STANDING CROP AND COMMUNITY STRUCTURE
OF PLANKTON IN OIL REFINERY
EFFLUENT HOLDING PONDS

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PREFACE

In a series of oil refinery effluent holding ponds, a study of plankton standing crop and community structure was made (1) to determine biomass as a) ash-free dry weight, b) chlorophyll a concentration, and c) plankton volumes; (2) to examine the plankton community structure; (3) to determine the effect of effluent upon the plankton composition and standing crop. This is the third in a series of investigations on the ecology of oil refinery effluent holding pond system. Copeland (1963) studied oxygen relationships and Tubb (1963) studied the ecology of herbivorous insects.

Dr. Troy C. Dorris served as major advisor. Drs. Roy W. Jones, Douglas E. Bryan, Glenn W. Todd, and George A. Moore served on the advisory committee and criticized the manuscript. Dr. William C. Vinyard assisted in identification of algae, and Dr. Dewey Bunting aided in identification of rotifers. Dr. Clinton Miller assisted in the preliminary experimental design and Dr. Robert Morrison assisted in the final analysis of data. Dr. B. J. Copeland, Dr. Richard Tubb, Dr. John Butler, Jerry Copeland, and Don Davis helped make field collections. Mrs. Jean Copeland and Gene Dorris assisted in enumeration of plankton data. Oil refinery personnel made available certain chemical data, descriptions of refinery operations and layouts of the effluent system. My wife Esther and Mrs. Karen Benson assisted in typing the rough draft and Mrs. Frank Roberts typed the manuscript. The help and assistance from all of these people is hereby acknowledged and gratefully appreciated.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

Appendix Tables

LIST OF FIGURES

Appendix Figure

CHAPTER I

INTRODUCTION

The literature dealing with algae in sewage lagoons is voluminous (Fitzgerald and Rohlich, 1958), however relatively little is known about the ecology of plankton in oil refinery effluent holding ponds. The functions of an industrial or sewage lagoon for reduction of effluent wastes largely represents the combined efforts of bacteria and algae (Hopkins and Neel, 1956). Effluents are held within the system for a sufficient period of time for bacteria to break down complex organic compounds, making them available for algal growth (Golueke, Oswald, and Gotaas, 1957). Algae function as a source of oxygen in the system to maintain an aerobic medium. As a result of biological processes within the ponds environmental conditions are improved. The disposal of algal biomass may be a problem in sewage ponds (ibid). Reduction of algal biomass is effected primarily by two processes, disposition and by grazing of herbivorous organisms (Bartsch and Allum, 1957).

Industrial effluents often contain toxic materials. In a series of ponds, toxicity may decrease from pond to pond. With improvement of water quality, an ecological successional series will occur from pond to pond.

A study of plankton standing crop and community structure in a series of oil refinery effluent holding ponds was made from 25 July 1961, to 19 July 1962. Thirty-four collections were made with 432 plankton samples examined. Plankton standing crop was determined from three estimates of biomass as ash-free dry weight, chlorophyll _a_ and plankton volumes. Species composition was used to show an increase in diversity, improvement of water quality, and longitudinal succession from the first pond to the last pond in the series. This study is the third in a series of investigations on the ecology of oil refinery effluent holding pond system. Copeland (1963) studied oxygen relationships and Tubb (1963) studied the ecology of herbivorous insects.

CHAPTER II

SURVEY OF LITERATURE

Productivity

Historically, estimates of plankton productivity have been based upon population studies. Early plankton studies were made by Kofoid (1908), Allen (1920), and Birge and Juday (1922). Forbes (1887) defined a lake as a microcosm in one of the first aquatic community studies. More recent planktonic community studies have been descriptive, taxonomic, and numerical or volumetric estimates of the "standing crop" (Damann, 1945; Chandler, 1944; Deevey, 1949; Pennak, 1949; Wallen, 1955; Claffey, 1955; and Davis, 1962). Clark (1946) defined "standing crop" as the amount of organisms or biomass existing in the area at the time of observation. Ryther (1956) considered "standing crop" as a poor index of production without the factor of time required for its formation. Ryther summarized methods for estimating biomass or "standing crop" during a period of time as (a) abundance of plankton, (b) volume of plankton, (c) ash-free dry weight, and (d) chlorophyll content of the water. Other measures of primary production are (a) rate of oxygen production, (b) rate of carbon dioxide uptake determined by pH changes, and (c) rate of fixation of carbon-14 by the phytoplankton (Ryther, 1956).

Population studies have been useful in developing concepts of community structure and their functions within the community (Park, 1946). The trophic-dynamic concept of ecology was proposed by Lindeman (1942) and has been used by others. As a result of Lindeman's work, study of a food chain becomes a problem of productivity and flow of energy through each trophic level. Thus, productivity becomes a fundamental problem in aquatic studies (Lund and Talling, 1957).

Numerous methods have been devised for measuring the amount of organic matter produced at the primary trophic level. Dineen (1953) determined "standing crop" as ash-free dry weight at each trophic level and arrived at an estimate of annual production. Dark- and light-bottle estimates of photosynthesis (primary production) have been made by Verduin (1956), Ratzlaff (1952), Wright (1958), Weber (1958), and Ragotzkie (1959). Verduin (1952), and Jackson and McFadden (1954) measured pH to calculate changes in carbon dioxide in dark- and light-bottles. McQuate (1956) compared CO_2 and O_2 changes in dark- and light-bottles. Estimates of productivity were similar but CO_2-based respiration rates were higher. Radioactive carbon-14 uptake by phytoplankton in dark- and light-bottles was used for estimating organic production in oceans (Steeman Nielsen, 1952; Ryther, 1956; Ryther and Yentsch, 1957; Menzel and Ryther, 1961). Changes of electrical conductivity in suspended bottles have been used as measures of photosynthesis (Meyer, et al., 1943).

Odum (1956) and Odum and Hoskins (1958) estimated community metabolism in streams and lakes by measuring diurnal changes of oxygen content. The diurnal curve method has been applied to oil refinery effluent holding ponds (Copeland and Dorris, 1962; Copeland, 1963), and to small farm ponds (Copeland, Butler, and Shelton, 1961; Minter and

Copeland, 1962). Beyers (1962) and Butler (1963) used the diurnal curve method, but measured pH changes, converting to carbon dioxide, to estimate primary productivity in laboratory microcosms.

Davis (1958) considered some problems of secondary productivity in the western Lake Erie region. Measurement of secondary production has been based primarily on standing crop. Wright (1958) compared phytoplankton-zooplankton relationships with measurements of production. Odum and Smalley (1959) compared energy flow of a herbivorous and a deposit-feeding invertebrate in a salt marsh. Tubb (1963) measured the herbivorous standing crop of midge flies and converted the biomass to energy units. McConnel (1963) estimated primary productivity by the diurnal curve method and related it to fish harvest. Other studies have related different measurements of standing crop to primary productivity and to phytoplankton-zooplankton relationships (Wright, 1958, 1959; Riley, Stommel, and Bumpus, 1949; Odum and Smalley, 1959; Teal, 1962).

Stabilization Ponds

Ponds are used in many areas of the United States for treatment of industrial and domestic sewage wastes. Holding ponds, oxidation ponds, lagoons, stabilization ponds and oxidation-evaporation ponds are names given to such ponds (Sidio, et al., 1961). Ponds for disposal of industrial wastes have been reported in use as early as 1910 and 1913 (Porges, 1961). The first domestic stabilization pond in the Northern Plains States was constructed in 1948. Towne, Bartsch, and Davis (1957) reported that 73 stabilization ponds had been constructed in North and South Dakota by 1956. In the United States approximately 2,000 industrial waste lagoons were in use by 1956 and six lagoon systems were reported for Oklahoma (Porges, 1961). Hodgkinson (1959) reported six lagoon systems in operation by six oil refineries in Kansas. Dorris and Copeland (1962) found holding ponds effective in treatment of oil refinery effluent. Jaffee (1956) reviewed some of the biological processes in sewage and industrial lagoons.

Most plankton investigations in stabilization ponds have been with reference to algae and bacteria (Bartsch and Allum, 1957; Neel et al., 1961; Towne et al., 1957; Eppley and Mocias, 1962). Hermann and Gloyna (1958) studied B.O.D. and algal counts in pilot models of waste stabilization ponds. Parker (1962) studied some of the microbiological aspects of lagoon treatment. Fitzgerald and Rohlich (1958) evaluated stabilization pond literature. Few authors refer to trophic levels above the primary producers. Tubb (1963) made an ecological investigation of herbivorous chironomid larvae in oil refinery effluent holding ponds. Further studies on carnivorous insect trophic levels are being made by Ewing (personal communications).

Indicator Organisms

Plants and animals have long been used in evaluating lake and stream conditions. In pollution studies, emphasis has been on establishing degree of pollution of a stream by the presence of certain indicator organisms. Kolkwitz and Marsson (1908) proposed classification of various organisms according to degree of pollution. Polysaprobes occurred in the reduction zone, mesosaprobes in the oxidation zone and oligosaprobes below the oxidation zone. Richardson (1921) and others have also stated that species changes are characteristic of varying degrees of pollution. Liebmann (1962) continued use of the "saprobe" classification even though Ellis (1937) pointed out that indicator organisms can live in normal conditions as well as in many polluted situations. Ellis believed the relative abundance of individual indicator species should be considered. Cholnoky (1960) presented evidence based on the importance of "nutrition content" to refute the classifications of Kolkwitz and Marsson. Cholnoky concluded that many associations of algae had no connection with "degree of pollution" as used by Kolkwitz and Marsson. Environmental changes inhibit multiplication of some species originally present and encourage others, so that the primary associations, i.e. the percentage composition and not the flora as such are changed. Cholnoky believes presence of individuals of a species has little ecological significance, and most lists of flora have led to faulty conclusions.

Patrick (1949) considered that the best type of biological measure should be based on all groups of plants and animals in a stream in order to assay degree of pollution. In a survey of the Conestoga Basin, Pennsylvania, Patrick made histograms which compared well with those of Kolkwitz (1911) and others which were based on sanitary wastes. She also found regions of toxic conditions in which there was complete absence of plant and animal life. Toxic pollutants produced a reduction in species number and often a great abundance of individuals of remaining species.

Organisms present in a community at a given point reflect water conditions for a considerable time before sampling, while a chemical test reveals only the condition at the time the sample was taken. Patrick concluded that a biological measure cannot be reduced to a simple standard, but the "healthy" stations of the system measured should be the basis of comparison rather than some arbitrary standard. Liebmann (1962) pointed out that polluted rivers, especially those receiving organic wastes such as sewage effluent, are poor in species and rich in numbers.

Lackey (1960) concluded that few, if any, species are reliable indicators of specific environments. Farmer (1960) found that in Black Warrior River, Alabama, phytoplankton generally was affected more adversely than zooplankton by pollution. He also found rotifers, Sarcodina and Volvocales were more tolerant, while flagellate protozoans, diatoms, and filamentous green algae showed highest sensitivity.

Species-diversity

A logarithmic species-diversity index has been found useful in comparing natural communities and in studies of laboratory microcosms. Odum, Cantlon, and Kornicker (1960) attributed the logarithmic method to Gleason (1922) and it has been used by Fisher, Corbet, and Williams (1943), Williams (1950, Yount (1956), Odum and Hoskins (1957), and Margalef (1958).

Fisher, et al., (1943) considered theoretical implications and derived a constant from the logarithmic series instead of the slope. Odum et al., (1960) reviewed principal methods of graphic presentation of relationships between species and numbers. They concluded that the slope of species vs. log individual graphs is useful as an empirical measure of diversity of communities. Thus, one may compare diversity in communities of all sizes, with different amounts of data and different methods of sampling and sample sizes. Yount (1956) compared species-diversity of diatom populations with chlorophyll estimates of productivity. Odum and Hoskins (1957) compared species diversities in microcosms and macrocosms. Beyers (1962) and Butler (1963) used species-diversity as a justification for regarding the microcosm as real miniature ecosystems. Margalef (1958) related the species-diversity index to the amount of informational content in the plankton composition of an estuary. Odum et al., (1960) used species-diversity to postulate a hierarchical organization in communities. Hulburt, Ryther, and Guillard (1960) applied the index of diversity derived by Fisher, et al., (1943) to phytoplankton populations in the Sargasso Sea. Hairston (1959) compared relative abundance of soil microarthropods from two similar old abandoned fields in relation to community organization using varied estimates of diversity. Patten (1962) applied several diversity methods in a plankton study of Raritan Bay, New York.

Succession

Concepts of succession have been related to many environments (Odum, 1959; Kendeigh, 1961; Clark, 1954; Welch, 1952; and Reid, 1961). Clements and Shelford (1939) found that communities change more or less continually until a more stable or climax stage is reached. Margalef (1958) considered some successional processes with reference to productivity and biomass relationships. He noted that as complexity of the community increases through successional stages, an increase in species-diversity usually occurs. MacArthur (1955) has shown that the greater the numbers of species existing in the same trophic level, the greater the stability of the community.

Most stream pollution studies illustrate the process of longitudinal succession (Reid, 1961; Odum, 1959). Sloan (1956) found a diversification sequence downstream from a cold spring. Odum (1958) used a single-station method of estimating primary production in a polluted stream with reference to longitudinal succession. Few authors have related successional phenonomena to the improvement in water quality in lagoons or effluent holding ponds (Neel et al., 1961; Hermann and Gloyna, 1958).

CHAPTER III

MATERIALS AND METHODS

Description of Refinery Operations and Treatment of Effluent Waters

Refinery operations included atmospheric and vacuum crude distillation, solvent treating and dewaxing of lubrication oils, wax pressing and sweating, blending and compounding of oils and greases, thermal and catalytic cracking, catalytic reforming and polymerization, hydrogen fluoride alkylation, aromatic extraction, delayed coking, gasoline distillate treating and blending operations, and treating of cooling tower and boiler feed water.

Effluents waters were carefully monitored and segregated. Caustic solutions rich in acid oils were sold for further refining. Other potentially harmful strong caustic solutions and chemical solutions were segregated and impounded in open pits. Sour water streams from the cracking operations are treated in a steam stripping tower for removal of sulfides and ammonia. Phenols were removed primarily by biological action in a bio-oxidation pond. Oil was removed in conventional traps. Effluents from the various divisions of the plant were discharged into an open ditch, and traveled approximately one and one-third miles to two large concrete basins for oil separation, settling of solids, smoothing out of surges from the plant or rainfall and some improvement by surface aeration and bio-oxidation. From the basins effluent was pumped into a series of ten holding ponds for final removal of oil and solids and for over-all improvement by oxidation and biological action (Fig. 1). These ponds were constructed so that effluent traveled the entire length of the series before being discharged to the receiving stream. Each pond was approximately 600 feet long, 22 feet wide, and 5 feet deep, and held less than one day's discharge (Tubb, 1963). Approximately 6 to 8 days were required for water to travel through the system.

Station Description

Pond 1 received effluent from the refinery and was most toxic. Preliminary survey showed that only small populations of plankters existed in this pond, and only one station was established, near outlets into Pond 2 (Fig. 1).

In Ponds 4, 7, and 10, four collecting stations were established approximately 12 feet from shore (Fig. 1). Stations were sampled about every 6 to 12 days except during winter when only one or two collections per month were made.

Chemical-Physical Methods

Temperature measurements and duplicated oxygen, dark- and light-bottle samples were made near Stations 1AB, 4D, 7B, and 10D (Fig. 1). Water samples for dissolved oxygen analysis were taken with a Kemmerer water bottle and immediately fixed by the Alsterberg (Azide) modification of the Winkler method (A.P.H.A., 1960). Iodine released by dissolved oxygen was measured colorimetrically with a Bausch and Lomb "Spectronic 20" photoelectric colorimeter at a wave length of 450

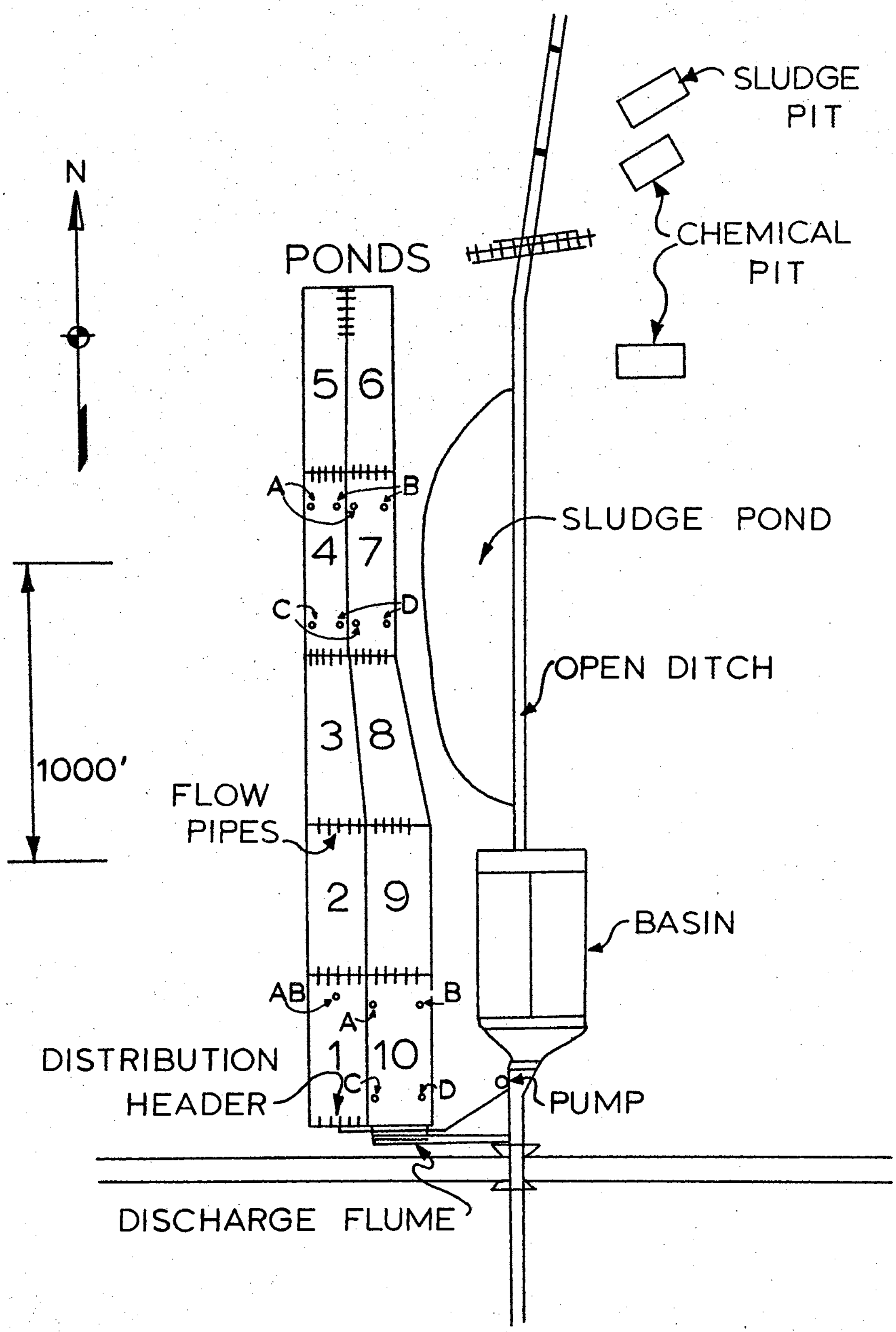

Fig. 1. Diagram of the oil refinery effluent holding pond system. O = sampling stations.

millimicrons. Optical density was converted to milligrams of dissolved oxygen per liter. Dark- and light-bottle estimates of productivity were made from 3 February, 1962, to the end of the collecting period. Glass-stoppered dark- and light-bottles of 250 milliliter capacity were filled and placed in the water for periods varying from 1/2 to 2 1/2 hours. Estimates of gross photosynthesis and respiration were made from changes in the oxygen concentration in dark- and light-bottles.

Depth of light penetration was determined with a submarine photometer. The euphotic zone was considered to be the depth at which light was 1% of surface intensity.

Ash-free Dry Weight and Chlorophyll a Analysis

Water samples for ash-free dry weight and chlorophyll analysis were taken at each station. Ash-free dry weight determinations were made on 100 ml aliquot water samples filtered through Millipore filters of 0.45 millimicron pore size. The filtered residue and filter, of known weight, were dried in an oven, cooled, weighed, and ashed in a muffle furnace. A dessicator was used for cooling to prevent uptake of moisture. Ashed weight was subtracted from dry weight for estimation of biomass as ash-free dry weight. For chlorophyll a analysis a 100 ml aliquot was filtered through Millipore filters of 0.45 millimicrons pore size. The residue was extracted in 90% acetone for 24 hours in the dark at about 5 C and centrifuged. Optical density of the chlorophyll extract was determined with a Bausch and Lomb "Spectronic 20" photoelectric colorimeter at a wave length of 663 millimicrons. Methods for spectophotometric determinations of chlorophyll a were developed by Richards and Thompson (1952). Odum, et al., (1958) compared results obtained with a Bausch and Lomb "Spectronic 20" colorimeter with those of Richard and Thompson. Copeland (1963), developed an equation for refinery ponds:

$$\text{Chlorophyll } \underline{a} \text{ in mg/l} = 1.5\ d_{663} \qquad (1)$$

where d = optical density at 663 millimicrons wave length and a 1.17 cm light path. Equation (1) was used in computing chlorophyll a concentrations in the present study.

