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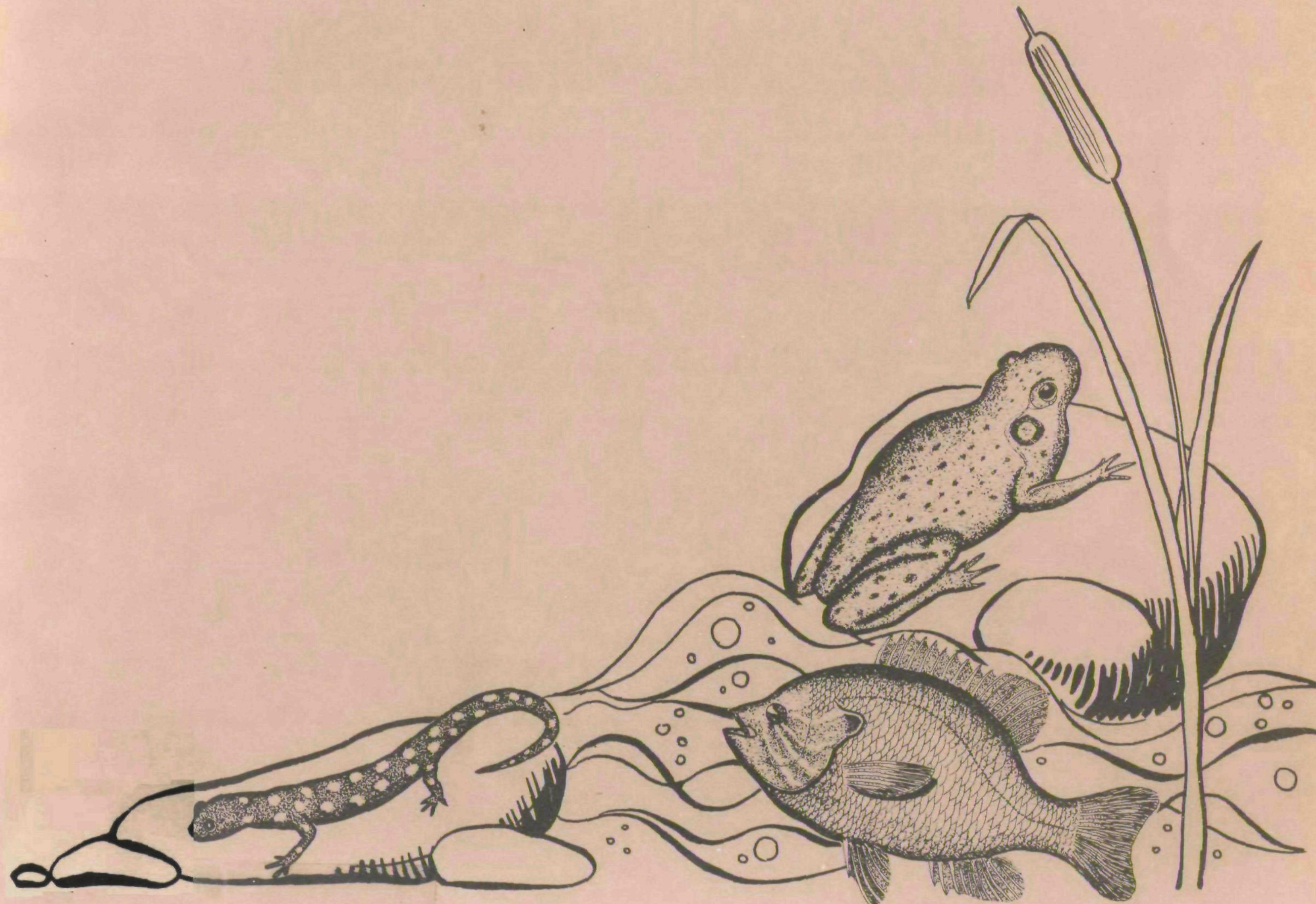
Acid Mine Pollution Effects on Lake Biology



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ACID MINE POLLUTION EFFECTS ON LAKE BIOLOGY

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ABSTRACT

Six coal stripmine lakes in southern Indiana encompassing a pH range of 2.5 to 8.2 were studied from July 1969 to December 1970. Generally, differences between the lakes indicated successional trends with increasing pH. Environmental trends in the surface waters included increasing levels of dissolved oxygen and decreasing concentrations of dissolved substances. These tendencies were somewhat obscured by differences in the annual cycles of stratification, four of the lakes proving to be unexpectedly meromictic. Biological changes associated with increasing pH included increasing diversity and increasing homeostasis. Biomass was influenced by both pH and circulation patterns (meromixis vs. holomixis), and bottom fauna was further limited by the steep-sided basin form. All the stripmine lakes had much higher solute concentrations and lower biological diversity than a small local non-stripmine reservoir studied as a control. A fertilization program in one lake has apparently produced elimination of all rooted aquatic plants, violent oscillations of plankton, and low fish populations. It is suggested that sport fishing in stripmine lakes, not presently very satisfactory, could be improved by management techniques adapted to their unique limnological nature.

CONTENTS

FIGURES

TABLES

No.		Page

SECTION I

CONCLUSIONS

1. Six coal stripmine lakes in a series of increasing pH exhibited sequential differences in both environmental parameters and community structure.

2. These differences were analogous to some developmental trends that characterize ecological succession.

3. Due to factors of morphometry and water chemistry some, perhaps many, coal stripmine lakes are meromictic.

4. This pattern of incomplete circulation can have marked influences on the biological community of a mine lake, including depression of the fish population.

SECTION II

RECOMMENDATIONS

1. Large areas of abandoned coal striplands that are not presently utilized could and should be reclaimed for residential, agricultural, wildlife, and recreational purposes.

2. Sport fishing in the stripmine lakes is quite compatible with such uses and should be incorporated into development plans for stripmine areas.

3. Stripmine lakes to be managed for sport fishing should be monitored regularly to determine their annual patterns of circulation and general limnological characteristics.

4. Fish production could probably be increased markedly in typical stripmine lakes by increasing the relative area of shallow littoral zone, increasing the habitat diversity and by the cautious use of fertilization.

SECTION III

INTRODUCTION

Surface mining for coal is carried out extensively in the United States. By 1965 approximately 3.2 million acres (1.3 million hectares) had been surface mined, about 41 percent for coal (U.S.D.I. 1967). Coal stripping is carried out primarily in the Appalachian region, the South, and the Midwest, including well over 100,000 acres (40,500 hectares) in Indiana by 1971. One result of the Area Stripmining Method (as opposed to Contour Stripping), usually practiced in flat terrain such as most of the Midwest, is the creation of large numbers of small lakes and ponds in the final cuts. These bodies of water vary in surface area from a few hundred square meters to several hectares.

In Indiana coal stripmining is almost entirely confined to the southwestern third of the state where Pennsylvanian age strata are exposed (Wier 1969, personal communication). This area is part of the "Eastern Interior Coal Province," which also includes most of Illinois. Stripmining has left several thousand large and small stripmine lakes in this area. In Pike County, the location of the present study, there are no less than 950 (by actual count on U.S. Geological Survey topographic maps) of these lakes. These "strip pits" as they are called are rightly regarded as having considerable recreational potential (Bass 1969, personal communication). Some old stripmine regions have already been developed to a limited extent as recreational and wildlife areas by the Indiana Department of Natural Resources, some coal mining companies, and a few local communities. Such areas are used primarily for picnicking, camping, hunting, and fishing. Unfortunately, the potentially great recreational value of these areas has not, in my view, been fully recognized and developed. Few natural wilderness areas remain in Indiana. The striplands, though not natural in origin, can provide semi-wilderness areas partially replacing those natural ones that have been lost.

