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Ecological Research Series

MUSKEGON, MICHIGAN INDUSTRIAL-MUNICIPAL WASTEWATER STORAGE LAGOONS: Biota and Environment

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U.S. Environmental Protection Agency
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MUSKEGON, MICHIGAN INDUSTRIAL - MUNICIPAL WASTEWATER STORAGE LAGOONS: BIOTA AND ENVIRONMENT

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Reponsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory, (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report describes the results of a two year limnological study of the largest industrial-municipal wastewater storage lagoon in the United States. It is important to have a better understanding of how such wastewater can be treated and utilized in an efficient manner. This report is a major step to identify elements of effective wastewater management.

A.F. Bartsch
Director, CERL

ABSTRACT

A limnological investigation was carried out on two 344 hectare (850 acre) industrial-municipal wastewater storage lagoons from August 1973 until August 1975. Besides monitoring physical and chemical parameters during the period of the initial filling, the biological community was critically examined for the purpose of documenting ecological succession over this two year period.

In general, the lagoons remained aerobic, well mixed vertically and slightly alkaline. The low transparency within the lagoons was an important factor which limited the phytoplankton population and excluded rooted aquatics and benthic algae. Ample nutrients were present for algal demands.

The lagoon's phytoplankton-protozoan assemblage was extremely variable with respect to both total abundance and distribution. The zooplankton community was composed of fourteen species of free living crustaceans and four species of rotifers. The benthic fauna consisted of a small number of organisms representing only a few taxonomic groups.

This report was submitted in partial fulfillment of order number 04J1P01534 by Western Michigan University, Biology Department, under the partial sponsorship of the U. S. Environmental Protection Agency. Work was completed as of August 1976.

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The partial financial support of this study by the United States Environmental Protection Agency is greatly appreciated.

SECTION I

INTRODUCTION

THE MUSKEGON, MICHIGAN, WASTEWATER MANAGEMENT SYSTEM

As the demands on water resources increase, the need for more effective wastewater management becomes apparent.

The Muskegon County, Michigan, Wastewater Management System is an alternative to conventional wastewater treatment and disposal methods. Rather than discharging the nutrient-rich wastewater to a river, stream, or lake, the Muskegon System uses it as irrigation water, allowing the soil and plants to "polish" the effluent.

This land treatment wastewater system does more than just clean the polluted water which is receiving treated effluents, for it is a biological system that recycles nutrients; reclaims water to meet drinking water standards; and retains wastewater constituents not suitable for recycling. The Muskegon facility was modeled largely on a 570 million liter per day (MLD) [150 million gallon per day (MGD)], 8094 hectare (ha) (20,000 acres) land treatment system in Melbourne, Australia (Ward, 1975) and the Pennsylvania State University forest land application experiments (Boyer and Reid, 1973).

This system treats both domestic and industrial wastewater from the greater Muskegon area. The major contributors to the system are, in decreasing magnitude of flow, a paper mill, 14 municipalities, three chemical companies, an engine manufacturing plant, a metal casting and plating firm, and over 150 smaller industries.

The 100-125 MLD (25-33 MGD) of combined wastewater is pumped 17.7 km (11 miles) to the 4,371 ha (10,800 acre) treatment site where it is discharged into three treatment cells. The biological activity in these cells is aided by mixing and aeration. With an average detention time of three days, these cells produce an effluent comparable in quality to that achieved by secondary treatment.

From these cells the wastewater is discharged into one or both of the storage lagoons for further stabilization or directly into the outlet pond. Throughout this investigation, except for a few weeks during high irrigation demands, the semi-treated wastewater was discharged into the lagoons prior to being used as irrigation water. Each storage lagoon covers 344 ha (850 acres), for a combined storage capacity of 19.3 billion liters (5.1 billion gallons). In order to prevent seepage from entering the groundwater outside of the treatment site, a drainage or interception ditch encircles both lagoons. Water collected from this ditch is returned to the West Lagoon.

In late May 1973, a small amount of industrial and municipal wastewater effluent was being discharged into both Muskegon lagoons. At that time, there was also some rainwater in the basins but the bottoms of the lagoons were not covered, due to evaporation and seepage, until August 1973. At this time, the flow had increased to about 106 MLD (28 MGD) and the constituents of the wastewater, notably waste paper and pulp fiber and waste clay filler, had helped to seal the bottom.

BACKGROUND LITERATURE

Little information exists on a world-wide basis concerning limnological investigations of storage ponds, especially large lagoons such as those described in this project.

This study is an attempt to gain greater insight into the intricate relationships that exist between the aquatic community and its environment.

The great majority of reports on wastewater lagoons deal with the design, engineering, and performance aspects of these facilities. Fewer are concerned with the physical-chemical aspects, and only a very limited number of studies discuss the biological aspects of combined municipal-industrial wastewater lagoons.

In an extensive study of the wastewater lagoons of the world, Gloyna (1971) devoted only a 15 page annex to their limnology. The organisms discussed were limited to bacteria, protozoa, and algae. The dominant and sub-dominant algae of an oxidation pond in Ahmedabad, India, over a seven month period of 1962 were reported (Jayangoudar and Ganapati, 1964). In a study concerned mainly with the physical-chemical characteristics of domestic sewage oxidation ponds, Lakshminarayana et al (1964) found that algae and zooplankton populations were small. Davis, et al (1964) investigated the bacteria and algae of ten small wastewater lagoons in Oklahoma and found that the green algae (Chlorophyta) predominate during the winter months whereas the blue-greens (Cyanophyta) were most prevalent during the summer and early fall. The flagellates (Euglenophyta) appeared intermittently throughout the year. Davis (1964) also reported on oxidation ponds in Texas, in which he described the biota in only one paragraph.

In a report on the experiences with wastewater lagoons in the United Kingdom, Potten (1972) referred to several genera of plankton as being "typical" lagoon inhabitants. A more complete report on municipal wastewater lagoon phytoplankton is a doctoral dissertation on algal periodicity and primary productivity (Raschke, 1968). The lagoon studied, however, was quite small (0.05 ha) and the detention time was only a few days. A summary of this study was later published (Raschke, 1970). Silva and Papenfuss (1953) investigated the phytoplankton of small wastewater lagoons in California.

Chlorella, *Chlamydomonas*, *Ankistrodesmus*, *Scenedesmus*, *Anacystis*, *Oscillatoria*, *Euglena*, and *Phacus* were cited as the dominant and subdominant phytoplankton in most of the above studies.

Microscopic crustaceans, notably *Daphnia* and *Cyclops*, comprised the dominant zooplankton in various lagoons (Gloyna, 1971). The midges (Chironomidae) dominated the benthic macroinvertebrate population of wastewater lagoons in California (Grodhaus, 1967), Missouri (Kimerle and Enns, 1968), and Michigan (Merritt, 1976). Additional information concerning the zooplankton and benthos of wastewater lagoons appears to be lacking.

The primary goal of this research was to generate baseline information concerning the limnological and especially the biological aspects of large wastewater lagoons.

SECTION II

CONCLUSIONS

1. The results of a two-year limnological study of the largest industrial-municipal wastewater storage lagoons in the United States are reported herein. This investigation began shortly after the construction of the wastewater facility.

2. In general, the lagoons remained aerobic except for a few weeks during ice-cover.

3. BOD_5 values between 15 and 20 mg/l were common.

4. Transparency, as measured by a secchi disk, was shallow and averaged only about 20 cm. The rapid vertical extinction of light limited the phytoplankton population and excluded rooted aquatics and benthic algae.

5. The lagoons remained slightly alkaline ($pH \approx 7.7$) even during periods of high photosynthetic activity.

6. Ample nutrients were present for algal demands.

7. The concentrations of several metals, most notably zinc, were relatively high.

8. The phytoplankton-protozoan assemblage was extremely variable with respect to total abundance and distribution. The range of this population was from less than 20 to more than 22,000 units/ml. The Chlorophyta were the dominant algae except for several weeks each summer when the Cyanophyta reached bloom proportions.

9. Several chlorophyll a and primary productivity peaks were noted, but in general, values near 12 mg/l chlorophyll a and 25 mg $C/m^3/hr$ were common.

10. Three species of *Daphnia*, the dominant zooplankter, were routinely collected. *Cyclops vernalis* was the most common cyclopoid copepod while *Diaptomus* was the only calanoid copepod recovered. The zooplankton community was composed of only four species of rotifers and fourteen species of free-living crustaceans.

11. The benthic fauna was very limited, and remained below 100 organisms/0.1 m^2 in 95% of the samples. Midges (Chironomidae) accounted for virtually all of the sparse population. *Procladius culiciformis* and *Glyptotendipes barbipes* were the most common benthic forms. It appears that the sparsity of this population can be attributed to the stressed lagoon environment in which the concentrations of several metals, most notably zinc, were relatively high.

SECTION III

RECOMMENDATIONS

1. It is important to investigate the environment and population of the Muskegon Lagoons, the largest wastewater lagoons in the U. S., in order to determine what wastewater treatment is needed and to determine how the wastewater can best be utilized. The Muskegon project is a pilot project, and limnological information gathered concerning these lagoons should help in future design and management of land treatment and/or lagoon wastewater systems.

2. A limnological investigation of the Muskegon Lagoons should be continued in order to further analyze the details of succession and colonization of the lagoons and to determine if a somewhat more stable community may be established.

3. The following special studies are also recommended:

   a. Benthos - Investigate why the benthic fauna is so limited. Even the normally ubiquitous oligochaetes were nearly absent during the first two years of study. Because the present study points to the involvement of metals, this parameter should be thoroughly studied including sediment analysis.

   b. Phytoplankton - Follow the seasonal dynamics of phytoplankton, chlorophyll *a*, and primary productivity. Investigate heterotrophic assimilation, which appears important in these lagoons, and its relationship to autotrophic production.

c. Zooplankton - Investigate the rate of incorporation of heterotrophic and autotrophic carbon by the indigenous zooplankton population. Investigate the population dynamics of the zooplankton.

SECTION IV

STUDY DESIGN AND METHODOLOGY

DESIGN

The limnology of the 688 ha (1,700 acre) Muskegon combined municipal and industrial wastewater lagoons was investigated from the time of the initial filling in August 1973 through August 1975. Special emphasis was placed upon the biological aspects of these bodies of water. Three stations were established in each lagoon (Figure 1). The station locations and designations corresponded to those used by the Muskegon County Department of Public Works, which served as manager of the system.

Each lagoon was sampled biweekly from September 1973 through 14 May 1975. For the remainder of the study, the samples from each lagoon were collected on a weekly basis. During periods of open water, all samples were taken within 50 feet of the station using an aluminum boat. When the lagoons were ice-covered, December through March, samples were taken 50 feet from and perpendicular to the shore and in line with the station. For safety reasons, Stations E-5 and W-5, the stations farthest from shore in both the East and West Lagoons, were not sampled during periods of ice cover.

A 2.2 liter, horizontal, opaque, non-metallic Van Dorn bottle was used to collect samples for analysis of the following parameters: plankton; chlorophyll; primary productivity; temperature; dissolved oxygen (DO); five-day biochemical oxygen demand (BOD_5); turbidity; conductivity; pH; total organic carbon; metals that included calcium,

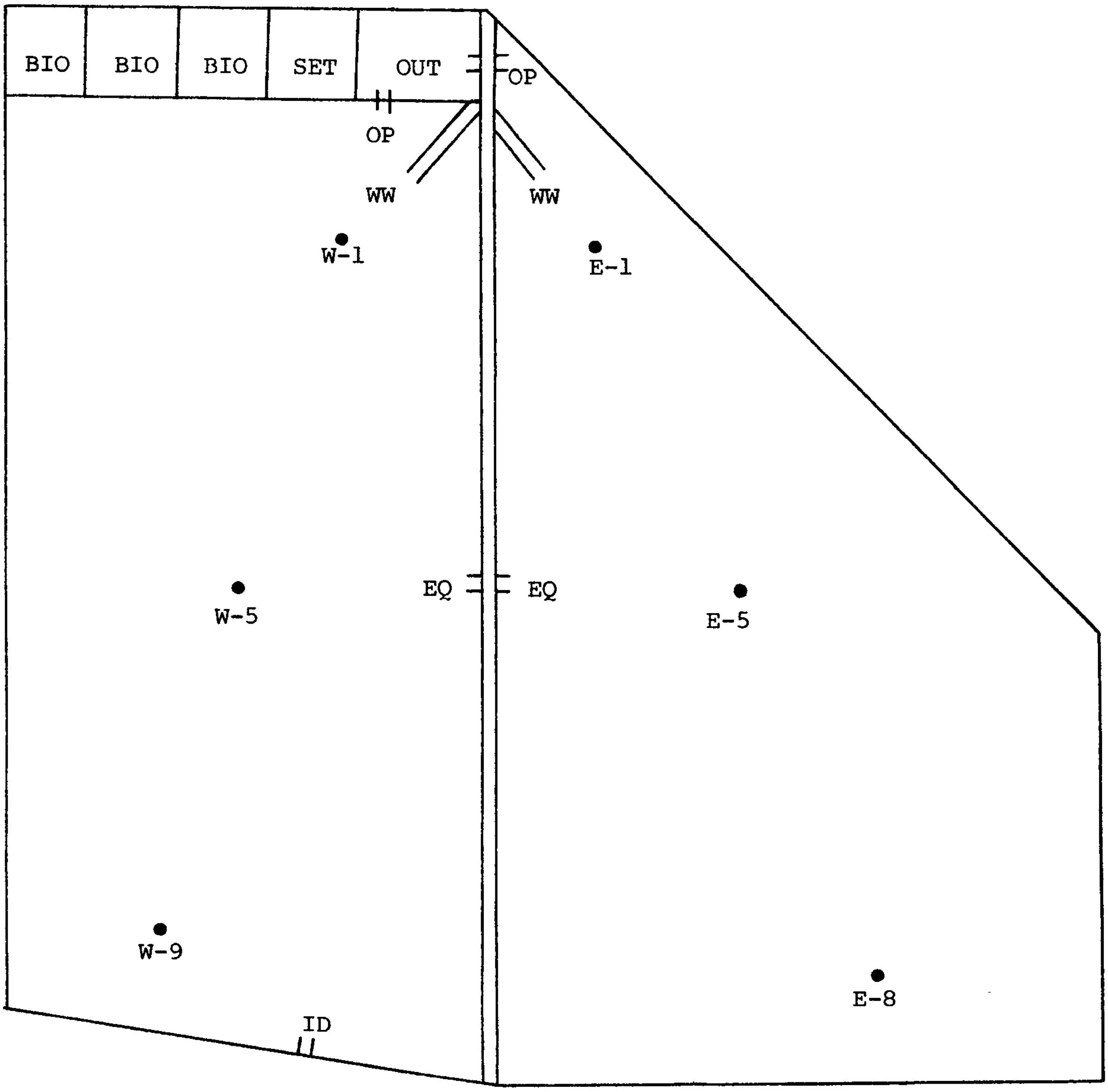

Figure 1 Muskegon Wastewater Lagoons

KEY

BIO = Biological Treatment Cell

OUT = Outlet Pond

SET = Settling Pond

EQ = Equalizing Gate

ID = Point of discharge of interception ditch water

OP = Point of discharge of lagoon water to outlet pond

WW = Point of discharge of wastewater to lagoon iron, magnesium, manganese, potassium, sodium, and zinc; nutrients which consisted of orthophosphate, nitrate, and ammonia nitrogen; chlorides; and sulfate. Samples were collected from several depths at each station. An Ekman dredge was used to collect replicate benthos samples, and a number 12 plankton net (mesh opeings equal to 0.12 millimeter) was employed to collect replicate zooplankton samples.