Plankton Sampling and Counting Procedure

Plankton samples were collected with a 3-liter Kemmerer water bottle. Six-liter plankton samples were taken at each station, 3 liters near the surface and 3 liters near the bottom. Plankton samples were concentrated by pouring samples through a Wisconsin plankton net fitted with #20 bolting silk (Welch, 1948). Concentrated plankton samples were placed in 130 ml glass bottles, preserved with formalin, and diluted to a volume of 90 ml. Unconcentrated samples were collected near the surface and nannoplankton counted immediately upon return to the laboratory.

Nannoplankton enumerations from live samples were made using a Spencer Brightline Hemocytometer (Silva and Papenfus, 1953). Nannoplankton counts from concentrated samples were made using a Palmer nannoplankton slide (Palmer and Maloney, 1954). A net factor was then determined for micro-cells in concentrated samples and counts adjusted for cells which passed through the plankton net (Welch, 1948). All cells of approximately 1 to 3 microns in diameter were called micro-cells (Davis, 1958).

Net plankton samples were resuspended and 1 ml aliquot transferred by a Hansen-Stumpel pipet to a Sedgewick-Rafter counting chamber. The total area of the chamber was examined and all large organisms counted under low power (100X). All organisms were counted in 10 to 20 fields selected at random. Each field was delimited by a Whipple ocular micrometer. Appropriate formulae were used to convert the counts to numbers per milliliter or liter (Jackson and Williams, 1962). The microscope and plankton counting equipment were calibrated according to procedures of Jackson and Williams (1962). Plankton organisms were identified by using standard taxonomic keys in Pennak (1953), Prescott (1951) and Edmondson (1959).

Volumes of each organism were calculated from the geometric figure each organism most nearly resembled from measures made with a Filar micrometer. Appropriate calculations were then made to determine the total volume, in cubic microns per milliliter for phytoplankton and zooplankton.

Species-Diversity Index

Species-diversity counts were made of 2 to 5 collections during each season. Approximately a 1 ml aliquot was removed from samples taken at each of four stations in a pond for a composite sample. From each composite sample an aliquot was removed by pipette, placed in a Palmer cell and examined with the high power objective (430X) of a binocular microscope. Cumulative species numbers were recorded for 10, 100, 500, 1000 cumulative individuals. Species-diversity plots were made according to procedures of Yount (1956).

Species-diversity is the slope of cumulative increase of species versus logarithm of cumulative increase of individuals:

$$\frac{\text{Increment in cumulative species}}{\text{Increment in logarithm of individuals counted}} \qquad (2)$$

The lines of the graph are approximately straight when cumulative occurrence of new species is plotted as a function of the logarithmic number of individuals for natural communities. Odum et al., (1960) concluded that the slope of species vs. log individuals graph is useful as an empirical measure of diversity of communities.

CHAPTER IV

CHEMICAL-PHYSICAL CONDITIONS

Temperature

Temperatures of effluents entering the pond system ranged from 47 to 91 F (Appendix Table I). The effluent was cooled several degrees by the time it flowed through the pond system. Mean temperature difference between first and last ponds was 5.82 F with the least variation of 1.5 degrees on 19 July 1962, and the largest difference of 12 degrees on 2 February 1962. Seasonal mean differences are shown in Table I. Heating of the effluent by refinery processes contributed to greater temperature differences between ponds during winter months.

TABLE I

MEAN SEASONAL TEMPERATURE DIFFERENCE
BETWEEN POND 1 AND POND 10

	Fall	Winter	Spring	Summer	Mean
No. Obs.	10	3	10	12	35
Diff. in F	5.64	9.25	6.40	4.80	5.82

Hydrogen-ion Concentration and Reduction of Phenol

Information on hydrogen-ion and phenol concentration was obtained from refinery personnel. Generally a decrease of pH occurred as effluent flowed through the system (Appendix Table I). Hydrogen-ion concentration of the effluent varied from 7.2 to 8.5 entering the pond system and from 7.2 to 8.4 when released by the last pond. Mean monthly pH values varied from 7.4 to 8.1. Lower pH values during the fall were probably a result of the "slug" effect of more toxic materials discharged into the holding pond system. As result of the "slug" effect, a decrease in volumes of plankters occurred (Appendix Table X) and respiration increased in the system with a lowering of pH values. Copeland (1963) discussed the effect of a "slug" upon oxygen demand in the holding pond system. Small (1954) summarized the effect of water pH in ecology and in relation to freshwater plankton. Based upon his summary, pH values were within optimum range for most plankton organisms.

Effective reduction of phenol compounds from two oil refinery holding ponds with different retention times was reported by Copeland (1963). Phenol was reduced about 99% during the summer months, 64% during the fall, 69% during winter and 98% during spring.

During the spring of 1962, a "slug" of phenol was traced through the holding pond system. Phenol concentration was reduced 25% within approximately 2 days in Pond 3 and 64% after about 4 days in Pond 5. After approximately 5 to 6 days phenol was reduced by 99% in Pond 7. Copeland (1963) found 60 days retention of the effluent to be more effective than 10 days during winter for reduction of phenols, but that 10 days was as effective as 60 days during the summer. Ettinger and Ruchhoft (1949) reported that removal of phenol from aerobic surface water was largely due to biological action.

Dissolved Oxygen Relationships

Sources of oxygen in bodies of water are photosynthetic activity and diffusion of oxygen at the air-water interface. In eutrophicated (enriched) bodies of water, such as refinery effluent holding ponds, oxidation of organic materials is a major factor in reducing oxygen concentration. Animal and plant respiration also place a demand upon the oxygen supply. Langley (1958) considered that oxygen relationships in polluted streams depended fundamentally on microorganisms in the water.

Oxygen determinations were made between 1000 and 1400 hours. Little or no dissolved oxygen was present from September to April in Pond 1. (Appendix Tables III and IV). During most of the year, Pond 1 was completely anaerobic (Copeland, 1963). Oxygen content in Pond 4 decreased rapidly during late summer of 1961 and did not rise as in Ponds 7 and 10 when an increase of algal biomass, or fall pulse, occurred. In early summer, Pond 4 oxygen content exceeded all other ponds. In Pond 7, oxygen content exceeded all ponds during August, September, and April. In Pond 10 dissolved oxygen concentration exceeded all ponds during the winter months. Apparently some photosynthetic activity occurred in Pond 10 during the winter.

In summary, dissolved oxygen content increased from small amounts in Pond 1 to maximum content in Pond 7, and decreased toward Pond 10 except during the winter months. Copeland (1963) studied community photosynthesis and respiration in oil refinery ponds, finding that photosynthesis exceeded respiration only during the vernal plankton pulse in Pond 10.

Euphotic Zone

Some light received at the surface of water is reflected. Light that enters does not penetrate to great depths because of absorption by algal populations and particulate matter. Euphotic zones varied from

0.05 to 1.21 m in Pond 1, 0.33 to 1.36 m in Pond 4, 0.23 to 1.63 m in Pond 7, and 0.51 to 1.88 in Pond 10 (Appendix Table II). Annual and seasonal mean euphotic zones are shown in Table II.

Particulate matter apparently was largely responsible for a shallower euphotic zone in the first part of the system, however, large algal populations were produced and prevented deep light penetration. In the last part of the system, algal populations were reduced and usually allowed greater light penetration in Pond 10. Copeland (1963) postulated that algae may use a portion of incoming solar energy to combat toxicity.

TABLE II

SEASONAL EUPHOTIC ZONE IN METERS

Season	Pond 1	Pond 4	Pond 7	Pond 10
Fall	0.89	1.10	1.26	1.34
Winter	0.64	0.79	0.86	1.22
Spring	0.57	0.58	0.69	0.91
Summer	0.60	0.80	1.03	1.31
Annual Mean	0.67	0.82	0.96	1.20

CHAPTER V

PRIMARY PRODUCTIVITY

Productivity estimates were made from oxygen measurements in standard dark- and light-bottles (Verduin, 1956). Length of incubation varied from about 45 minutes to 4 hours. Long periods of incubation often result in errors due to changes in bacterial and algal populations. Short periods of 4 hours or less in highly productive waters should reduce such errors (Strickland, 1960). If initial oxygen concentrations were high, time of incubation was shortened to decrease possibility of bubble formation in light bottles (Hephner, 1962). Dark- and light-bottle experiments are comparable to manometric techniques (Ryther, 1956).

Rate of oxygen change (mg/l/hr = $gm/m^3/hr$) was determined from the difference between initial and final oxygen concentrations in light- and dark-bottles (Appendix Table IV). Change in light-bottles gives a measure of net evolution of oxygen arising from photosynthesis, or net photosynthesis. Change in dark-bottles gives the amount of oxygen used in respiration. Gross photosynthesis is the gain of oxygen in the light-bottle plus the loss of oxygen in the dark-bottle when loss of oxygen is assumed to be same as in light-bottle. Net photosynthesis and respiration values were converted from $gm/m^3/day$ to $gm/m^2/day$ by multiplying by euphotic zone depth in meters.

Net photosynthesis fell to zero at times in all ponds. It was assumed that oxygen demand for respiration exceeded oxygen produced by photosynthesis in the light-bottles. Maximum net photosynthesis in gm/m^2/day was 59.48 in Pond 1, 66.27 in Pond 4, 66.39 in Pond 7, and 82.45 in Pond 10. Net photosynthesis increased each month from February to a maximum mean production in July, except in Pond 1. Mean net photosynthesis in gm/m^2/day for the six month period was 12.20 in Pond 1, 19.68 in Pond 4, 20.82 in Pond 7, and 19.29 in Pond 10.

In all ponds, initial oxygen content was zero at times, and respiration could not be measured under such conditions (Table III and Appendix Table IV). Maximum respiration in gm/m^2/day was 21.52 in Pond 1, 14.78 in Pond 4, 27.63 in Pond 7, and 5.65 in Pond 10. Mean respiration in gm/m^2/day for the six month period was 3.97 in Pond 1, 4.79 in Pond 4, 6.53 in Pond 7 and 5.65 in Pond 10.

Gross productivity estimates were compared with estimates for other communities (Table IV). Oil refinery dark- and light-bottle estimates are much higher than for most fresh and marine waters. Estimates are apparently in the same order of magnitude as sewage ponds and polluted streams. It was difficult to make adequate comparison because the day-length varied among different investigators. Day-length for this study varied from 10 to 13 hours, depending on time of year. High gross productivity of 93.55 mg/m^2/day was obtained on 10 July 1962. A suitable explanation of such a phenomenon is not known at this time, however very short periods of exposure may result in such high values (Verduin, Whitwer and Cowell, 1959).

Comparisons of dark- and light-bottle experiments with community metabolism as measured by the diurnal curve method (Copeland, 1963), showed considerable variation (Table V). Diurnal curve respiration values were about two times higher than dark-bottle respiration. Diurnal

TABLE III

PRODUCTIVITY ESTIMATES FROM DARK- AND LIGHT-BOTTLES IN gm $O_2/m^2/day$

Date	Pond 1		Pond 4		Pond 7		Pond 10	
	R	P	R	P	R	P	R	P
2/3/62	---[a]	0.00	---[a]	0.00	---[a]	0.00	0.52	0.65
2/16/62	---[a]	0.00	---[a]	0.00	1.43	0.48	0.66	2.95
Mean	---[a]	0.00	---[a]	0.00	0.72	0.24	0.59	1.78
3/10/62	---[a]	0.00	>0.40	0.11	1.27	0.00[b]	8.26	0.00[b]
3/17/62	---[a]	0.00	3.31	0.00	1.33	1.73	0.87	0.00[b]
3/26/62	---[a]	0.00	---[a]	0.00	12.18	4.03	3.41	0.00[b]
Mean	---[a]	0.00	1.34	0.03	4.93	1.92	4.18	0.00[b]
4/7/62	---[a]	0.00	---[a]	0.00	1.71	2.09	7.78	12.93
4/13/62	---[a]	0.00	---[a]	0.44	0.00	2.30	0.00	4.95
4/20/62	---[a]	0.00	6.64	10.58	4.70	7.24	7.83	4.65
4/26/62	---[a]	0.00	16.13	19.05	37.09	13.71	11.69	17.27
Mean	---[a]	0.00	5.69	7.52	10.86	6.34	6.83	9.95
5/4/62	---[a]	0.00	---[a]	5.68	0.00	22.15	7.07	11.83
5/12/62	---[a]	0.00	---[a]	0.00	1.60	13.36	3.32	30.97
5/26/62	---[a]	49.90	>8.46	52.32	6.54	45.80	2.98	34.67
Mean	---[a]	16.63	2.82	19.33	2.71	27.10	4.46	25.82
6/5/62	---[a]	59.48	7.85	58.01	5.47	57.51	7.53	40.24
6/11/62	>4.64	10.82	4.36	31.44	---[a]	23.22	9.27	5.02
6/19/62	9.24	36.15	5.75	24.64	---[a]	15.60	---[a]	0.60
6/26/62	14.69	35.01	9.22	54.00	15.69	55.12	8.49	56.79
Mean	9.52	30.37	6.80	42.02	5.29	37.86	6.32	25.66
7/5/62	7.69	12.14	14.50	30.53	13.97	28.98	6.15	26.96
7/10/62	21.52	20.54	6.99	49.76	27.63	66.39	11.09	82.45
7/19/62	13.74	45.87	14.78	66.27	2.46	58.97	17.28	48.10
Mean	14.32	26.18	12.09	48.85	14.69	51.45	11.51	52.50

P = Net production
R = Respiration

[a]No initial oxygen
[b]Decrease, thus R > P in light-bottles
> Dark-bottle final reading zero

TABLE IV

DARK- AND LIGHT-BOTTLE ESTIMATES OF GROSS PHOTOSYNTHESIS FROM VARIOUS COMMUNITIES

Source	P ($gm\ O_2/m^2/day$)	R ($gm\ O_2/m^2/day$)
Canyon Ferry Reservoir, Montana, (Wright, 1959)	0.77--6.79	0.38--14.9
Deadman Lake, New Mexico, (Megard, 1961)	0.52	
Sargasso Sea, (Menzel and Ryther, 1960)	0.35--5.3	
Erom Sø, Denmark, (Jonasson and Mathiesen, 1959)		
March	0.16	
April	2.96	
August	4.29	
Lyngby Sø, Denmark (ibid)	4.82	
San Diego Bay, (Nusbaum and Miller, 1952)	2.8	4.4
Sewage Ponds, Lemmon, S.D. (Towne, et al., 1957)	10.08	2.4
White River, Indiana, (Denham, 1938, calculated by Odum, 1956), zone of recovery,	57*	18*
near pollution outfall	0.24*	29*
Florida Springs (Odum, 1956)	0.6--58*	
Fish Ponds, Israel (Hepher, 1962)		
Unfertilized	4.4--6.1	
Fertilized	16.5--22.7	
Sewage Ponds, S.D. (Bartsch and Allum, 1957)	19--36	22-36
River Lark, England (Butcher, et al., 1930, calculated by Odum, 1956)	0.53--39*	35--53*
Oil Refinery Ponds (Copeland, 1963)	0.0--29.2*	2.1--50.5*
Oil Refinery Ponds (Present Study)	0.0--54.01	0.0--37.09

*Diurnal Curve Calculations

TABLE V

COMPARISON OF DARK- AND LIGHT-BOTTLE PRODUCTIVITY
WITH COMMUNITY PRODUCTIVITY FROM
DIURNAL CURVE METHOD
(COPELAND, 1963)

Date	L & DB R $gm/m^3/hr$	L & DB P $gm/m^3/hr$	Diurnal Curve R $gm/m^3/hr$	Diurnal Curve P $gm/m^3/hr$	L & DB R $gm/m^3/hr$	L & DB P $gm/m^3/hr$	Diurnal Curve R $gm/m^3/hr$	Diurnal Curve P $gm/m^3/hr$
	Pond 1				Pond 4			
2/3/62	---[a]	0.00	1.00	0.00	---[a]	0.00	1.00	0.00
3/26/62	---[a]	0.00	1.10	0.00	---[a]	0.00	1.10	0.00
4/26/62	---[a]	0.00	1.75	0.00	0.80	2.69	1.25	1.40
6/5/62	---[a]	5.33	1.24	0.11	0.34	4.94	0.51	0.82
7/19/62	0.97	6.95	1.58	1.55	0.80	7.42	1.61	2.15
	Pond 7				Pond 10			
2/3/62	---[a]	0.00	1.00	0.00	0.02[c]	0.07	1.00	0.00
3/26/62	0.54	0.93	0.75	0.95	0.10	0.00[b]	0.15	0.28
4/26/62	1.38	2.40	0.20	2.20	0.29	1.23	0.28	0.90
6/5/62	0.20	4.08	0.35	1.33	0.22	2.40	0.53	1.57
7/19/62	0.19	8.59	0.68	1.85	0.72	4.42	0.66	2.12

L & DB = Light- and Dark-Bottle
R = Respiration
P = Gross Photosynthesis

a = No initial O_2
b = Decrease in O_2
c = Low initial O_2

curve respiration values included both plankton and bottom communities. Dark-bottles give only the respiration values contributed by the plankton community.

Light-bottle estimates of gross photosynthesis were usually two to five times greater than those from the diurnal curve method (Table V). Differences between the methods were generally more pronounced when chlorophyll concentrations were high (Appendix Table V). Chlorophyll a concentration was 0.945 mg/l and light-bottle photosynthesis was four and one-half times higher than diurnal photosynthetic estimates in Pond 7 on 19 July 1962. The difference between the values obtained was probably due to slightly higher temperatures with little or no mixing of the phytoplankton within the light-bottle. Mixing occurs in the natural plankton community, and as a result many phytoplankton cells rarely come into contact with maximum sunlight as in a light-bottle held near the surface of the water. (Verduin, et al., 1959). During winter and spring when phytoplankton concentrations were low, the difference between the two methods was less pronounced and the euphotic zone was deeper (Appendix Table II).

CHAPTER VI

STANDING CROP OF PLANKTON

Ash-free Dry Weight Biomass

Ash-free dry weight standing crop (biomass) has been used to estimate production of water bodies (Pennak, 1949; Davis, 1958; Wright, 1959). Pennak (1949) considered ash-free dry weight (suspended organic matter) to be the most reliable measure of annual standing crop.

Means of ash-free dry weight biomass were determined from samples taken at four different stations in each pond, except Pond 1 (Appendix, Table VI). Maximum variation of ash-free dry weight of 1.0 to 101 mg/l occurred in Pond 1. Considerable fluctuation occurred among weekly samples. Monthly means varied from 3.5 to 65 mg/l (Table VI). Seasonal means ranged from 4.08 to 34.55 mg/l (Table VII). Annual means varied from 24.71 mg/l in Pond 1 to 16.52 mg/l in Pond 10. Annual ash-free dry weight was probably higher in Pond 1 than the fewer measurements indicated. Probably a larger part of the organic matter in the effluent in the first part of the system came from the oil refinery. Ash-free dry weight biomass generally decreased as effluent passed through the pond system. Ash-free dry weights from oil refinery effluent holding ponds were much higher than in other fresh waters, but lower than in sewage ponds (Table VIII).

TABLE VI

MONTHLY MEAN ASH-FREE DRY WEIGHT (AFDW) AND STANDARD DEVIATION (SD) IN MG/L

Date	Pond 1*	Pond 4	Pond 7	Pond 10
1961				
Aug.	24.00	34.25 ± 19.44	21.58 ± 7.56	18.25 ± 12.02
Sept.	38.75	34.88 ± 14.77	44.06 ± 20.75	29.88 ± 13.62
Oct.	9.33	18.00 ± 4.81	19.83 ± 3.46	15.00 ± 6.09
Nov.	8.00	9.08 ± 3.26	7.50 ± 4.17	4.25 ± 2.53
Dec.	20.00	7.25 ± 1.26	3.50 ± 2.65	5.00 ± 2.94
1962				
Feb.	4.50	5.19 ± 1.46	4.50 ± 2.56	3.63 ± 2.62
Mar.	9.00	10.08 ± 8.22	9.42 ± 5.98	6.50 ± 4.89
Apr.	8.25	16.00 ± 9.84	14.94 ± 10.22	18.88 ± 11.76
May	36.67	22.00 ± 7.37	34.50 ± 14.56	18.00 ± 4.84
June	31.25	37.44 ± 15.69	21.88 ± 7.41	14.81 ± 9.05
July	65.00	27.88 ± 9.38	31.56 ± 13.41	27.43 ± 14.70

*Sample from one station only, SD not calculated.

TABLE VII

SEASONAL AND ANNUAL MEAN ASH-FREE DRY WEIGHT (AFDW) AND STANDARD DEVIATION (SD) IN MG/L

	Pond 1*	Pond 4	Pond 7	Pond 10
Fall	20.70	22.08 ± 14.75	25.83 ± 20.61	17.73 ± 14.22
Winter	9.67	5.88 ± 1.68	4.17 ± 2.52	4.08 ± 2.68
Spring	17.00	16.03 ± 9.67	19.15 ± 14.80	14.90 ± 9.88
Summer	34.55	33.09 ± 15.19	25.32 ± 10.92	20.34 ± 13.12
Annual	24.71	22.43 ± 15.40	21.79 ± 16.14	16.52 ± 12.72

*Sample from one station only, SD not calculated.