One aim of the present study is to provide certain fundamental limnological information about stripmine lakes in Indiana as a basis for sound management of these lakes. Techniques developed for encouraging fish production in farm ponds, natural lakes, and reservoirs are unlikely to be very satisfactory for stripmine lakes. It is my hope that this work will contribute to greater realization of the recreational potential of stripmine lakes in Indiana and elsewhere. A second and more theoretical aspect of this work is discussed below.

In the majority of instances the water of newly formed coal stripmine lakes is moderately to highly acid. High concentrations of various ions occur in such lakes. This unique water chemistry results from the leaching of substances contained in the cast overburden (materials such as shale, clay, and sandstone overlying the coal seams) into the lakes by surface runoff and ground water. The acid condition in particular is a result of the formation of sulfuric acid by the oxidation of iron sulfide. Typically, the chemistry of these lakes comes gradually to resemble that of the more natural small lakes and ponds of the region. The rate of this evolutionary process is quite variable and depends on such factors as the nature of the cast overburden, kinds and amounts of materials exposed, vegetative cover, nature of the lake bottom materials, and patterns of ground water drainage and rainfall. Thus there is no good correlation between the chronological age of a mine lake and its chemical condition (Lewis and Peters 1955, Campbell et al. 1965a). Some mine lakes do not undergo this entirely successional sequence. When the overburden associated with the coal is low in toxic and acid-forming materials or when modern mining and reclamation practices are followed, the lake need not begin its existence as an environment hostile to most kinds of aquatic life.

The biota of highly acid mine lakes (pH 2.5 or less) is quite restricted. As the chemical conditions of the water and substrate become more moderate, the diversity and abundance of organisms increases. Acid mine lakes may properly be regarded as an example of gross industrial pollution. Yet for the limnologist, they offer a rather unique opportunity to study the adaptive mechanisms by which certain organisms do manage to survive in these extremely hostile environments and the successional patterns that emerge as the ecosystem gradually comes to resemble a more natural aquatic situation.

A variety of studies have been carried out on coal stripmine lakes. Most have emphasized either the chemical and physical aspects or the biological aspects. Few investigators have dealt with both ecosystem components. The chemical and physical attributes of stripmine lakes have, perhaps, received more attention than their biological communities. The most important of previous stripmine lake studies are summarized below.

The physical and chemical conditions that can occur in stripmine lakes are reasonably well known, at least in their broad outlines. Studies such as those of Lewis and Peters (1955), Dinsmore (1958), Simpson (1961), Parsons (1964), Campbell et al. (1965a, 1965b), and the series by Waller (1967), Gash (1968), and Tobaben (1969) have contributed to knowledge of these conditions. Nevertheless, a strikingly different pattern has emerged in the Indiana stripmine lakes dealt with in the present paper.

Perhaps the most dramatic feature of coal stripmine lakes is their acidity. pH values of 2.0 to 2.5 are rather common, and lakes of pH less than 2.0 are known to occur. The only parallels in nature are volcanic lakes in Japan and Indonesia and bog lakes (Hutchinson 1957). Stripmine lakes with pH values below 2.5 are usually in basins that were used for washing coal. These "tipples," as they are called, differ from final-cut lakes in having very shallow basins and bottoms covered with thick layers of coal and shale fragments. In these lakes total acid may exceed 6,500 mg/l as $CaCO_3$ (Campbell et al. 1965a).

Because of the low pH and the nature of the surrounding materials (cast overburden or "spoil banks"), a great variety of substances is dissolved in the water of acid mine lakes, often in very high concentrations. Sulfate may reach 12,000 mg/l, and iron, aluminum, copper, zinc, lead, arsenic, free carbon dioxide, and sometimes other substances are unusually high. Aluminum, for example, is usually present in lake waters in concentrations less than 0.1 mg/l (Hutchinson 1957), whereas in stripmine lakes it may reach 180 mg/l or more (Parsons 1964). Oxygen is usually present in stripmine lakes in amounts considered adequate for aquatic life. Calcium and magnesium are typically quite high. Perhaps the most striking physical characteristic of these lakes is their range of apparent colors. Very acid lakes often appear a deep, clear red-brown or red-black. These red hues are probably caused by a combination of iron compounds and humic substances leached from the exposed coal and shale. Lakes of higher pH exhibit many shades of blue, yellow, green, brown, and various combinations of these. Many lakes undergo striking color changes at various times during the annual cycle because of algal blooms, upwelling of deep water leading to precipitation of iron compounds, and perhaps other causes. Conductivity due to dissolved substances is ordinarily high in the very acid lakes, reaching values of 12,000 µmphos/cm or more in some instances. As noted above, these chemical and physical features change as the mine lake matures, eventually approaching those of natural small water bodies in the area.

Studies emphasizing the biological aspects of stripmine lake ecosystems have been mainly qualitative descriptions of the organisms present. In a pioneering study, Lackey (1938, 1939) surveyed 92 localities (mine lakes and streams) influenced by acid-mine drainage. He found very few species in the most acid waters, but observed that these were often very abundant. Lackey's work, incidentally, is one of the two studies known to the writer that deal to any extent with stripmine lakes in Indiana. The other is Riley's 1952 survey of abandoned coal striplands as wildlife habitats. Most of the subsequent studies of mine lake biota have been limited to one or a few taxa or qualitative surveys of organisms present. Examples of such work includes the papers of Yeager (1942), Galler (1948), Levin (1948), Myers (1948), Ruhr (1951), Maupin, Wells, and Leist (1954), Bell (1956), Dixon (1957), Brewer (1958), Arata (1959), Ehrle (1960), Stockinger and Hays (1960), Harp and Campbell (1967), and Houde and Forney (1970).

Few studies have attempted to deal with the entire ecosystems of stripmine lakes. Riley (1965) has studied four lakes in Ohio, and Dinsmore (1958) studied 12 in Pennsylvania. Unfortunately, both these works suffer from inadequate sampling programs (samples taken at long intervals and only at the surface). The best description to date of the annual cycle in an acid-mine water ecosystem is that of Parsons (1968), which, however, is concerned not with mine lakes but with a stream subject to acid-mine drainage. Parsons sampled 11 stations on Cedar Creek in central Missouri at monthly intervals over a 27-month period. He has provided a good account of the responses of the stream ecosystem to acid pollution and of recovery from heavy pollution. His data indicate a pattern of linear succession somewhat analogous to that which occurs in streams undergoing organic pollution.

The most comprehensive body of work on ecosystem changes in coal stripmine lakes is contained in several studies carried out in central Missouri. Four small lakes were investigated in 1940 by Crawford (1942). In 1950 these lakes were restudied by Heaton (1950, 1951) in order to document changes associated with aging. Since 1962 Campbell and his co-workers (Campbell et al. 1965a, 1965b) have resumed investigation of three of these lakes. The increase in diversity of organisms and the modification of chemical and physical characteristics associated with aging are well documented in these studies.