METHODOLOGY

When feasible, standard procedures and techniques, as described in Standard Methods for the Examination of Water and Wastewater (American Public Health Association, et al, 1976) and in Biological Field and Laboratory Methods for Measuring the Quality of Surface Waters and Effluents (Weber, 1973), were adhered to as closely as possible. Specifics for each parameter are further described below.

Benthos

A 15.8 cm Ekman Dredge was used to collect replicate benthos samples. Because of the limited benthic population and since this dredge sampled only 0.025 square meter, results were reported as number of organisms per 0.1 square meter. After retrieval of the bottom sample, the contents of the dredge were washed through a No. 30 sieve (11 meshes per centimeter) and the retained portion was dumped into a white enamel pan. The organisms then were hand picked and preserved in 70% ethanol.

Numerous taxonomic references aided the identification of the benthic macroinvertebrates (Beck, 1968; Chernovskii, 1949; Curry, 1962; Edmondson, 1959b; Grodhaus, 1967; Johannsen, 1934-37; Mason, 1973; Pennak, 1953; Peterson, 1967; Robeck, 1957; Ross, 1944; Usinger, 1956).

For species identifications of the midges, it was necessary to prepare head and body mounts of these organisms. Rather than using the conventional but very time consuming technique of clearing the midges in KOH, rinsing, and then mounting (American Public Health Association, 1976; Mason, 1973; Weber, 1973), the midges were mounted directly into polyvinyl lactophenol. This substance acts as both a clearing agent and a mounting media.

Data from replicate samples were averaged, and the results reported as number of individuals per tenth square meter. The mean diversity, $\bar{d}$, and equitability, e, were calculated for each station using the formulas presented in the Biological Methods Manual (Weber, 1973).

Zooplankton

Replicate vertical tows were taken from 0.3 m above the bottom. Although a number 20 net is recommended for the capture of nauplii, protozoa, small rotifers, and other nannozooplankton, a number 12 net (aperture size 0.12 mm) was used to prevent clogging by the unusually large quantities of suspended matter. The samples were preserved with Koechie's preservative, a saturated sucrose - 4% buffered formalin solution.

Several one milliliter subsamples were withdrawn from each zooplankton replicate with a Hensen-Stemple pipette. Each subsample was deposited in a nine-depression glass culture dish and analyzed quantitatively and qualitatively. Genus and species identifications of cyclopoid copepods were based on minute anatomical details of specimens dissected between the fourth and fifth thoracic segments and mounted, ventral side up. Several taxonomic references were valuable aids to identification (Bousfield, 1958; Brooks, 1957 and 1959; Edmondson, 1959a and 1959b; Gannon, undated; Pennak, 1953; Torke, 1974; Wilson and Yeatman, 1959). Data from replicate samples were averaged and the results were reported as the number of organisms per liter.

Plankton

Throughout this report, the word "Plankton" will be used to refer to phytoplankton and protozoa.

Sampling depths were related to the transparency within each lagoon. Routine sample collection was at the depth of the secchi disk reading and also at one-half of this depth.

At times, due to the very low transparency, collection was at the secchi disk transparency and also at 0.45 meter. In addition to sample gathering at these depths, samples were also taken at 0.3 meter above the bottom from April 1975 throughout the remaining period of the study. With the exception of primary productivity, all parameters collected with the Van Dorn bottle were analyzed at these identical depths.

The samples were preserved with Lugol's solution and allowed to settle for several weeks. Due to the few plankton present, the samples were concentrated by a factor of 16 by withdrawal of the supernatant with a suction tube. Centrifugation proved unsuitable as a concentration technique in this study. The centrifuged samples remained cloudy and microscopic examination revealed that some species were still remaining in the supernatant. Davis (1966) has had similar results with centrifugation.

A Palmer-Maloney cell, rather than the Sedgwick-Rafter cell, was used for quantitative and qualitative analysis because of the higher magnification required for nannoplankton. Twenty fields were examined in each of several slide preparations. The results were averaged for each sample and reported as the number of units per milliliter (ml). The clump count was used, with all filamentous or colonial organisms counted as one unit.

Diatom mounts were initially made by ashing and mounting the diatoms. Up to 2.5 ml were evaporated through successive dryings on 18 mm circular coverslips.

This subsample was then ashed on a hot plate at 570°C for at least one hour. Hyrax, with a refractive index of 1.82, was used as a mounting media. The silicious frustules were examined under oil immersion. The concentration of diatoms, however, was normally inadequate for this technique. The recommended 250 cells per slide (Weber, 1973) could not be examined. Further sample evaporation on the cover slip was not appropriate due to the high collodial clay content of the lagoons. Crushing and masking of the diatoms occurred with any higher sample concentration. Therefore, the membrane filter technique (Stoermer *et al*, 1972) with modifications of Lugol fixation, filtration and subsequent clearing and embedding in clove oil was utilized for diatom counts from August 1974 through the remainder of the study.

References relied upon for the analysis of the plankton included Berges (1971), Drouet (1959), Edmondson (1959a), Kudo (1971), Lackey (1959), Noland (1959), Parrish (1968), Patrick (1959), Patrick and Reimer (1966), Prescott (1962 and 1968), Thompson (1959), and Weber (1966).

Primary Productivity

The uptake of inorganic carbon by phytoplankton during photosynthesis was measured with the carbon-14 method of Steeman-Nielson (1952), incorporating only minor modifications (Jordon, 1970; Saunders, *et al*, 1962; Weber, 1973). The four hour *in situ* incubation depths were determined by the secchi disk transparency. Secchi readings as low as 6 to 12 cm often dictated productivity incubation at only one depth. Following incubation and filtration, filters were air dried and their beta activity subsequently counted. Productivity is expressed in the amount of carbon fixed per hour from the equation in Table 1.

TABLE 1. CONVERSION OF CPM TO CARBON FIXED

Conversion equation	$P = \frac{r}{R} \times C \times f$ (Saunders, *et al*, 1962)
P	Photosynthesis in mg C/m^3
r	cpm counted (uptake of radioactive carbon)
C	19.2×10^3 mg C/m^3 (available inorganic carbon in the lagoons)
f	1.06 (Isotope conversion factor)
R	4.27×10^5 (total available radioactive carbon in cpm: microcuries used X counter efficiency X millipore absorption factor X disintegration per minute per microcurie)
Microcuries used	$\frac{37,000}{40,290}$ (scintillation cpm/microcurie)
Counter efficiency	0.25
Membrane absorption factor	0.838
Disintegrations per minute per microcurie	2.22×10^6
Final equation for lagoons	$P = r \times 0.0477$

Chlorophyll

This analysis was accomplished *in vitro* from acetone extracts by fluorometry. The samples were drawn from the same locations and at the same time as the plankton samples. Immediately after collection of the sample, $MgCO_3$ was added in the field. After filtering 100 ml, the 0.45 micron membrane filters were frozen until analysis at a later time. Results were reported as mg/m^3 of chlorophyll *a* and phaeophytin.

Dissolved oxygen

The DO samples were fixed in the field immediately after collection and were titrated in the laboratory. The azide modification of the iodometric method was used. Results were reported as milligrams (mg) DO/1.

Biochemical oxygen demand

The five day BOD test was used with incubation in the dark at 20°C. Results were reported as mg $BOD_5/1$.

Secchi disk transparency

A 20 cm diameter black and white secchi disk was used. Results were reported in centimeters.

Turbidity

A Hach Model 2100A Turbidometer was used for direct measurement of turbidity by the Nephelometric method. Results were reported in Formazin Turbidity Units (FTU), equivalent to Jackson Turbidity Units.

pH

A hydrogen ion selective glass electrode in combination with a saturated calomel reference electrode were used to determine pH by the electometric method. Results were reported in standard pH units.

Conductivity

A platinum electrode type specific conductance cell with a cell constant of 1.0 $\pm$ one per cent was used. Conductance measurements were taken at ambient temperature utilizing a Barnstead Conductance Bridge. Results were reported in micro-mhos per cm.

Nitrate nitrogen

The concentration of nitrate nitrogen was determined through a copper-cadmium reduction of nitrate to nitrite. The nitrite thus produced was quantified using sulfanilamide (diazotizer) and N-1-naphthyl-ethylenediamine (couplet). The resulting highly colored dye was measured colorimetrically and the results were reported as mg NO_3-N/l.

Ammonia nitrogen

The concentration of ammonia nitrogen was determined by distillation followed by nesslerization. Results were reported as mg NH_4^+/l.

Orthophosphate

The concentration of orthophosphate was determined by colorimetry, without preliminary filtration, digestion, or hydrolysis, using ammonium molybdate in the vanadomolybdophosphoric acid method. Results were reported as mg PO_4-P/l.

Sulfate

The concentration of sulfate was determined using the Barium-Methythymol Blue colorimetric procedure. Results were reported as mg $SO_4^{=}$/l.

Chlorides

The concentration of chloride was determined by liberation of the thiocyanate ion from mercuric thiocyanate, followed by a reaction with the ferric ion. Results were reported as mg Cl^-/l.

Total organic carbon

The concentration of total organic carbon (TOC) was determined using a Beckman Model 915 Total Carbon Analyzer. Results were reported as mg carbon/l.

Metals

The concentrations of calcium (Ca), iron (Fe), magnesium (Mg), manganese (Mn), sodium (Na), potassium (K), and zinc (Zn) were determined using flame ionization photometry and atomic absorption spectroscopy. Results were reported as mg of the specific metal/l.

SECTION V

RESULTS AND DISCUSSION

The data gathered during this investigation are presented in the appendices and only summary data appear in this section. The results of each parameter will be discussed individually and the trends, or relationships, among parameters will be elucidated where appropriate.

The water depths in the lagoons fluctuated from approximately one meter to 3.5 meters. The only exception was at W-9, which, due to a depression was 2.5 meters deeper than the other stations.

WASTEWATER FLOW PATTERNS DUE TO GATE OPERATING POSITIONS

During this investigation, the operating positions of the gates that controlled inflow, outflow, and mixing between lagoons were altered as indicated in Table 2.

From 18 August 1973 through 26 September 1973 the wastewater was discharged into both lagoons, with the exception of three days when it was used directly for irrigation water. From 27 September 1973 through 3 March 1975 the wastewater was discharged only into the East Lagoon, with the exception of 13 days when it was employed directly for irrigation water. On 4 March 1975 there was a major change in the flow pattern, with the wastewater being discharged into the West Lagoon for the first time since September 1973. The West Lagoon received the wastewater throughout the remainder of the study, with the exception of a two-week period and a one-week period when the wastewater was used directly for irrigation water. In summary, the East Lagoon received virtually all the wastewater throughout the first 18 months of this investigation.

TABLE 2. WASTEWATER FLOW PATTERNS AND GATE OPERATING POSITIONS

GE = Gate to East Lagoon
GW = Gate to West Lagoon
EL = East Lagoon
WL = West Lagoon
EQU = Equalizing gate between East and West Lagoons
OUTE = Outlet gate from East Lagoon to irrigation
OUTW = Outlet gate from West Lagoon to irrigation
WMDS = Outlet gate from West Lagoon to Mosquito Creek (draining the West Lagoon

DATE	FLOW TO	OPEN	CLOSED
8-13-73 - 8-17-73	Irrigation		EL, WL
8-18-73 - 9- 4-73	EL, WL	EQU	OUTE, OUTW
9- 5-73 - 9- 7-73	Irrigation	EQU	EL, WL
9- 8-73 - 9-26-73	EL, WL	EQU	OUTE, OUTW
9-27-73 - 3-29-74	EL		OUTE, OUTW, EQU
3-30-74 - 4-29-74	EL	EQU	OUTE, OUTW
4-30-74 - 7- 5-74	EL	EQU, OUTW	OUTE
7- 6-74 - 9-19-74	EL	OUTE	OUTW, EQU
9-20-74 -11-13-74	Irrigation	OUTE	OUTW, EQU
11-14-74 -12-13-74	EL		OUTE, OUTW, EQU
12-14-74 - 3- 3-75	EL	WMDS	OUTE, OUTW, EQU
3- 4-75 - 4-11-75	WL		OUTE, OUTW, EQU
4-12-75 - 6-24-75	WL	OUTW	OUTE, EQU
6-25-75 - 7-18-75	Irrigation	OUTE	OUTW, EQU
7-19-75 - 8- 6-75	WL	OUTW	OUTE, EQU
8- 7-75 - 8-13-75	Irrigation		OUTE, OUTW, EQU
8-14-75 - 8-19-75	WL	OUTW	OUTE, EQU

During this period, the West Lagoon received mainly the interception ditch water. During the last six months of study the wastewater was discharged predominantly into the West Lagoon, while the East Lagoon did not receive any discharge. In the analyses that follow, the estimation of 18 months wastewater flow into the East Lagoon followed by six months wastewater flow into the West Lagoon was used for comparing results during periods of wastewater flow with those during periods of no wastewater flow.

BIOLOGICAL PARAMETERS

Benthos

There were variations in bottom substrate types in the lagoons. Sludge accumulated appreciably only at E-1 where about 20 cm of mainly paper pulp and detritus accumulated on the medium-sandy type bottom. The other substrates varied from a fine-sand at E-5, a hard-clay at E-8, a coarse-sand at W-5, to a medium-sand at W-1 and W-9.

During this two year investigation, 360 benthos samples were collected and analyzed. The macroinvertebrate population was very limited. This community consisted of only a few organisms representing only a few taxonomic groups. As shown in Figure 2, the benthos remained below 150 organisms per tenth square meter throughout this investigation, and in 94.6% of the samples the population was less than 100 organisms. Thus the number of benthic organisms remained quite low throughout this study, in sharp contrast to the more common values of 1,000 to 16,000 Chironomidae per tenth square meter in other wastewater lagoons (Kimerle and Enns, 1968).

