigula closteriodes (Bohlin) Printz

Q. lacustris (Chodat) G. M. Smith

Scenedesmus abundans (Kirch.) Chodat

S. abundans var. brevicauda G. M. Smith

S. abundans var. longicauda G. M. Smith

S. acuminatus (Lagerh.) Chodat

S. acutiformis Schroeder

S. anomalus (G. M. Smith) Ahlstrom & Tiffany

S. arcuatus var. platydisca G. M. Smith

Appendix A5 (cont'd.).

<u>S</u>. <u>armatus</u> (Chod.) G. M. Smith

<u>S</u>. <u>bernardii</u> G. M. Smith

<u>S</u>. <u>bijuga</u> (Turp.) Lagerheim

<u>S</u>. <u>bijuga</u> var. <u>alternans</u> (Reinsch) Hansgirg

<u>S</u>. <u>bijuga</u> var. <u>flexuosos</u> (Lemm.) Collins

<u>S</u>. <u>brasiliensis</u> Bohlin

<u>S</u>. <u>denticulatus</u> Lagerheim

<u>S</u>. <u>dimorphus</u> (Turp.) Kuetzing

<u>S</u>. <u>hystrix</u> Lagerheim

<u>S</u>. <u>longus</u> Meyen

<u>S</u>. <u>opoliensis</u> P. Richter

<u>S</u>. <u>quadricauda</u> (Turp.) de Brébisson

<u>S</u>. <u>quadricauda</u> var. <u>alternans</u> G. M. Smith

<u>S</u>. <u>quadricauda</u> var. <u>longispina</u> (Chodat) G. M. Smith

<u>S</u>. <u>quadricauda</u> var. <u>maximum</u> W. & G. S. West

<u>S</u>. <u>quadricauda</u> var. <u>parvus</u> G. M. Smith

<u>Scenedesmus</u> <u>quadricauda</u> var. <u>westii</u> G. M. Smith

<u>S</u>. sp.

<u>Schroederi</u> <u>setigera</u> (Schroed.) Lemm.

<u>Selenastrum</u> <u>bibraianum</u> var. <u>gracile</u> (Reinsch) Tiffany and Ahlstrom

<u>S</u>. <u>minutum</u> (Naeg.) Collins

<u>S</u>. <u>westii</u> G. M. Smith

Appendix A5 (cont'd.).

Sorastrum spinulosum Naegeli

Sphaerocystis schroeteri Chodat

Staurastrum chaetocerus (Schroeder) S. M. Smith

S. paradoxum Meyen

Stylosphaeridium stipatum (Bachm.) Geitler and Gimesi

Tetradesmus wisconsinense G. M. Smith

Tetraedron arthrodesmiforme (G. S. West) Woloszynska

T. assymetricum Prescott

T. caudatum (Corda) Hansgirg

T. enorme (Ralfs) Hansgirg

T. incus (Teiling) G. M. Smith

T. minimum (A. Br.) Hansgirg

T. muticum (A. Br.) Hansgirg

T. sp

Tetrastrum glabrum (Roll) Ahlstrom and Tiffany

T. heteracanthum (Nordst.) Chodat

T. staurogeniaeforme (Schroeder) Lemm.

Trochisia granulata (Reinsch.) Hansgirg

**Ulothrix subtillissima* Rabenhorst

Unknown colony #1

Unknown colony #2

Unknown filament

Appendix A5 (cont'd.)

Unknown green algae-damaged

Unknown unicell #1

Unknown unicell #2

Westella botryoides (W. West) de Wildemann

W. botryoides var. *major* G. M. Smith

CLASS CHRYSOPHYCEAE

Dinobryon sp.

Mallomonas alpina Pascher and Ruttner

M. pseudocoronata Prescott

Ophiocytium cochleare (Eichw.) A Braun

CLASS CRYPTOPHYCEAE

Cryptomonas ovata Ehrenberg

CLASS CYANOPHYCEAE

Agmenellum quadriduplicatum Bréb.

A. trolleri (Bachmann) Drouet and Daily

Anabaena sircinalis Rabenhorst

A. spp.

Anacystis cyanea Drouet and Daily

A. dispersus (Keissl.) Drouet and Daily

A. grevellei (Hass.) Drouet and Daily

A. incerta Drouet and Daily

A. marina Drouet and Daily

A. minimus (Keissl.) Drouet and Daily

Appendix A5 (cont'd.).

A. montana f. minor Drouet and Daily

A. montana f. montana Drouet and Daily

A. thermalis f. major (Lagerheim) Drouet and Daily

Aphanizomenon flos-aquae (L.) Ralfs

*A. gracile ? Lemm.

Coccochloris clathrata (G. S. West) Drouet and Daily

C. peniocystis Drouet and Daily

C. stagina Sprengel

Dactylcoccopsis fasicularis Lemm.

Gomphosphaeria aponina Kütz.

G. dubium (Grunow) Drouet and Daily

G. lacustris Chodat

Marssoniella elegans Lemm.

*Oscillatoria spp.

O. tenuis C. A. Agardh

Rhaphidiopsis curvata Fritsch and Rich

Spirulina laxissima G. S. West

Unknown blue-green alga-damaged

Unknown colony-Chlorococcales

Unknown filament-Nostocales

Unknown filament-Oscillatoriales

Unknown unicell

Appendix A5 (cont'd.).

CLASS DINOPHYCEAE

Glenodinium sp.

Gymnodinium varians

CLASS EUGLENOPHYCEAE

Colacium vesiculosum Ehrenberg

Euglena acus Ehrenberg

**E. gracilis* Klebs

E. minuta Prescott

Euglena sp.

E. viridis Ehrenberg

Trachelomonas dybowskii Drezepolski

T. hispida (Perty) Stein

T. pulchella Drezepolski

T. pulcherrima var. *minor* Playfair

T. sp.

**T. volvocina* Ehrenberg

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[1]An asterick (*) before a name indicate that species had 1% or more of the total station volume for at least one sampling seasonal set.

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