Some very basic aspects of coal stripmine lake ecosystem, however, have not been adequately described. A few of the more important features awaiting careful study include:

1. The seasonal cycles and stratification patterns of environmental parameters such as dissolved oxygen, pH, temperature, light penetration, and dissolved substances, especially the differences in these cycles and patterns between lakes of different pH.

2. The seasonal cycles and depth patterns of occurrence and abundance of the organisms inhabiting mine lakes at different stages of recovery from acid pollution.

3. The relative importance of autochthonous primary production and allochthonous organic matter input (dead leaves, etc.) as food sources in lakes at different stages.

4. The physiological significance for aquatic organisms of the unique water chemistry, including adaptive mechanisms that allow survival in very acid lakes.

5. The importance to aquatic life, particularly benthos and fish, of the low habitat diversity found in mine lakes.

6. The significance for benthic organisms and fish (in terms of spawning for example) of the typical U-shaped basins of most stripmine lakes.

7. The changes in community structure and ecosystem dynamics that accompany recovery from acid pollution.

The present paper attempts to remedy certain of these deficiencies. In addition, it provides information basic to the establishment of water quality standards and fisheries management practices for coal stripmine lakes.

Coal stripmine lakes provide a nearly unique opportunity to analyze the maturation of evolution of an ecosystem type. A regular sequence of changes occurs in these lakes during recovery with regard to both the biotic and abiotic components of the ecosystem. A major aim in this work has been to use a graded series of mine lakes as a natural model for learning about ecosystem evolution in general. I have assumed that a set of lakes at different pH levels closely approximates a series of stages in the ecological succession of a single lake during recovery from acid pollution. Beginning with the idea that there should be regular patterns of change or trends in the ecosystem associated with increase in pH, I have attempted to identify and quantify them with regard to:

1. The physical and chemical components of the ecosystem, especially the differences in annual cycles of pH, temperature, conductivity, turbidity, dissolved oxygen, and major ions.

2. The diversity of species in the various biological components, including rooted plants, algae, zooplankton, benthos, fish, and other vertebrates.

3. Annual cycles of biological production.

4. Overall ecosystem organization including community structure, patterns of energy flow, etc.

An attempt to evaluate the significance of allochthonous organic materials relative to autochthonous primary production was not successful because of the difficulty of measuring primary production in lakes with such a unique water chemistry and because of disturbance of installations by beavers, muskrats, and humans. This comparison is of such fundamental importance that I hope to make another attempt in the near future.

SECTION IV

DESCRIPTION OF STUDY AREA

The stripmine area studied by Corbett (1965) was chosen for this study, because it is the closest area to Indiana University with large numbers of mine lakes having the desired features. This area lies in Pike County, Indiana, and is contained on the Augusta and Oakland City quadrangle maps of the U.S. Geological Survey. A survey of this area was conducted from October 1968 to July 1969 for the purpose of selecting suitable lakes for extended study according to the following major criteria:

1. Accessibility. Lakes that could not be reached by motor vehicle or that had steep banks precluding the launching of a heavy workboat were rejected. Two of the lakes selected were not fully accessible during wet weather because of a clay road surface. At such times, limited work was accomplished from a canoe portaged in.

2. pH. Hydrogen ion concentration was used as a measure of acidity and as an indication of other chemical characteristics. The aim was to select a reasonable number of lakes embracing the widest possible pH range.

An effort was made to select lakes that were as uniform as possible with regard to morphometry and other factors, differing mainly in their degree of recovery from acid pollution. About 110 lakes were visited during the survey. Most of them were excluded because of inaccessibility. Many of the very acid lakes were rejected because they were, in fact, abandoned mine tipples rather than final-cut lakes.

The six lakes finally selected for study range in pH from 2.5 to 8.2. All are in basins formed as the final cuts of stripmining operations. The lakes have been designated by Roman numerals I through VI in order of ascending pH. Lakes II through V were under continuous surveillance from July 1969 through December 1970. Lakes I and VI were monitored throughout 1970. Following is a brief description of each of the lakes.

Lake I (Fig. 1). This lake varies in apparent color from a rather turbid red-brown ("tomato soup") to a brilliant red-black. It is located in the SW $\frac{1}{4}$ Sec. 17, T 2S, R. 7W in Pike County. Lake I is, at three meters, the shallowest of the study lakes, and it also has the least area and volume (Table 1). Lake I was formed in 1940.

Lake II (Fig. 2). This lake has the long narrow outline typical of stripmine lakes. The water is generally a very clear green due to low turbidity. The most striking thing about Lake II is the uniformity of chemical and physical conditions that it exhibits. This lake tends to be remarkably constant in pH, dissolved substances, etc., both throughout the water column and throughout the year. Thus the ranges of the various parameters given in Tables 3 and 4 are quite restricted for Lake

II as compared to the others. Lake II was formed in 1960 and is located in the NE $\frac{1}{4}$ Sec. 4, T. 3S, R. 8W in Pike County.

Lake III (Fig. 3). This lake is located adjacent to Lake IV on one subunit of the Patoka Fish and Game Area of the Indiana Department of Natural Resources. Lakes I, V, and VI are on other subunits of this management area. Lake III has greater flow-through than the other study lakes. It has, apparently as a result of this, greater short-term changes in such parameters as pH, temperature, and turbidity. This effect is confined mainly to the surface layers because of a stratification situation considered below. Lake III has greater variation in pH from inlet to outlet, from surface to bottom, and over the annual cycle than any of the other lakes. Lakes III and IV were completed in 1958.

Lake IV (Fig. 4). This lake is directly connected to Lake III by a very short channel approximately 4 meters wide and 20 centimeters deep. The direction of water flow is from IV to III at all times. This lake has the greatest maximum depth of the six (Table 1). Lake IV has had a resident fish population for several years (Bass 1964), and during times when water quality moderates, these fish may invade Lake III. During the winter of 1969-70 the stream that formerly flowed into the upper end of Lake III changed its course to the lower end of Lake IV (and thence into Lake III). No water quality or biotal changes have been observed that can be attributed to this change in stream channel. Lakes III and IV are located in the NW $\frac{1}{4}$ Sec. 12, T. 3S, R. 8W, Pike County, Indiana.

Lake V (Fig. 5). This is the most irregular of the lakes in shape. There are five small islands in the main body of the lake and three long "fingers" pointing to the southwest. Lake V is being fertilized during the summer months by the Department of Natural Resources in an attempt to increase fish production. The advisability of this procedure is considered below. Lake V was formed in 1940 and is located in the SW $\frac{1}{4}$ Sec. 17, T. 2S, R. 7W in Pike County.

Lake VI (Fig. 6). This lake is one of the smaller of the study lakes and is roughly Y-shaped. Construction of an access road in the autumn of 1969 allowed this lake to be added to the series as a relatively high pH lake that was not fertilized or otherwise managed. Lake VI was formed in 1950 and is located centrally on the border between Secs. 3 and 4, T. 3S, R.7W in Pike County.