Table 3 indicates the percentage composition of the major taxa in the benthic population, as well as the number of samples per station. The eight

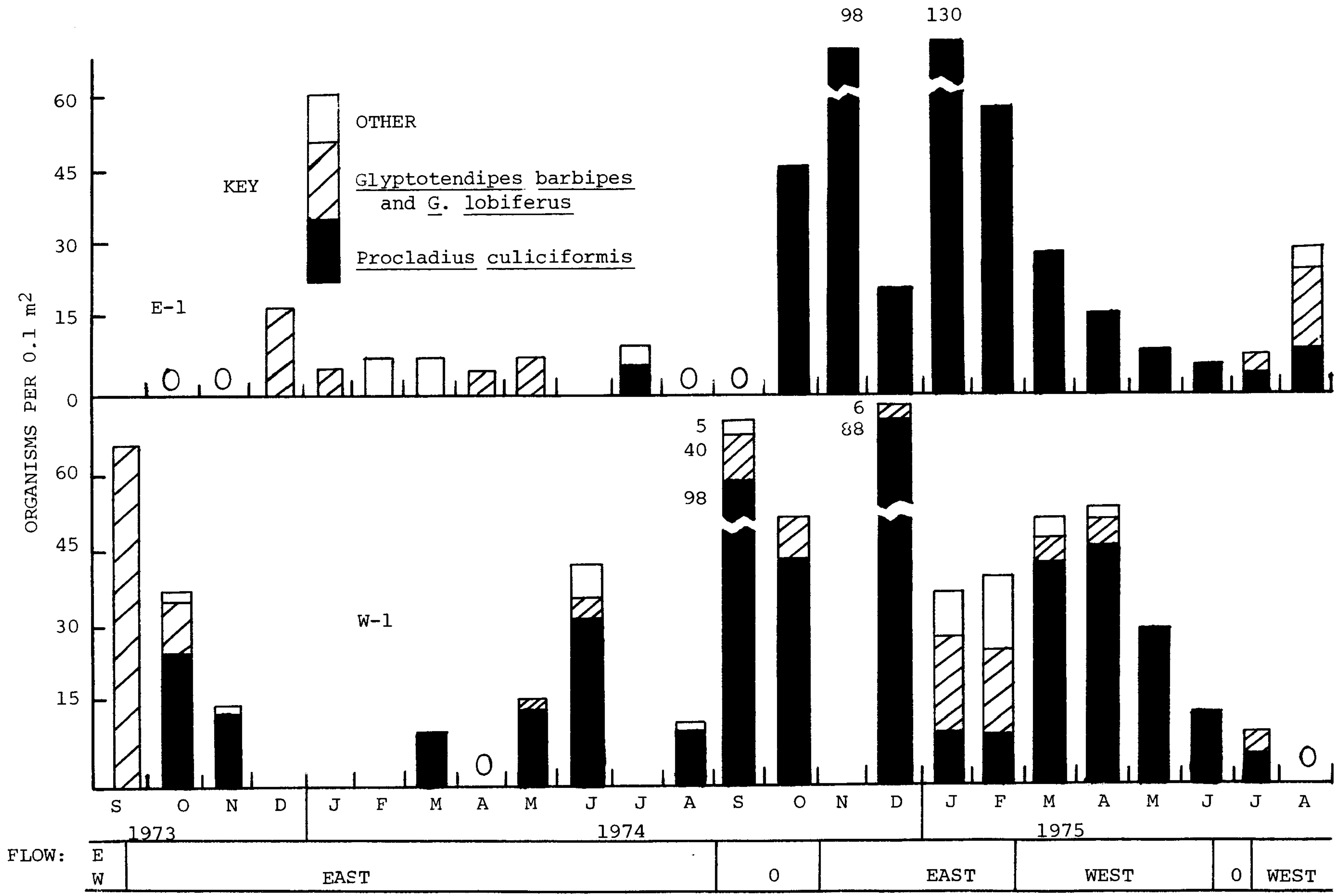

Figure 2 Changes in the abundance and composition of the benthos at E-1 and W-1

TABLE 3. PERCENTAGE COMPOSITION OF BENTHIC POPULATION, MAJOR TAXA ONLY

KEY

T = TOTAL STUDY WW = PERIOD OF WASTEWATER FLOW NWW = PERIOD OF NO WASTEWATER FLOW

TAXA		STATIONS							
		E-1	E-5	E-8	W-1	W-5	W-9	EAST, TOTAL	WEST, TOTAL
No. of samples		76	46	62	70	46	60	184	176
ARTHROPODA, INSECTA	T	97.2	100	100	99.8	99.9	100	99.2	99.9
	WW	97.2	100	100	100	100	100	99.0	100
	NWW	100	100	100	99.6	99.8	100	100	99.8
Diptera, Chironomidae (larvae)	T	96.0	99.1	97.9	96.8	96.9	98.2	97.9	97.3
	WW	95.4	98.7	97.5	97.8	99.5	100	97.4	99.3
	NWW	100	99.7	100	96.6	96.2	97.9	99.9	96.6
a) *Chironomus plumosus*	T	2.4	17.5	17.1	0.1	2.2	0.1	12.2	0.8
	WW	0.9	21.0	19.2	0.0	0.7	0.2	12.9	0.3
	NWW	11.5	10.7	6.5	0.2	2.5	0.0	9.9	0.9
b) *Glyptotendipes* spp.	T	5.5	71.6	45.6	25.7	44.4	3.1	40.5	24.0
	WW	2.8	75.9	53.4	12.5	2.1	0.0	40.7	3.4
	NWW	21.8	63.2	5.2	28.6	55.3	5.2	39.7	31.4
1) *G. barbipes*	T	4.0	54.3	33.9	19.7	42.1	3.0	30.4	21.2
	WW	1.7	58.6	39.4	9.5	2.1	0.0	30.6	2.7
	NWW	18.2	45.8	5.2	22.0	52.4	5.0	29.7	27.8

TABLE 3 CONCLUDED

TAXA		STATIONS							
		E-1	E-5	E-8	W-1	W-5	W-9	EAST, TOTAL	WEST, TOTAL
2) <u>G. lobiferus</u>	T	1.5	17.3	11.7	6.0	2.3	0.1	10.1	2.8
	WW	1.1	17.3	14.0	3.0	0.0	0.0	10.1	0.7
	NWW	3.6	17.4	0.0	6.6	2.9	0.2	10.0	3.6
c) <u>Procladius culiciformis</u>	T	85.0	5.5	27.2	69.0	50.0	92.8	40.5	70.7
	WW	90.7	1.2	18.2	83.9	95.3	99.8	40.6	94.9
	NWW	63.8	15.0	74.2	64.5	38.4	88.4	40.4	62.0

species of chironomids that were recovered accounted for virtually all, 98.6%, of the benthos. Of these eight species only four, *Procladius culiciformis*, two species of *Glyptotendipes*, and *Chironomus plumosus*, were common and they accounted for 95.5% of the total macroinvertebrate population. The non-biting midges have been found to be the most common organisms of other wastewater lagoons (Grodhaus, 1967; Kimerle and Enns, 1968; and Merritt, 1976). However, the populations are usually not limited to chironomids and other forms are also common.

During the first year of this investigation, *Glyptotendipes barbipes* was the dominant benthic form at all stations in the East Lagoon. *P. culiciformis* was sub-dominant at E-8, but rare at E-1 and E-5. *C. plumosus* was sub-dominant at E-5, and common at E-1 and E-8. The predominant form during the second year changed to *P. culiciformis* at E-1 and E-8, while *G. barbipes* remained dominant at E-5. The change in dominance occurred at the start of the second year at E-1, immediately after the depositional phase for midges, but not until three months later at E-8. Clear population shifts could not be discerned during the last six months of this study when the wastewater flow to this lagoon was eliminated.

In the West Lagoon, the benthic community was dominated by *P. culciformis* at W-1 and W-9, while *G. barbipes* was dominant at W-5 and also common at W-1. However, *G. barbipes* was the most prevalent form in the West Lagoon during the first year. C. plumosus was a rare form in this lagoon throughout the study. At the start of the second year, the population shifted and *P. culiciformis* became dominant while *G. barbipes* became only a common form. With the onset of wastewater discharge to this lagoon during the last six months of study, the composition of the benthos had changed further. The occurrence of *P. culiciformis* increased, but *G. barbipes* became rare. The variety of incidental forms was greatly reduced. The greatest change in the benthos occurred at the station closest to the point of wastewater inflow, W-1, where the number of species dropped from 11 prior to discharge to only 4 after discharge. C. plumosus, a species known for its ability to survive for a considerable length of time under low dissolved oxygen concentrations, (Chernovskii, 1949) may become more common in the West Lagoon as the sludges accumulate.

A change in the composition of the benthic population, due to an alteration of the wastewater flow, occurred for several reasons in the West Lagoon but not in the East Lagoon. The East Lagoon received the majority of the wastewater during the first 16 months of this study. The wastewater input was eliminated only during the final six months of study, a period of time probably too short for recovery. Also, the depositional phase for the insects had passed when the flow was shifted. New forms in this system cannot appear until the next reproductive cycle, but organisms can be eliminated almost immediately by the addition of pollutants, as was the situation in the West Lagoon.

The change in the dominant form for both lagoons from G. barbipes to P. culiciformis may be due, in part, to the changes that occurred in the zooplankton and phytoplankton, and the decay of the terrestial vegetation that was growing in the lagoons prior to filling. Immature glyptotendipeds are phytophagous and probably fed on both aquatic plants and terrestial vegetation that had fallen into or was growing in the basin. The young larvae of P. culiciformis are mainly carnivorous but also feed on some large diatoms (Chernovskii, 1949). During the second year appreciably more organisms from the zooplankton and zoobenthos were captured in the benthos samples, especially Hyallela azteca and Daphnia spp. In the zooplankton samples during the second year, rotifers were much more abundant, notably Keratella and Brachionus. The phytoplankton population declined dramatically, with the exception of the large diatom Stephanodiscus niagarae and a summer blue-green bloom. These changes appear to favor P. culiciformis at the expense of G. barbipes. Station E-5, the only location where G. barbipes remained dominant during the second year, had a very high density of terrestrial vegetation remaining as compared with all other stations. The different dominant and common benthic forms at the stations may also be attributed to the varying substrates and water quality, two factors which play an important role in determining the benthic population (Hynes, 1960).

The type of midges found in the Muskegon storage reservoirs appear to be representative of a normal lagoon fauna. In a study of 18 Missouri lagoons (Kimerle and Enns, 1968) G. barbipes, C. plumosus, and Tanypus punctipennis comprised more than 94% of the total number of insects collected in all lagoons. T. punctipennis is in the same sub-family, Tanypodinae, as is P. culiciformis.

Based on Bureau of Vector Control records of larvae collected from 22 localities, nine species of chironomids are considered to be common inhabitants of lagoons in California. These species are Procladius sp., Cricotopus sp., G. barbipes, two species of Tanypus, and four species of Chironomus (Grodhaus, 1967).

Contrary to expectations, the oligochaetes never became established. Limnodrilus was found on only two occasions, both within the first four months of this two-year study. No other oligochaetes were recovered. The gastropods were represented only by Physa, which was found on two occasions. Leeches, namely Helobdella stagnalis, were noted in only one sample. The only other organisms that were recovered from the lagoons were immature insects. They were rare and included, in decreasing order of abundance, four other species of chironomids (Dicrotendipes modestus, Tantarsus lobatifrons, Parachironomus sp. and Cricotopus sp.); Trichoptera (Hydroptilidae, only in the West Lagoon, and 95% of them prior to wastewater discharge); Ephemeroptera (Baetidae, only in the West Lagoon prior to wastewater discharge) and Odonata (Coenagrionidae).

Species diversity indices were calculated for each station, using the monthly averages of the number of organisms in each species. As recommended by the United States Environmental Protection Agency (Weber, 1973), the Shannon-Weaver index was used to evaluate mean diversity (d) and the Lloyd and Ghelardi index, in which a broken stick model is used, was employed to determine equitability (e). This index of diversity is based on information theorgy and takes into account the number of species (i.e., richness of species) as well as the numerical distribution of individuals among the species (i.e., the relative importance of each species). The indices are presented in Table 4.

Organic pollution usually results in the depression of diversity in the biotic community, while relatively undisturbed environments have a higher diversity index. Aquatic ecosystems without environmental perturbations usually support communities having large numbers of species without individual species present in overwhelming abundance. Thus, if all individuals belonged to the same species, the diversity would be minimal; whereas if each individual belonged to a separate species the diversity would be maximal. Wilhm (1970) and Wilhm and Dorris (1968) report that values for (d) of less than 1 are usually obtained in heavily polluted aquatic environments, values between 1 and 3 in areas of moderate pollution, and values above 3 in unpolluted waters.

At stations E-1, E-5, W-1, and W-5, ($\bar{d}$) was much lower during the period of wastewater flow as compared with that during the period of no wastewater flow. At stations E-8 and W-9 the opposite was true. These stations, however, are farthest from the point of wastewater discharge in each lagoon. The hardest substrate was at E-8 and the deepest station was W-9, which was also the closest station to the inflow of the interception ditch water. W-9 probably received

TABLE 4. SPECIES DIVERSITY INDICES THE BENTHIC MACROINVERTEBRATE COMMUNITY

STATIONS		E-1	E-5	E-8	W-1	W-5	W-9
TIME PERIOD							
TOTAL STUDY	No. species	9	8	8	11	5	7
	d	0.89	1.93	2.27	1.56	1.29	0.56
	e	0.24	0.62	0.81	0.34	0.60	0.24
NO WASTEWATER FLOW	No. species	6	7	6	11	4	6
	d	1.09	2.34	1.39	1.66	1.30	0.66
	e	0.43	0.98	0.54	0.36	0.75	0.30
WASTEWATER FLOW	No. species	7	5	7	4	4	2
	d	0.64	1.47	2.40	0.47	0.32	0.89
	e	0.26	0.70	1.03	0.39	0.35	0.55

organisms that normally live in the ditch. These complicating factors must be taken into account when interpreting the meaning of the indices. In the East Lagoon ($\bar{d}$) increased as the distance from the point of discharge of wastewater increased. The low diversity indices in the West Lagoon, even prior to the inflow of wastewater, reflect the severity of the natural environment within this lagoon.

Equitability is calculated by evaluating the component of diversity that is due to the distribution of individuals within the species. This index is reported to be more sensitive than $\bar{d}$, and in fact very sensitive to even slight levels of degradation (Weber, 1973). Its range is normally from 0 to 1. Organic wastes reduce equitability below 0.5 and generally in the range of 0.0 to 0.3. Values between 0.6 and 0.8 are indicative of water not affected by oxygen demanding wastes. In the East Lagoon, equitability also increased as the distance from the point of wastewater discharge increased. This relationship held during the period of wastewater flow as well as during no flow. When the wastewater flow ceased, (e) increased at all stations in the East Lagoon. The relationships are not so clear for the West Lagoon. Equitability increased rather than decreased at W-1 and W-9 during the period of wastewater flow.

It may not be appropriate in this study to calculate diversity and equitability, to compare the results with those from historical work, and to compare the results during periods of wastewater flow to those during periods of no flow. The periods of flow and no flow were greatly unequal in time. Almost all reports in which ($\underline{d}$) and ($\underline{e}$) were used have been in studies with over 100 individuals per sample, in established lotic communities, and in communities receiving predominantly organic wastes. These conditions were not met in this investigation. Industrial wastewater, especially paper mill waste, accounts for 60% of the wastewater flow into the lagoons investigated. These lagoons also represent a new aquatic habitat, one which was not present just weeks prior to this investigation. They were man-made and covered with terrestial vegetation prior to September 1973. From the beginning, the East Lagoon has been a very heavily stressed aquatic environment. Colonization of the benthic community may take much longer, due in part to the relatively long generation time, than for the development of the planktonic community.

Zooplankton

A total of 392 zooplankton samples were analyzed during this investigation. Fourteen species of free-living crustaceans and four species of rotifers were found to compose the known zooplankton community of the Muskegon Wastewater Storage lagoons (Table 5). Due to their small size, a portion of the rotifers may have escaped capture and therefore they are included only in the qualitative and not in the quantitative analysis.

Although there was considerable fluctuation in numbers, and various taxa were dominant throughout this investigation, certain trends can be noted. The zooplankton population remained at a minimum during both winters of investigation, rose during the spring and summer, and peaked in late July to early August. In the lagoon receiving wastewater during the spring and summer, there was a more rapid decline in the population after the summer maxima than in the lagoon not receiving the wastewater. During periods of ice cover, the abundance of zooplankton in the lagoon that received wastewater throughout both winters of study was less than that of the other lagoon. This phenomenon was apparently caused by the reduced DO levels during periods of ice cover.

Three species of *Daphnia* were routinely collected, *D. magna*, *D. galeata*, and *D. Pulex*. Large seasonal fluctuation were noted in this cladoceran (Figure 3).