TABLE VIII

ASH-FREE DRY WEIGHT ESTIMATES OF STANDING CROP FROM VARIOUS COMMUNITIES

Source	AFDW mg/l
Canyon Ferry Reservoir, Montana (Wright, 1959)	2.35
Fresh-water Pond, New Zealand (Byars, 1960)	2.88 to 4.6
Pond, Minnesota (Dineen, 1953)	0.75 to 7.82
Pond, Kansas (Minter, 1952)	0.9 to 22.0
Colorado Lakes (Pennak, 1949)	1.19 to 13.64
Paddy Fields, Japan (Ichimura, 1954)	0.45 to 5.80
Sewage Ponds	
Contra Costa Ponds, California (Allen, 1955)	
Influent Pond	90 to 102
Effluent Pond	45 to 123
Santa Rosa Ponds, California (ibid.)	
Influent Pond	10 to 159
Effluent Pond	0.6 to 50.2
Oil Refinery Ponds (Present Study)	
Pond 1	1 to 101
Pond 4	3.5 to 57.25
Pond 7	3.0 to 69
Pond 10	2.25 to 57.5

Chlorophyll *a* Biomass

Estimates of chlorophyll *a* standing crop biomass have been used to measure primary production (Wright, 1958, 1959; Edmondson, 1955, Ryther and Yentsch, 1957). Mean chlorophyll *a* was estimated from samples taken at four different stations in each pond, except Pond 1 (Appendix Table V). Chlorophyll concentration ranged from 0.005 to 1.35 mg/l in Pond 1. Monthly means varied from 0.008 to 0.965 mg/l (Table IX). Seasonal means ranged from 0.034 to 0.648 mg/l (Table X). Annual means varied from 0.258 mg/l in Pond 1 to 0.297 mg/l in Pond 7, and decreased to 0.222 mg/l in Pond 10.

Chlorophyll concentration usually decreased somewhat as the effluent passed through the last ponds in the series. This was a desirable result because the ponds thus discharged minimal amounts of organic matter to the receiving stream. An increase in chlorophyll in the middle of the system indicated more inorganic nutrients were available for conversion into algal cells. Chlorophyll concentrations in oil refinery effluent holding ponds are normally higher than natural fresh and marine waters and may be of the same order of magnitude as in sewage stabilization ponds (Table XI).

Chlorophyll *a* and Ash-free Dry Weight Relationships

Chlorophyll *a* and ash-free dry weight concentrations usually showed seasonal succession (Fig. 2 and 3 and Appendix Fig. 1). From November through February, biomass estimates were low when algal populations were low. As algal populations increased in late spring ash-free dry weight and chlorophyll increased. Spring increase in biomass was probably

TABLE IX

MONTHLY MEAN CHLOROPHYLL a AND STANDARD DEVIATION (SD) IN MG/L

Date	Pond 1*	Pond 4	Pond 7	Pond 10
1961				
Aug.	0.427	0.607 ± .162	0.430 ± .246	0.335 ± .250
Sept.	0.131	0.217 ± .124	0.660 ± .274	0.384 ± .170
Oct.	0.225	0.079 ± .054	0.245 ± .152	0.264 ± .189
Nov.	0.008	0.014 ± .004	0.029 ± .022	0.055 ± .045
Dec.		0.090 ± .024	0.076 ± .019	0.045 ± .017
1962				
Feb.	0.038	0.054 ± .024	0.028 ± .021	0.029 ± .013
Mar.	0.053	0.045 ± .033	0.050 ± .039	0.064 ± .060
Apr.	0.025	0.154 ± .150	0.109 ± .091	0.182 ± .126
May	0.270	0.165 ± .037	0.418 ± .111	0.200 ± .040
June	0.505	0.567 ± .267	0.349 ± .193	0.222 ± .140
July	0.965	0.530 ± .251	0.491 ± .301	0.387 ± .185

*Sample from only one station, SD not calculated.

TABLE X

SEASONAL AND ANNUAL MEAN CHLOROPHYLL a AND STANDARD DEVIATION (SD) IN MG/L

	Pond 1*	Pond 4	Pond 7	Pond 10
Fall	0.141	0.115 ± .121	0.346 ± .322	0.249 ± .202
Winter	0.041	0.066 ± .028	0.044 ± .031	0.034 ± .016
Spring	0.107	0.125 ± .110	0.184 ± .178	0.152 ± .105
Summer	0.648	0.564 ± .233	0.423 ± .252	0.313 ± .200
Annual	0.258	0.259 ± .265	0.297 ± .277	0.222 ± .188

*Sample from one station only, SD not calculated.

TABLE XI

CHLOROPHYLL a CONCENTRATIONS FROM VARIOUS COMMUNITIES

Source	Chlorophyll a mg/l
Estuarine Waters, Georgia (Ragotzkie, 1959)	0.005 to 0.019
Canyon Ferry Reservoir, Montana (Wright, 1960)	0.005 to 0.021
Forge River, N.Y. (Barlow et al., 1963)	0.025 to 0.049
Stabilization Ponds, Lebanon, Ohio (Bartsch, 1961)	0.184 to 0.328
Five Dakota Stabilization Ponds, S.D. (ibid.)	0.080 to 7.320
Sewage Ponds, Kadoka, S.D. (Bartsch and Allum, 1957)	0.080 to 2.820
Sewage Pond, Denmark (Steeman Nielson, 1957)	0.30
Fish Ponds, Israel (Hepher, 1962) unfertilized	0.009 to 0.115
fertilized	0.103 to 0.212
Oil Refinery Effluent Holding Ponds (Present Study)	
Pond 1	0.008 to 1.350
Pond 4	0.010 to 0.836
Pond 7	0.012 to 0.945
Pond 10	0.014 to 0.778

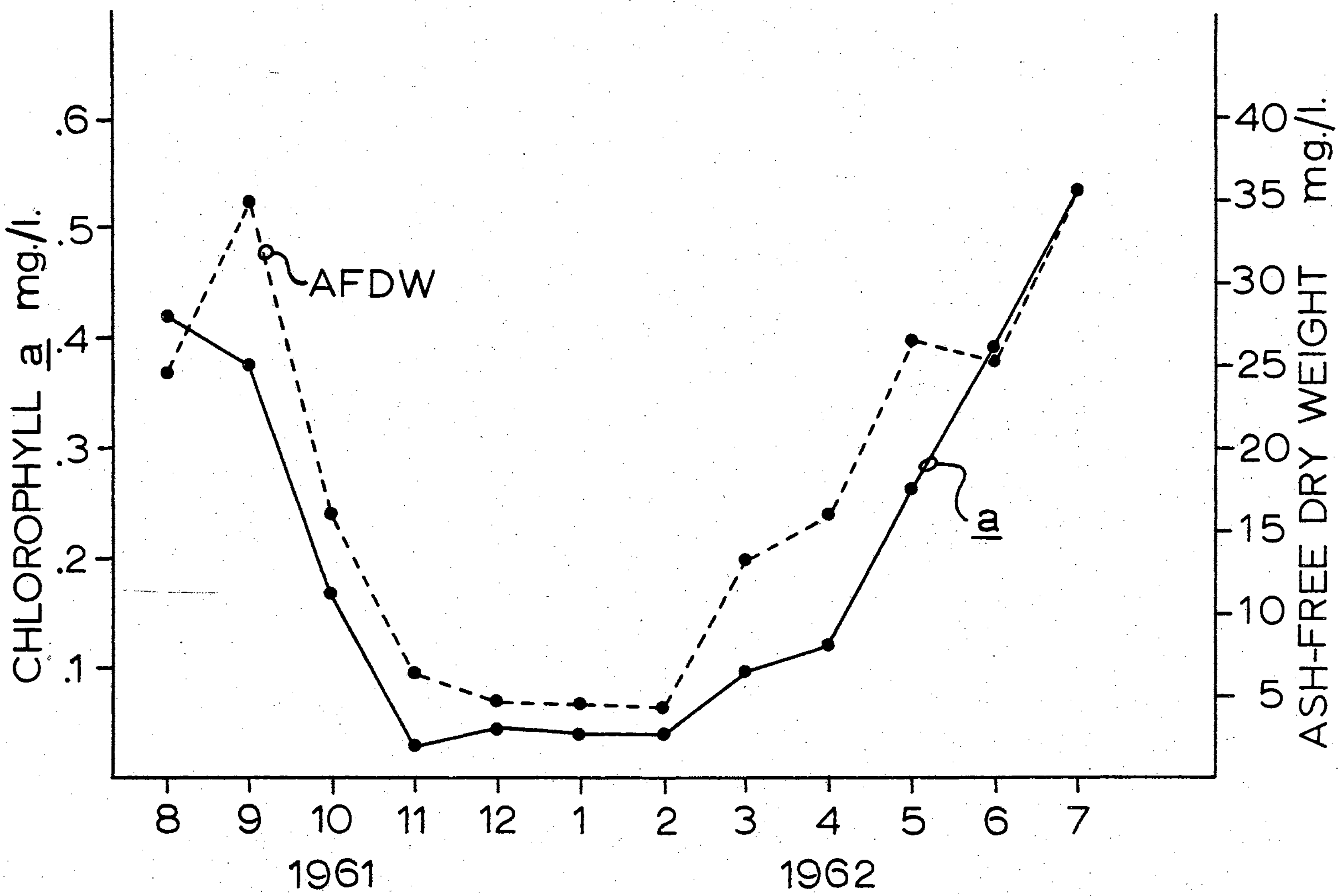

Fig. 2. Monthly mean chlorophyll a and ash-free dry weight.

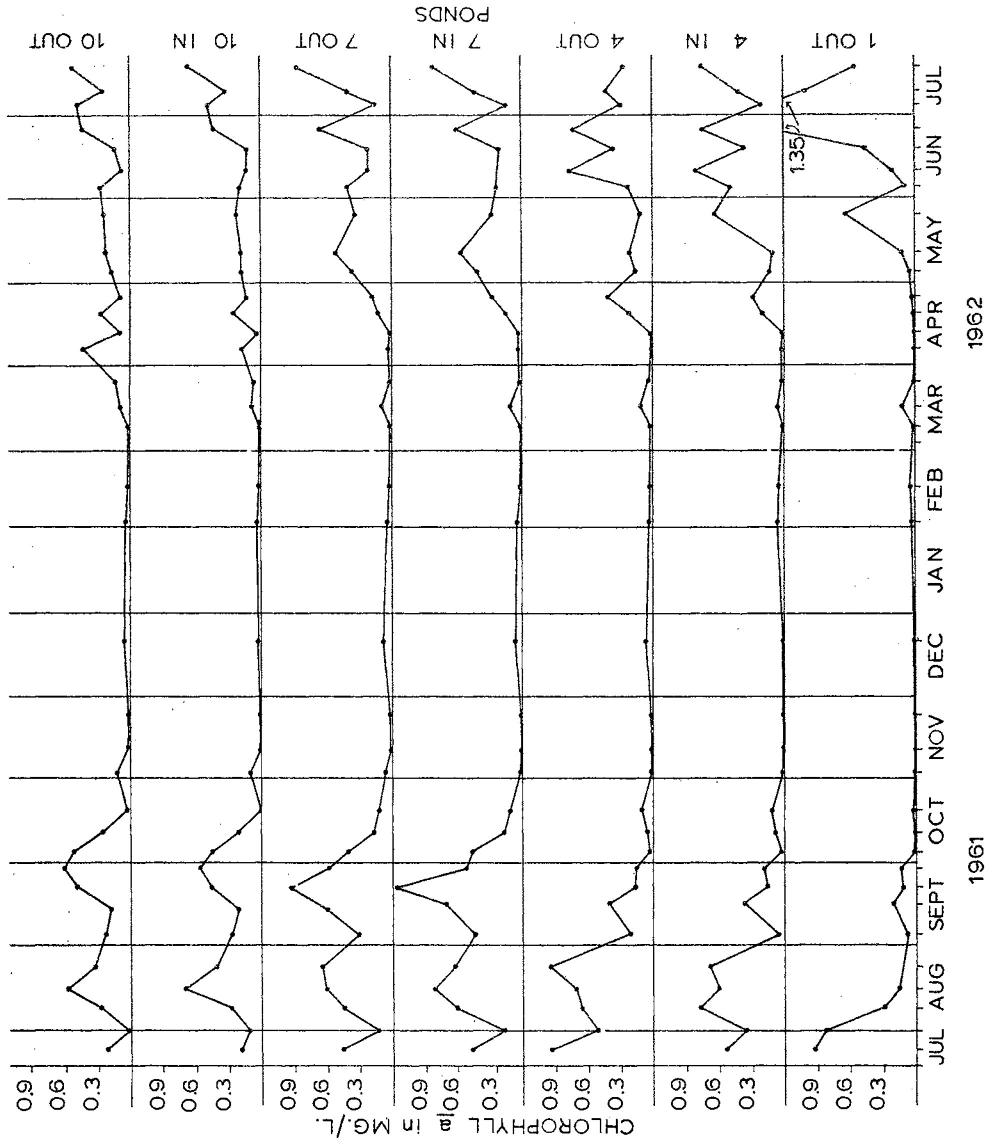

Fig. 3. Chlorophyll a concentration into and out of each pond from 25 July 1961 to 19 July 1962.

somewhat retarded because of the limiting environment.

Mean monthly chlorophyll concentrations in mg/l were plotted against ash-free dry weight for each pond (Fig. 4). With chlorophyll a assumed to be relatively constant (Riley, 1949), regression of ash-free dry weight on chlorophyll may be determined. The equation for all ponds is

$$C_a = .014 \text{ AFDW} - .034 \qquad (3)$$

where C_a is chlorophyll a in mg/l, and AFDW is ash-free dry weight in mg/l. Regression equations for each pond are shown in Fig. 4. Regression equations and 95% confidence belts were determined according to Snedecor (1956). Scatter of points for Ponds 1 and 4 indicate that it is more difficult to predict with confidence the relationship between the two units of biomass for these ponds. With high concentrations of chlorophyll, ash-free dry weight generally varied from 20 to 40 mg/l. If relatively low concentrations of chlorophyll were associated with high ash-free dry weight, a large portion of the organic matter must have been from the refinery. Pond 1 contained less chlorophyll per unit of ash-free dry weight, and Pond 7 contained more chlorophyll per unit of ash-free dry weight.

Ash-free dry weight was usually highest in the first part of the system (Tables VI and VII), but maximum chlorophyll concentration usually occurred in Pond 4 or 7 (Tables IX and X). High ash-free dry weight in the first ponds was partly contributed by the refinery. Increase in chlorophyll in the middle of the system was due to increase in algal populations, and may indicate that more nutrients were available and toxicity was reduced. A decrease in both estimates of biomass usually occurred in the system.

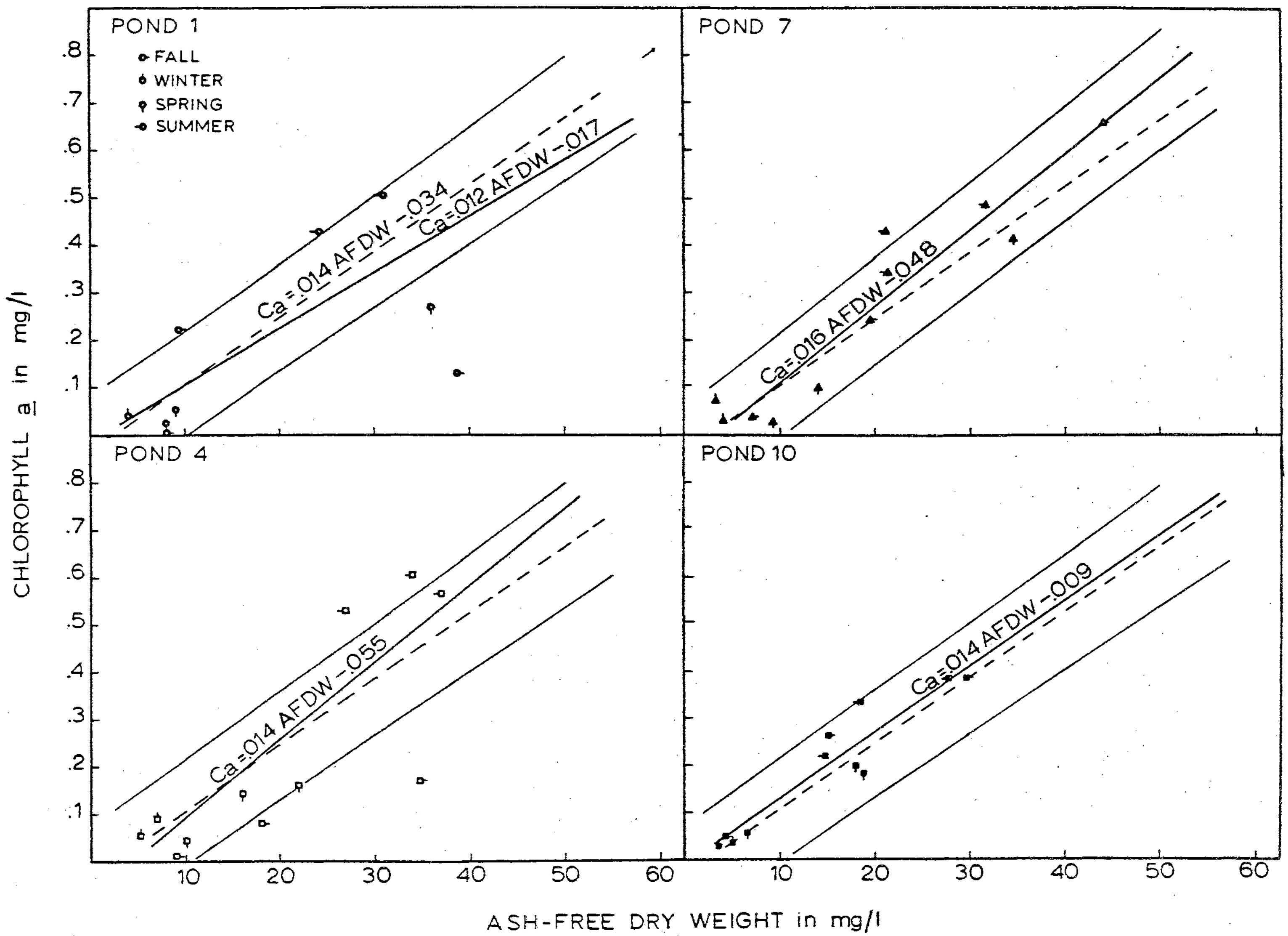

Fig. 4. Linear regression of chlorophyll a on ash-free dry weight. Broken line represents the mean linear regression for all ponds, C_a = chlorophyll a, AFDW = ash-free dry weight. Two boundary lines indicates the 95% confidence belt.

Chlorophyll to ash-free dry weight ratios were relatively constant throughout the year (Table XII). Manning and Juday (1941) found the ratios to be lowest in the summer and to increase in winter. Wright (1958) found a chlorophyll to ash-free dry weight ratio of about 0.003 in Canyon Ferry Reservoir. Ratios from enriched waters are often higher than those from many natural or less productive waters. Oil refinery holding pond ratios tended to be higher in summer than other seasons. The chlorophyll to ash-free dry weight ratio tended to increase slightly as the effluent passed through the system except during summer. Ponds 1 and 4 were usually subjected to greater environmental changes because of toxic materials and organic matter from the refinery. As a result, chlorophyll tended to decrease more than ash-free dry weight in the first part of the system, but increased during summer when a greater supply of nutrients became available. The last two ponds in the system were more stable with less variation in the chlorophyll to ash-free dry weight ratios.

TABLE XII

RATIO OF CHLOROPHYLL a TO ASH-FREE DRY WEIGHT

Season	Pond 1 mg/l	Pond 4 mg/l	Pond 7 mg/l	Pond 10 mg/l
Fall	0.007	0.005	0.013	0.014
Winter	0.004	0.011	0.011	0.008
Spring	0.006	0.008	0.010	0.010
Summer	0.019	0.017	0.017	0.015

Chlorophyll concentration (Fig. 3) in Pond 1 decreased earlier in the fall. Chlorophyll concentration increased progressively earlier into the spring from the last pond to the first pond. The converse of this was true during fall. Chlorophyll concentration in Pond 10 increased earlier in the spring. Increase in chlorophyll concentration occurred progressively later into the spring from Pond 10 to Pond 1. Primary producers were affected by more adverse conditions in the first part of the system. Ponds 7 and 10 were able to develop algal populations earlier in the spring and to maintain the populations later into the fall. Thus, Ponds 7 and 10 were more productive over a longer period of time.

In Pond 4, current flow was to the north, while in Ponds 7 and 10 the effluent flowed toward the south (Fig. 1). The west side of Pond 4 was used as a roadway, while the dikes separating each pond were covered with tall, annual plants. These plants probably reduced the effect of the wind in Ponds 7 and 10 since prevailing winds were from the southwest. Ash-free dry weight means were determined for each end of each pond (Appendix Table VIII and Appendix Fig. 1). Mean chlorophyll concentrations were determined for each end of each pond (Fig. 3 and Appendix Table VII). Seasonal and annual concentrations are summarized in Table XIII. All ponds during most seasons had slightly higher concentrations on the downwind side of the ponds (Stations 4AB, 7AB, and 10AB). Chlorophyll increased more within Pond 4 than the other ponds, indicating that current and prevailing winds probably caused some plankton drift. Seasonal means indicated Ponds 7 and 10 probably had more uniform distribution of plankton.

Mean chlorophyll a concentrations and ash-free dry weight were determined for each side of each pond, except Pond 1 (Appendix Table IX). Both estimates were usually larger on the east side in Pond 4, but larger on the west sides of Ponds 7 and 10. Plants on the dikes apparently reduced the effect of the wind in Ponds 7 and 10, and more uniform distribution of organic matter occurred.

TABLE XIII

SEASONAL AND ANNUAL MEAN CHLOROPHYLL a CONCENTRATION IN MG/L, INTO AND OUT OF EACH POND

	Pond 1	Pond 4		Pond 7		Pond 10	
	Out	In	Out	In	Out	In	Out
Summer, 61	0.553	0.574	0.709	0.463	0.413	0.328	0.283
Fall, 61	0.066	0.108	0.121	0.369	0.324	0.242	0.259
Winter, 61-62	0.041	0.079	0.053	0.040	0.047	0.031	0.037
Spring, 62	0.106	0.114	0.135	0.193	0.175	0.129	0.175
Summer, 62	0.702	0.504	0.537	0.401	0.427	0.338	0.298
Annual Mean	0.293	0.275	0.311	0.293	0.277	0.213	0.210

Plankton Biomass

A wide range of cell size and numbers exists among phytoplankters (Wright, 1958; Davis, 1958), thus for comparative purposes volumes were determined for plankton. Reference to total phytoplankton includes all micro-cells and algal cells. References to algal cells excludes micro-cells.