Control Lake. This lake was selected as representative of non-stripmine small lakes of the region. It is owned jointly by three rural families upon whose property it was constructed in 1963 for recreational purposes, primarily for fishing by the owners and their guests. Because of time limitations and relatively poor access this lake was visited less frequently than the others, but it has provided some comparative data on water chemistry and biota. It is located in the SW $\frac{1}{4}$ Sec. 31, T. 2S, R. 6W in Pike County.

Table 1 (see p. 17) contains a summary of morphometric data for the six study lakes and the control lake.

TABLE 1. Some morphometric characteristics of the Pike County study lakes and control lake.

Lake	Year formed	Total length (m)	Mean width (m)	Maximum depth (m)	Mean depth (m)	Surface area (10 m)	Volume (10 m)
I	1940	415	43	3.0	1.9	17.7	34.5
II	1960	1,300	73	6.0	3.8	94.5	355.3
III	1958	975	49	8.0	5.6	47.5	265.0
IV	1958	900	56	10.5	5.5	50.4	275.4
V	1940	960	31	5.5	3.4	29.5	100.6
VI	1950	510	41	7.0	4.4	20.8	90.8
Control	1963	850	95	7.0	3.0	80.8	242.3

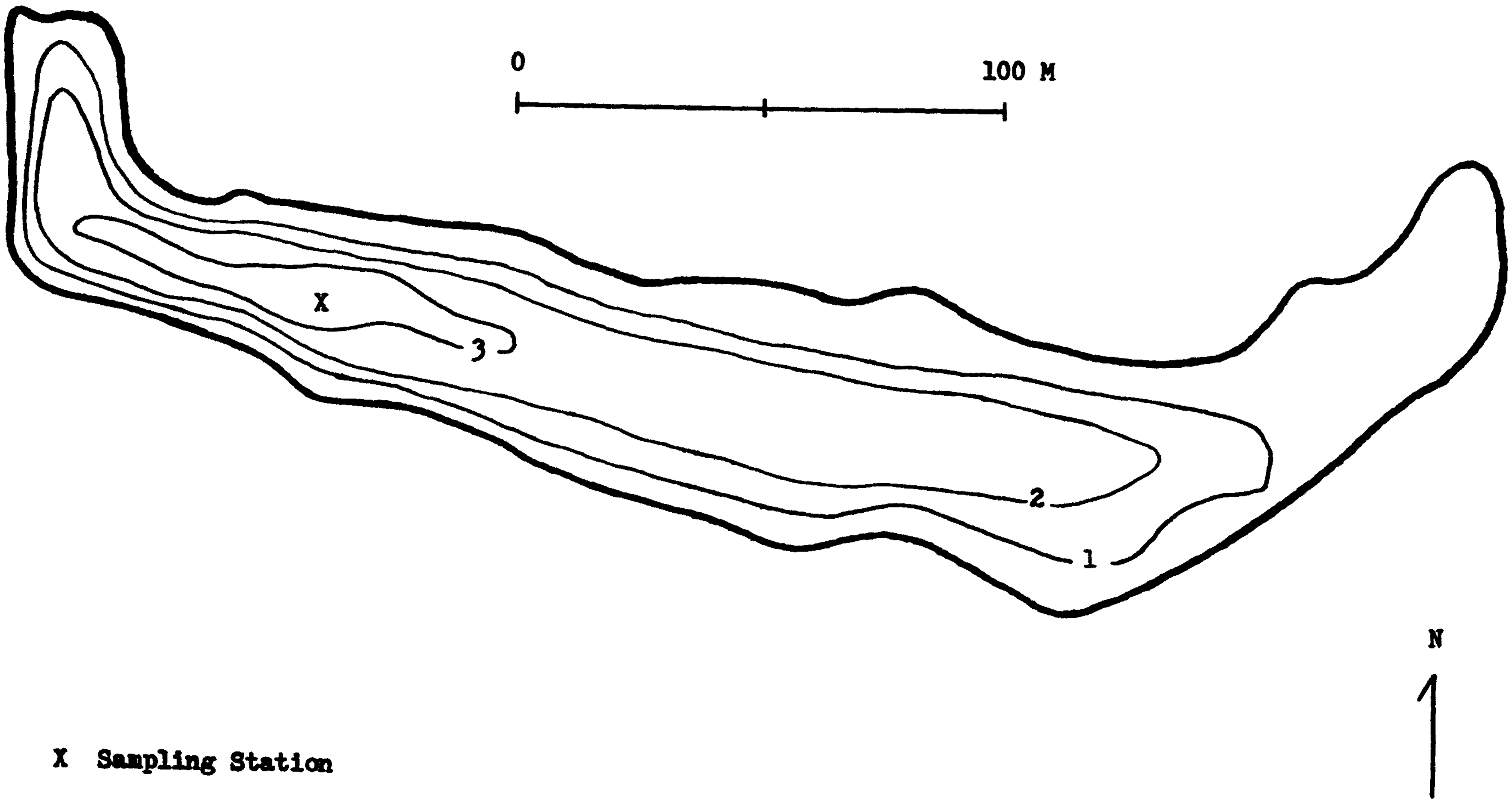


FIG. 1. Bathymetric map of Lake I (depths in m).