TABLE 5. PERCENTAGE COMPOSITION OF ZOOPLANKTON

KEY

WW = Period of wastewater flow NWW = Period of no wastewater flow

TAXA		STATIONS							
		E-1	E-5	E-8	EAST, TOTAL	W-1	W-5	W-9	WEST, TOTAL
No. of samples		72	54	66	192	74	54	72	200
A. Copepoda, Cyclopoida	WW	44.2	32.3	52.0	41.0	52.3	49.5	55.8	52.0
	NWW	15.8	13.7	24.1	18.1	19.6	15.3	11.2	15.5
1. *Cyclops*	WW	30.0	21.1	34.5	27.3	45.9	44.3	41.5	43.9
	NWW	15.6	13.4	23.0	17.7	10.4	9.1	7.5	9.1
a. *C. vernalis*	WW	18.7	12.0	19.3	16.0	31.9	32.1	35.2	32.9
	NWW	12.6	11.7	17.2	14.0	5.1	5.2	2.5	4.4
b. *C. sp.*	WW	6.3	6.3	9.4	7.0	11.0	9.1	4.2	8.2
	NWW	2.2	1.4	5.1	3.0	4.4	3.4	3.1	3.6
c. *C. excilis*	WW	5.0	2.9	5.8	4.3	3.0	3.1	2.0	2.8
	NWW	0.8	0.3	1.0	0.7	0.9	0.5	1.9	1.1

TABLE 5 CONCLUDED

TAXA		STATIONS							
		E-1	E-5	E-8	EAST, TOTAL	W-1	W-5	W-9	WEST, TOTAL
2. *Mesocyclops*	WW	14.2	11.2	17.5	13.7	6.4	5.2	14.5	8.1
	NWW	0.2	0.3	0.8	0.4	9.2	6.2	3.7	6.4
a. *M. edax*	WW	8.3	8.3	12.7	9.3	6.1	5.2	14.3	8.0
	NWW	0.2	0.3	0.7	0.4	6.3	3.9	3.6	4.6
b. *M.* sp.	WW	5.9	2.9	4.8	4.4	0.3	0.0	0.2	0.1
	NWW	0.0	0.0	0.1	0.0	2.9	2.3	0.1	1.8
c. *M. dybowskii*	WW	1.1	0.5	0.0	0.6	0.0	0.0	0.0	0.0
	NWW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
B. Copepoda, Calanoida									
1. *Diaptomus* (3 species)	WW	6.1	4.7	10.6	6.5	33.4	35.4	32.3	34.1
	NWW	24.9	28.3	35.0	29.6	27.4	25.3	23.9	25.6
C. Cladocera	WW	49.7	63.0	37.4	52.5	14.2	15.1	11.9	13.9
	NWW	59.3	58.0	40.9	52.3	53.1	59.4	64.9	58.9
1. *Daphnia* (3 species)	WW	49.3	63.0	37.2	51.3	14.1	15.1	11.8	13.9
	NWW	59.3	58.0	40.9	52.3	43.3	51.4	60.0	51.3
2. *Bosmina longirostris*	WW	0.2	0.0	0.0	0.1	0.0	0.0	0.0	0.0
	NWW	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.1
3. *Chydorus sphaericus*	WW	0.2	0.0	0.2	1.1	0.1	0.0	0.0	0.0
	NWW	0.0	0.0	0.0	0.0	9.8	7.6	4.9	7.5

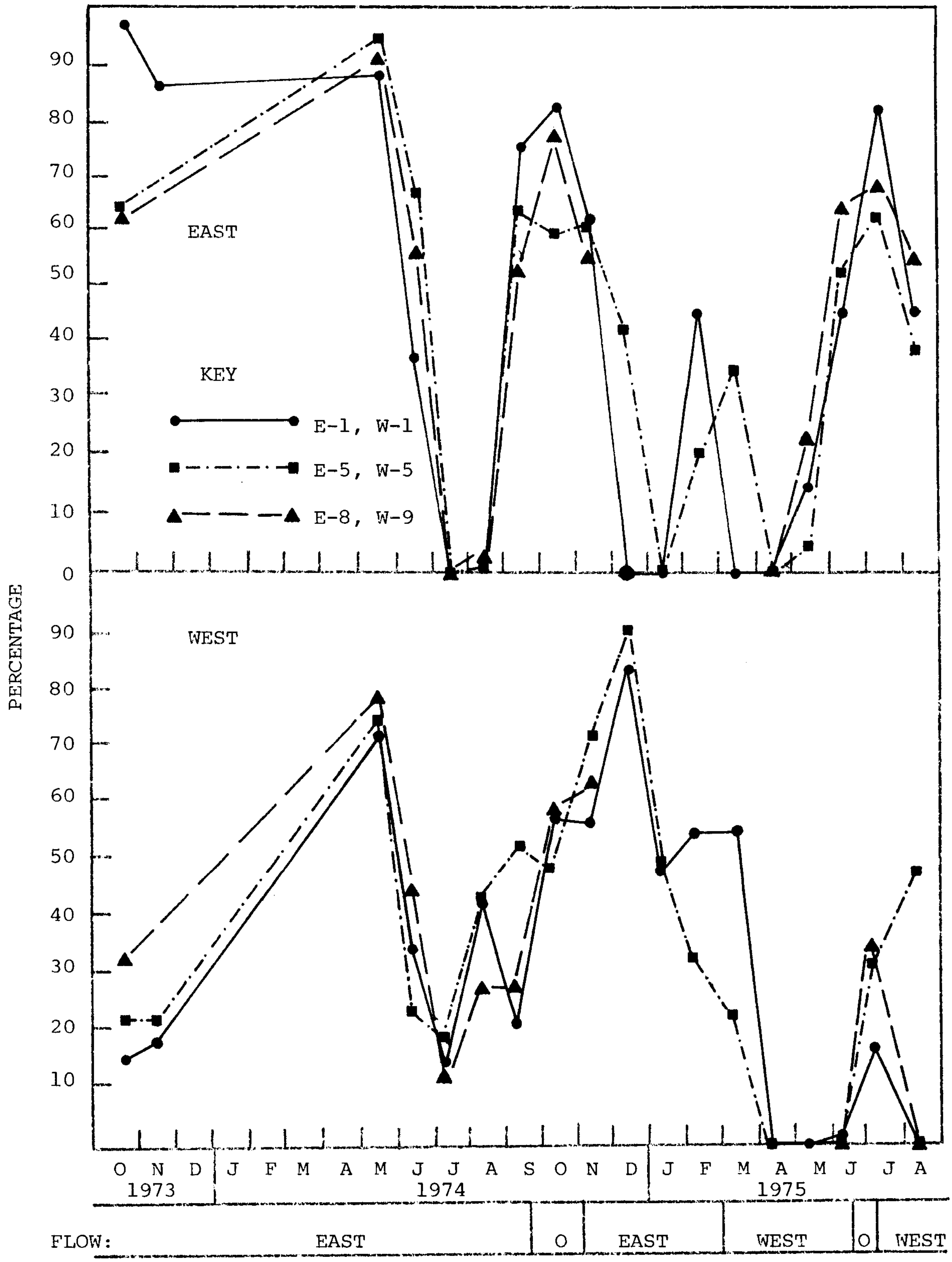

Figure 3. Daphnia as a percentage of the total zooplankton population

In the West Lagoon the fluctuations in the numbers of *Daphnia* were much less marked as the population remained below 100 *Daphnia*. The general trends in this lagoon, however, were quite similar to those in the East Lagoon.

Daphnia comprised 51% of the zooplankton in the East Lagoon during the 18 month period this lagoon received wastewater, and 52% during the period of no wastewater flow. The cessation of wastewater influent to this lagoon during the last six months of study had little apparent effect on the *Daphnia* assemblage. The population change in the West Lagoon before and during wastewater flow was somewhat different. During the 18 month period of no wastewater influent to this lagoon *Daphnia* accounted for 51% of the zooplankton. However, with the onset of wastewater discharge into this lagoon, the abundance of this cladoceran declined, comprising only 14% of the zooplankters during the remaining six month period. This may be due to the dramatic change in water quality with the onset of wastewater discharge as compared to the slow recovery after the cessation of wastewater inflow.

The only other cladoceran commonly recovered was *Chydorus sphaericus*. This cladoceran comprised 7.5% of the total zooplankton in the West Lagoon during the period of no wastewater flow, but was virtually eliminated during the period when wastewater was discharged into this lagoon. The greatest abundance of *C. sphaericus* was noted during August and September 1974 when about 20 per liter were recovered. This cladoceran never became a common form in the East Lagoon. *Bosmina longirostris* remained scarce in both lagoons throughout this investigation.

Cyclopoid copepods were more common during the period of wastewater flow than during the period of no flow (Figure 4). In the East Lagoon during the first 18 months of study, cyclopoids accounted for 41% of the zooplankton population, but when the discharge of wastewater to this lagoon ceased, their abun-

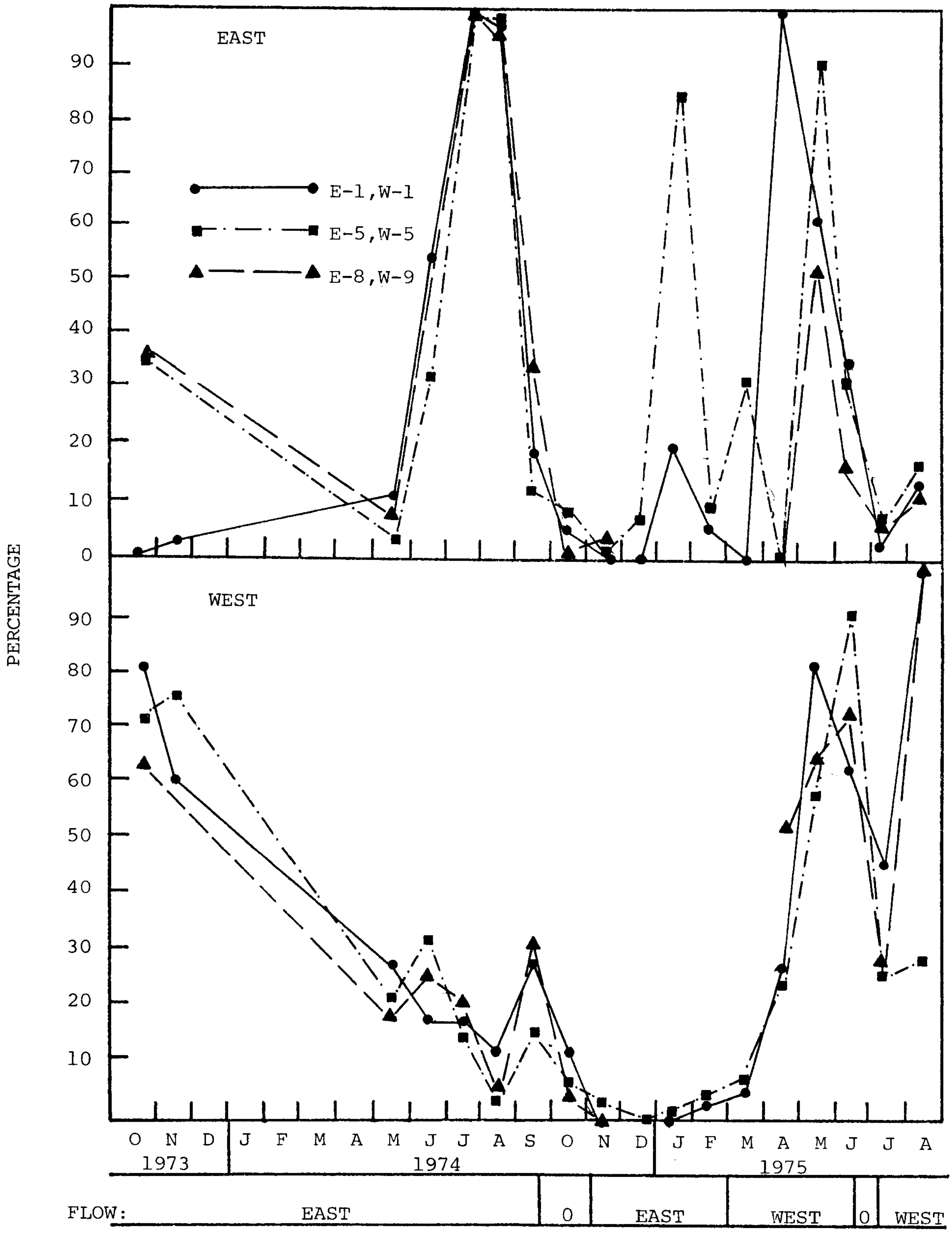

Figure 4 Cyclopoid copepods as a percentage of the total zooplankton Population

dance dropped to 18% of the population. Similarly, cyclopoids comprised only 15% of the zooplankters during the period of no wastewater flow into the West Lagoon. They rapidly increased in number during the last six months of study when wastewater was discharged into this lagoon and comprised 52% of the zooplankton during this time.

Cyclops vernalis remained the dominant cyclopoid throughout this study. The abundance of this cyclopoid was also greater during periods of wastewater flow than during no flow. An abundance of over 50 C. vernalis per liter was common during the summer months. Mesocyclops edax was a common cyclopoid, followed in decreasing order of abundance by C. sp., C. excilis, and M. sp. Mesocyclops dybowskii remained scarce.

Cyclopoid copepods were most common from May through September during both years of investigation. The population quickly plunged after September, remained at a minimum throughout both winters, and increased rapidly during May.

Diaptomus was the only common calanoid copepod noted during this study. The seasonal population fluctuations of this copepod were very similar to the cyclopoid fluctuations. The abundance of Diaptomus increased greatly after the elimination of wastewater flow into the East Lagoon in March 1975. During the summer of 1974, the Diaptomus population in the East Lagoon generally remained below 10 per liter, but during the summer of 1975 an abundance of over 100 was frequently noted. The abundance of this calanoid also increased in the West Lagoon during the summer of 1975, although not as much as in the East Lagoon.

The shifts which occurred in the cyclopoid population upon alteration of the direction of wastewater flow correspond well to the general trend for changing zooplankton composition as waters go from oligotrophic to eutrophic. The proportion of calanoids decreases while the predominance of cyclopoids increases (Patalas, 1972).

Rotifers appeared to form only a minor component of the lagoon zooplankton. Because rotifers are largely sessile organisms and are associated with substrata (Wetzel, 1975), they are mostly littoral inhabitants. Rotifers are commonly found only in waters of low organic content, for they require an environment containing several mg/l of DO. In these respects, the Muskegon lagoons do not appear to offer a favorable environment. However, the diet of rotifers consists primarily of bacteria and small algae, and may also include small organic particles. A rich food source appears to exist in these reservoirs for the rotifers. Filinia longiseta was recovered only during the first few months of study. Keratella quadrata, Brachionus calyciflorus, and B. urceolares were rare forms during the first year but were more common during the second. It has been suggested that certain algae, such as some species of Chlorella, may be inhibitory to planktonic rotifers (Hutchinson, 1967). Chlorella was a major component of the phytoplankton throughout the first year of this investigation, but rapidly diminished in numbers after that time.

K. quadrata was common in most of the collections from December 1974 through June 1975. A slight increase in abundance was noted during the period of wastewater discharge to this lagoon. It was surprising to note K. quadrata, a cold stenothermic form, as a common taxa in June.

It is apparent that at times zooplankton, as a result of direct cropping, can have appreciable effects on phytoplankton populations. Through selective grazing, they can influence the seasonal succession of the phytoplankton (Wetzel, 1975). There does not appear to be any clear relationship between the zooplankton and phytoplankton populations in the Muskegon lagoons, however. This could be caused partly by the methods used to enumerate the zooplankton and phytoplankton since numbers were determined and not biomass. There are several other difficulties in determining a relationship among the plankters. There is a difference in the digestibility of the various algae, depending upon the thickness and other properties of the cell wall.

A major component of the zooplankton was composed of cyclopoid copepods. The two genera present, Cyclops and Mesocyclops, are largely carnivorous forms. The food of these carnivores in the Muskegon lagoons included microcrustaceans and dipteran larvae, and therefore they had little direct effect upon the phytoplankton. Although the collection of fine particles appeared to be a prevalant mode of nutrition for the calanoid copepods, they also seize small animals, especially other zooplankton (Mullin, 1966). In the Muskegon lagoons the filter-feeding Daphnia probably consume the greatest quantities of algae, particularly the unicellulars. Daphnia are among the most efficient filter-feeders of the zooplankton (Brooks, 1969), and show a preference for Chlorella vulgaris and C. pyrenoidosa (Hutchinson, 1967). If it is desirable to reduce the algal content of the lagoon effluent, studies on the Daphnia assemblage should be continued.