Mean volumes for total phytoplankton, micro-cells, and algae are shown in Figures 5 and 6 and in Appendix Table X for each collection and month. The greatest variation in phytoplankton occurred in Pond 1. Pond 1 had more fluctuation in conditions, which probably resulted in an almost complete disappearance of algae at times. Maximum total

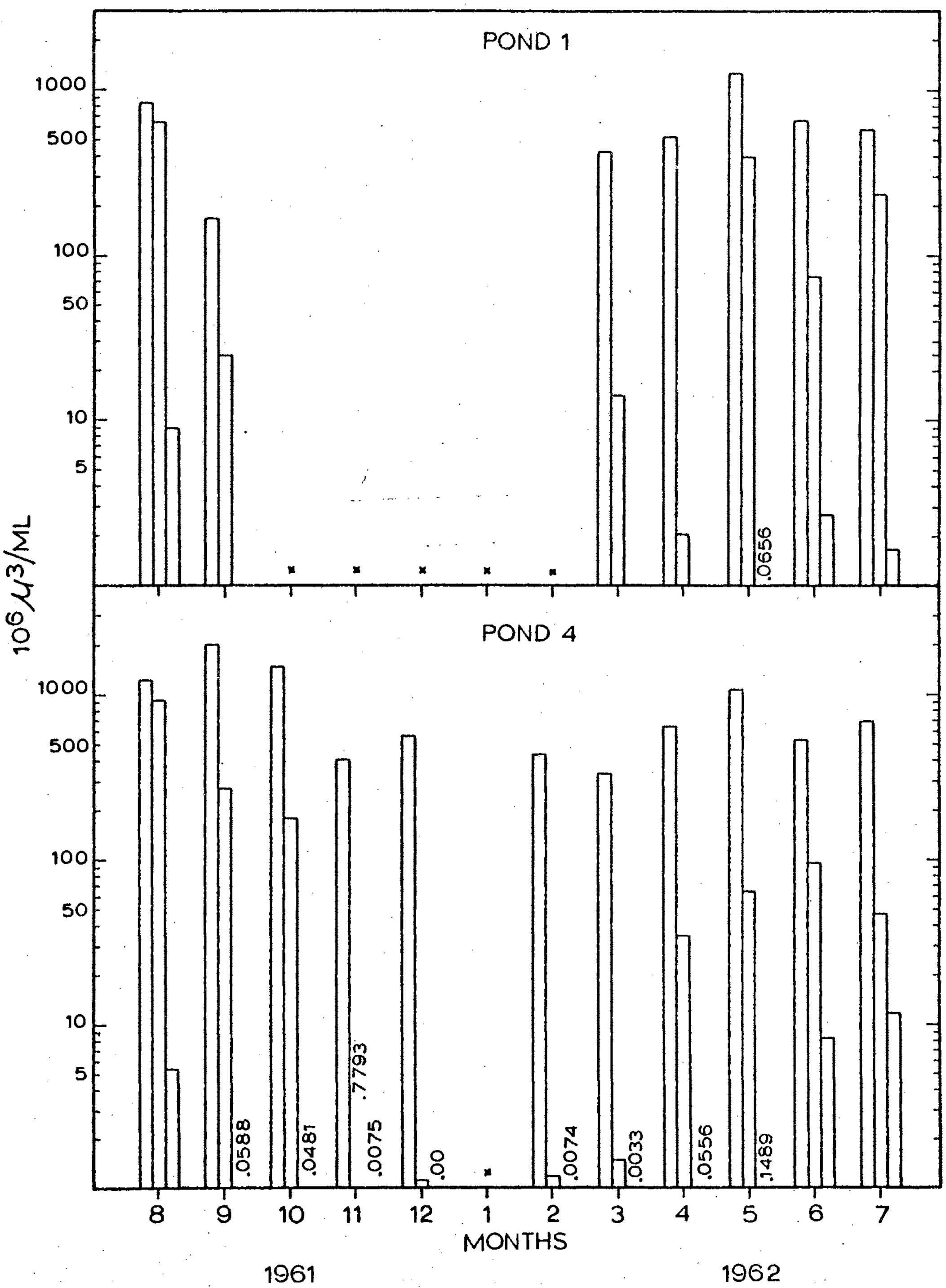

Fig. 5. Monthly volumes of organisms in ponds 1 and 4. Each bar represents micro-cells, algae, and zooplankton respectively. x = no collections.

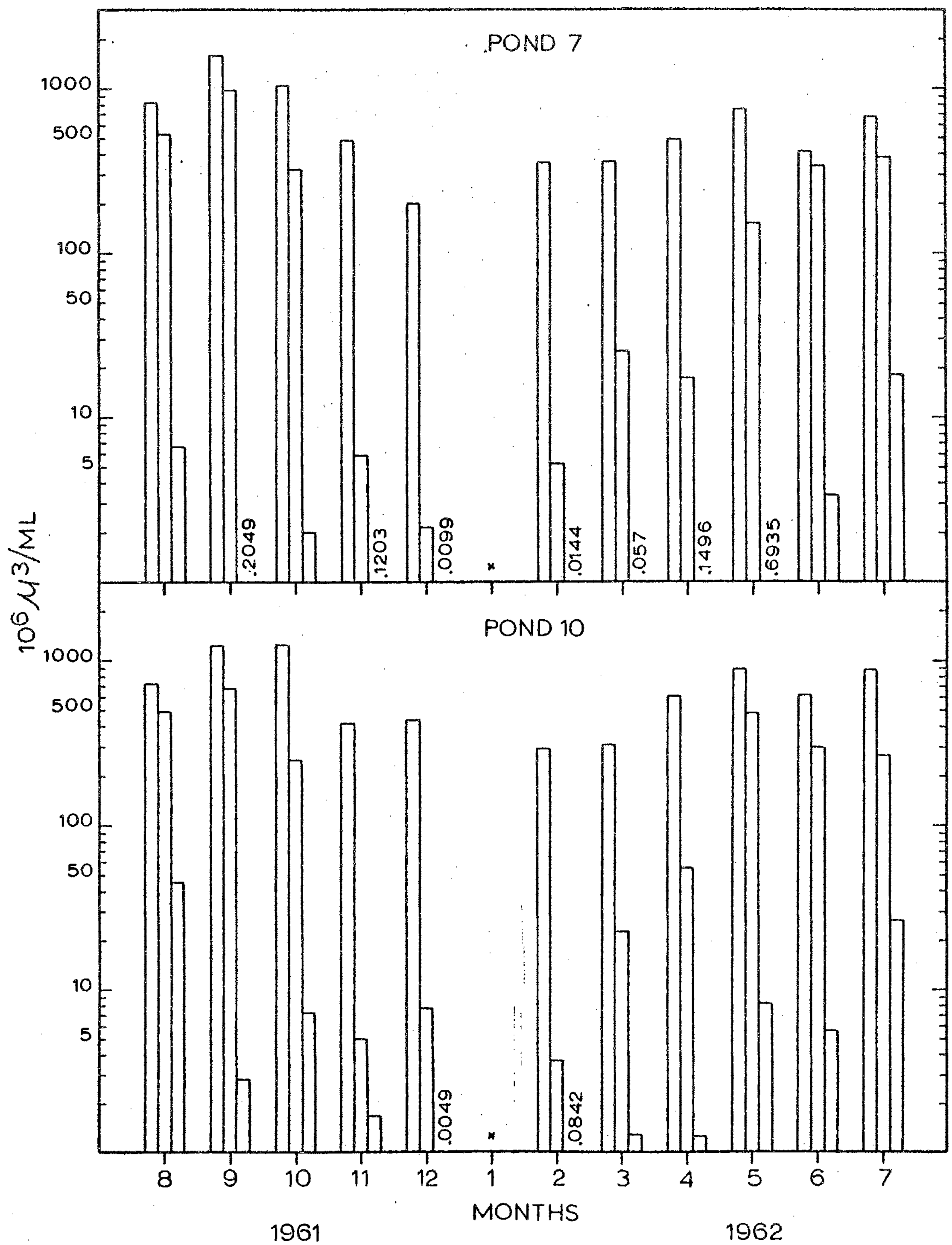

Fig. 6. Monthly volumes of organisms in pond 7 and 10. Each bar represents micro-cells, algae, and zooplankton volumes respectively. x = no collections.

phytoplankton volumes usually occurred in Ponds 4 or 7. Algal volumes were generally lower in Pond 10 than in other ponds.

Mean phytoplankton volumes for each month are shown in Figs. 5 and 6 for each pond. Micro-cell volumes composed 56 to 99% of total phytoplankton volumes. The largest volumes of phytoplankton occurred in August and September, even though a "slug" of high phenol content effluent passed through the system during this period. After passage of the "slug", phytoplankton was reduced in Pond 1 during September, but in Pond 4 micro-cells increased and algal cells decreased. Production of cells in Ponds 7 and 10 in the last part of September was greater than in August. It was apparent that micro-cells increased after the inflow of the "slug". In the first part of the system, particularly in Pond 1, algal volumes were reduced from August to September, but increased toward the latter part of the system. Improved environmental conditions such as increase in nutrients and decrease in toxicity at the end of the system may be indicated by the increase in volume of algal cells.

Minimum volumes occurred during December and February, with greatest volumes of algal cells in Ponds 7 and 10, indicating better conditions within these ponds. Micro-cell volumes increased during spring and fall but decreased during summer. Peak algal volumes appeared earlier in Pond 10, indicating that unfavorable conditions may have retarded earlier spring development in the other ponds.

Seasonal and annual mean plankton volumes are given in Table XIV. Maximum phytoplankton volumes occurred during fall in Pond 7, but Pond 4 yielded the largest annual volume. Fall and annual maximum micro-cell volumes occurred in Pond 4. Micro-cell volumes composed 77 to 85% of the annual total phytoplankton. Fall and annual maximum algal cell

TABLE XIV

SEASONAL AND ANNUAL MEAN VOLUMES OF TOTAL PHYTOPLANKTON, MICRO-CELLS, ALGAE AND ZOOPLANKTON X 10^3 u^3/ml

Season	Pond	Total Phyto-plankton	Micro-cells	Algae	Zoo-plankton
Fall	1	197113.2	171800.0	25313.2	
	4	1464781.6	1314476.5	150314.1	38.12
	7	1483007.5	1045717.8	437209.7	789.95
	10	1282824.1	971839.0	310985.1	3938.17
Winter	1				
	4	505261.0	505105.0	1156.0	3.71
	7	283845.7	280140.0	3705.7	12.11
	10	369915.2	364245.0	5670.2	44.55
Spring	1	795257.5	743026.7	52230.8	65.60
	4	722174.8	688550.8	33625.9	68.95
	7	637625.5	572553.3	65072.2	300.40
	10	653164.6	611800.0	41364.6	3634.07
Summer	1	1032765.4	710600.0	322165.4	1800.90
	4	1170541.1	806082.2	364458.5	8495.27
	7	883447.9	649274.2	234173.7	27997.85
	10	1014301.3	748008.5	266292.7	26005.05
Annual	1	675045.4	541808.9	133236.5	622.16
	4	965689.6	828301.4	137388.6	2151.50
	7	821981.6	636921.3	185060.3	7277.32
	10	830051.3	673973.1	156078.2	8405.71

volumes occurred in Pond 7. Algal volumes in Pond 10 were usually less than maximum volumes in other ponds. Relatively little difference in mean annual phytoplankton volumes occurred between Pond 7 and 10. The reduction of phytoplankton volume toward the end of the system following peak volumes earlier in the system was an important characteristic of the pond system.

Total phytoplankton volumes in oil refinery effluent holding ponds exceeded reported volumes from natural bodies of water, ranging from 195,113.2 to 6,326,035 x 10^3 u^3/ml in the holding ponds. In Lake Erie, total phytoplankton volumes ranged from 1,331 to 88,934 x 10^3 u^3/ml (Davis, 1958). Algal volumes from Canyon Ferry Reservoir, Montana ranged from 1,070 to 6,010 x 10^3 u^3/ml (Wright, 1958) as compared to 2,640,435 x 10^3 u^3/ml maximum in refinery holding ponds. Similar volumes from Lake Osybsjon, Sweden ranged from 547.4 to 3032.2 x 10^3 u^3/ml (Willen, 1961). Algal volumes from raw sewage lagoons varied from 511 to 35,773 x 10^6 u^3/ml at Fayette, Missouri (Neel, et al., 1961), which was much higher than refinery algal volumes.

Zooplankton volumes in each pond were computed and means determined for each collection and month (Appendix Table X). In general, there was an increase in zooplankton volume from pond to pond. The greatest variation of volumes occurred in Pond 7, with the smallest variation in Pond 1.

The monthly means are represented graphically in Figs. 5 and 6. Monthly means decreased considerably from August to September. The "slug" in August resulted in a sharp decrease in zooplankton volumes from August to September in all ponds. Recovery of the zooplankton began to appear within a few weeks; however only Pond 10 developed large volumes. Zooplankton populations apparently were affected by the toxicity of the "slug" through all the system and did not develop large populations before late fall and winter conditions occurred. Relatively few individuals were collected in the winter. Zooplankton volumes in Pond 10 increased earlier during the spring than in the other ponds. Pond 4 usually produced smaller volumes of zooplankters than Pond 7. Pond 10 generally had the greatest volumes. Largest volumes occurred in July or August in all ponds except Pond 1 where peak volumes occurred in June.

Annual and seasonal means for zooplankton volumes are given in Table XIV. Except during the fall, there was generally a four-fold increase in zooplankton volumes from Pond 4 to Pond 7. Peak volumes of zooplankton occurred in Pond 7 and 10 during the summer. Pond 10 consistently produced larger volumes of zooplankton during all seasons except during summer when Pond 7 had a slightly larger population. Annual mean volumes increased from pond to pond with Pond 10 producing the largest volume of zooplankton.

Zooplankton volumes were somewhat larger than most natural bodies of water except in the first part of the system. Zooplankton volumes range from an average of 4,652 to a maximum of 68,303 x 10^3 u^3/ml in Lake Erie (Davis, 1958) as compared with the annual mean of 2,151.5 x 10^3 u^3/ml in Pond 4, 8405.71 x 10^3 u^3/ml in Pond 10 (Table XIV) and a maximum volume of 179,950.04 x 10^3 u^3/ml in Pond 7.

Algae to zooplankton ratios (A:Z) were determined from seasonal and annual mean volumes. Seasonal algae to zooplankton ratios varied from 161:1 to 634:1 in Pond 7 and 10:1 to 126:1 in Pond 10. Pond 10 consistently had a lower ratio. Summer algae to zooplankton ratio was approximately 8:1 in Pond 7 and 10:1 in Pond 10 while much higher ratios of 161:1 and 45:1 were found in Ponds 1 and 4, respectively.

During the more optimal summer growing season, decrease in chlorophyll, decrease of algal biomass, increase in zooplankton biomass, and lower A:Z ratios suggest that the grazing of zooplankton was probably sufficient to reduce the algal biomass. Other factors contributing to the removal of algal cells were grazing by herbivorous insect larvae (Tubb, 1963) and the deposition of old cells.

Biomass Relationships

Biomass values were examined statistically by the correlation coefficient $r = \frac{xy}{\sqrt{\Sigma x^2 \Sigma y^2}}$. Correlation between two or more variables is an index of the intensity of a relationship between variables or the degree of accuracy with which the value of one variable may be predicted, if given the value of the other (Simpson, Roe and Lewontin, 1960). Biomass estimates were composed of four variables, chlorophyll a (1); ash-free dry weight (2); phytoplankton volumes (3); and zooplankton volumes (4). Simple correlation coefficients were calculated between each of four variables with six coefficients being obtained for all possible combinations. A correlation matrix for estimates of biomass is presented in Fig. 7 and in Table XV. Oklahoma State University Computing Center COR IV 650 Program was used for computing correlation coefficients and for standard deviations.

Correlation coefficient for annual chlorophyll to ash-free dry weight (r_{12}) was 0.75 for all ponds, which is statistically significant at the 5% level. Annual correlation was highest in Pond 7 at 0.82. A higher correlation between chlorophyll and ash-free dry weight may indicate that more chlorophyll may be present per unit of ash-free dry

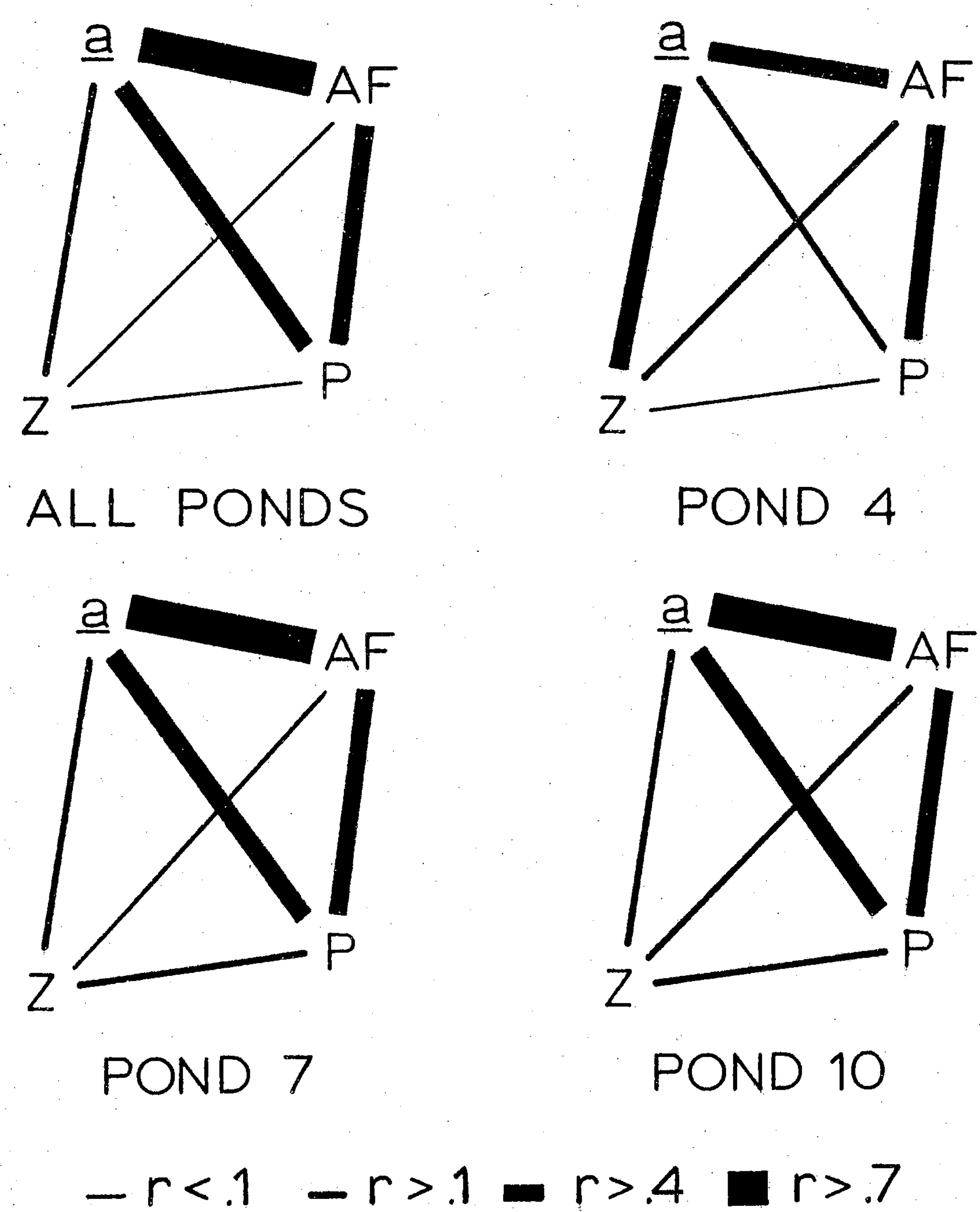

Fig. 7. Correlation matrices for biomass. a = chlorophyll a, AF = ash-free dry weight, P = total phytoplankton, Z = zooplankton and r = correlation coefficient.

TABLE XV

CORRELATION COEFFICIENTS MATRIX

Chlorophyll a (variable 1), Ash-free dry wt. (variable 2), Phytoplankton volume (variable 3) and Zooplankton volume (variable 4)

Ponds	r_{12}	r_{13}	r_{14}	r_{23}	r_{24}	r_{34}
Annual All Ponds	.7497	.4741	.1425	.4693	.0669	.0769
Annual P_4	.6879	.2455	.4630	.3968	.2464	-.0193
P_7	.8216	.6552	.1062	.5900	.0310	.1382
P_{10}	.7261	.5737	.1726	.4068	.1512	.0768
Seasonal						
Fall P_4	.5142	.4734	.3192	.6034	.2858	.4603
P_7	.8170	.9175	-.1955	.8350	-.1216	-.0269
P_{10}	.6800	.8705	.1695	.7840	-.1071	.1975
Winter P_4	.4849	.1160	.1643	.0910	-.1414	-.2132
P_7	-.0342	-.5210	.1406	-.2352	.0310	.2316
P_{10}	-.3521	.1005	-.3851	-.1343	-.2541	-.1595
Spring P_4	.6407	.2288	.0790	.5381	.0143	-.1289
P_7	.8561	.6581	.5802	.6733	.6746	.4436
P_{10}	.8134	.2673	.3216	.2819	.2633	.3397
Summer P_4	.6481	.3391	.0443	.0356	-.0457	-.1343
P_7	.8384	.2183	-.0247	-.0423	.0791	.3306
P_{10}	.6730	.2755	.0299	.0163	.1053	.0357

weight and a larger part of the ash-free dry weight would be composed of plant cells. Seasonal correlations for r_{12} were most significant during fall and spring, but remained high during summer. Winter correlations were low in all ponds, with negative values in Ponds 7 and 10. Most organic matter during winter was from refinery effluent or bacteria.