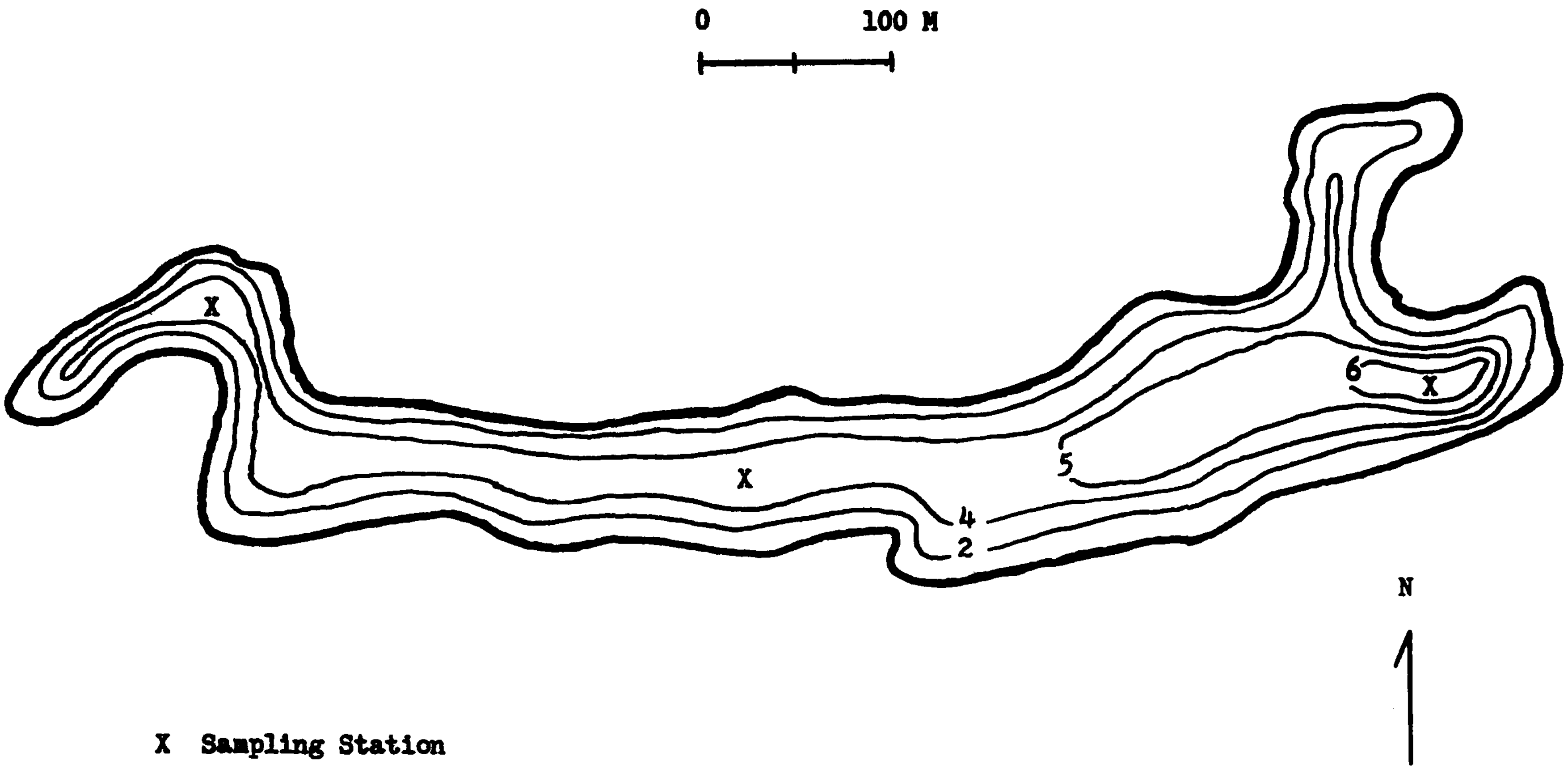


FIG. 2. Bathymetric map of Lake II (depths in m).

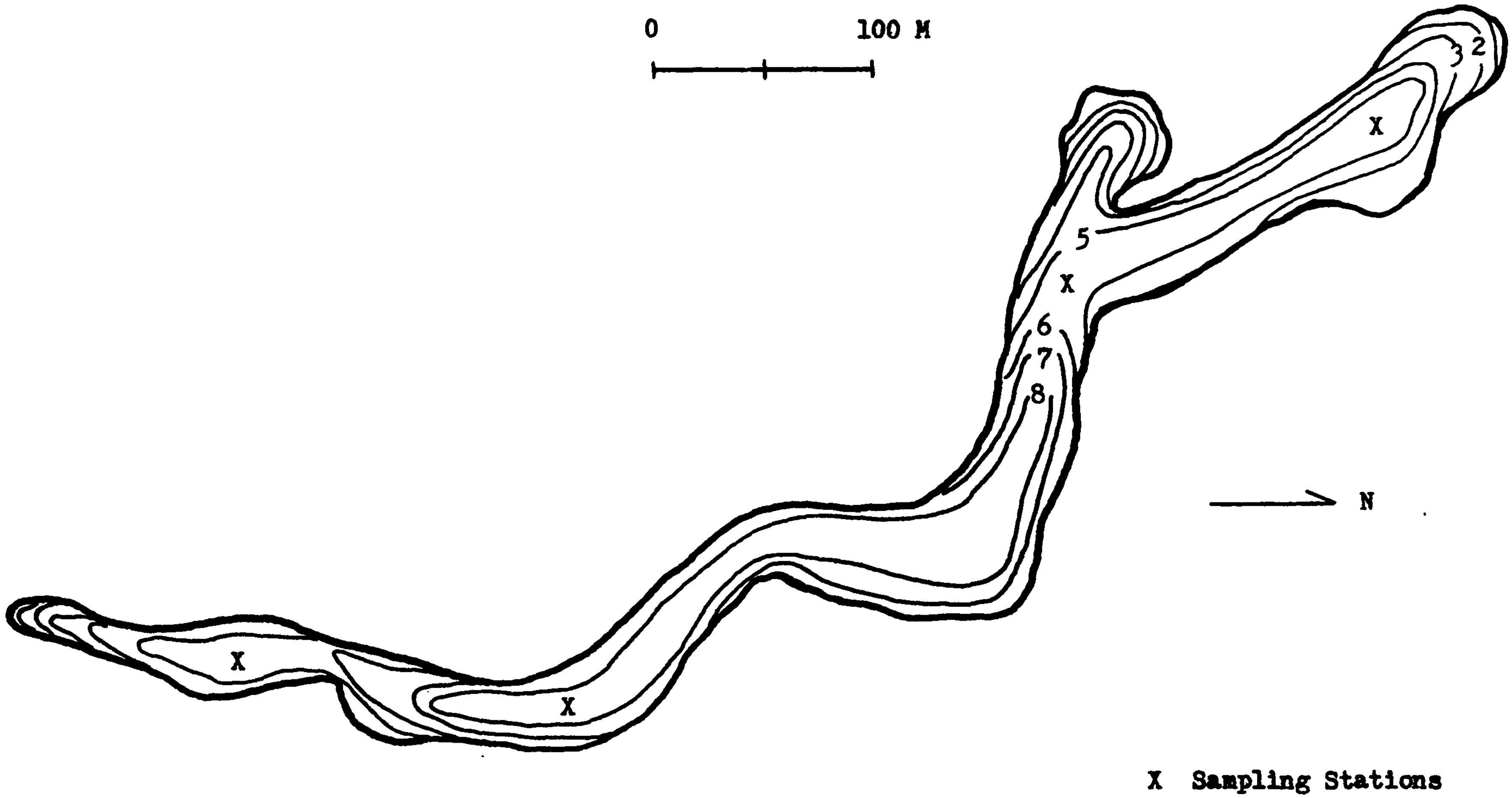


FIG. 3. Bathymetric map of Lake III (depths in m).