With the absence of predators by planktivorous fish, the small planktonic herbivores such as the rotifers and Bosmina will continue to be reduced competitively in numbers by the larger more efficient food gathering zooplankton. Thus, it appears that Daphnia and Diaptomus will continue to be among the dominant zooplankton of the Muskegon lagoons. The blue-green algae inhibit either mechanically or chemically the filtering rate of these zooplankton (Saunders, 1969). Since the dominant zooplankton do little grazing upon the Cyanophyta, an increase in the abundance of Daphnia and Diaptomus may give a competitive edge to the blue-green algae over other algal forms.

Plankton

A total of 541 samples were analyzed, identified, and enumerated during this two year investigation. Perhaps the most striking feature of these data is the extreme variability of this assemblage, both with respect to total abundance and to the distribution of particular entities (Figure 5). This variability is attributed to the diverse assemblage of organisms with differing physiological requirements and variations in terms of limits of tolerance to physical and chemical environmental parameters.

Plankton trends and dominants

The percentage composition of this group is found in Table 6. Although the water quality differed greatly between the two lagoons because of the discharge of wastewater into only one lagoon, the green algae clearly dominated the plankton population of both lagoons during the first year of study. It is interesting to note that the percentage of this population comprised of green algae increased in the East Lagoon as the distance from the point of wastewater discharge increased.

Several Chlorophyta blooms were noted during the winter, spring, and summer of 1974 (Figure 6). After the August 1974 pulse, the green algae population rapidly plummeted and remained reduced in number during the rest of this study. Smaller numbers of the three most abundant green algae, *C. vulgaris*, *C. pyrenoidosa*, and *Chlamydomonas* spp., account for most of this reduction in the Chlorophyta population. These species were frequently the cominant forms during the first year of study, but were only common components of the green algae during the second. Their continued presence is important,

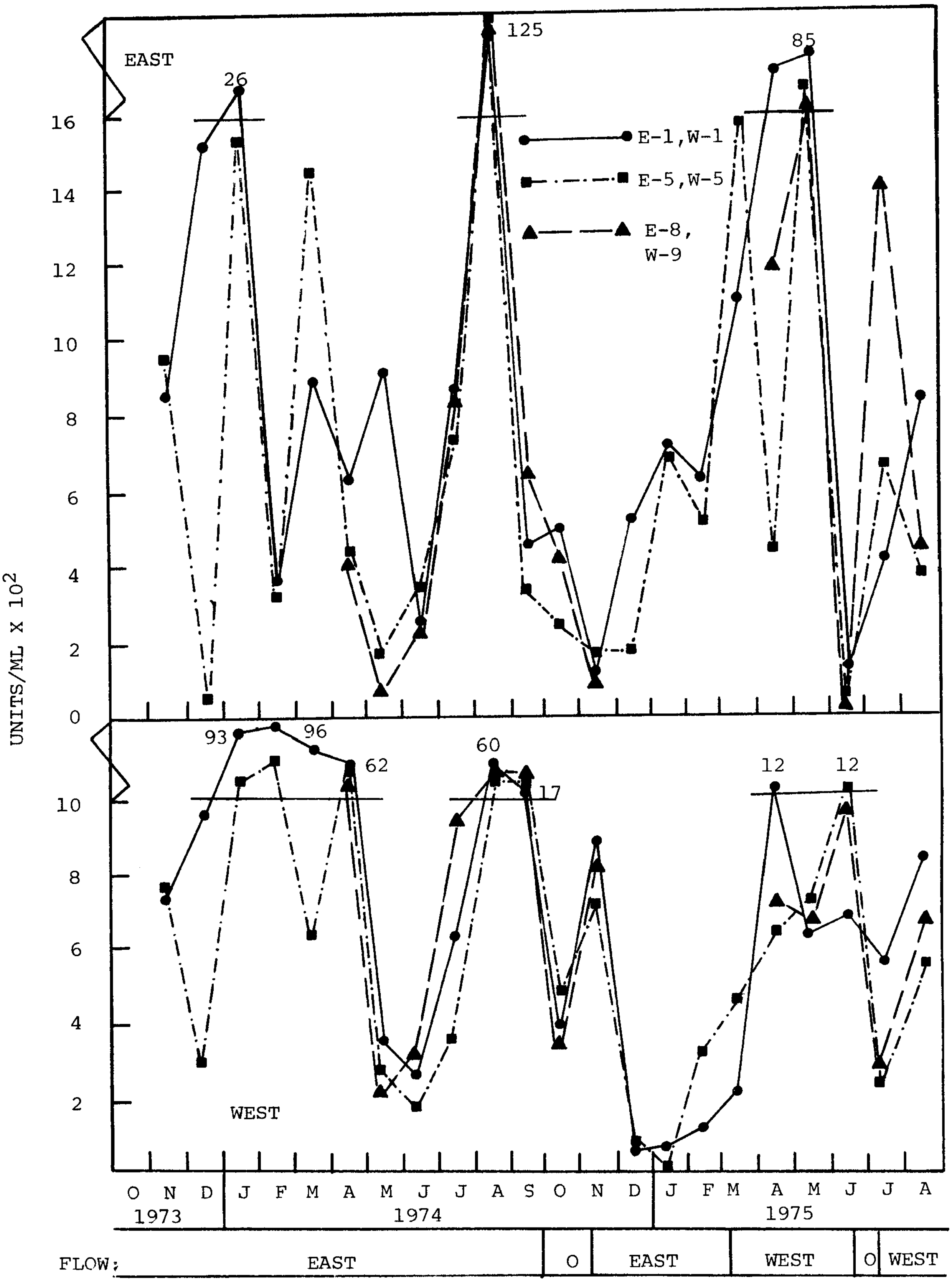

Figure 5 Number of Plankton in the Muskegon Lagoons

TABLE 6. PERCENTAGE COMPOSITION PLANKTON

KEY

WW = Period of wastewater flow NWW = Period of no wastewater flow

TAXA		STATIONS							
		E-1	E-5	E-8	EAST, TOTAL	W-1	W-5	W-9	WEST, TOTAL
No. of samples		103	70	98	271	100	70	100	270
A. Chlorophyta, Chlorophceae	WW	38.5%	46.5%	66.8%	53.4%	11.9%	10.0%	14.9%	12.5%
	NWW	5.3	14.4	11.4	8.4	82.2	41.3	68.0	72.3
B. Cyanophyta, Myxophyceae	WW	4.7	6.2	2.9	4.2	7.9	7.0	5.8	6.9
	NWW	17.3	19.7	15.6	17.3	11.1	34.7	18.5	16.6
C. Chrysophyta,	WW	21.1	27.0	10.3	17.0	16.2	19.1	23.2	19.6
Bacillariophyceae	NWW	2.3	9.3	5.7	4.4	3.1	7.2	6.1	4.4
1. Pennate	WW	0.4	0.8	0.6	0.6	6.5	7.0	13.6	9.3
	NWW	0.2	0.2	1.2	0.5	0.8	1.4	1.4	1.0
2. Centric	WW	20.7	26.2	9.7	16.4	9.7	12.1	9.6	10.3
	NWW	2.1	9.1	4.5	3.9	2.3	5.8	4.7	3.4
D. Euglenophyta,	WW	6.5	5.4	2.3	4.3	10.8	4.8	5.3	7.1
Euglenophyceae	NWW	1.5	4.7	2.5	2.3	0.6	2.7	2.3	1.4

TABLE 6 CONCLUDED

TAXA		STATIONS							
		E-1	E-5	E-8	EAST, TOTAL	W-1	W-5	W-9	WEST, TOTAL
E. Ciliophora	WW	9.5	2.8	3.7	5.4	27.2	11.7	6.3	15.2
	NWW	0.3	1.5	1.3	0.8	0.9	0.9	1.3	1.0
F. Mastigophora	WW	20.4	12.2	13.9	15.7	26.0	47.3	43.8	38.6
	NWW	73.1	50.3	63.4	66.8	2.1	13.2	4.0	4.3

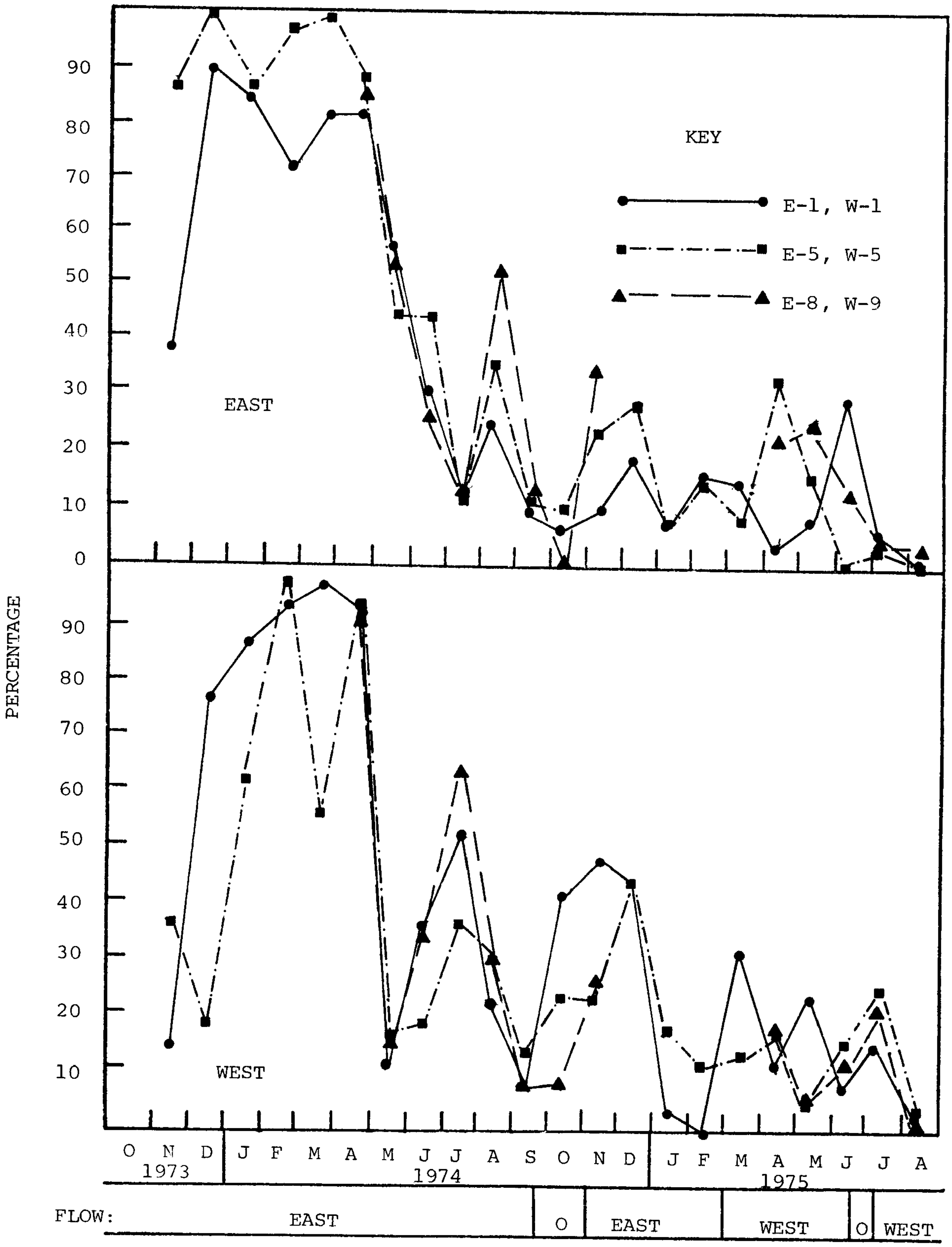

Figure 6 Chlorophyta as a percentage of the total plankton population

since they are significant in maintaining a desired free oxygen level in the lagoons, especially during periods of ice cover when the numbers of other oxygen producers are greatly reduced. It appears that C. vulgaris, C. pyrenoidosa, and Chlamydomonas spp. will remain common forms in the Muskegon lagoons in the future. These algae have been among the first genera to have become established in other lagoons worldwide, and they have remained typical components of the Chlorophyta throughout the year (Davis, 1964; Davis, et al, 1964; Gloyna, 1971; Jayangoudar and Ganapati, 1964; Potten, 1972; Raschke, 1968, Silva and Papenfuss, 1953).

The above authors also cite Ankistrodesmus and Scenedesmus as common lagoon phytoplankton. In the Muskegon lagoons, these genera together with Golenkina and Pediastrum were common green algae during the summer months.

The Cyanophyta were more abundant during periods without wastewater discharge than during periods of wastewater flow. During the first 18 months of study, when wastewater was discharged into the East Lagoon, the blue-greens accounted for 4.2% of the population in the East Lagoon and 16.6% in the West Lagoon. During the next six months, when wastewater was discharged into the West Lagoon, the blue-greens comprised 17.3% of the protistan population in the East Lagoon and 6.9% in the West Lagoon.

O. rubescens was the dominant blue-green in late spring, followed by Anabaena spp. in early summer. A.(Microcystis) aeruginosa and A. flos-aquae bloomed in late summer. Although not numerically dominant, A. (Chroococcus) dispersus and A. (Chroococcus) minor were common cyanophytes throughout the year.

Greater numbers of diatoms, euglenophytes, and ciliophores were noted during periods of wastewater flow than during those periods without. The only diatom noted by Gloyna (1971) as being typical of the lagoon biota was

Nitzschia. N. palea is also the only diatom included in a list of over 200 organisms common in trickling filters (Cooke, 1967). The four dominant centric diatoms in the Muskegon lagoons are all common representatives of the diatom population in eutrophic waters (Hutchinson, 1967; Schelske and Roth, 1973).

Euglenophytes were noted in greatest abundance during the summer months, decreased during the fall, remained at or near zero during ice cover, and increased in numbers during the spring. Trachelomonas, Euglena, and Phacus were the principal euglenoids in the Muskegon lagoons. The latter two genera are common dominants of the Euglenophyta in other lagoons (Davis, et al, 1964; Gloyna, 1971) whereas all three genera are common in polluted waters rich in nitrogenous organic compounds (Hutchinson, 1967).

During the winter months, the ciliophore population was at or near zero in the lagoon not receiving wastewater but was near the summer maximum in the lagoon that was receiving wastewater. Cyclidium, Glaucoma, and Vorticella were dominant. The latter genus is often the dominant protozoan present in secondary wastewater effluent (Yarma, et al, 1975), and all three genera are common Ciliophora in trickling filters (Cooke, 1967). These three genera can grow well in greatly reduced oxygen or anaerobic conditions (Wetzel, 1975). This microaerophillic ability allows for their development in the organic-rich and polluted lagoons, even during periods of ice cover when free oxygen was almost lacking.

The ciliophores of the Muskegon lagoons apparently feed mainly on algae and supplement this nutrition by feeding on bacteria and particulate detritus. Due to their small size and limited numbers, however, the ciliophores are not expected to have appreciable effects on the algal population in the Muskegon lagoons.

The abundance of mastigophores was not noted to be related to the direction of wastewater flow, but rather greater numbers were present in both lagoons during the spring and summer of 1975 (Figure 7). *Bodo*, *Chilomonas*, *Trimastigamoeba*, *Chroomonas*, and *Cryptomonas* were the common microflagellates. Several monad blooms were noted in the East Lagoon during the last six months of study while *Trimastigamoeba* and *Bodo* remained common in the West Lagoon.