Annual chlorophyll to phytoplankton volume correlation (r_{13}) for all ponds was 0.47 and was significant in Ponds 7 and 10. Comparatively low correlations indicate that phytoplankton volumes were probably low. This may be due to collecting procedure error as many small cells such as chlorella passed through the net and were missed in counting, or a high percentage of the total phytoplankton was composed of micro-cells which were not photosynthetic.

Annual chlorophyll to zooplankton volumes correlation (r_{14}) for all ponds was 0.14, which was to be expected; however, a rather high value of 0.45 occurred in Pond 4. A high chlorophyll to zooplankton correlation may indicate both populations were increasing at the same time. This appeared to be true in late September and October in Pond 4 and in Pond 10 during the spring. All other correlations were not significant.

Annual ash-free dry weight to zooplankton volume correlation (r_{24}) for all ponds was low at .07. Annual phytoplankton to zooplankton volume correlation (r_{34}) was .08 for all ponds. Little relationship apparently existed between zooplankton and ash-free dry weight or phytoplankton. Pennak (1949) found rotifers and cladocerans poorly correlated with organic matter and phytoplankton.

A correlation matrix graph (Fig. 7) was constructed to show annual relationships between the four sets of variables. Chlorophyll *a* ash-free dry weight and phytoplankton show a triad arrangement or close association between the three estimates of biomass. Cassie (1961) found correlation matrix graphs useful for illustrating association between organisms. Matrix graphs tend to show associations but not the cause and effect of such relationships (Cassie, 1961).

CHAPTER VII

COMMUNITY CHARACTERISTICS

Incidence of Phytoplankton

The ponds supported relatively few genera of plankton. Incidence of algal genera in each season are shown in Table XVI. Five phytoplankton phyla were represented. Phylum Chlorophyta included 11 genera. There was one genus each in Euglenophyta and Pyrrophyta, two genera in Chrysophyta, and three genera in Myxophyta. Micro-cells, approximately four or five forms, consisted mostly of large bacterial forms and small blue-green algal cells of unknown identity. Wallen (1949) reported 67 algal genera for a small pond in Oklahoma. Leake (1945) found 208 species in an Oklahoma lake, with 118 species reported for the first time.

In Pond 1, 11 genera occurred, mostly during summer months. Fourteen genera occurred in Pond 4 and 13 genera in Pond 7 during summer months. Sixteen genera occurred in Pond 10 during 12 summer collections. Usually few genera were observed during winter. An increase in number of genera did not occur until late spring. Toxic substances in the effluent may have restricted development of some genera. Other possible factors restricting occurrence of genera might have been non-availability of nutrients, lower temperature than normal, and anaerobic conditions. Copeland (1963) found anaerobic conditions occurring until the effluent

TABLE XVI

INCIDENCE OF ALGAL GENERA DURING EACH SEASON FROM OIL REFINERY EFFLUENT HOLDING PONDS

Algae	Pond 1				Pond 4				Pond 7				Pond 10			
	F[b]	W	Sp	Su	F	W	Sp	Su	F	W	Sp	Su	F	W	Sp	Su
	1[c]	0	4	11	10	3	10	12	10	3	10	12	10	3	10	12
Chlorophyta																
<u>Chlorella</u>	1		1	9	7	1	5	12	7	1	3	12	8		5	11
<u>Chlamydomonas</u>			1	7	6		6	9	7		4	9	7		5	8
<u>Chlamydobotrys</u>								1				2				2
<u>Eudorina</u>				3				4				5	1			9
<u>Ankistrodesmus</u>				3	1		1	5	3			7	3			2
<u>Actinastrum</u>								1				1				
<u>Pediastrum</u>				2				4				4	1			8
<u>Scendesmus</u>								2				6	1			8
<u>Staurastrum</u>																1
<u>Closteriopsis</u>					1											1
<u>Selenastrum</u>																1
Euglenophyta																
<u>Euglena</u>				11	7	2	9	12	8	2	10	11	9	2	8	12
Pyrrophyta																
<u>Ceratium</u>								1								
Chrysophyta																
<u>Navicula</u>			1	9	4			7	5		1	10	6		2	9
<u>Synura</u>				1												
Myxophyta																
<u>Merismopedia</u>																2
<u>Anabaena</u>				1				1				1				
<u>Oscillatoria</u>	1		4	11	10	3	10	12	10	3	10	12	10	3	10	12
u-cells	1		4	11	10	3	10	12	10	3	10	12	10	3	10	12

[a]Each entry shows the number of collections in which the genus was present.

[b]Seasons, F = Fall; W = Winter; Sp = Spring; Su = Summer.

[c]Total number of collections in each season.

reached Pond 6 in late March.

Chlorella and Chlamydomonas were dominant green algal forms. Euglena occurred in all ponds and was also a dominant or common form present in most collections. Micro-cells and Oscillatoria occurred in most collections and all ponds. However, Oscillatoria was not considered a dominant algal form. Ankistrodemus and a diatom, Navicula were found in many collections, but were never dominant. Eudorina, Pediastrum and Scendesmus were common summer forms. Ceratium and Synura were observed only once in plankton samples. Most genera occurred in all ponds, except Pond 1. No algal genera appeared to be indicators of pollution. All algal forms present are found in most natural environments in Oklahoma (Wallen, 1949; Leake, 1945). Chlorella, Chlamydomonas and Scenedesmus are commonly associated with domestic sewage waste stabilization systems (Neel et al., 1961).

Incidence of Zooplankton

Twelve zooplankton genera were collected (Table XVII). Phylum Protozoa contained four genera of indentifiable ciliates. Rotifers included a few uncertain or immature forms among six genera. Two species of crustaceans were found.

The enumeration of ciliate Vorticella included a few related genera of uncertain identity, but of similar size. Two genera, Gastrostyla and Euplotes were common ciliates during most seasons, but were not common in Pond 1 until aerobic conditions returned during summer months. Ciliates were collected during all seasons in Pond 10.

Common genera of omnivorous rotifers occurring in the ponds were Brachionus calyciflorus Pallas, Keratella, Polyarthra and Hexarthra.

TABLE XVII

INCIDENCE OF ZOOPLANKTON GENERA DURING EACH SEASON FROM OIL REFINERY EFFLUENT HOLDING PONDS[a]

Zooplankton	Pond 1				Pond 4				Pond 7				Pond 10			
	F[b]	W	Sp	Su	F	W	Sp	Su	F	W	Sp	Su	F	W	Sp	Su
	1[c]	0	4	11	10	3	10	12	10	3	10	12	10	3	10	12
Ciliata																
<u>Vorticella</u>	1			10	7		4	12	9		3	11	10	3	3	11
<u>Gastrostyla</u>				6	6			8	8			8	8		1	5
<u>Euplotes</u>				3	3			6	2			6	5			6
<u>Didium</u>				2			2	5	5		1	4	2	1	1	4
Rotifera																
<u>Asplanchna</u>				1			1	5	3		2	6	8	1	5	10
<u>Brachionus</u>	1			6	3		3	12	7		4	11	9	1	4	11
<u>Keratella</u>												2			1	5
<u>Polyarthra</u>				2				2				3			1	6
<u>Hexarthra</u>								2				4				7
<u>Filinia</u>							1									
Others				3	6	2	5	8	8	3	6	9	8	2	4	9
Cladocera																
<u>Moina</u>								1				4				4
Copepoda																
Nauplii												3	1			5
Copepodid								1				1				4
<u>Tropocyclops</u>												1				2

[a]Each entry shows the number of collections in which the genus was present.

[b]Seasons, F = Fall; W = Winter; Sp = Spring; Su = Summer.

[c]Total number of collections in each season.

Asplanchna was the only carnivorous rotifer. Brachionus were the dominant rotifers in most collections. Spine lengths and configurations of B. calyciflorus showed considerable variation. On some occasions other species occurred in large numbers (Appendix Table XII). Asplanchna was common in many collections but never in very large numbers. Rotifers occurred only a few times in Pond 1. Klimowicz (1961) found Brachionus calyciflorus and Asplanchna sieboldi as dominant species in industrial sewage canals.

One species of Cladocera, Moina brachiata, (Jurine) occurred on one occasion in Pond 4 and in four summer collections in Ponds 7 and 10 (Table XVII). M. brachiata was observed in large swarms at night in Ponds 8, 9, 10, and in a ditch carrying effluent from the ponds. Jones (1955, 1958) reported 60 forms (53 species) of cladocerans in Oklahoma.

One species of Copepoda, Tropocyclops prasinus (Fisher), was found on only three occasions. Immature forms were collected on 15 occasions, but usually in the last part of the pond system.

Few zooplankton genera could be considered indicators of pollution. Since fewer numbers of zooplankton genera occurred in the earlier part of the system, a relatively higher degree of toxicity may be indicated (Appendix Table XII).

Generic lists and incidence have shown little in the way of ecological conditions of each pond. Hohn (1959) found comparisons of flora and fauna from two similar habitats to show about the same diversity of species unless disturbed by some external force such as toxicity. A similar conclusion may be made when comparing oil refinery holding ponds. During the summer optimal period, toxicity effects are apparently reduced. According to Cholnoky (1960) a list of flora or fauna may lead to faulty conclusions.

Species-Diversity

Species-diversity graphs were made following the procedure of Yount (1956). The degree of organization of an ecosystem is measured by the number and variety of single components (Margalef, 1962). Counts for species-diversity are contained in Appendix Table XI. Cumulative numbers of plankton species were plotted against log of cumulative numbers of individuals (Figs. 8, 9, and 10). For comparative purposes, a species-diversity index may be derived from the slope of the line and expressed as species per cycle (Odum and Hoskins, 1957). A cycle is defined as a ten-fold (1-10, 10-100, 100-1000) increase in individuals counted. Species per cycle was determined by equating the line with a straight (logarithmic) reference line and recorded to the nearest whole number. Species-diversity index as species per cycle is shown on the right hand ordinate of all species diversity figures.

Difference in diversity between samples is indicated when slopes of lines diverge (Fig. 8). Differences among holding ponds result in diverging lines with an increasing difference between species per cycle. Species-diversity curves that converge or remain close together have about the same degree of organization or diversity. Similar slopes or species per cycle among ponds should indicate similar environmental conditions and species composition. As toxicity decreases, species-diversity should increase from pond to pond. The highest number of species per cycle is associated with the most complex community. Pond 10 with highest diversity is considered to have more organization or niches and thus is a more stable community (MacArthur, 1955; Margalef, 1962).

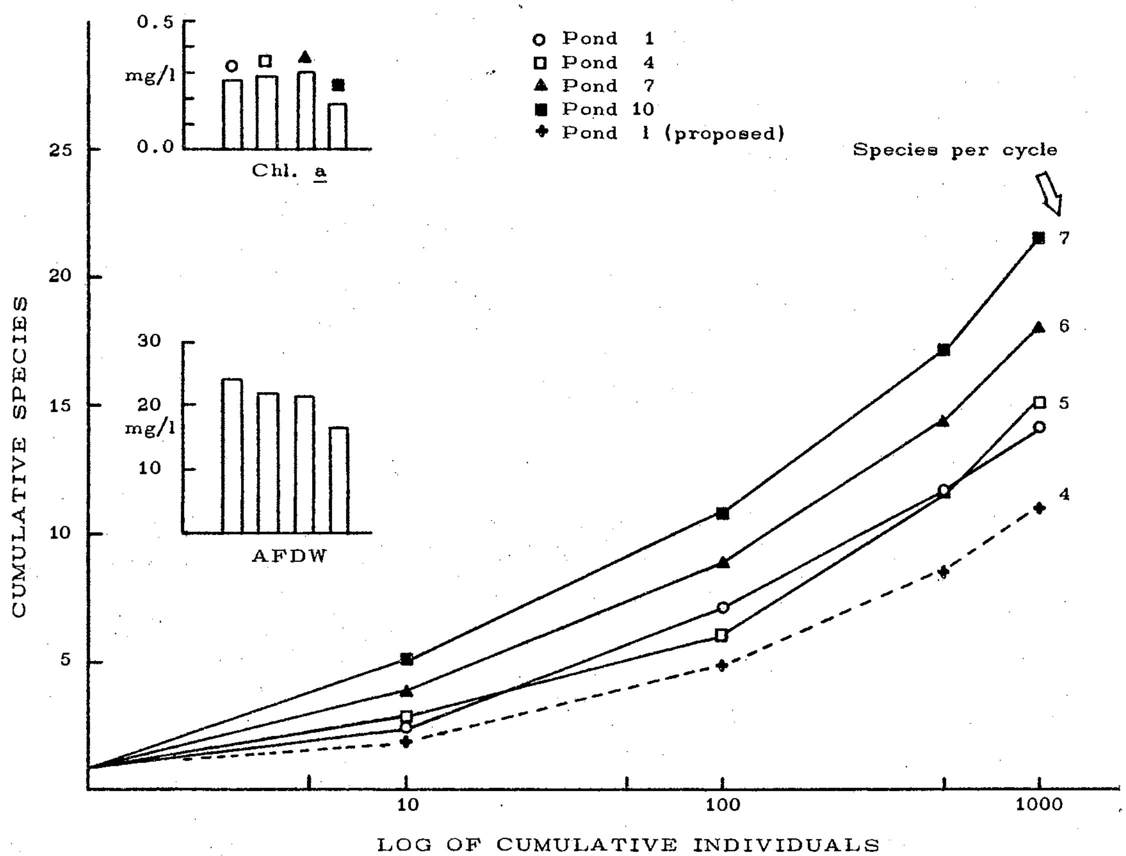

Fig. 8. Mean species diversity in oil refinery effluent holding ponds.

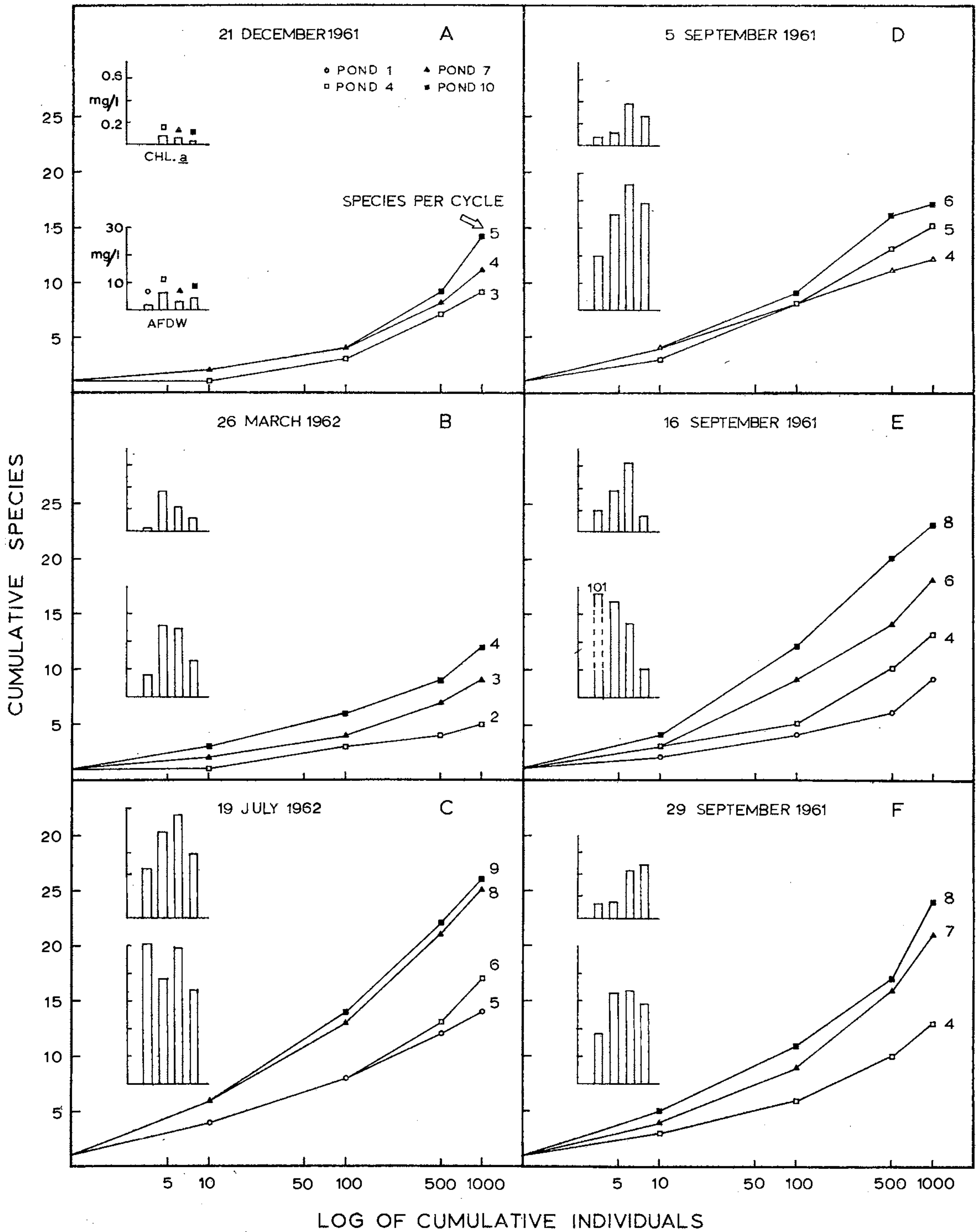

Fig. 9. Selected Species Diversity Curves for Oil Refinery Effluent Holding Ponds. Key to each subfigure in A.

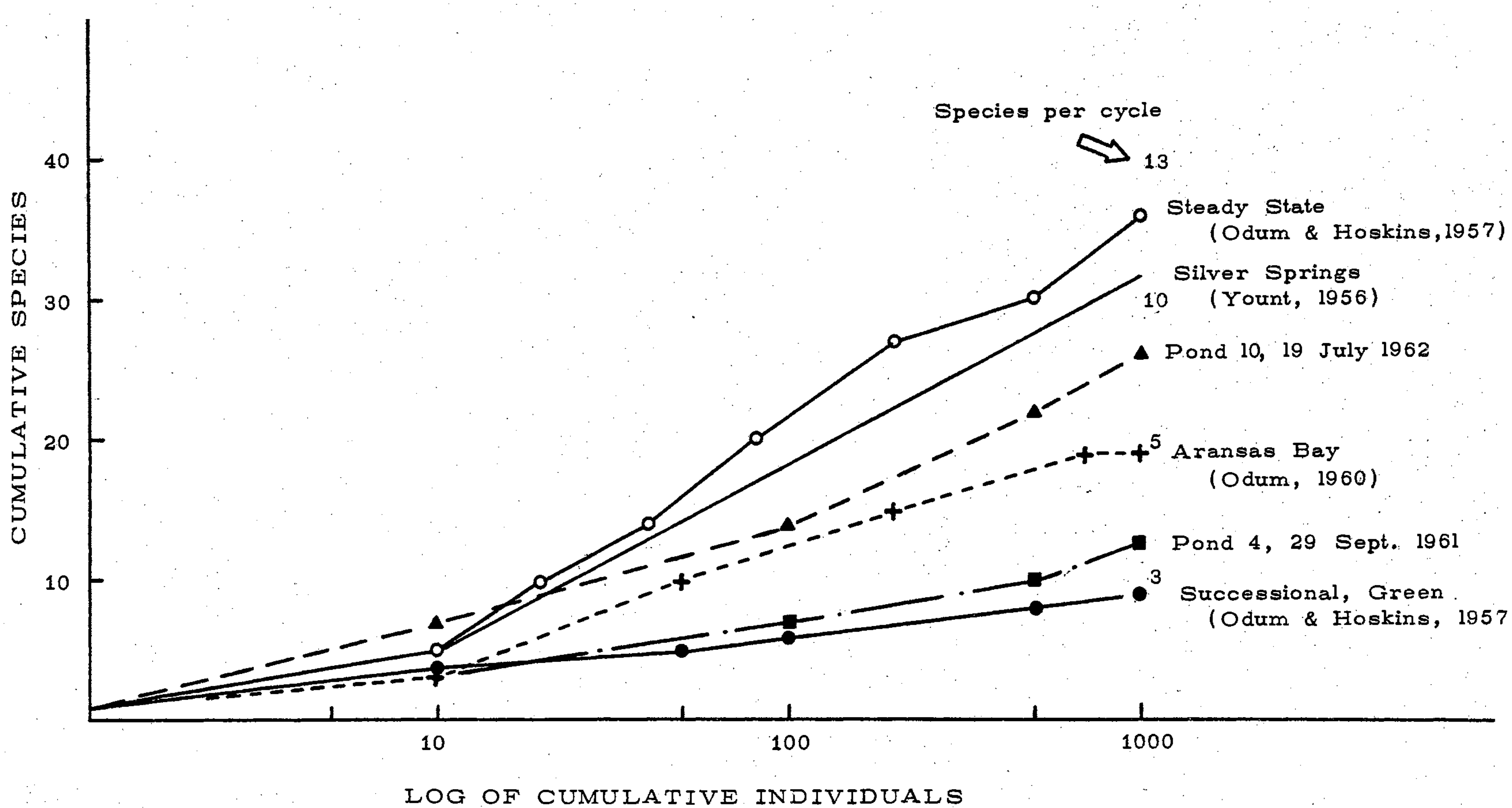

Fig. 10. Species diversity curves comparing oil refinery effluent holding ponds with various communities.