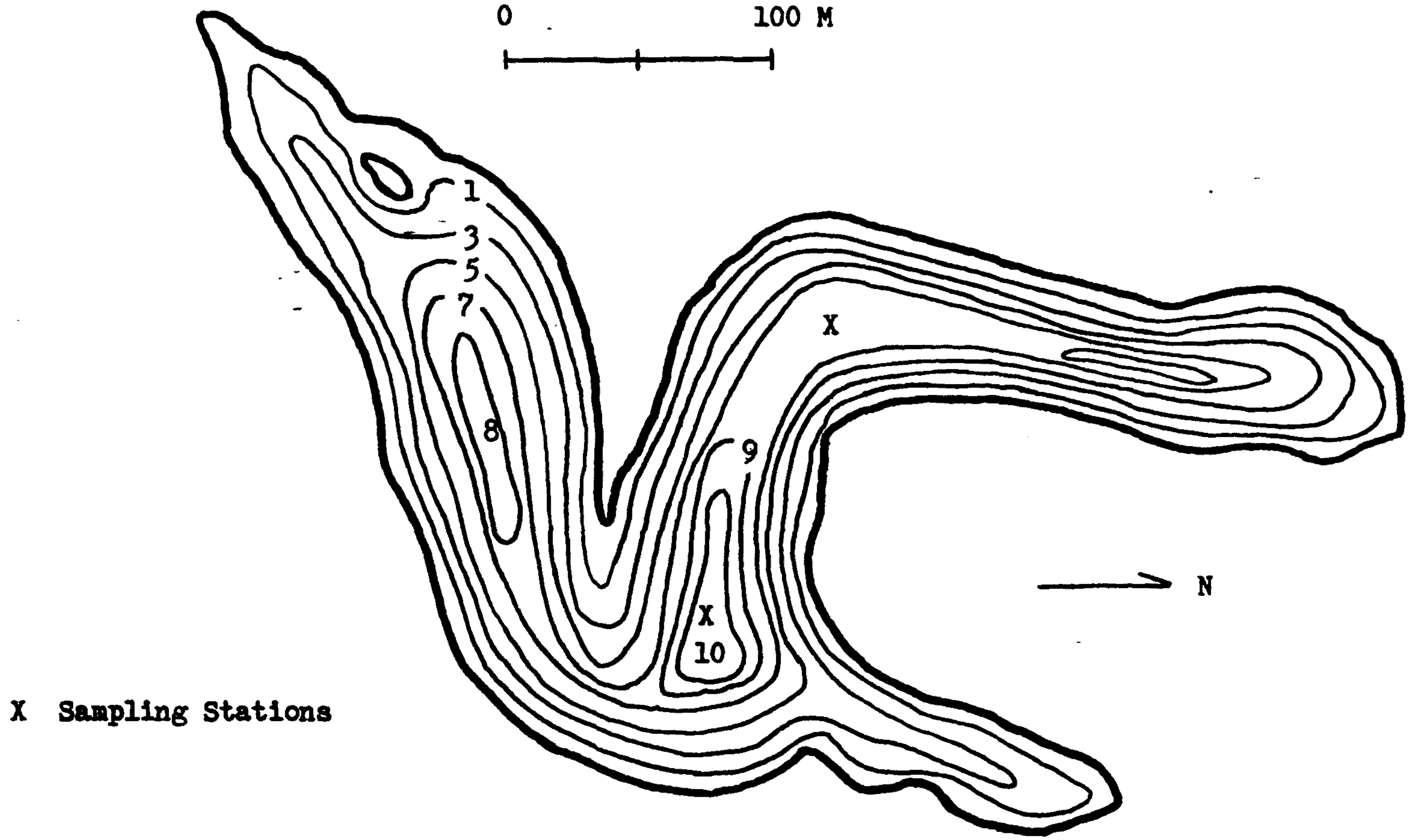


FIG. 4. Bathymetric map of Lake IV (depths in m).

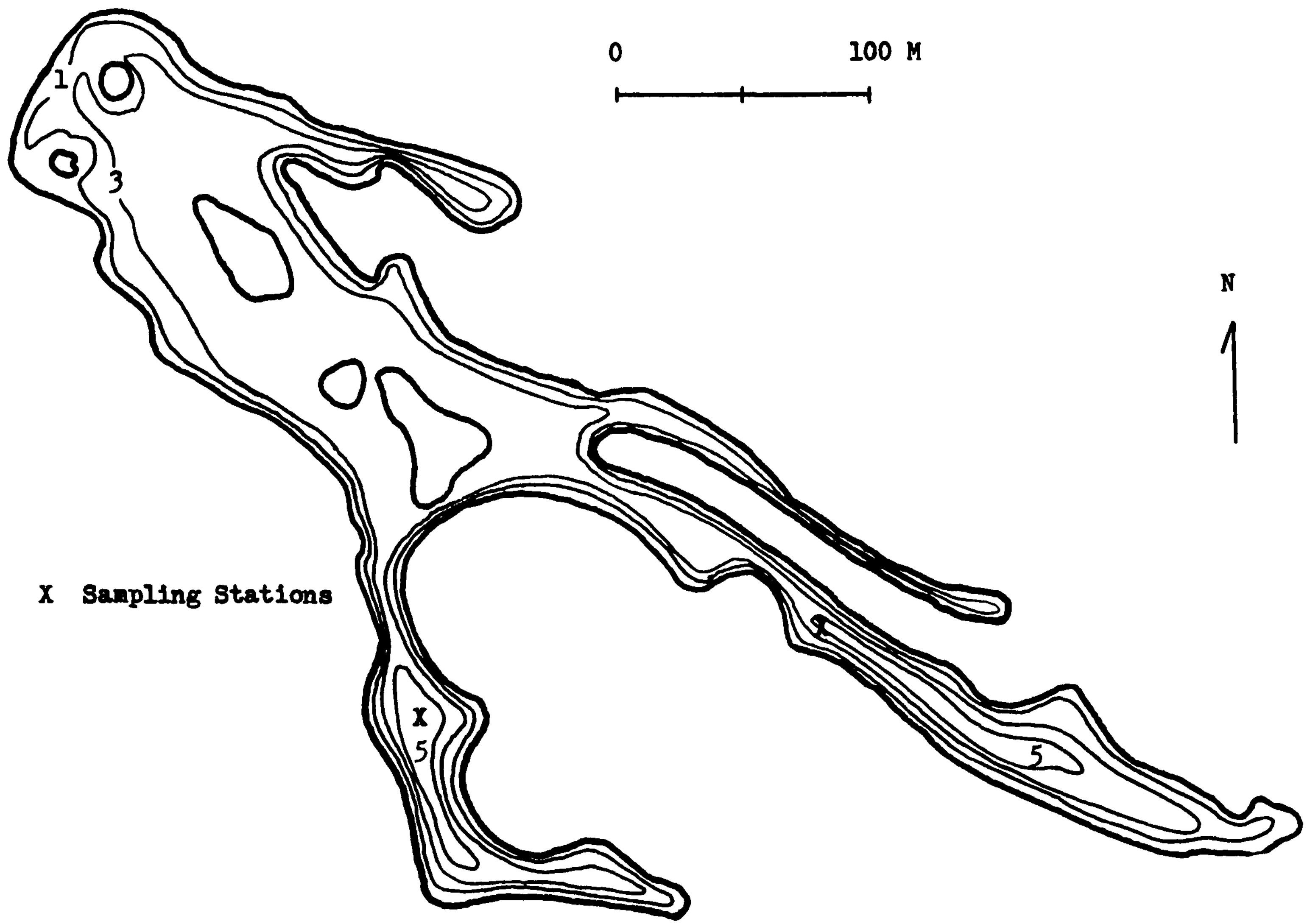


FIG. 5. Bathymetric map of Lake V (depths in m).