Implications of lagoon plankton --

The plankton remove a good portion of the various nutrients and trace elements from the lagoons by incorporating them into protoplasm. Research of many workers has shown that these organisms can accumulate more of these substances than they need for growth (Patrick, 1969). This luxury consumption results in this group exerting a significant effect on the improvement of water quality in the lagoons. However, the use of a biological-lagoon system alone can not be expected to be a dependable method of water pollution control at this time. It appears that this community will remain rather unstable and will experience population pulses and crashes, as well as seasonal changes. These large fluctuations hinder the system's manageability. Other difficulties also exist. Upon death, the protistan cells sink to the bottom, retaining nutrients and trace elements within the water body. Harvesting of the concentrated components, in the form of live or dead protistan cells, is not yet feasible. The food web in the Muskegon lagoons is not complex enough to control the periodic protistan blooms.

Chlorophyll *a*

In aquatic plants, as in terrestial plants, chlorophyll is the initiator

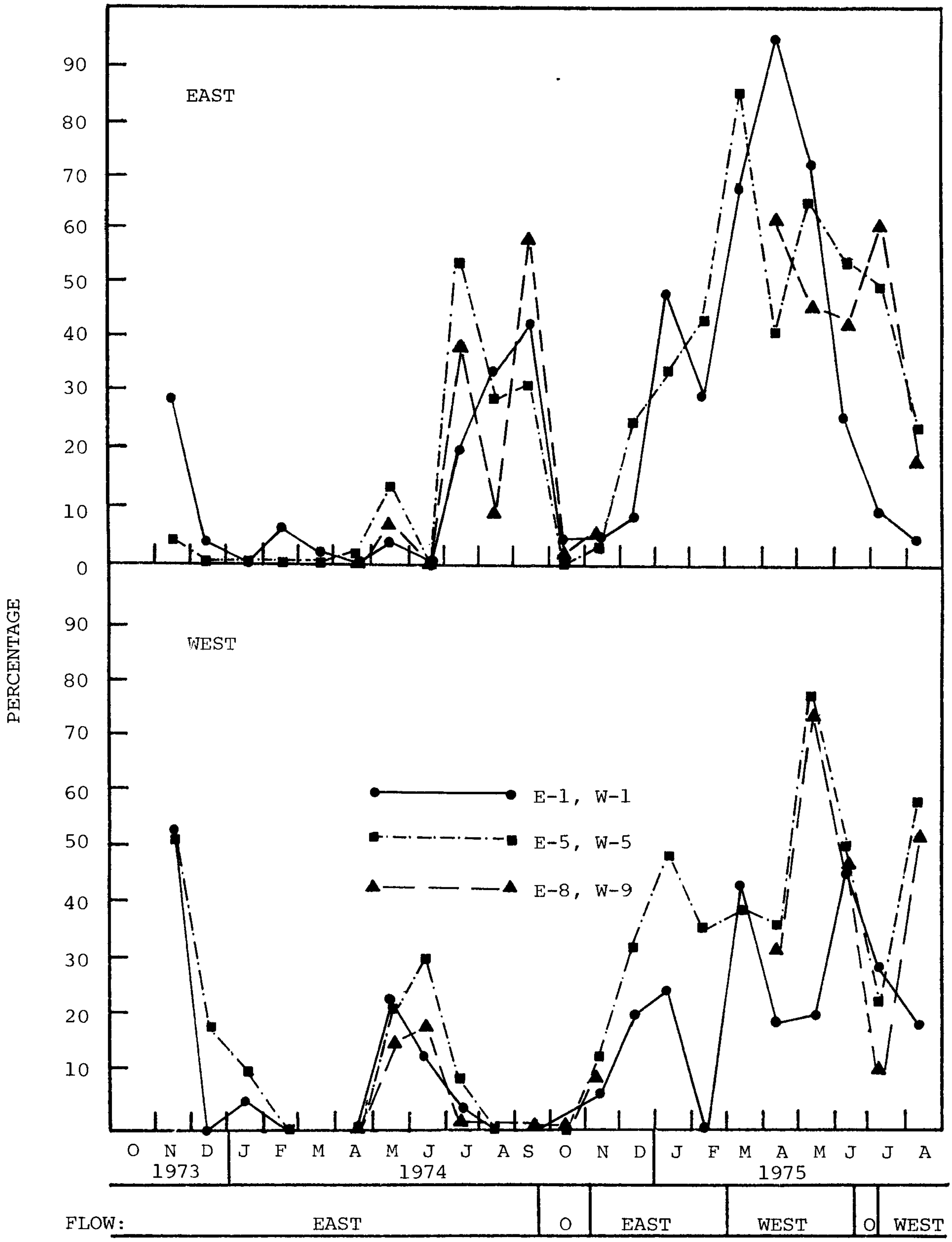

Figure 7 Mastigophora as a percentage of the total plankton population

in a series of physical-chemical changes which are responsible for the culmination of the flora and fauna. Due to chlorophyll's importance in photosynthesis, chlorophyll measurements may be used as indirect indices of potential productivity (Prescott, 1962; Odum, 1971). Since the amount of chlorophyll increases in bodies of water as the water becomes more eutrophic, chlorophyll measurements may also provide comparative data on eutrophication (Mackenthun, 1973). Chlorophyll _a_ is the most abundant and important pigment in algae (Vollenweider, 1974) and hence was measured.

A total of 574 chlorophyll _a_ samples were analyzed during this investigation. As indicated in Figure 8, there was a great deal of variability in the quantity of chlorophyll _a_ present in the Muskegon lagoons. Although a few of the chlorophyll _a_ peaks occurred during algal blooms, in general a clear relationship between the two parameters was not evident.

During the winter of 1973-1974 a major peak occurred in the level of chlorophyll _a_ in the West Lagoon but not in the East Lagoon. On 13 February 1974, 43 mg/m^3 of this pigment were present at W-1, and 58 mg/m^3 at W-9. On this date the algal population was approximately 9,400 units/ml at W-1 but only 4,400 at W-9. By 27 February 1974 the level of chlorophyll _a_ increased to 56 at W-1 and decreased sharply to 9.7 at W-9, yet the number of phytoplankton remained fairly constant at W-1 and increased sharply to over 11,000 at W-9. Since the environmental conditions did not fluctuate greatly during this two week period and because the same species, _C. vulgaris_, was dominant, it appears that the viability of the algal cells varied during this period. Due to this large variation in a short period of time, the use of chlorophyll measurements as indices of productivity, biomass and/or eutrophy should be cautioned, at least in the Muskegon lagoons.

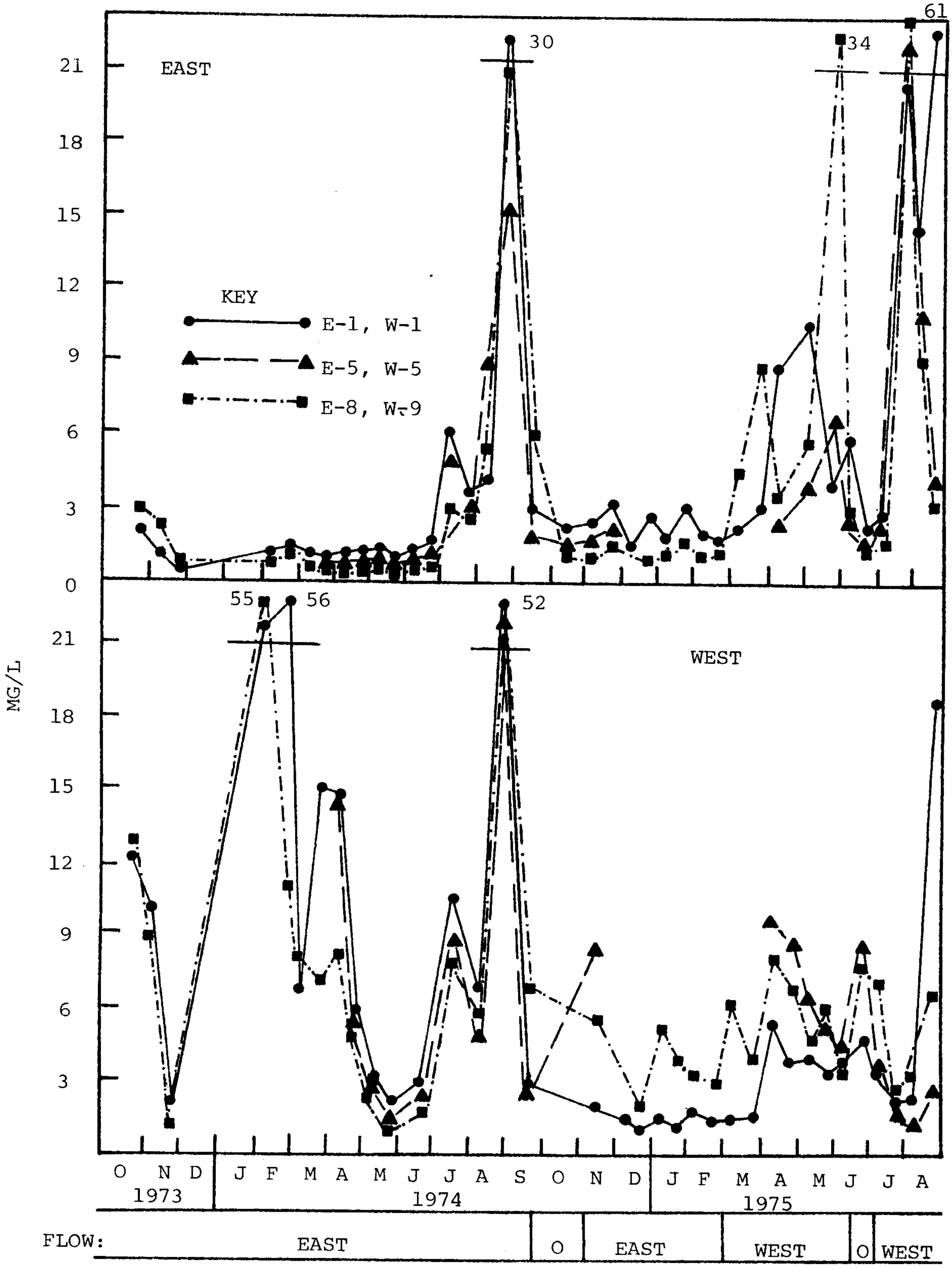

Figure 8 Quantity of chlorophyll a in the Muskegon Lagoons

No peak in chlorophyll a was noted in the East Lagoon during ice cover in 1974, although a green algae pulse did occur. During August 1974, a diatom and green algae bloom in the East Lagoon and a blue-green algae bloom in the West Lagoon were reflected in chlorophyll a pulses. The concentration of chlorophyll a again peaked in both lagoons during August of the following year, although no phytoplankton bloom was noted at this time.

The levels of chlorophyll a are not exceedingly high compared to natural waters. Caution must be exercised, however, in making comparisons since the quantity of chlorophyll per unit of algae present is influenced by various environmental, nutritional, and internal factors as well as the species and age or viability of the algal cells present (Vollenweider, 1974; Weber, 1973).

Primary productivity

The basic aim of these measurements was to provide an estimate of the quantity of organic matter which was produced from inorganic substances within the lagoons. It is assumed that during photosynthesis one molecule of oxygen is released for each atom of carbon assimilated (American Public Health Association, et al, 1976). These measurements, therefore, also provided information concerning the rate of oxygen production, an important consideration in the heavily stressed lagoon environment.

As shown in Figure 9 , there was a great deal of variability in the primary productivity in the Muskegon lagoons, and, as was the case with chlorophyll a and the plankton population, there was little similarity from one year to the next, with greater values occurring in 1974 than in 1975. During 1974 the rates of carbon fixation ranged from lows of less than 1 mg $C/m^3/hr$ during spring in both lagoons to highs in August of 137 in the East Lagoon and 126 in the West Lagoon. The maxima occurred concurrently with the summer 1975 highs for chloro-

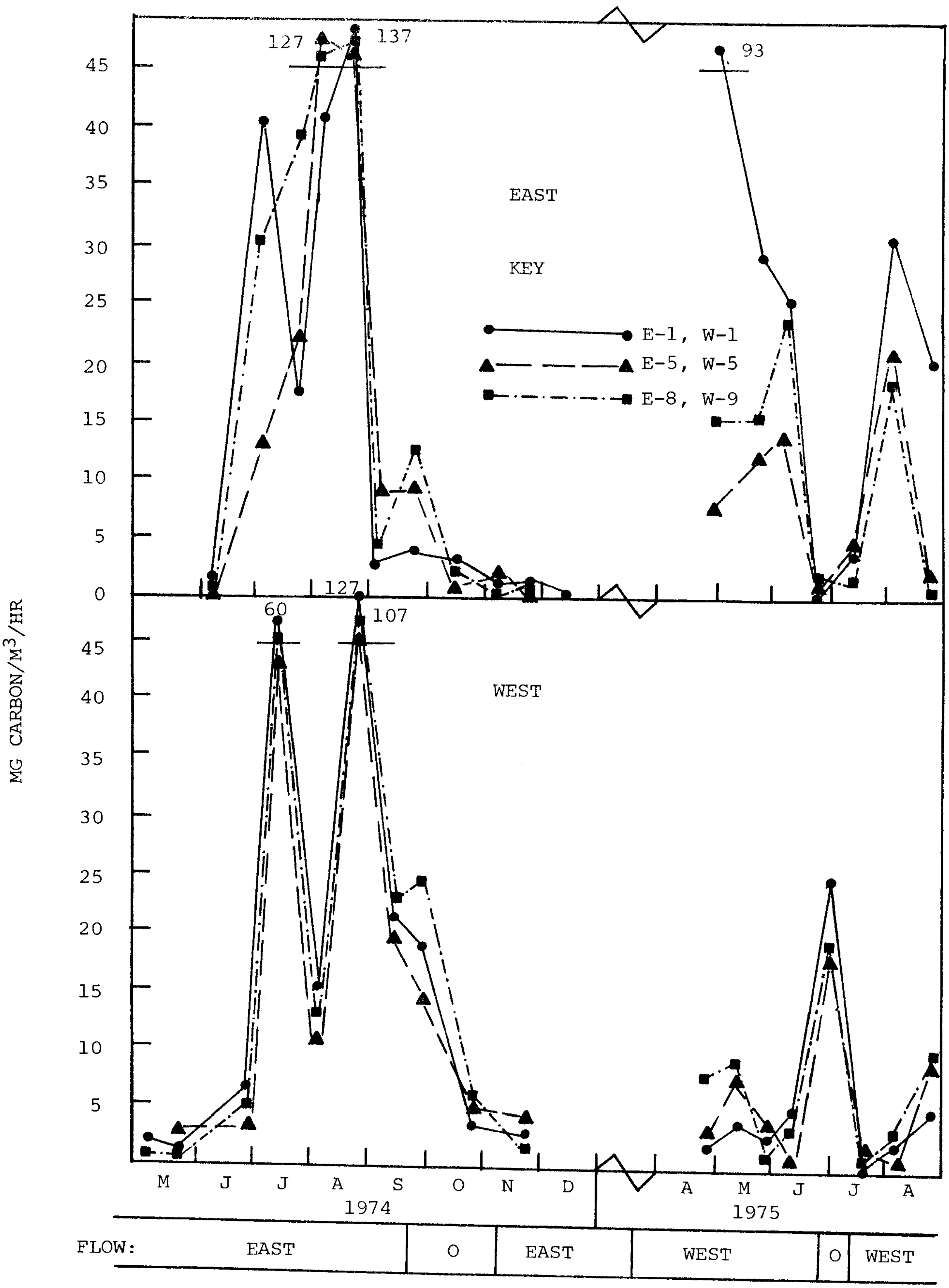

Figure 9 Primary productivity in the Muskegon Lagoons

phyll *a* levels or number of phytoplankton.