Species-diversity graphs should show differences in both longitudinal and seasonal succession from less to more complex communities or in the case of oil refinery ponds from influent pond to the last pond. Patrick (1949) refers to a "healthy" stream as one with a balance of environmental conditions which is capable of supporting a great variety of organisms. The "healthiest" stream was used as a reference in comparing polluted streams. Pond 10 is considered the "healthiest" pond because it is more diverse in community structure.

Mean species-diversity from 18 collections for each pond is shown in Fig. 8. Species-diversity ranged from five to seven species per cycle. Pond 1 appears to be similar to Pond 4; however, only nine collections were available for counting. A mean slope or diversity index of about four species per cycle is postulated for Pond 1. In Ponds 7 and 10, slopes of the lines diverge, indicating a difference between the two ponds.

Species-diversity curves during winter had similar slopes with little difference indicated among ponds. Levels of toxicity were higher and phenol reduction was less during winter months; however, greater temperature differences but lower temperatures occurred during this time among ponds. Plankton populations were composed mostly of micro-cells with few other algal cells. Anaerobic conditions also might have lowered species-diversity.

Spring species-diversity decreased slightly in species per cycle from winter (Fig. 9B). A greater difference between ponds may be indicated, since the curves diverge slightly more than winter curves. An increase in diversity during the spring months may have been retarded by high levels of toxicity and anaerobic conditions, which continued in most ponds until April, 1962 (Appendix Table III).

Environmental conditions were optimal in summer months. All ponds were more diverse than at other seasons (Fig. 9C). Pond 7 had developed to a state of diversity similar to Pond 10. Greatest difference in diversity existed between Ponds 4 and 7.

Species-diversity in Pond 10 was used as a reference to evaluate the effect of toxicity as a "slug" of toxic material passed through the system. A "slug" of unusually toxic materials had reduced species-diversity in all ponds on 5 September, 1961 (Fig. 9D). Similar diversity curves indicate little difference between ponds. Pond 7 had the lowest diversity and its effluent was probably more toxic. Passage of the "slug" through the system produced a diversity curve similar to the winter curve. The pond system was recovering from the main effect of the "slug" on 16 September (Fig. 9E) when diversity curves indicate uniformly progressive difference from pond to pond. This curve is somewhat like a spring curve. By 29 September, species-diversity appeared to correspond to summer diversity (Fig. 9E), and Pond 7 was again like Pond 10. Recovery of the system from effects of the "slug" indicated decrease in toxicity, increase in community structure or organization, and longitudinal succession.

Biomass estimates were compared with species-diversity as proposed by Yount (1956) (Figs. 8 and 9). Yount postulated that with production low and other factors constant, species variety will be high with small numbers of individuals. Conversely, with production high and other factors constant, species variety will be low with large numbers of individuals. Environmental conditions in Ponds 7 and 10 were relatively constant and species-diversity increased with decrease in biomass estimated by chlorophyll a and ash-free dry weight. Toxicity was greatest in the first part of the pond system and the influent was subject to frequent change. Biomass estimates in the last two ponds tend to support Yount's postulate.

Margalef (1962) reported a negative correlation between the ratio primary production/total biomass and degree of organization. Degree of organization, as species-diversity, increased and production decreased as effluent passed through the pond system. Increase in species-diversity was associated with increase in numbers and volume of zooplankton (Appendix Tables X and XII) but with a decrease in phytoplankton volumes (Appendix Table X). Increase in species-diversity was usually associated with decrease in light-bottle production (Table XVIII).

TABLE XVIII

RELATIONSHIPS BETWEEN LIGHT-BOTTLE PRODUCTION AND SPECIES-DIVERSITY UNDER OPTIMAL CONDITIONS (19 July, 1962)

	Pond 1	Pond 4	Pond 7	Pond 10
Production (gm O_2/m^2/day)	45.87	66.27	58.97	48.10
Species per cycle	4	6	8	9

Species-diversity in oil refinery effluent holding ponds is compared with other communities in Fig. 10. Species-diversity in Pond 10 was lower than steady-state diversity in stream microcosms and species-diversity index in Pond 4 was similar to successional stages of green algal communities (Odum and Hoskins, 1957).

High order zooplankton species were not common in the ponds (Table XVII).

Species present apparently had a degree of organization of high survival value within the limited environment. Community structure may have developed to about its maximum in the last ponds, while establishment of new species were probably at a minimum. Depression of curves in the first two cycles resulted from large populations of only a few species. As more individuals were counted, more area was examined on the slide. Chance for observing more species was increased, thus including "rarer" species at a faster rate (Odum, et al., 1960).

Odum et al., (ibid.) presented an organizational hierarchial postulate for an ecological community. They assumed that a curve which turns upward indicates more organization and diversity than the straight (logarithmic) comparison line. A downward curve would be the reverse. If this assumption is true, Ponds 7 and 10 were more diverse and highly organized, since the curves usually turned upward. Odum assumed an upward curve may be expected in a homogeneous area with higher survival values. Continuous flow of the effluent may have resulted in some turbulent mixing, thus the ponds may have been relatively homogeneous. Since all curves turned upward (Fig. 9), there must be high survival value for those species in the ponds as many species were able to build up large populations in a short period.

Succession and Community Dynamics

In a longitudinal series of ponds or a river, linear succession of factors will occur until the community becomes stabilized and with sufficient time a steady state will be established (Odum, 1959, Reid, 1961). Thus, within an environment limited by toxicity of oil refinery effluents, successional stages will develop with an increase in holding time and with a decrease in toxicity. Therefore, as holding time increases, the ability for organisms to survive will increase.

Chemical-physical factors measured indicated successional stages within the system. Toxicity as indicated by reduction of phenolic compounds decreased with increased holding time (Appendix Table I). Dorris, Patterson and Copeland (1963) have shown that toxicity of the water and chemical components decrease with longer holding time. Euphotic zone depth usually increased with holding time (Table II). Oxygen concentrations (Appendix Tables III and IV) during sub-optimal conditions increased in the last ponds of the system, while under optimal conditions oxygen concentration increased earlier in the system associated with an increase in algal populations (Table XIV), but decreased after peak oxygen concentrations, chlorophyll concentrations (Table IX) and algal populations were reached.

An increase in light-bottle production from May to July, 1962, occurred toward the center of the pond system, followed by a decrease (Table III). Dark-bottle respiration for this same period decreased and then remained about the same from Ponds 4 to 10. Copeland (1963) reported a similar pattern of succession and that photosynthesis exceeded community respiration during the last part of the system. Odum (1956) demonstrated linear succession of community metabolism in a sewage polluted river in Indiana. Copeland (1963) found that ten days holding time was not sufficient for the refinery holding ponds to become stabilized but another system with 60 days holding time the same patterns of productivity and respiration developed as in a sewage polluted river under optimal conditions.

Biomass data (Tables VI, VII, IX and X) indicated two basic trends, with total phytoplankton volumes increased to a maximum and then decreased toward the end of the system. Zooplankton volumes increased with decrease in toxicity. Ash-free dry weight decreased from a maximum in Pond 1 to a minimum in Pond 10. Particulate matter from the refinery probably contributed to the large amounts in Pond 1 while phytoplankton composed a larger percentage in Ponds 4 and 7. Chlorophyll concentration increased toward the middle of the system and decreased in the later part. Apparently as nutrients become available to algal cells, and toxicity decreased the algal population and chlorophyll increased. Algal populations and chlorophyll concentrations decrease downstream may be due to a decrease in available nutrients in the last ponds while some algal cells were beginning to sludge out or were removed by increased grazing pressures of herbivorous insects (Tubb, 1963) and rotifers. According to Bartsch and Allum (1957), Odum, et al. (1958) Wright (1960) and others, concentrations of chlorophyll is dependent upon the amounts of nutrients available. If stability is to be reached, then productivity, respiration and algal populations will decrease simultaneously after the algal population is decomposed. Since respiration has not decreased and algal populations are still relatively large (Figures 5 and 6) considerable decomposition was probably taking place. A stabilized community was not reached in the system.

The results of biomass data, dark- and light-bottle production support the assumptions made by Copeland (1963) from the diurnal curve method of measuring productivity of a community. More information may be obtained from the diurnal curve than from weekly dark- and light-bottles taken only during the optimal productive period in a 24-hour day. Addition of chlorophyll data to productivity data will add to understanding of the dynamics in any community, and with time successional stages may be studied. Chlorophyll concentrations, ash-free dry weight and phytoplankton volumes were significantly related (Fig. 7). The chlorophyll extractions required much less time than plankton counting procedures.

As toxicity decreased, species number and species-diversity increased (Figs. 8 and 9). Pond 10 was considered the most stable pond in the system based upon its increased complexity as measured by species-diversity. Margalef (1958) found an increase in species-diversity as a community increased in complexity through successional stages. Determination of species-diversity in this study yielded more information, required less time and it was considered a more accurate indicator of community structure than plankton counts and the conversion of counts to volumetric data.

In a series of ponds or a river receiving toxic wastes, biomass and productivity will increase from pond to pond until maximum production is reached as toxicity decreases. If conditions are optimal, maximum production of oxygen and biomass may occur with less holding time. After maximum production, biomass and oxygen production will decrease, species-diversity will increase as organisms less tolerant to toxicity will survive and the last communities of the system will become more complex and thus more stable. Therefore, in a system of ponds or a river, there is a longitudinal succession of events that may be adequately measured by oxygen production, chlorophyll concentration and species-diversity. A decrease in biomass should show an inverse relationship to species-diversity in the improvement of the effluent. Species-diversity provides a useful technique in monitoring a system receiving toxic or sewage effluents.

All data tend to support the notion that longitudinal succession is a dynamic phenomenon in improvement of an effluent as it passes through the holding pond system before the effluent is released into a public stream.

CHAPTER VIII

SUMMARY

1. Plankton standing crop as ash-free dry weight, chlorophyll a concentration and plankton volumes were determined and evaluated in a series of oil refinery effluent holding ponds during a one-year period. Certain chemical and physical conditions, primary productivity, incidence of plankton and species diversity were studied.

2. Mean temperature difference between first and last pond was 5.82 F. Generally, pH decreased as the effluent passed through the system. The pH range was 7.2 to 8.5. Phenol compounds were reduced 64 to 99%, with most effective reduction occurring during periods of greatest biological activity. Mid-day dissolved oxygen concentrations varied from zero to 16.60 mg/l. Euphotic zone varied from 0.05 m in Pond 1 to 1.88 m in Pond 10.

3. Primary productivity fell to zero in all ponds at some time. Annual net photosynthesis (light-bottle estimate) varied from 12.20 $gm/m^2/day$ in Pond 1 to 20.82 $gm/m^2/day$ in Pond 7, with a slight decrease in Pond 10. Mean respiration varied from 3.97 $gm/m^2/day$ in Pond 1 to 6.53 $gm/m^2/day$ in Pond 7, with a slight decrease in Pond 10. Productivity was much higher than in natural bodies of water, but apparently of the same order of magnitude as in sewage lagoons and polluted streams. Dark-bottle estimates of respiration were two times larger than estimates from diurnal curve methods, and estimates of

gross photosynthesis were 2 to 5 times higher.

4. Ash-free dry weight generally decreased as effluent passed through the system. Annual ash-free dry weight varied from 24.71 mg/l in Pond 1 to 16.52 mg/l in Pond 10. Ash-free dry weight was much higher than in fresh waters, but lower than in sewage ponds.

5. Chlorophyll a generally increased from 0.258 mg/l in Pond 1 to 0.297 mg/l in Pond 7 and decreased to 0.222 mg/l in Pond 10. Chlorophyll a concentrations were higher than in fresh or marine waters, and of the same order of magnitude in sewage ponds.

6. Ash-free dry weight and chlorophyll a generally indicated normal seasonal succession, except that development was retarded in the spring. Regression of ash-free dry weight on chlorophyll was determined. Chlorophyll to ash-free dry weight ratio varied less in Pond 10, indicating a more stable environment.

7. Maximum total phytoplankton volumes occurred in Pond 4 followed by a reduction in the volume of biomass in Pond 10. Micro-cell volumes were consistently larger than algal volumes. Micro-cells composed 56 to 99% of total phytoplankton volumes. Maximum algal volumes occurred in July and August. "Slug" effect reduced phytoplankton populations, but they were generally able to recover to near normal or maximum size within a relatively short period of time.

8. Zooplankton volumes generally increased as conditions improved from pond to pond. Algae to zooplankton ratio was smaller in Pond 10, indicating a possible grazing effect by herbivorous zooplankters.

9. Correlation matrix graphs were constructed for annual estimates of biomass. Correlation coefficients were 0.75 for chlorophyll to ash-free dry weight, 0.07 for chlorophyll to phytoplankton, 0.14 for

chlorophyll to zooplankton, 0.07 for ash-free dry weight to phytoplankton, and 0.08 for ash-free dry weight to zooplankton.

10. Eleven genera of phytoplankton occurred in Pond 1 and 16 genera in Pond 10. Chlorella and Chlamydomonas were dominant green algal forms.

11. Twelve zooplankton genera were observed. Brachionus calyciflorous Pallas, was the common omnivorous rotifer and Asplanchna, the only carnivorous rotifer. Larger forms of zooplankton were almost absent from the system. No species could be considered an indicator species.

12. Species-diversity increased from pond to pond, with Pond 10 being the most diverse. Species-diversity varied from 5 to 7 species per cycle. As biomass, productivity and toxicity decreased, species-diversity increased. Increase in species-diversity indicated a more stable biological community in the last pond of the series. The last pond was the most highly organized and diverse pond in the system.

13. Reduction in total biomass, increase in zooplankton volumes and increase in species-diversity were important characteristics of the oil refinery effluent holding system.

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APPENDIX

TABLE I

TEMPERATURE AND HYDROGEN-ION CONCENTRATION

Date	Temperature in F				pH	
	Pond 1	Pond 4	Pond 7	Pond 10	Into Pond 1	Out of Pond 10
7/25/61	90.0	88.0	86.0	85.0	7.4	7.7
8/1/61	90.0	85.2	85.4	85.0	7.9	7.6
8/9/61	90.0	85.2	85.4	85.0	8.0	7.8
8/16/61	91.0	89.5	88.0	87.5	8.6	7.2
8/24/61	91.0	90.0	89.5	89.0	8.1	7.8
9/5/61	89.0	87.5	87.0	86.5	7.8	7.5
9/16/61	85.0	80.5	80.7	80.3	7.6	7.8
9/22/61	80.0	76.0	75.5	74.0	7.3	7.5
9/29/61	75.0	73.0	70.0	67.0	7.5	8.4
10/5/61	70.0	68.0	67.0	65.0	8.0	8.1
10/12/61	75.0	73.0	73.0	71.5	7.5	7.7
10/20/61	69.5	66.0	65.0	63.0	7.3	7.5
11/3/61	60.0	58.0	56.0	56.0	7.2	7.3
11/11/61	62.0	57.0	54.0	51.5	7.2	7.3
11/24/61	54.0	53.0	51.5	49.5	7.7	7.5
12/21/61	47.0	45.0	40.0	38.0	8.2	7.7
2/3/62	63.0	61.0	59.5	56.0	7.9	7.3
2/16/62	63.0	56.5	53.5	51.5	8.5	7.6
3/10/62	55.0	51.0	48.0	45.0	7.7	7.5
3/17/62	56.0	52.0	46.0	48.0	8.2	7.5
3/26/62	63.0	61.0	59.0	60.0	7.4	7.6
4/7/62	63.0	59.0	56.5	53.5	7.5	7.3
4/13/62	63.0	61.0	59.0	56.5	7.8	7.5
4/20/62	76.0	73.0	71.0	68.0	8.2	7.9
4/26/62	75.0	74.0	73.5	71.0	8.1	7.7
5/4/62	78.5	74.0	73.5	71.0	8.2	7.9
5/12/62	81.0	82.0	80.0	77.0	7.7	7.5
5/26/62	78.5	77.0	75.0	75.0	7.9	8.2
6/5/62	82.0	79.0	81.0	76.0	7.8	7.6
6/11/62	83.0	82.0	79.0	80.0	7.8	7.4
6/19/62	88.0	83.0	82.0	82.0	7.8	7.6
6/26/62	87.0	83.5	83.0	81.5	8.3	7.6
7/5/62	91.0	86.0	84.5	84.0	8.1	7.3
7/10/62	86.0	83.5	82.5	81.5	8.2	7.6
7/19/62	87.5	86.0	87.5	84.5	8.3	8.0

TABLE II

EUPHOTIC ZONE IN METERS

Date	Pond 1	Pond 4	Pond 7	Pond 10
8/1/61	0.41	0.87	1.33	1.85
9/16/61	0.05	0.49	0.58	0.50
10/12/61	1.12	1.27	1.32	1.19
11/11/61	1.21	1.36	1.63	1.80
11/24/61	1.16	1.27	1.52	1.88
12/21/61	0.89	1.14	1.27	1.83
2/3/62	0.91	0.66	0.66	1.30
2/16/62	0.51	0.61	0.66	0.91
3/10/62	0.56	0.56	0.66	0.86
3/17/62	0.69	0.69	0.70	0.91
3/26/62	0.84	0.56	0.94	1.42
4/7/62	0.84	0.74	0.79	0.81
4/13/62	0.38	0.46	0.66	0.48
4/20/62	0.30	0.35	0.35	0.51
4/26/62	0.91	0.84	1.12	1.68
5/4/62	0.20	0.43	0.51	0.64
5/12/62	0.30	0.33	0.23	0.51
5/26/62	0.66	0.86	0.94	1.24
6/5/62	0.82	1.00	1.15	1.43
6/11/62	0.71	0.58	1.27	1.68
6/19/62	0.41	0.46	0.50	0.66
6/26/62	0.51	0.61	0.86	1.22
7/5/62	0.74	1.14	1.42	1.22
7/10/62	0.61	0.94	1.14	1.40
7/19/62	0.59	0.77	0.54	1.00

TABLE III

DISSOLVED OXYGEN CONCENTRATION IN MG/L

Date	Pond 1	Pond 4	Pond 7	Pond 10
Summer				
8/1/61	1.50	6.00	4.60	2.20
8/16/61	0.00	7.00	10.40	9.20
Fall				
9/16/61	0.00	2.64	10.70	4.10
9/22/61	0.00	0.20	5.30	6.50
9/29/61	0.00	0.32	9.05	9.35
10/5/61	0.00	0.20	7.90	8.00
10/21/61	0.00	1.28	3.93	5.35
10/20/61	0.00	0.72	2.98	2.51
11/3/61	0.00	0.00	1.39	4.20
11/11/61	0.00	0.00	0.24	0.64
11/24/61	0.00	0.00	2.95	4.10
Winter				
12/12/61	0.00	0.53	2.57	3.34
*				

*Additional O_2 data from 3 February to 19 July 1962, is contained in Appendix Table IV.