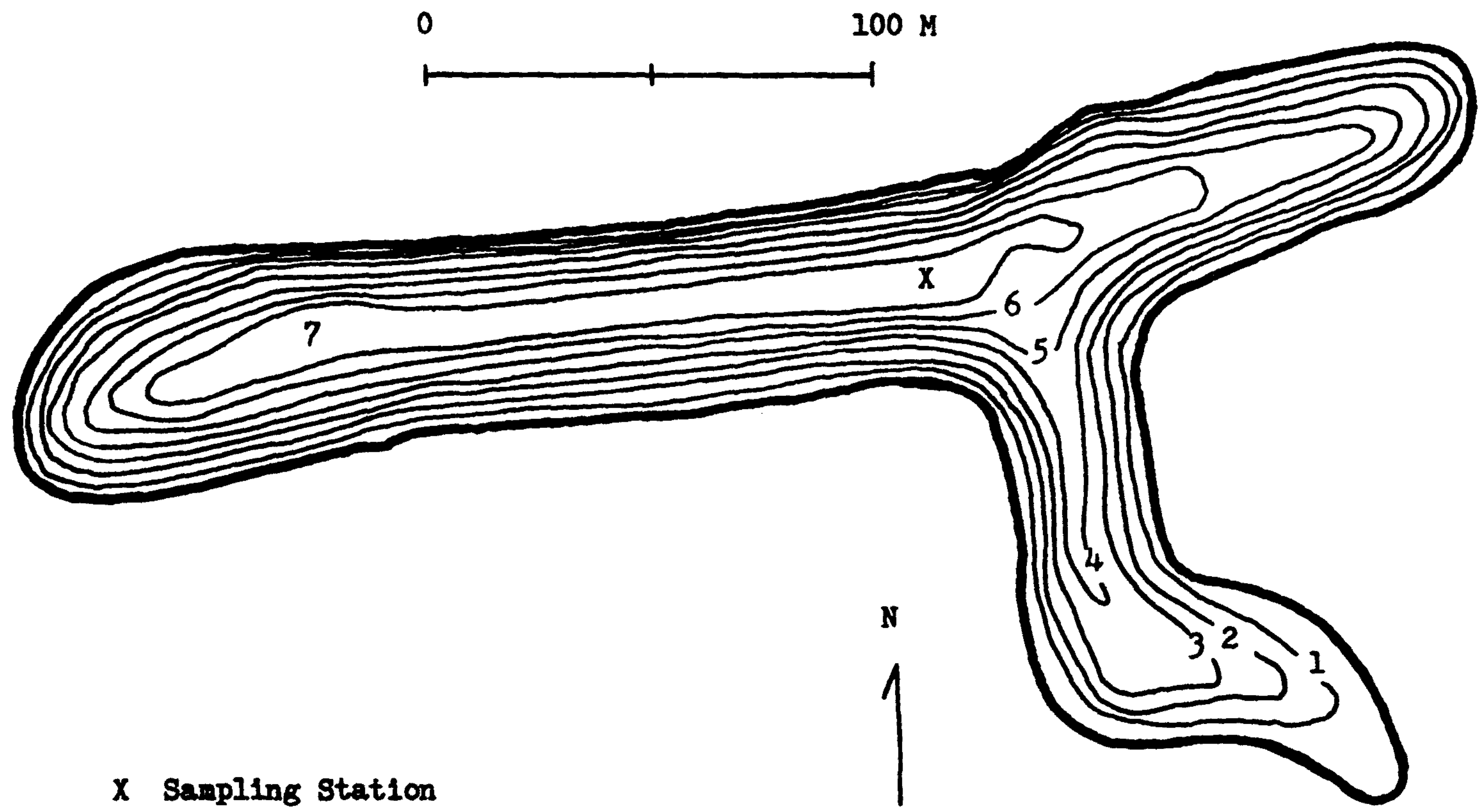


FIG. 6. Bathymetric map of Lake VI (depths in m).

SECTION V

METHODS

Standard procedures and equipment have been used in this study whenever they were available and applicable. The selection and execution of methods was guided by the publications of the American Public Health Association (1965), Golterman (1969), Lagler (1956), Ricker (1968), Vollenweider (1969), and Welch (1948). The specific instruments and techniques used are briefly noted below.

A. Lake morphometry

Bathymetric maps of the study lakes were constructed as follows:

a. An outline map of each lake was prepared from aerial photographs and U.S. Geological Survey topographic maps.

b. Each lake was then measured in situ with a 250 m cord graduated in 5-meter intervals plus the workboat with 1-meter graduations marked on the starboard gunwale. For each lake the total length and the width at several places (widest, narrowest, several intermediates) were measured.

c. Final outlines were drawn to scale based on the field measurements.

d. Depth contours were added based in each case on at least 100 soundings.

e. Total areas and the areas within each contour interval were determined by the Cross-section Paper method (Welch 1948).

f. Other data (mean depth, mean width, volume) were calculated from the area data according to methods given by Welch (1948).

B. Sampling program

1. Schedule. Initially an effort was made to visit each lake at two-week intervals. This proved impractical, mainly because of the time required to process the resultant biological collections. Hence with the addition of Lakes I and VI to the series, the schedule was revised to one of three-to four-week sampling intervals. Weather occasionally interfered with sampling, especially when ice cover was too thick to break through with the boat but too thin to walk and work on with safety.

2. Stations. During the first six months of the study (July to December 1969) horizontal variation in environmental parameters and plankton was monitored by studying two to four stations in each lake. The magnitude of horizontal variation encountered was quite small in all cases. It was, therefore, judged profitable to extend the overall range of the lake series by adding Lakes I and VI at the expense of the multiple

stations. Throughout 1970 a single station in the deepest area of each lake was sampled (exclusive of benthos grab samples and various other kinds of biological collections).

C. Physical and chemical parameters

1. Water samples were collected with two types of non-metallic water samplers, a 3-liter van Dohrn bottle and (very briefly during the winter of 1970) a 4-liter Kemmerer. The water samples were transported to the laboratory in polyethylene bottles.

2. Water temperature was measured in situ by means of a Whitney Underwater Thermometer (thermistor type), Model TC-5A.

3. Light penetration was measured in situ with a Whitney Underwater Light Meter.

4. Turbidity was measured in the laboratory with a Hellige turbidimeter.

5. pH was measured in the laboratory with a Beckman Model N pH meter on water samples adjusted to 25 C in a water bath.

6. Specific conductance was measured at 25 C by means of a conductivity bridge manufactured by Industrial Instruments, Inc. (Model RC).

7. Dissolved oxygen was determined in the laboratory on samples fixed in the field. The iodine-difference procedure of Ohle (1953) was used, because it compensates well for all inorganic oxidizing and reducing substances present. Two dissolved oxygen meters (Yellow Springs Instruments, Models 51 and 54 RC) gave such erratic and patently false results in the stripmine lakes that their use was impossible.

8. Ionic determinations were made professionally by Calgon Corporation of Pittsburgh, Pennsylvania. Ions monitored were calcium, magnesium, sodium, potassium, total iron, dissolved iron, manganese, aluminum, chloride, sulfate, silica, nitrate, and total phosphate. In addition, total acidity, free mineral acidity, hardness, and dissolved solids were determined. Ions were monitored for the surface and bottom strata on a schedule of approximately two-month sampling intervals (see Appendix 2 for details).

D. Biological parameters

1. Plankton was collected in three different ways: (a) by means of a Wisconsin style tow net, (b) with a 10-liter plexiglass plankton trap of the sort designed by Schindler (1969), and (c) by centrifugation of 1-liter water samples in a Foerst centrifuge. Both the tow net and the bucket of the trap were made of number-20 bolting silk. All plankton samples were preserved with acid Lugol's solution (Edmondson 1959)

immediately upon collection, except when live collections were required to facilitate identification. Both trap and centrifuge samples were taken at 1-meter intervals throughout the water column. Depending on the density of organisms, either the entire sample or appropriate aliquots were counted microscopically.

2. Benthos was collected quantitatively with a Ponar Grab Sampler. Samples were taken from all areas of each lake, and initially, at all depths. Early experience indicated, however, that samples taken from the deepest parts of Lakes III, IV, and V never contained organisms. Therefore, later sampling was conducted mainly in the shallower areas of these lakes (where the bottom was within the mixolimnion). An effort was made to sample each 1-meter depth interval proportionately to its percentage of total bottom area.