PHYSICAL AND CHEMICAL PARAMETERS

Dissolved oxygen

Only minor differences in DO concentrations were noted with depth. This homogeneous distribution with depth was apparent in most of the physical and chemical parameters investigated, and indicates a lack of stratification in the Muskegon lagoons. The shallowness of the lagoons, combined with wind action, aided in keeping the waters vertically mixed.

Dissolved oxygen is one of the more indicative and affected parameters of biological interactions in aquatic systems. The DO levels in the lagoon receiving wastewater consistently remained lower than those levels in the other lagoon, with the exception of several weeks following the change in direction of wastewater flow in March 1975 (Table 7). During the first few months of investigation the DO levels at E-1, the station nearest to the point of wastewater discharge in the East Lagoon, were much lower than at E-8. During the same time period, BOD_5 and ammonia nitrogen were much higher at E-1 than at E-8. By February, these large differences between stations had decreased and the DO had dropped at E-8. The distribution of DO remained more uniform between stations in most subsequent samples.

During the first 18 months of study, free oxygen was never abundant in the East Lagoon. Peak values were noted only in October and November 1974 when the wastewater was used directly as irrigation-water rather than being discharged into the lagoon. At this time DO values of 7 mg/l were common, whereas during the other 16 months of wastewater flow, 4 mg DO/l and less were frequent in the East Lagoon. There were three periods of especially low DO in this lagoon, during ice cover of 1974 and 1975 and during the summer of

TABLE 7. COMPARISON OF TEMPERATURE, DISSOLVED OXYGEN, AND BIOCHEMICAL OXYGEN DEMAND IN THE MUSKEGON LAGOONS. DATA ARE PRESENTED AS THE MONTHLY MEAN ± ONE STANDARD DEVIATION.

KEY

TEMP = Temperature, ^{o}C = Dissolved Oxygen, mg/l BOD = Five Day Biochemical Oxygen Demand, mg/l

DATE	LAGOON					
	EAST			WEST		
	TEMP	DO	BOD_5	TEMP	DO	BOD_5
10-73	10.3 ± 0.3	3.1 ± 1.9	14.7 ± 13.3	10.0 ± 0.0	8.4 ± 0.2	3.7 ± 2.5
11	8.7 ± 0.8	6.7 ± 4.0	23.7 ± 23.0	8.6 ± 0.9	11.3 ± 0.7	2.2 ± 0.3
12	0.8 ± 0.3	3.7 ± 2.5	34.5 ± 27.5	0.5 ± 0.0	11.3 ± 0.1	6.5 ± 0.7
1-74	1.6 ± 1.0	2.3 ± 2.3	13.1 ± 5.9	0.5 ± 0.7	12.2 ± 0.7	7.0 ± 0.0
2	1.9 ± 0.5	0.2 ± 0.1	16.9 ± 3.4	0.8 ± 0.3	11.5 ± 0.3	6.5 ± 3.1
3	3.4 ± 0.6	5.1 ± 0.6	16.7 ± 1.4	2.3 ± 1.1	13.7 ± 0.9	4.9 ± 0.5
4	10.5 ± 2.4	2.8 ± 0.7	12.2 ± 7.3	9.3 ± 4.7	9.4 ± 0.3	5.8 ± 1.4
5	15.8 ± 2.4	2.1 ± 0.2	12.5 ± 3.3	13.5 ± 3.5	7.7 ± 0.5	3.2 ± 0.1
6	10.8 ± 0.0	2.1 ± 1.0	31.3 ± 3.4	23.3 ± 0.7	5.4 ± 0.2	7.3 ± 1.2
7	25.6 ± 1.9	0.0 ± 0.1	17.4 ± 4.7	25.6 ± 0.2	6.4 ± 0.3	3.6 ± 0.9

TABLE 7 CONCLUDED

DATE	LAGOON					
	EAST			WEST		
	TEMP	DO	BOD_5	TEMP	DO	BOD_5
8-74	24.9 ± 0.1	2.0 ± 1.6	13.5 ± 5.1	23.1 ± 0.2	9.1 ± 0.3	3.0 ± 0.4
9	16.5 ± 4.2	2.5 ± 1.5	4.1 ± 1.0	17.0 ± 3.5	8.0 ± 0.3	3.4 ± 0.3
10	12.0 ± 0.0	7.4 ± 0.4	5.6 ± 2.3	9.0 ± 0.0	10.6 ± 0.2	2.3 ± 0.2
11	8.0 ± 2.8	7.6 ± 0.7	5.1 ± 1.5	7.5 ± 2.1	10.9 ± 0.2	4.6 ± 3.0
12	3.0 ± 2.8	4.8 ± 0.4	21.3 ± 8.9	0.6 ± 0.5	11.7 ± 0.3	4.3 ± 1.2
1-75	1.3 ± 1.8	6.1 ± 2.5	17.7 ± 8.4	0.6 ± 0.9	12.3 ± 0.1	5.3 ± 0.3
2	2.3 ± 0.3	0.4 ± 0.1	16.7 ± 5.9	0.9 ± 0.5	9.1 ± 2.5	2.6 ± 0.1
3	1.7 ± 1.4	0.6 ± 0.1	17.7 ± 0.4	1.5 ± 0.3	4.1 ± 2.6	10.2 ± 6.6
4	11.2 ± 0.8	6.3 ± 0.4	8.1 ± 0.3	10.2 ± 3.5	5.0 ± 0.8	16.2 ± 7.7
5	20.0 ± 4.7	2.5 ± 0.4	20.0 ± 1.0	19.9 ± 6.0	1.0 ± 0.1	10.9 ± 6.7
6	21.3 ± 2.3	4.0 ± 0.1	8.1 ± 3.0	22.6 ± 2.2	1.2 ± 0.6	8.8 ± 5.6
7	28.3 ± 1.7	5.4 ± 0.2	3.8 ± 0.5	27.3 ± 1.0	1.0 ± 0.4	10.9 ± 1.3
8	23.0 ± 2.8	6.1 ± 0.7	3.7 ± 1.0	23.5 ± 3.5	0.7 ± 0.1	15.4 ± 4.5

1974. During these periods less than 1 mg DO/1 was frequently noted, especially at E-1. After the cessation of wastewater flow to this lagoon in March 1975, the DO levels slowly increased and a summer minimum did not occur in the East Lagoon in 1975.

The oxygen demanding wastes in the heavily stressed East Lagoon environment masked any DO pulses that may have occurred due to phytoplankton blooms. Such was not the case in the West Lagoon that did not receive significant amounts of wastewater until March 1975. A green algal bloom in this lagoon during ice cover in 1974 kept the DO levels at or near saturation during this period. A decline in DO was noted as the water temperature rose and the phytoplankton population decreased greatly during the spring. A minimum of 5.5 mg DO/1 was reached in June, coinciding with the smallest phytoplankton population in the West Lagoon during this study. The DO levels increased to over 9 during the blue-green algal bloom in August, and remained near saturation until March 1975. The DO levels in the West Lagoon quickly plummeted when wastewater flowed into this lagoon, and from May through August 1975 remained close to 1.

Although periods of low DO were noted in the Muskegon lagoons, on the whole they remained aerobic. It appears that this situation will continue and possibly the DO minima will become less severe as the phytoplankton assemblage becomes better acclimatized to this wastewater lagoon environment and become more diverse.

Biochemical oxygen demand (BOD_5)

Because of the high amount of organic matter in wastewater, the BOD_5 was consistently greater in the lagoon receiving wastewater than in the other lagoon (Table 7). Similar to the situation for DO, there were large differences in the BOD_5 at E-1, 5, and 8 during the first several months of this study. By February, however, the wastewater constituents had obtained a more homogeneous distribution within this lagoon and smaller differences in BOD_5 from station to station were noted.

Large variations in BOD_5 through time were apparent, especially in the East Lagoon. The levels at E-1 initially increased to a high of 54 mg/l by December 1973, but then quickly plummeted to 17 early in January. BOD_5 remained near this level for the next four months throughout the East Lagoon before increasing to over 30 mg/l in June 1974. BOD_5 then decreased to its pre-June level for the next two months before reaching a minimum of 4.1 mg/l in September. At this time the direction of wastewater flow was directly to irrigation. From December through March BOD_5 remained near 20 mg/l and continued to fluctuate while on a general downward trend after the flow of wastewater to this lagoon ceased in March.

The fluctuations of BOD5 in the West Lagoon were not nearly as large and therefore a mean is more meaningful. During the 18 month period without wastewater flow to this lagoon, the mean was 4.48 mg/l $\pm$ 1.68. However, the BOD5 quickly increased when wastewater was discharged into the West Lagoon for the next six months. The mean BOD_5 during this period was 12.1 mg/l $\pm$ 3.0. BOD_5 was highest at W-1 compared to W-5 and 8 because of this station's proximity to the point of discharge.

Temperature

Water temperature followed air temperature in a normal manner, with little response to transient climatological phenomena (Table 7). Thermal stratification was not evident which indicated vertical mixing.

Generally, temperatures were slightly greater in the lagoon receiving wastewater. This relationship was most evident at the station nearest the point of wastewater discharge. Heat budgets are complex and even just one phase of this budget, the absorption of solar energy by the lagoon water, is influenced by an array of physical, chemical, and, under certain conditions, biotic properties of the water. However, it appears that a combination of three factors, each taking on different importance during the year, account for the difference in temperature between the lagoons. The higher content of dissolved organic matter in the lagoon receiving wastewater increases the absorption of light energy. During cooler weather the temperature of the incoming wastewater was above ambient. Greater biological, especially microbial, activity occurred in the lagoon receiving wastewater.

Of greatest significance to the water quality and biological productivity of the lagoons is the fact that the water temperature maintained levels in the 20-24° C range over essentially a four month period each year.

Secchi disk transparency

The transparency in the East Lagoon during the period of wastewater flow was small and consistently remained much less than in the West Lagoon (Table 8). During this time period, the mean in the East Lagoon, 17.0 cm, was only 14.5% of the mean in the West Lagoon, 117.5 cm. The lowest values were at E-1 on all but one occasion, 9 August 1974. On this date the exit to the outlet lagoon (Figure 1) was open and it appears, from these and from other chemical data, that the incoming wastewater was not mixing completely with the lagoon wastewater but rather was short-circuiting directly to the outlet.

After the flow of wastewater was shifted to the West Lagoon in March 1975, the transparency slowly increased in the East Lagoon but rapidly plummeted in the West, especially at W-1.

TABLE 8. COMPARISON OF TURBIDITY, SECCHI DISK TRANSPARENCY, pH, CONDUCTIVITY AND TOC IN THE MUSKEGON LAGOONS. DATA ARE GIVEN AS THE MEAN ± ONE STANDARD DEVIATION.

KEY

WW = Period of wastewater flow   NWW = Period of no wastewater flow

PARAMETER		STATIONS					
		E-1	E-5	E-8	W-1	W-5	W-9
Turbidity	WW	17.3 ± 8.7	10.6 ± 7.0	12.0 ± 7.1	21.7 ± 2.9	6.9 ± 1.1	6.8 ± 2.0
	NWW	7.5 ± 2.0	6.4 ± 0.9	6.7 ± 1.1	3.1 ± 1.0	3.1 ± 1.0	3.1 ± 0.9
Secchi Disk	WW	14.4 ± 5.4	21.9 ± 5.1	21.7 ± 5.1	22.6 ± 8.0	24.6 ± 8.0	41.3 ± 21.0
Transparency, cm	NWW	27.3 ± 16.2	31.0 ± 10.0	31.2 ± 17.9	112.6 ± 32.9	121.5 ± 41.6	119.3 ± 36.0
pH	WW	7.69 ± 0.18	7.76 ± 0.13	7.77 ± 0.20	7.61 ± 1.40	7.68 ± 0.90	7.68 ± 0.08
	NWW	7.84 ± 0.32	7.86 ± 0.23	7.87 ± 0.30	8.13 ± 0.27	8.24 ± 0.38	8.18 ± 0.29
Conductivity,	WW	1030 ± 225	1170 ± 215	1010 ± 214	949 ± 117	954 ± 108	907 ± 137
micro-mho	NWW	1030 ± 85	1020 ± 91	1020 ± 94	776 ± 171	876 ± 129	754 ± 157
TOC, mg/l	WW	40.0 ± 13.3	35.6 ± 13.3	33.9 ± 8.4	73.0 ± 43.2	56.4 ± 49.1	64.2 ± 42.8
	NWW	54.8 ± 23.4	44.4 ± 18.9	49.2 ± 17.9	21.2 ± 4.5	20.9 ± 4.5	21.3 ± 8.3

No seasonal trends were evident and the plankton pulses did not appear to reduce transparency.

The limited transparency, and hence the rapid vertical extinction of light in the lagoon receiving wastewater, has several implications. The very narrow photic zone limits oxygen production and productivity, at least autotrophic productivity. It gives a competitive advantage to heterotrophic and mixautrophic organisms over the obligate photoautotrphs. Most phytoplankton fall into the latter category. The limited transparency excludes rooted aquatics, plants that could be managed and harvested more easily than the algae. It also excludes benthic algae and periphyton and is one of several factors keeping the lagoon food web or chain relatively short and unstable.

Turbidity

Turbidity was consistently greater in the lagoon receiving wastewater than in the other lagoon (Table 8). Values were similar at each depth and among stations in the same lagoon, with the exception of higher turbidity at stations E-1 and W-1. Fluctuations were noted, however, through time. During the periods of wastewater discharge, the range at E-1 was from 4.2 to 34 FTU and from 3.7 to 22 FTU at E-5 and 8, whereas the range at W-1 was from 14 to 34 and 4.0 to 10 at W-5 and 9. During the periods without wastewater discharge, the mean in the West Lagoon was 3.1 FTU $\pm$ 0.9 and 6.9 FTU $\pm$ 1.2 in the East Lagoon.

Since turbidity and transparency did not correspond with the fluctuating plankton population and because the lowest transparency and highest turbidity was at W-1 and E-1 during wastewater flow, it appears that suspended particulate matter such as clay, silt and finely divided organic and inorganic detritus, rather than aquatic organisms, exert the greater influence upon these parameters.

Conductivity

The specific conductance of both lagoons was quite high and remained greater in the East Lagoon than in the West Lagoon, even during the final six months of study when wastewater was discharged only into the latter lagoon (Table 8). The mean conductance during the first 18 months of study was 1020 micro-mhos $\pm$ 217 in the East Lagoon and 768 $\pm$ 156 in the West Lagoon. The mean in the West Lagoon increased to 925 $\pm$ 128, but remained at 1020 $\pm$ 86.7 in the East Lagoon during the final six months of study. As evidenced by the large standard deviation, a wide range of conductance was recorded through time. The lowest values in both lagoons, 800 micro-mhos in the East and 549 in the West, occurred in March 1974. A high was reached in the East Lagoon during September 1974, 1,480 micro-mhos, and in the West Lagoon during July, 1,037.

pH

The lagoon receiving wastewater was slightly less alkaline than the lagoon not receiving wastewater (Table 8). Only very minor variations occurred among stations and depths within each lagoon. Little variation was noted through time, other than when the flow of wastewater was altered. Periods of high photosynthetic activity usually elevate the pH in natural bodies of water due to photosynthetic removal of CO_2. This phenomenon was not experienced in the Muskegon Lagoons, indicating a good buffering capacity in these waters. Due to the abundance of bicarbonate and calcium, it is unlikely that the pH will change greatly in the future.

Total organic carbon (TOC)

TOC levels were generally greater in the lagoon receiving watewater than in the lagoon not receiving wastewater (Table 8). During the first 18 months of study the mean TOC was 37.36 mg/l ± 10.25 in the East Lagoon and 20.75 ± 7.80 in the West. During the last six months of study the mean increased to 64.16 ± 41.23 in the West and to 51.98 ± 21.30 in the East Lagoon. Large fluctuations in TOC occurred throughout this investigation, with monthly means ranged from 24 to 82 in the East Lagoon and from 11 to 133 mg/l in the West Lagoon. The pulses did not correspond with any plankton pulses and apparently are due to bacteria, detritus, and the re-suspension of sediments.