TABLE IV

DARK- AND LIGHT-BOTTLE ESTIMATION OF RESPIRATION AND NET PHOTOSYNTHESIS

Date	Pond	D.O. mg/l		Diff.	R	R	P	P	EZ
		Initial	Final		$gm/m^3/hr$	$gm/m^3/day$	$gm/m^3/hr$	$gm/m^3/day$	m
Winter									
2/3/62	1	0.00	0.00	0.00					0.91
	4	0.00	0.00	0.00					0.66
	7	0.00	0.00	0.00					0.66
	10D	0.32	0.31	0.02	0.02	0.40			1.30
	L	0.32	0.46	0.14			0.05	0.50	
2/16/62	1	0.00	0.00	0.00					0.51
	4	0.00	0.00	0.00					0.61
	7D	0.59	0.41	0.18	0.09	2.16			0.66
	L	0.59	0.74	0.15			0.08	0.72	
	10D	1.96	1.91	0.06	0.03	0.72			0.91
	L	1.96	2.68	0.72			0.36	3.24	
Spring									
3/10/62	1	0.00	0.00	0.00					0.56
	4D	0.08	0.00	>0.08	>0.03	>9.72			0.56
	L	0.08	0.13	0.05			0.02	0.20	
	7D	0.44	0.20	0.24	0.08	1.92			0.66
	L	0.44	0.24	-0.24			0.00[a]	0.00[a]	
	10D	3.87	2.70	1.17	0.40	9.60			0.86
	L	3.87	2.90	-0.97			0.00[a]	0.00[a]	

R = Respiration
P = Net Production
EZ = Euphotic Zone
Diff. = Difference

D.O. = Dissolved Oxygen
m = meter
a = No initial oxygen

TABLE IV (Continued)

Date	Pond	D.O. mg/l		Diff.	R	R	P	P	EZ
		Initial	Final		gm/m^3/hr	gm/m^3/day	gm/m^3/hr	gm/m^3/day	m
3/17/62	1	0.00	0.00	0.00					0.69
	4D	2.00	1.70	0.30	0.20	4.80			0.69
	L	2.00	2.00	0.00			0.00	0.00	
	7D	0.42	0.29	0.13	0.08	1.92			0.69
	L	0.42	0.80	0.38			0.25	2.50	
	10D	0.36	0.30	0.06	0.04	0.96			0.91
	L	0.36	0.24	-0.12			0.00[a]	0.00[a]	
3/26/62	1	0.00	0.00	0.00					0.84
	4D	0.00	0.00	0.00					0.56
	7D	1.05	0.24	0.81	0.54	12.96			0.94
	L	1.05	1.64	0.58			0.39	4.29	
	10D	12.55	12.25	0.30	0.10	2.40			1.42
	L	12.55	11.68	-0.87			0.00[a]	0.00[a]	
4/7/62	1	0.00	0.00	0.00					0.84
	4	0.00	0.00	0.00					0.74
	7D	1.16	0.96	0.20	0.09	2.16			0.79
	L	1.16	1.42	0.26			0.12	2.64	
	10D	1.71	0.81	0.90	0.40	9.60			0.81
	L	1.71	4.65	2.94			1.33	15.96	
4/13/62	1	0.00	0.00	0.00					0.38
	4D	0.00	0.00	0.00					0.46
	L	0.00	0.13	0.13			0.08	>0.96	
	7D	3.50	3.60	+0.10	0.00	0.00			0.66
	L	3.50	4.00	0.50			0.29	3.48	
	10D	4.00	4.00	0.00	0.00	0.00			0.48
	L	4.00	5.50	1.50			0.86	10.32	

TABLE IV (Continued)

Date	Pond	D.O. mg/l		Diff.	R	R	P	P	EZ
		Initial	Final		gm/m^3/hr	gm/m^3/day	gm/m^3/hr	gm/m^3/day	m
4/20/62	1	0.00	0.00	0.00					0.30
	4D	4.40	2.43	1.97	0.79	18.96			0.35
	L	4.40	10.70	6.30			2.52	30.24	
	7D	5.80	4.40	1.40	0.56	13.44			0.35
	L	5.80	10.10	4.30			1.72	20.64	
	10D	11.25	9.65	1.60	0.64	15.36			0.51
	L	11.25	13.15	1.90			0.76	9.12	
4/26/62	1	0.00	0.00	0.00					0.91
	4D	4.90	2.24	2.66	0.80	19.20			0.84
	L	4.90	11.00	6.10			1.89	22.68	
	7D	16.60	12.00	4.60	1.38	33.12			1.12
	L	16.60	20.00	3.40			1.02	12.24	
	10D	10.40	9.40	1.00	0.29	6.96			1.68
	L	10.40	13.60	3.20			0.94	10.28	
5/4/62	1	0.00	0.00	0.00					0.20
	4D	0.00	0.00	0.00	0.00	0.00			0.43
	L	0.00	1.10	1.10			1.10	13.20	
	7D	10.55	11.00	+0.45	0.00	0.00			0.51
	L	10.55	16.60	6.05			3.62	43.44	
	10D	6.20	5.40	0.80	0.46	11.04			0.64
	L	6.20	8.90	2.70			1.54	18.48	
5/12/62	1	0.00	0.00	0.00					0.30
	4	0.00	0.00	0.00					0.33
	7D	1.71	1.05	0.66	0.29	6.96			0.23
	L	1.71	12.60	10.89			4.84	58.08	
	10D	2.85	2.24	0.61	0.27	6.50			0.51
	L	2.85	12.20	11.35			5.06	60.72	

TABLE IV (Continued)

Date	Pond	D.O. mg/l Initial	D.O. mg/l Final	Diff.	R gm/m^3/hr	R gm/m^3/day	P gm/m^3/hr	P gm/m^3/day	EZ m
5/26/62	1D	0.00	0.00	0.00	0.00	0.00			0.66
	L	0.00	12.60	12.60			6.30	75.60	
	4D	0.24	0.00	> 0.24	> 0.41	> 9.84			0.86
	L	0.13	3.09	2.96			5.07	60.84	
	7D	5.88	5.30	0.58	0.29	6.96			0.94
	L	5.88	14.00	8.12			4.06	48.72	
	10D	7.75	7.55	0.20	0.10	2.40			1.24
	L	7.75	12.40	4.65			2.33	27.96	
Summer 6/5/62	1D	0.00	1.00	+1.00	0.00	0.00			0.86
	L	0.56	6.40	4.44			5.33	69.16	
	4D	5.08	3.90	1.18	0.34	8.09			0.97
	L	2.20	6.80	4.60			4.60	59.80	
	7D	12.00	11.30	0.70	0.20	4.80			1.14
	L	9.80	14.00	4.20			3.88	50.44	
	10D	6.65	6.30	0.35	0.22	5.30			1.42
	L	6.65	10.11	3.45			2.18	28.34	
6/11/62	1D	0.50	0.00	>0.50	>0.27	> 6.53			0.71
	L	0.50	2.65	2.15			1.17	15.24	
	4D	8.60	8.00	0.60	0.31	7.51			0.58
	L	8.60	16.60	8.00			4.17	54.21	
	7D	0.00	0.00	0.00	0.00	0.00			1.27
	L	0.00	2.82	2.82			1.41	18.33	
	10D	1.18	0.72	0.46	0.23	5.52			1.68
	L	1.18	1.64	0.46			0.23	2.99	
6/19/62	1D	6.40	4.60	1.80	0.94	22.54			0.41
	L	6.40	18.40	13.00			6.78	88.17	

TABLE IV (Continued)

Date	Pond	D.O. mg/l Initial	D.O. mg/l Final	Diff.	R gm/m³/hr	R gm/m³/day	P gm/m³/hr	P gm/m³/day	EZ m
6/19/62	4D	6.90	5.90	1.00	0.52	12.50			0.46
	L	6.90	14.80	7.90			4.12	53.57	
	7D	0.00	0.00	0.00					0.50
	L	0.00	4.80	4.80			2.40	31.20	
	10D	0.00	0.00	0.00					0.66
	L	0.00	0.13	0.13			0.07	0.91	
6/26/62	1D	12.40	10.40	2.00	1.20	28.80			0.51
	L	12.40	16.80	4.40			5.28	68.64	
	4D	4.65	3.60	1.05	0.63	15.12			0.61
	L	4.65	16.00	11.35			6.81	88.53	
	7D	6.30	5.10	1.20	0.76	18.24			0.86
	L	6.30	14.10	7.80			4.93	64.09	
	10D	1.74	1.23	0.51	0.29	6.96			1.22
	L	1.74	8.00	6.26			3.58	46.54	
7/5/62	1D	12.00	10.70	1.30	0.43	10.39			0.74
	L	12.00	15.80	3.80			1.27	16.40	
	4D	4.35	2.72	1.63	0.53	12.72			1.14
	L	4.35	10.70	6.35			2.06	26.78	
	7D	3.15	2.57	0.58	0.41	9.84			1.42
	L	3.15	6.60	3.45			1.57	20.41	
	10D	7.50	6.80	0.70	0.21	5.04			1.22
	L	7.50	19.10	11.60			3.40	44.20	
7/10/62	1D	9.95	7.60	2.35	1.47	35.28			0.61
	L	9.95	14.10	4.15			2.59	33.67	
	4D	3.70	3.20	0.50	0.31	7.44			0.94
	L	3.70	10.10				4.00	52.00	

TABLE IV (Continued)

Date	Pond	D.O. mg/1 Initial	D.O. mg/1 Final	Diff.	R $gm/m^3/hr$	R $gm/m^3/day$	P $gm/m^3/day$	P $gm/m^3/day$	EZ m
7/10/62	7D	9.50	7.90	1.60	1.01	24.24			1.14
	L	9.50	16.60	7.10			4.48	58.24	
	10D	4.20	3.70	0.50	0.33	7.92			1.40
	L	4.20	11.00	6.80			4.53	58.89	
7/19/62	1D	6.80	5.00	1.80	0.97	23.28			0.59
	L	6.80	12.60	5.80			5.98	77.74	
	4D	5.95	4.40	1.55	0.80	19.20			0.77
	L	5.95	11.80	5.85			6.62	86.06	
	7D	12.20	11.80	0.40	0.19	4.56			0.54
	L	12.20	19.90	7.70			8.40	109.20	
	10D	5.00	3.40	1.60	0.72	17.28			1.00
	L	5.00	9.50	4.50			3.70	48.10	

TABLE V

MEAN CHLOROPHYLL *a* ESTIMATE OF BIOMASS AND STANDARD DEVIATION (SD) IN MG/L

	Pond 1*	Pond 4	Pond 7	Pond 10
Summer				
7/25/61	0.930	0.744 ± .240	0.458 ± .011	0.210 ± .020
8/1/61	0.831	0.431 ± .093	0.151 ± .031	0.778 ± .016
8/9/61	0.293	0.724 ± .075	0.431 ± .026	0.281 ± .031
8/16/61	0.158	0.667 ± .131	0.709 ± .111	0.647 ± .073
Fall				
9/5/61	0.075	0.127 ± .100	0.371 ± .086	0.261 ± .035
9/16/61	0.208	0.396 ± .077	0.655 ± .069	0.195 ± .010
9/22/61	0.110	0.166 ± .011	1.058 ± .162	0.486 ± .031
9/29/61	0.132	0.179 ± .040	0.559 ± .040	0.594 ± .067
10/5/61	0.015	0.040 ± .008	0.445 ± .030	0.495 ± .017
10/12/61		0.079 ± .066	0.170 ± .009	0.237 ± .018
10/20/61	0.030	0.118 ± .047	0.119 ± .017	0.061 ± .005
11/3/61	0.008	0.017 ± .005	0.056 ± .015	0.116 + .009
11/11/61	0.005	0.010 ± .003	0.012 ± .001	0.028 ± .003
11/24/61	0.015	0.015 ± .000	0.020 ± .007	0.022 ± .002
Winter				
12/21/61		0.090 ± .020	0.076 ± .019	0.045 ± .016
2/3/62	0.038	0.062 ± .026	0.043 ± .020	0.040 ± .007
2/16/62	0.045	0.046 ± .022	0.013 ± .001	0.017 ± .005
Spring				
3/10/62	0.023	0.021 ± .007	0.022 ± .004	0.014 ± .002
3/17/62	0.120	0.083 ± .029	0.102 ± .003	0.085 ± .012
3/26/62	0.015	0.031 ± .011	0.028 ± .014	0.094 ± .089
4/7/62	0.023	0.022 ± .004	0.036 ± .011	0.293 ± .116
4/13/62	0.023	0.024 ± .002	0.031 ± .003	0.062 ± .022
4/20/62	0.023	0.214 ± .040	0.137 ± .032	0.261 ± .026
4/26/62	0.030	0.357 ± .079	0.234 ± .056	0.113 ± .019
5/4/62	0.045	0.152 ± .013	0.390 ± .041	0.167 ± .009
5/12/62	0.120	0.210 ± .012	0.548 ± .067	0.197 ± .043
5/26/62	0.645	0.132 ± .017	0.315 ± .035	0.235 ± .028
Summer				
6/5/62	0.090	0.265 ± .071	0.321 ± .149	0.227 ± .061
6/11/62	0.218	0.836 ± .043	0.210 ± .044	0.100 ± .048
6/19/62	0.360	0.368 ± .026	0.225 ± .023	0.130 ± .025
6/26/62	1.350	0.799 ± .059	0.641 ± .014	0.433 ± .025
7/5/62	1.350	0.226 ± .025	0.143 ± .018	0.473 ± .014
7/10/62	1.088	0.433 ± .022	0.416 ± .191	0.280 ± .050
7/19/62	0.458	0.716 ± .012	0.945 ± .022	0.585 ± .173

*Sample from one station only, SD not calculated.

TABLE VI

MEAN ASH-FREE DRY WEIGHT AND STANDARD DEVIATION (SD) IN MG/L

	Pond 1*	Pond 4	Pond 7	Pond 10
Summer				
7/25/61	40.00	30.25 ± 7.14	28.25 ± 4.92	9.75 ± 4.65
8/1/61	36.00	23.25 ± 8.35	15.25 ± 2.87	7.00 ± 4.08
8/9/61	8.00	50.25 ± 18.46	23.00 ± 9.70	25.00 ± 14.28
8/16/61	28.00	29.25 ± 20.97	26.50 ± 4.36	22.75 ± 7.27
Fall				
9/5/61	20.00	35.25 ± 15.69	46.25 ± 2.22	39.75 ± 3.30
9/16/61	101.00	32.50 ± 17.33	27.25 ± 5.32	10.50 ± 1.73
9/22/61	15.00	38.50 ± 16.76	69.00 ± 14.02	40.25 ± 10.66
9/29/61	19.00	33.25 ± 15.33	33.75 ± 23.87	29.00 ± 4.97
10/5/61	3.00	14.25 ± 3.69	20.25 ± 4.79	18.50 ± 6.76
10/12/61	7.00	17.25 ± 2.06	21.00 ± 2.94	12.50 ± 6.40
10/20/61	18.00	22.50 ± 4.51	18.50 ± 2.63	14.00 ± 4.83
11/3/61	13.00	10.00 ± 1.63	8.00 ± 2.45	6.75 ± 2.99
11/11/61	5.00	11.50 ± 2.52	11.50 ± 2.65	3.50 ± 0.58
11/24/61	6.00	5.75 ± 2.52	3.00 ± 1.41	2.50 ± 1.00
Winter				
12/12/61	20.00	7.25 ± 1.29	3.50 ± 2.65	5.00 ± 2.94
2/3/62	1.00	5.00 ± 0.25	4.75 ± 3.20	2.25 ± 1.50
2/16/62	8.00	5.25 ± 2.22	4.25 ± 2.22	5.00 ± 2.94
Spring				
3/10/62	6.00	5.75 ± 0.86	9.50 ± 6.35	4.25 ± 0.96
3/17/62	13.00	3.50 ± 1.29	5.75 ± 5.12	5.75 ± 4.86
3/26/62	8.00	21.00 ± 1.83	13.52 ± 5.69	9.50 ± 6.61
4/7/62	5.00	15.50 ± 4.51	11.25 ± 5.85	29.50 ± 7.49
4/13/62	2.00	22.50 ± 0.95	22.50 ± 1.89	4.00 ± 2.16
4/20/62	16.00	19.75 ± 3.95	20.75 ± 1.26	28.75 ± 2.87
4/26/62	10.00	26.50 ± 5.42	25.50 ± 7.51	13.25 ± 2.06
5/4/62	36.00	26.50 ± 7.14	28.50 ± 3.87	18.50 ± 5.32
5/12/62	45.00	23.00 ± 3.83	52.00 ± 9.09	16.50 ± 5.51
5/26/62	29.00	16.50 ± 8.06	23.00 ± 6.83	19.00 ± 4.76
Summer				
6/5/62	16.00	22.52 ± 3.16	21.25 ± 4.11	19.50 ± 7.77
6/11/62	16.00	57.25 ± 15.74	14.25 ± 3.78	11.00 ± 7.44
6/19/62	43.00	31.00 ± 5.48	19.75 ± 1.71	57.51 ± 1.26
6/26/62	50.00	39.50 ± 6.40	32.25 ± 3.60	23.00 ± 6.68
7/5/62	84.00	15.50 ± 1.73	14.75 ± 3.86	42.25 ± 14.73
7/10/62	62.00	27.50 ± 2.38	33.50 ± 4.12	23.75 ± 6.24
7/19/62	51.00	38.25 ± 4.99	49.75 ± 2.98	34.52 ± 4.16

*Sample from one station only, SD not calculated.

TABLE VII

CHLOROPHYLL a CONCENTRATION IN MG/L INTO AND OUT OF OIL REFINERY EFFLUENT HOLDING PONDS

	Pond 1	Pond 4		Pond 7		Pond 10	
	Out	In	Out	In	Out	In	Out
Summer							
7/25/61	0.930	0.544	0.944	0.460	0.457	0.194	0.226
8/1/61	0.831	0.357	0.505	0.174	0.129	0.121	0.035
8/9/61	0.293	0.787	0.662	0.413	0.450	0.288	0.275
8/16/61	0.158	0.606	0.728	0.803	0.615	0.708	0.585
Fall							
9/5/61	0.075	0.051	0.201	0.439	0.303	0.286	0.237
9/16/61	0.208	0.382	0.411	0.704	0.606	0.201	0.190
9/22/61	0.110	0.159	0.172	1.175	0.941	0.476	0.497
9/29/61	0.132	0.192	0.165	0.524	0.593	0.564	0.624
10/5/61	0.015	0.034	0.047	0.478	0.413	0.450	0.540
10/12/61		0.095	0.064	0.171	0.169	0.222	0.253
10/20/61	0.030	0.129	0.108	0.109	0.128	0.060	0.062
11/3/61	0.008	0.015	0.020	0.062	0.051	0.109	0.123
11/11/61	0.005	0.009	0.011	0.012	0.012	0.027	0.029
11/24/61	0.015	0.015	0.015	0.018	0.023	0.021	0.023
Winter							
12/21/61		0.103	0.078	0.068	0.084	0.037	0.053
2/3/62	0.038	0.076	0.049	0.042	0.045	0.041	0.040
2/16/62	0.045	0.060	0.033	0.012	0.014	0.015	0.020
Spring							
3/10/62	0.023	0.015	0.027	0.019	0.024	0.015	0.014
3/17/26	0.120	0.060	0.105	0.107	0.096	0.078	0.092
3/26/62	0.015	0.023	0.040	0.027	0.030	0.054	0.134
4/7/62	0.023	0.024	0.021	0.036	0.036	0.158	0.428
4/13/62	0.023	0.025	0.023	0.033	0.030	0.045	0.079
4/20/62	0.023	0.205	0.223	0.158	0.116	0.250	0.273
4/26/62	0.030	0.289	0.424	0.282	0.186	0.128	0.098
5/4/62	0.045	0.143	0.162	0.422	0.359	0.173	0.162
5/12/62	0.120	0.218	0.203	0.570	0.525	0.173	0.222
5/26/62	0.645	0.143	0.122	0.285	0.345	0.222	0.248
Summer							
6/5/62	0.090	0.285	0.245	0.240	0.402	0.188	0.267
6/11/62	0.218	0.810	0.863	0.203	0.218	0.136	0.064
6/19/62	0.360	0.375	0.360	0.229	0.220	0.128	0.132
6/26/62	1.350	0.758	0.840	0.615	0.668	0.443	0.424
7/5/62	1.350	0.206	0.246	0.143	0.143	0.485	0.462
7/10/62	1.088	0.420	0.447	0.443	0.390	0.319	0.240
7/19/62	0.458	0.675	0.758	0.938	0.953	0.668	0.503

TABLE VIII

ASH-FREE DRY WEIGHT IN MG/L INTO AND OUT OF OIL REFINERY EFFLUENT HOLDING PONDS

	Pond 1	Pond 4		Pond 7		Pond 10	
	Out	In	Out	In	Out	In	Out
Summer							
7/25/61	40.00	24.50	36.00	25.50	31.00	6.50	13.00
8/1/61	36.00	18.00	28.50	13.00	17.50	7.00	7.00
8/9/61	8.00	38.00	62.50	26.50	19.50	17.00	33.00
8/16/61	28.00	11.50	47.00	28.50	24.50	27.00	18.50
Fall							
9/5/61	20.00	34.00	36.50	46.00	46.50	38.50	41.00
9/16/61	101.00	46.50	18.50	28.50	26.00	9.50	11.50
9/22/61	15.00	44.00	33.00	78.50	59.50	47.00	33.50
9/29/61	19.00	27.50	39.00	24.00	43.50	31.00	27.00
10/5/61	3.00	14.50	14.00	16.50	24.00	15.50	21.50
10/12/61	7.00	18.50	16.00	20.50	21.50	13.00	12.00
10/20/61	18.00	21.00	24.00	17.50	19.00	11.50	16.50
11/3/61	13.00	9.00	11.00	9.50	6.50	5.50	8.00
11/11/61	5.00	10.00	13.00	10.50	12.50	3.00	4.00
11/24/61	6.00	4.00	7.50	2.50	3.50	3.00	2.00
Winter							
12/21/61	2.00	6.50	8.00	2.50	4.50	6.50	3.50
2/3/62	1.00	5.00	5.00	4.50	5.00	2.00	2.50
2/16/62	8.00	6.50	4.00	6.00	2.50	7.50	2.50
Spring							
3/10/62	6.00	6.50	5.00	12.50	6.50	4.00	4.50
3/17/62	13.00	2.50	4.50	7.00	4.50	4.00	7.50
3/26/62	8.00	21.00	21.00	17.50	8.50	8.00	11.00
4/7/62	5.00	14.00	17.00	6.50	16.00	23.50	35.50
4/13/62	2.00	2.00	2.50	3.00	1.50	2.50	5.50
4/20/62	16.00	18.50	21.00	20.50	21.00	30.00	27.50
4/26/62	10.00	23.00	30.00	31.50	19.50	13.00	13.50
5/4/62	36.00	21.50	31.50	30.50	26.50	21.50	15.50
5/12/62	45.00	20.00	26.00	45.00	59.00	16.00	17.00
5/26/62	29.00	16.00	17.00	22.00	24.00	19.00	19.00
Summer							
6/5/62	16.00	22.50	21.50	19.00	23.50	13.50	25.50
6/11/62	16.00	62.00	52.50	12.00	16.50	15.50	6.50
6/19/62	43.00	33.00	29.00	18.50	21.00	6.00	5.50
6/26/62	50.00	36.00	43.00	31.50	33.00	17.50	28.50
7/5/62	84.00	16.50	14.50	11.50	18.00	38.50	46.00
7/10/62	62.00	26.00	29.00	35.50	31.50	27.50	20.00
7/19/62	51.00	36.50	40.00	47.50	52.00	36.00	32.00

TABLE IX

ASH-FREE DRY WEIGHT AND CHLOROPHYLL a IN MG/L
STATIONS AC (WEST SIDE) VS. BD (EAST SIDE)