Ammonia nitrogen

High levels of ammonia nitrogen are present in domestic and industrial wastewater, and the level of this parameter was generally much higher in the lagoon receiving wastewater than in the lagoon lacking this input (Table 9). In the West Lagoon during the first 18 months of study the concentration of ammonia nitrogen consistently remained less than 0.4 mg/l and was often below 0.1. The mean concentration during this period was 0.15 mg NH_4 - N/l ± 0.12 in the West Lagoon and 3.1 ± 1.7 in the East Lagoon.

In the East Lagoon from January through June 1974 there was a general increase in the amount of ammonia nitrogen from a low of 1.0 mg/l to a high of 5.6. During August and October the wastewater flow pattern was altered for short periods of time and the levels of ammonia nitrogen plummeted to less than 0.6 mg/l. From the flow of surface foam and from the color pattern that developed when the gate to the outlet cell was opened, it appeared that the incoming wastewater was short-circuiting and flowing out of the East Lagoon before appreciable mixing with the lagoon water occurred. There was also a short period when wastewater was used directly for irrigation and did not flow into the lagoons. Ammonia nitrogen was the only parameter related to a great extent to these tempor-

TABLE 9. COMPARISON OF NUTRIENT AND ANION LEVELS IN THE MUSKEGON LAGOONS DATA ARE GIVEN AS THE (mg/l) ± ONE STANDARD DEVIATION.

KEY

WW = Period of wastewater flow

NWW = Period of no wastewater flow

PARAMETER		STATIONS					
		E-1	E-5	E-8	W-1	W-5	W-9
Ammonia nitrogen,	WW	3.39 ± 1.97	2.55 ± 2.16	2.62 ± 1.87	4.32 ± 1.91	4.56 ± 1.91	3.87 ± 2.42
NH_4 - N	NWW	2.76 ± 2.76	2.02 ± 2.63	2.50 ± 2.84	0.15 ± 0.12	0.13 ± 0.13	0.15 ± 0.13
Nitrate nitrogen,	WW	1.04 ± 0.85	1.70 ± 0.99	1.31 ± 0.96	0.76 ± 1.17	0.93 ± 1.25	0.93 ± 1.35
NO_3 - N	NWW	2.38 ± 2.08	2.83 ± 1.79	2.35 ± 1.86	0.52 ± 0.35	0.58 ± 0.41	0.47 ± 0.33
Orthophosphate,	WW	1.48 ± 0.33	1.51 ± 0.37	1.39 ± 0.43	1.24 ± 0.50	1.25 ± 0.33	1.14 ± 0.65
P	NWW	1.54 ± 0.35	1.43 ± 0.28	1.52 ± 0.32	0.13 ± 0.11	0.16 ± 0.10	0.11 ± 0.10
Sulfate,	WW	97 ± 12	89 ± 8	97 ± 12	79 ± 8	76 ± 9	76 ± 9
SO_4	NWW	99 ± 7	92 ± 9	95 ± 6	74 ± 11	68 ± 9	75 ± 11
Chloride,	WW	166 ± 16	162 ± 9	163 ± 15	140 ± 23	139 ± 22	131 ± 23
CL	NWW	168 ± 24	160 ± 23	166 ± 24	105 ± 18	109 ± 10	106 ± 12

ary changes in flow patterns. This probably resulted from the rapid oxidation of this parameter to nitrite and then to nitrate nitrogen, or its release to the atmosphere as ammonia gas. Therefore a continual influx was required in order to maintain the high levels of ammonia nitrogen that were present. Without constant replenishment, the concentration of this form of nitrogen declined. Most of the other physical-chemical parameters do not change form so rapidly and thus their levels did not fluctuate as quickly. During the last six months of study when wastewater was discharged only to the West Lagoon, the ammonia nitrogen levels decreased to a minimum of 0.3 mg/l in the East Lagoon and rose to a maximum of 6 mg/l in the West Lagoon.

Nitrate nitrogen

The levels of nitrate nitrogen fluctuated greatly with time (Table 9). In the East Lagoon the range of monthly means was from 0.05 to 2.94 mg NO_3 - N/l during the six month period without such flow. In the West Lagoon, the range was from 0.15 to 1.47 during the 18 month period without wastewater flow and from 0.09 to 3.60 during the six month period with such flow. As indicated in Table 9, however, the nitrate nitrogen concentration was generally greater in the East Lagoon throughout this study. Highest levels of this nutrient generally occurred during the summer months.

Although nitrate nitrogen is the principal source of nitrogen for algal growth, the supplies of nitrate were not depleted during phytoplankton blooms. Ample amounts of both ammonia nitrogen and nitrate nitrogen were present in the Muskegon Lagoons to allow for algal demands, and it appears that nitrogen will not become a limiting factor in the near future.

Orthophosphate

The most available and important form of phosphorus for plan nutrition is orthophosphate, which is found in great quantities in wastewater. The mean concentration of orthophosphate was quite high, 1.44 mg P/l $\pm$ 0.39, in the East Lagoon during the 18 month period of wastewater flow. It also remained near this level during the six-month period without wastewater discharge into this lagoon due in part to the rapid biotic cycling of phosphorus. Only minor spatial and seasonal variations were noted in the East Lagoon (Table 9).

Larger fluctuations occurred in the West Lagoon. Without the input of wastewater during the first 18 months, the orthophosphate levels in this lagoon varied from a below detectable level in February 1974 to 0.32 mg P/l in July 1974. Higher values were continually noted during the summer months. In September the concentration of this nutrient declined rapidly in the West Lagoon and remained less than 0.8 mg P/l throughout February 1975. When wastewater was discharged into this lagoon in the following month, the concentration increased quickly, reached a high of 1.6 by June, and remained near this level through the remainder of this investigation.

Compounds containing phosphorus play major roles in nearly all phases of metabolism, particularly in energy transformation associated with phosphorylation reactions in photosynthesis. Phosphorus is required in the synthesis of nucleotides, phosphatides, sugar phosphates, and other phosphorylated intermediate compounds. Further, phosphate is bonded usually as an ester in a number of low molecular weight enzymes and vitamins essential for algal metabolism (Wetzel, 1975). Despite the importance of phosphorus in algal physiology, phytoplankton blooms were not reflected in reduced levels of orthophosphate.

This nutrient was present in the lagoon in amounts far beyond the needs of algae. Therefore, unlike the situation in many natural waters, it appears that phosphorus will not limit phytoplankton growth or control standing crops in the Muskegon lagoons.

Sulfate

High levels of sulfate, an abundant anion in natural bodies of water, were common in both Muskegon lagoons (Table 9). Small spatial and seasonal variations were noted in the levels of this anion, even before and after the discharge of wastewater. During the first 18 months of study the mean was 97 mg SO_4/l ± 12 in the East Lagoon and 74 ± 10 in the West Lagoon. Only minor changes were noted during the final six months of study when the West Lagoon received the wastewater. During this period the mean decreased to 95 ± 4 in the East Lagoon and increased to 77 ± 8 in the West Lagoon.

Chloride

The concentrations of chloride remained high in each lagoon throughout this study with a rather homogeneous spatial and seasonal distribution (Table 9). The lack of major fluctuations partly result from the fact that chloride is a conservative ion and metabolic utilization or biotically mediated changes in the environment do not cause large variations in its level.

The concentration of this ion was consistently higher in the East Lagoon than in the West Lagoon, even during the period of wastewater flow to the West Lagoon. During the first 18 months, the mean chloride level was 165 mg/l ± 13 in the East Lagoon and 105 ± 15 in the West Lagoon. During the six month period of wastewater flow to the West Lagoon, the mean chloride level increased to 135 ± 30 in this lagoon, but remained near the previous average in the East

Lagoon, 166 $\pm$ 23. Wastewater normally contains a high concentration of chloride ions since sodium chloride passes unchanged through the digestive system.

Calcium

Only minor variations in the concentration of calcium occurred vertically and among stations, with no apparent seasonal trends (Table 10). Throughout this investigation, the concentration of calcium in the East Lagoon, approximately 60 mg/l, remained slightly higher than the concentration in the West Lagoon of 55. Calcium is not present in high concentrations in wastewater, and the levels of this cation in the Muskegon lagoons are largely controlled by the mineralogical characteristics of the basins and the surrounding land.

Magnesium

Magnesium is required universally by the algae as the porphyrin component of the chlorophyll molecules. It is also needed as a micronutrient in enzymatic transformations of organisms, especially in transphosphoralations of algae, fungi and bacteria (Wetzel, 1975). Only minor fluctuations in this cation were noted during this study, because the demands for magnesium in metabolism are minor in comparison to the quantities available (Table 10).

This cation is a common constituent in natural waters, and levels remained slightly higher in the West Lagoon than in the East Lagoon due to the inflow of interception ditch water into the West Lagoon. The concentration of magnesium in both lagoons remained near 16 mg/l.

TABLE 10. COMPARISON OF METAL AND CATION LEVELS IN THE MUSKEGON LAGOONS DATA ARE GIVEN AS THE MEAN (mg/l) ± ONE STANDARD DEVIATION.

KEY

WW = Period of wastewater flow　　NWW = Period of no wastewater flow

PARAMETER		STATIONS					
		E-1	E-5	E-8	W-1	W-5	W-9
Calcium	WW	64.3 ± 6.6	62.0 ± 7.9	63.5 ± 6.6	58.7 ± 2.4	57.8 ± 3.7	57.5 ± 4.3
	NWW	59.3 ± 1.6	58.4 ± 2.3	59.8 ± 3.3	53.3 ± 8.7	54.5 ± 2.3	53.9 ± 5.5
Magnesium	WW	16.0 ± 1.5	17.0 ± 1.1	16.0 ± 1.5	16.8 ± 1.6	16.0 ± 0.6	16.0 ± 1.4
	NWW	15.7 ± 1.3	15.7 ± 1.1	15.3 ± 1.4	17.0 ± 1.0	17.3 ± 0.6	16.7 ± 1.2
Sodium	WW	248 ± 13	141 ± 9	147 ± 11	137 ± 16	137 ± 14	130 ± 22
	NWW	161 ± 8	163 ± 9	161 ± 9	93 ± 12	98 ± 8	92 ± 10
Potassium	WW	11.5 ± 1.6	11.3 ± 0.5	11.5 ± 1.9	8.3 ± 0.7	8.2 ± 1.0	7.9 ± 1.2
	NWW	9.7 ± 0.6	9.8 ± 0.6	9.7 ± 0.7	5.9 ± 1.0	6.0 ± 0.7	5.8 ± 0.9
Manganese	WW	0.21 ± 0.05	0.18 ± 0.09	0.20 ± 0.72			
	NWW				0.04 ± 0.02	0.03 ± 0.18	0.04 ± 0.02
Zinc	WW	0.21 ± 0.04	0.17 ± 0.05	0.21 ± 0.04	0.11 ± 0.03	0.09 ± 0.03	0.09 ± 0.03
	NWW	0.13 ± 0.03	0.11 ± 0.01	0.11 ± 0.03	0.09 ± 0.03	0.08 ± 0.04	0.07 ± 0.03
Iron	WW	1.07 ± 0.32	1.06 ± 0.40	1.15 ± 0.36	0.79 ± 0.30	0.77 ± 0.33	0.78 ± 0.31
	NWW	1.17 ± 0.07	1.10 ± 0.08	1.10 ± 0.09	0.68 ± 0.33	0.51 ± 0.17	0.71 ± 0.40

Sodium

Throughout this investigation the levels of sodium remained higher in the East Lagoon than in the West Lagoon (Table 10). The concentration of this cation in the East Lagoon was less during the period of wastewater flow, 148 mg/l $\pm$ 12, than during the following period without such flow, 161 $\pm$ 9, yet the level of sodium increased from 93 $\pm$ 11 prior to wastewater flow, to 133 $\pm$ 18 during the flow in the West Lagoon.

The high concentration of sodium in wastewater is probably caused by synthetic detergents and domestic sewage. The sodium input to domestic sewage comes from sodium chloride passing unchanged through the digestive system.

Potassium

Potassium was distributed uniformly throughout the lagoons with little seasonal variation, indicative of the conservative nature of this cation similar to sodium and magnesium (Table 10). The levels of potassium were elevated in each lagoon during the period of wastewater flow. Although the concentration of this cation declined in the East Lagoon and increased in the West Lagoon when the flow of wastewater was changed from the East to the West Lagoon, the concentration remained greater in the East Lagoon.

Manganese

Higher levels of manganese, an essential micronutrient, were present in the East Lagoon than were present in the West Lagoon (Table 10). The mean during the period of wastewater flow to the East Lagoon was 0.24 mg/l $\pm$ 0.02 in the West Lagoon. Because of these low concentrations, manganese data were not collected after February, 1975.

It appears that manganese will not reach levels inhibitory to phytoplankton in the Muskegon lagoons, since the highest value during this period was only 0.27 mg/l, and toxic effects do not appear until levels are over 1 mg/l (Patrick, et al, 1966).

Iron

The concentration of iron was high in each lagoon and fluctuated through time (Table 10). During the first 18 months of study the levels of iron ranged from 0.64 to 1.8 mg/l in the East Lagoon and from 0.35 to 1.4 in the West Lagoon. Because of the high content of iron in Muskegon industrial wastewater, the levels remained greater in the East Lagoon than in the West Lagoon. The large variations in time mask much of the difference that was apparently related to wastewater flow patterns.

Iron levels in the Muskegon lagoons are more than adequate to allow the biota to use this essential micronutrient.

Zinc

Due to industrial waste pollution, high concentrations of zinc, greater than 0.25 mg/l, occurred in the East Lagoon during the period of wastewater flow to this lagoon (Table 10). During the same time period, levels of zinc less than 0.08 mg/l were common in the West Lagoon. After March 1975, the zinc levels decreased to a mean of 0.12 in the East Lagoon and rose to a mean of 0.09 in the West Lagoon.

The zinc levels in the Muskegon lagoons are in the toxic range for many organisms. Levels exceeding 0.2 mg/l are toxic to many invertebrates (Hynes, 1960), whereas levels exceeding 0.1 constitute a hazard in the aquatic environment (Committee on Water Quality Criteria, 1972). The above cited Committee found zinc in concentrations as low as 0.1 mg/l to be toxic to *Daphnia*.

It should be noted that there is a synergistic effect when other heavy metals, such as copper and cadmium, both of which are components of the Muskegon lagoons, are present with zinc (La Roche, 1972). Bioaccumulation of zinc through the food web, with high concentrations occurring particularly in the invertebrates, may also increase the zinc toxicity problem in the Muskegon lagoons.

SECTION VI

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16. ABSTRACT

A limnological investigation was carried out on two 344 hectare (850 acre) industrial-municipal wastewater storage lagoons from August 1973 until August 1975. Besides monitoring physical and chemical parameters during the period of the initial filling, the biological community was critically examined for the purpose of documenting ecological succession over this two year period.

In general, the lagoons remained aerobic, well mixed vertically and slightly alkaline. The low transparency within the lagoons was an important factor which limited the phytoplankton population and excluded rooted aquatics and benthic algae. Ample nutrients were present for algal demands.

The lagoon's phytoplankton-protozoan assemblage was extremely variable with respect to total abundance and distribution. The zooplankton community was composed of fourteen species of free living crustaceans and four species of rotifers. The benthic fauna consisted of a small number of organisms representing only a few taxonomic groups.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Lagoons	Stabilization Ponds	06/F
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Limnology	Sewage disposal	08/H
Municipal Wastewater	Phytoplankton	
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