	Pond 4				Pond 7				Pond 10			
	Ash-free		Chlorophyll		Ash-free		Chlorophyll		Ash-free		Chlorophyll	
	West	East	West	East	West	East	West	East	West	East	West	East
Summer												
7/25/61	32.5	28.0	0.735	0.753	31.5	25.0	0.464	0.453	12.0	7.5	0.211	0.209
8/1/61	27.0	19.5	0.442	0.420	14.5	16.0	0.162	0.141	10.5	3.5	0.079	0.077
8/9/61	42.5	58.0	0.732	0.717	19.0	27.0	0.443	0.420	20.0	30.0	0.274	0.289
8/16/61	30.0	28.5	0.606	0.728	28.5	24.5	0.728	0.690	19.0	26.5	0.648	0.645
Fall												
9/5/61	22.0	48.5	0.096	0.157	47.0	45.5	0.366	0.376	42.0	37.5	0.246	0.277
9/16/61	37.0	28.0	0.333	0.460	23.0	31.5	0.684	0.626	10.0	11.0	0.190	0.201
9/22/61	48.0	29.0	0.173	0.159	76.5	61.5	1.112	1.004	34.0	46.5	0.485	0.488
9/29/61	22.5	44.0	0.201	0.156	25.5	42.0	0.563	0.554	27.5	30.5	0.555	0.633
10/5/61	16.5	12.0	0.042	0.039	18.5	22.0	0.439	0.452	13.5	23.5	0.480	0.510
10/12/61	16.0	18.5	0.098	0.061	19.5	22.5	0.167	0.173	12.0	13.0	0.234	0.240
10/20/61	20.5	24.5	0.079	0.158	19.5	17.0	0.124	0.113	11.0	17.0	0.064	0.058
11/3/61	11.0	9.0	0.020	0.015	8.0	8.0	0.064	0.049	6.5	7.0	0.114	0.118
11/11/61	13.0	10.0	0.009	0.011	13.5	9.5	0.012	0.012	3.5	3.5	0.030	0.025
11/24/61	6.0	5.5	0.015	0.015	2.5	3.5	0.023	0.018	3.0	2.0	0.022	0.022
Winter												
12/21/61	6.5	8.0	0.074	0.107	5.5	1.5	0.066	0.086	7.0	3.0	0.048	0.042
2/3/62	5.0	5.0	0.046	0.079	5.0	4.5	0.059	0.028	1.0	3.5	0.046	0.034
2/16/62	6.0	4.5	0.057	0.036	4.5	4.0	0.012	0.014	5.0	5.0	0.020	0.015
Spring												
3/10/62	5.5	6.0	0.019	0.023	6.5	12.5	0.019	0.024	4.0	4.5	0.014	0.015
3/17/62	4.0	3.0	0.090	0.075	7.0	4.5	0.102	0.101	2.0	9.5	0.092	0.078
3/26/62	20.5	21.5	0.035	0.028	12.5	13.5	0.040	0.017	15.0	4.0	0.059	0.129

TABLE IX (Continued)

	Pond 4				Pond 7				Pond 10			
	Ash-free		Chlorophyll		Ash-free		Chlorophyll		Ash-free		Chlorophyll	
	West	East	West	East	West	East	West	East	West	East	West	East
Spring												
4/7/62	17.5	13.5	0.025	0.019	10.0	12.5	0.033	0.039	27.5	31.5	0.315	0.270
4/13/62	1.5	3.0	0.023	0.025	3.5	1.0	0.033	0.030	5.0	3.0	0.068	0.057
4/20/62	17.5	22.0	0.182	0.247	20.0	21.5	0.154	0.120	27.5	30.0	0.278	0.245
4/26/62	23.5	29.5	0.353	0.360	25.5	25.5	0.237	0.231	15.0	11.5	0.109	0.117
5/4/62	25.5	27.5	0.147	0.158	26.0	31.0	0.407	0.374	18.5	18.5	0.169	0.165
5/12/62	22.0	24.0	0.203	0.218	55.0	49.0	0.495	0.600	15.0	18.0	0.222	0.173
5/26/62	23.0	10.0	0.139	0.126	18.0	28.0	0.315	0.315	23.0	15.0	0.255	0.214
Summer												
6/5/62	21.0	23.0	0.210	0.320	21.5	21.0	0.237	0.405	22.5	16.5	0.244	0.211
6/11/62	47.5	67.0	0.833	0.840	16.5	12.0	0.233	0.188	14.0	8.0	0.113	0.087
6/19/62	28.5	33.5	0.353	0.383	20.0	19.5	0.232	0.218	5.0	6.5	0.147	0.113
6/26/62	36.0	43.0	0.805	0.793	35.5	31.0	0.660	0.623	24.0	22.0	0.424	0.443
7/5/62	16.5	14.5	0.234	0.218	14.0	15.5	0.154	0.132	53.0	31.5	0.594	0.353
7/10/62	26.5	28.5	0.420	0.447	33.5	33.5	0.383	0.450	26.5	21.0	0.282	0.278
7/19/62	42.0	34.5	0.713	0.720	50.0	49.5	0.960	0.930	31.0	37.0	0.690	0.480

TABLE X

VOLUMES OF ORGANISMS ($10^3 \times u^3/ml$)

Date	Pond 1 Total Phytoplankton	Pond 1 Micro-cells	Pond 1 Algae	Pond 1 Zooplankton	Pond 4 Total Phytoplankton	Pond 4 Micro-cells	Pond 4 Algae	Pond 4 Zooplankton
7/25	6326035.8	3695600.0	2640435.8	143.28	2102342.5	948170.0	1154172.5	4915.71
8/1	2220313.2	629600.0	1590713.2	163.44	2441116.5	682310.0	1758806.5	4792.29
8/9	1630007.1	1349480.0	280527.1	891.99	2022110.5	1583630.0	438480.5	10847.43
8/16	721797.3	630440.0	91357.3	1647.36	1974311.8	1348850.0	625461.8	543.75
Mean	1524039.2	869840.0	654199.2	900.90	2145846.2	1204930.0	940916.2	5394.52
9/5	*				1449436.9	1358300.0	91136.9	69.68
9/16	197113.2	171800.0	25313.2		1633681.5	999200.0	634481.5	42.76
9/22	*				3395925.3	3149390.0	246535.3	17.85
9/26	*				2795737.0	2679200.5	116536.5	105.05
Mean					2318695.2	2046522.6	272172.6	58.84
10/5	*				2330401.5	2253740.0	76661.5	28.80
10/12	*				1399002.5	1245950.0	153052.5	57.81
10/20					1265657.3	961400.0	304257.3	57.55
Mean					1665020.4	1487030.0	177990.4	48.05
11/3	*				324436.1	323400.0	1036.1	7.78
11/11	*				438360.5	437220.0	1140.5	14.69
11/24	*				469091.3	468930.0	161.3	0.00
Mean					410629.3	409850.0	779.3	7.49

*No collection.

TABLE X (Continued)

Date	Pond 1 Total Phytoplankton	Pond 1 Micro-cells	Pond 1 Algae	Pond 1 Zooplankton	Pond 4 Total Phytoplankton	Pond 4 Micro-cells	Pond 4 Algae	Pond 4 Zooplankton
12/21	*				576933.8	575820.0	1113.8	0.00
2/3	*				478233.3	475860.0	2373.3	9.90
2/16	*				388943.1	388920.0	23.1	4.95
Mean					433588.2	432390.0	1198.2	7.43
3/10	*				348226.1	348180.0	46.1	0.00
3/17	*				247208.1	245910.0	1298.1	4.95
3/26	451094.2	436800.0	14294.2		417452.5	414330.0	3122.5	4.95
Mean					337628.9	336140.0	1488.9	3.30
4/7	704032.0	701400.0	2630.0		869055.7	864990.0	4065.7	39.44
4/13	522616.9	519120.0	3496.9		519052.5	514500.0	4552.5	4.95
4/20	*				718548.0	676200.0	42348.0	177.85
4/26	318360.0	318360.0	0.0		607390.3	519120.0	88270.3	0.21
Mean	515002.3	512960.0	2042.3		678511.6	643702.5	34809.1	55.61
5/4	1895040.0	1895040.0	0.0		1991315.9	1857660.0	133655.9	7.18
5/12	*				1024740.5	976200.0	48540.5	19.57
5/26	944311.8	663600.0	280711.8	262.36	435082.9	423570.0	11512.9	417.07
Mean	1419675.9	1279320.0	140355.9	65.60	1150379.8	1085810.0	64569.8	147.94
6/5	1066007.7	1019760.0	46247.7		367647.1	270900.0	96747.1	59.83
6/11	349117.1	309960.0	39157.1		657923.5	498754.0	159169.5	13.32
6/19	718102.3	637560.0	80542.3	812.65	667368.1	603330.0	64038.1	13006.84
6/29	876491.5	737520.0	138971.5	10053.45	769914.7	696780.0	73134.7	20201.26
Mean	752429.7	676200.0	76229.7	2716.50	615713.3	517440.0	98272.4	8320.31

TABLE X (Continued)

Date	Pond 1 Total Phytoplankton	Pond 1 Micro-cells	Pond 1 Algae	Pond 1 Zooplankton	Pond 4 Total Phytoplankton	Pond 4 Micro-cells	Pond 4 Algae	Pond 4 Zooplankton
7/5	432313.3	336840.0	95473.3	3493.86	498968.6	487200.0	11768.6	14778.72
7/10	918317.5	519120.0	399197.5	283.58	728903.1	694490.0	34413.1	5766.04
7/19	1114851.3	901132.0	213531.3	1578.68	1024038.3	905940.0	118098.3	14768.19
Mean	821827.4	585760.0	236067.4	1785.40	750063.7	695876.7	54187.0	11770.99
7/25	1376072.0	597260.0	278812.0	31037.36	1164607.5	710460.0	454147.5	20403.12
8/1	1147073.4	233750.0	913323.4	20940.22	822878.1	457590.0	365288.1	20924.27
8/9	1106066.5	931580.0	174486.5	179950.04	1258572.4	914770.0	743802.4	110531.43
8/16	1842867.5	1342760.0	500107.5	2182.70	1625387.8	841150.0	784237.8	5355.24
Mean	1365335.8	836030.0	529305.8	67691.11	1235612.7	737503.0	498109.4	45603.65
9/5	1738315.5	1456370.0	281945.5	39.78	1792474.3	1426760.0	365714.3	28.28
9/16	2047891.5	797810.0	1250081.5	411.74	1138812.2	537200.0	601612.2	6053.10
9/22	4782035.5	3072740.0	1709295.5	245.38	2619895.5	1608200.0	1011695.5	2744.54
9/26	1768650.8	1089080.0	679570.8	122.95	2080532.0	1344230.0	736302.0	2549.27
Mean	2584223.3	1604000.0	980223.3	204.96	1907928.5	1229097.0	678831.5	2843.80
10/5	1477388.6	925910.0	551478.6	1085.58	2023376.3	1558850.0	464526.3	8345.07
10/12	1191537.4	955520.0	236017.4	3245.81	1459896.5	1221800.0	238096.5	7327.18
10/20	1457661.1	1267980.0	189681.1	1883.41	1043145.9	988340.0	44805.9	6218.76
Mean	1375529.0	1049803.3	325725.7	2071.60	1508806.2	1259663.3	249142.9	7297.00
11/3	593076.1	576030.0	17046.1	294.32	516897.9	507570.0	9417.9	4121.14
11/11	474137.6	473550.0	587.6	8.81	513453.6	509800.0	3653.6	856.92
11/24	400596.7	400470.0	126.7	57.71	264771.1	262900.0	1871.1	43.07
Mean	489270.1	483350.0	5920.1	120.30	431737.5	426756.6	4980.9	1673.71
12/21	205007.0	202860.0	2147.0	9.88	442303.2	434700.0	7603.2	4.95

TABLE X (Continued)

Date	Pond 1 Total Phytoplankton	Pond 1 Micro-cells	Pond 1 Algae	Pond 1 Zooplankton	Pond 4 Total Phytoplankton	Pond 4 Micro-cells	Pond 4 Algae	Pond 4 Zooplankton
2/3	358861.2	348390.0	10471.2	29.70	375284.3	368970.0	6314.2	5.16
2/6	366507.6	366450.0	57.6	0.00	219770.8	218610.0	1160.8	163.16
Mean	362684.4	357420.0	5264.4	14.35	297527.2	293790.0	3737.2	84.16
3/10	301381.1	296100.0	5281.1	4.95	333486.2	332430.0	1056.2	14.69
3/17	326612.1	323190.0	3422.1	0.00	328100.7	328020.0	80.7	4.95
3/26	531184.2	464310.0	66874.2	168.11	345522.0	277830.0	67692.0	3911.77
Mean	386392.5	361200.0	25192.5	57.87	335703.0	312760.0	22943.0	1311.80
4/7	809637.1	796740.0	12897.1	74.25	673874.8	635460.0	38414.8	178.31
4/13	531994.1	516810.0	15184.1	4.95	824867.7	808290.0	16577.7	0.00
4/20	564537.3	551040.0	13497.3	355.69	692460.8	544110.0	148350.8	3465.56
4/26	545198.9	516810.0	28388.9	163.58	512407.0	505260.0	7747.0	1468.42
Mean	612841.9	595350.0	17491.9	149.62	675902.6	623280.0	52622.6	1278.08
5/4	918958.4	721560.0	197398.4	58.53	1078516.2	1010940.0	67576.2	7313.48
5/12	1324274.6	1074570.0	249704.6	1094.72	1275610.5	1227030.0	48580.5	7413.98
5/26	497693.3	487200.0	10493.3	927.52	489538.0	460110.0	29428.0	10218.53
Mean	913642.1	761110.0	152532.1	693.59	947888.2	899360.0	48528.2	8315.33
6/5	440052.8	371280.0	68772.8	76.05	403991.1	357210.0	46781.1	13597.02
6/11	474316.0	448560.0	25756.0	89.35	468752.3	441630.0	27122.3	2032.32
6/19	451832.6	425880.0	25943.6	7098.36	701254.5	687540.0	13714.5	4719.29
6/26	452356.4	429530.0	12826.4	6551.56	1048251.8	1014510.0	33741.8	2565.86
Mean	454637.2	421312.5	33324.7	3453.84	655562.4	625222.5	30339.9	5728.37
7/5	478722.1	455280.0	23442.1	24181.64	634437.1	514710.0	119727.1	30524.47
7/10	1055999.2	821730.0	234269.2	5017.48	1333558.6	897540.0	436018.6	21316.83
7/19	956389.9	794430.0	161959.9	9346.71	1487190.9	1231650.0	255540.9	28208.15
Mean	830370.7	690480.0	139890.7	12848.61	1151728.9	881300.0	270428.9	26683.15

TABLE XI

SPECIES-DIVERSITY INDEX COUNTS[a]

Date	Pond 1				Pond 4				Pond 7				Pond 10			
	10[b]	100	500	1000	10	100	500	1000	10	100	500	1000	10	100	500	1000
6/25/61	2	7	15	18	3	8	13	16	4	10	17	19	5	14	23	29
8/16/61	2	10	14	18	3	5	13	18	6	10	15	19	7	14	19	21
9/5/61					3	8	13	15	4	8	11	12	4	9	16	17
9/16/61	2	4	6	9	3	5	10	13	3	9	14	18	4	12	20	23
9/29/61					3	6	10	13	4	9	16	21	5	11	17	24
10/5/61					2	6	12	16	2	11	15	20	4	8	17	22
11/3/61					3	7	15	19	5	12	19	24	6	14	21	26
12/21/61					1	3	7	9	2	4	8	11	2	4	9	14
2/2/62					2	4	9	13	3	5	10	15	4	8	12	16
3/26/62					1	3	4	5	2	4	7	9	3	6	9	12
4/6/62	2	5	9	12	2	5	9	13	4	8	14	17	5	9	15	20
5/12/62					4	7	13	19	2	14	20	23	6	14	20	26
6/5/62					4	7	14	18	7	12	16	19	7	16	21	25
6/11/62	2	6	12	14	3	7	14	17	3	7	14	18	6	9	16	20
6/19/62	4	8	12	14	4	8	15	19	5	8	17	21	6	9	17	22
6/26/62	3	8	12	14	4	8	15	19	5	7	14	16	6	13	18	20
7/10/62	3	8	14	16	2	6	9	13	3	6	12	17	6	9	19	24
7/19/62	4	8	12	14	4	8	13	17	6	13	21	25	6	14	22	26
Mean	2.6	7.1	11.7	14.3	2.9	6.3	11.6	15.1	3.9	8.7	14.4	18.0	5.1	10.7	17.3	21.5

[a]Each number represents the cumulative number of species per cycle.

[b]Cumulative numbers of individuals counted.

TABLE XII

AVERAGE NUMBER OF ZOOPLANKTON PER LITER

Date	Pond 1	Pond 4	Pond 7	Pond 10
7/25/61	1110.00	2501.25	1322.25	9415.00
8/1/61	2580.00	2578.75	6395.75	4473.75
8/9/61	1135.00	7273.00	51753.25	33744.00
8/16/61	1500.00	9450.00	6330.00	5806.75
8/24/61	*	6525.00	6285.00	4610.00
9/5/61	*	990.00	453.75	247.50
9/16/61		270.00	1687.50	5503.50
9/22/61	*	150.00	2456.25	5346.25
9/29/61	*	52.50	8850.00	4192.50
10/5/61	*	63.75	2583.75	1143.75
10/12/61	*	93.75	1762.50	2891.25
10/20/61	*	213.75	3191.25	253.00
11/3/61	*	15.00	568.75	1620.00
11/11/61	*	3.75	33.75	933.75
11/24/61	*		63.75	112.50
12/12/61	*		7.50	3.75
2/3/62		7.50	22.50	7.50
2/16/62	*	3.75		3.75
3/10/62	*		3.75	3.75
3/17/62	*	3.75		3.75
3/26/62		3.75	7.50	90.00
4/7/62		22.50	56.25	15.00
4/13/62		3.75	3.75	
4/20/62	*	7.50	15.00	93.75
4/26/62		3.75	11.25	33.75
5/4/62		128.75	135.00	2422.50
5/12/62	*	157.50	1975.50	2606.75
5/26/62	4705.00	648.75	633.75	1856.25
6/5/62		22.50	30.00	3588.75
6/11/62		112.50	270.00	1890.00
6/19/62	2550.00	5508.25	1987.50	3935.00
6/26/62	3045.00	6382.00	2295.00	3152.50
7/5/62	945.00	2258.00	9318.75	1363.50
7/10/62	600.00	1320.00	1368.75	28796.25
7/19/62	750.00	5760.00	1121.25	1880.25

*No collections, water appeared oily and dark gray.

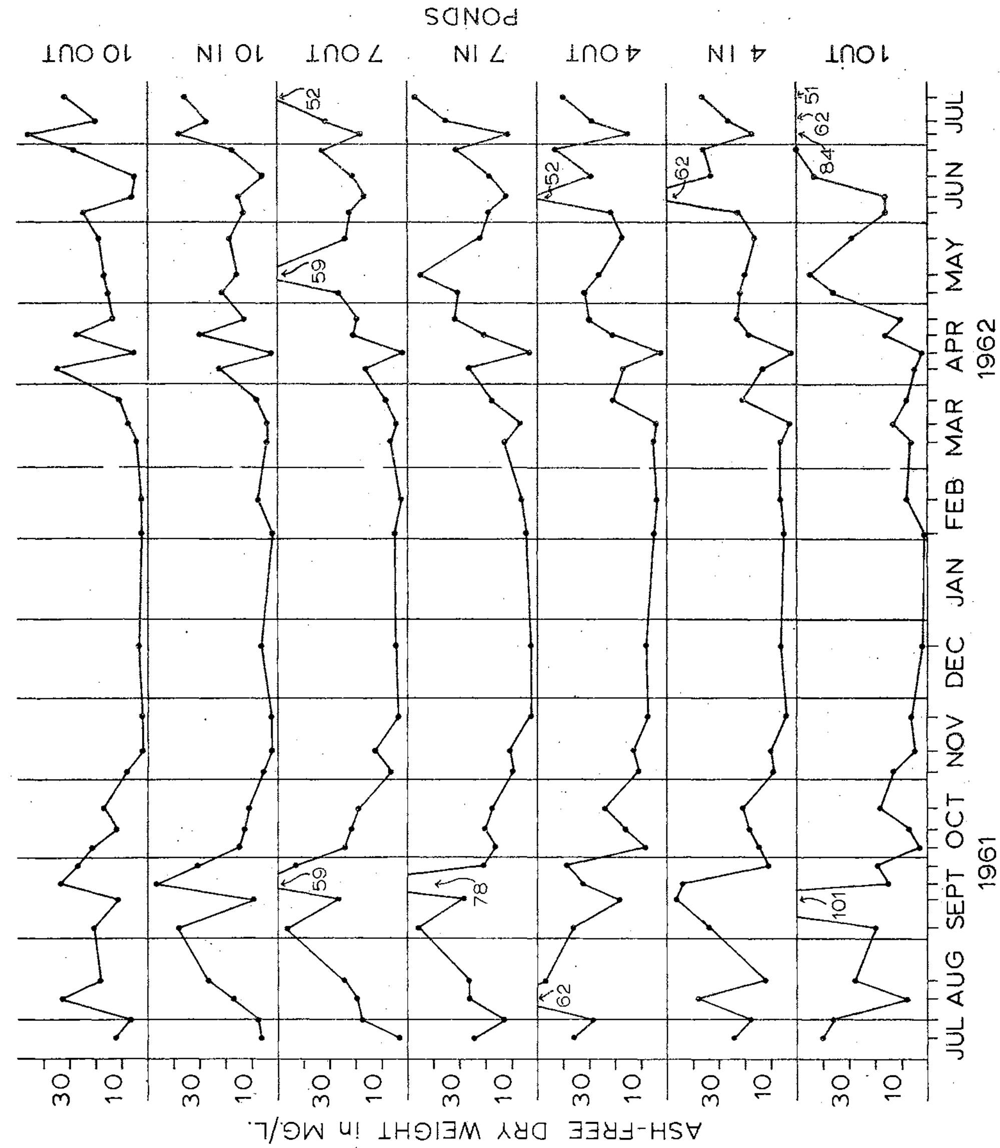

Fig. 1. Ash-free dry weight into and out of each pond from 25 July 1961 to 19 July 1962.

VITA

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Candidate for the Degree of

Doctor of Philosophy

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