Each collection consisted of ten samples (grabs), which was about the maximum that could be processed carefully within a reasonable period of time. Including initial rough sorting, specific sorting, counting, drying, weighing, and recording, a minimum mean processing time of two hours per sample (not including time spent in taxonomic identification) was required to reach the stage of raw data. Thus the 670 samples processed required about 1350 hours. Additional time could have been devoted to the bottom fauna only at the expense of other aspects of the study.

The ponar sampled an area of 0.05 m^2 and collected approximately 10 kilograms (clay) or a bit less (leaves or loose detritus) of bottom materials per grab. The samples were placed individually in 20-liter plastic buckets for transport to the laboratory. Ordinarily, initial processing was completed within 24 hours of collection. Each sample was washed through a graded series of three large (35 x 48 cm) screens of mesh sizes: 121.0 mm^2, 1.0 mm^2, and 0.25 mm^2. Organisms were picked from the sorting screens and preserved in formalin. Subsequently, each species was counted and weighed (constant weight at 105 C). In addition, qualitative surveys of the bottom fauna were conducted at irregular intervals with dip nets and artificial substrate samplers of the condenser type (Hester and Dendy 1962).

3. Fish were collected with funnel traps constructed of hardware cloth (12 x 12 mm mesh) and by means of seining in shallow water. Specimens kept for analyses were preserved in formalin. Vertebrates other than fish (frogs, snakes, muskrats, and beavers) were not studied specifically.

4. Taxonomic identification. In any study such as this, in which one attempts to deal with all major ecological categories, the broad taxonomic spectrum dealt with makes the identification of organisms one of the more difficult and time-consuming tasks. Some taxa are relatively straightforward, while others are virtually impossible for the nonspecialist. In many aquatic groups, the immature stages are not sufficiently well known to allow identification to specific level.

Although the compilation of exhaustive species lists was not a major objective of this work, as many taxa as possible have been identified or at least recognized. The following works have been useful in this regard: Ahlstrom (1940, 1943), Burt and Grossenheider (1964), Chu (1949), Eddy (1957), Edmondson (1959), Fassett (1966), Hotchkiss (1967), Jahn and Jahn (1949), Muenscher (1944), Needham and Needham (1962), Needham and Westfall (1955), Nelson and Gerking (1968), Pennak (1953), Prescott (1964), Smith (1950), and Usinger (1963).

5. Morphometric correction. The following method was adopted as the most straightforward approach to compensating for morphometric differences between the study lakes. For each category of organisms (zooplankton and benthos) dealt with, in each lake, the data were treated by 1-meter depth intervals. The mean standing crop for each depth interval was then multiplied by the percentage of the lake (percent area for benthos and percent volume for zooplankton) at that depth. The sums of these percent-weighted means are reported in Tables 5, 6, 14, 17, and 18.

E. Experimental studies

1. Allocthonous organic matter entering the lakes in the form of dead leaves was studied. Newly fallen leaves of the following four types were collected in the autumn of 1969 from the shores of the study lakes: River Birch (*Betula nigra*), Sycamore (*Platanus occidentalis*), Cottonwood (*Populus deltoides*), and a mixture of the less common kinds of leaves including Black Locust, Willow, Pines, Maples, etc. In each group the leaves were thoroughly mixed, dried to constant weight at 105 C, and bagged in nylon mesh bags at 25 grams per bag. The bags were sewn shut, and pieces of color-coded plastic tape were attached to facilitate identification upon recovery. These bags were placed in the lakes in Decmeber 1969 with the intention of recovering them after 1 to 1.5 years to obtain information concerning the relative decomposition rates in different lakes and of different kinds of leaves. These leaf bags were apparently regarded by the resident aquatic mammals as either food sources or hostile objects because during the first 6-8 months the bags in four of the lakes disappeared without a trace. Only in Lake VI was there evidence of human interference with the experimental installations of various sorts (rifle slugs in the fish trap floats, artificial substrate samplers on the beach, etc.).

In conjunction with this work, an effort was made to estimate the amount of annual input of leaves into each lake. Several trays of hardware cloth (0.5 m^2 area) were placed in each lake in early autumn of 1970 in representative locations with respect to bank vegetation, prevailing winds, etc. Together with their collections of fallen leaves they were to have been recovered after completion of the autumn leaf fall. Unfortunately, the rate of deterioration of galvanized metal in acid mine lakes was badly misjudged, so that when the time came to recover the trays (late November and early December 1970) those in Lakes I, II, and III were found to have been almost completely eaten away. It proved impossible to distinguish with any certainty between newly fallen leaves and those from previous years. Hence the quadrat method could not be used. Thus the attempt to study the relative importance of allochthonous food sources came to naught.

2. Primary productivity was studied *in situ* by means of the light-and-dark-bottle technique. Anomalous results such as an increase of oxygen in the dark bottle, or remarkable increases or decreases in both bottles, gave little confidence in the results. Quite likely, these anomalies resulted from chemical oxygen demand and the activities of chemosynthetic bacteria.

SECTION VI

RESULTS AND DISCUSSION

The primary aim of this section is to analyze those trends in the study lakes that seem to be associated with increasing pH. Such trends would be expected in both the biotic and abiotic components of the ecosystems. During the course of the study, however, it became apparent that a second pattern, in addition to increasing pH, was present in the six lakes. This was the persistent chemical stratification or meromixis of Lakes III, IV, V, and VI. This pattern is clearly reflected in the diagrams of annual variation in temperature and conductivity (Appendix 1) and in the differences between the surface and bottom waters in many physical and chemical parameters (Tables 2 and 3). The temperature and conductivity diagrams indicate that each of the meromictic lakes is behaving as two separate lakes: an upper one that overturns twice annually and a lower one that does not. This condition is substantiated by a complete lack of overlap in the observed ranges of conductivity, and of calcium, and other ions in the surface vs. bottom waters of Lakes III through VI.

The influence of meromixis on the ecosystems of these lakes seems quite marked in Lakes III, IV, and V, but less so in Lake VI. It affects the distribution of heat, turbidity, and dissolved substances, and the penetration of light. These, in turn, have a profound influence on the biological communities of the lakes. The overall impact is such that meromixis is probably as responsible as pH for the differences observed between the six ecosystems.

In the following discussion the ecosystem of each lake in turn is briefly described. The emphasis in these descriptions has been placed on annual cycles, the details of which may be found in the time depth diagrams of Appendix 1. This is followed by a discussion of those trends in the ecosystem series that seem attributable to the pH spectrum or to the influence of meromixis. The pertinent data for this discussion are presented in Tables 2 through 7.

A. Patterns within the lakes

Lake I was quite acid throughout the period of study, varying in surface pH from 2.5 to 3.2 with 2.8-2.9 typical. The greatest vertical variation in pH observed in any of the lakes occurred in Lake I in March 1970 when a surface-to-bottom difference of two pH units (3.2-5.2) was noted (Fig. 24). Thermal stratification persisted throughout 1970 except for periods of near homothermy in mid-August and from late September to mid-October (Fig. 30). The integrity of stratification was maintained through the warming period, indicating that the entire water mass was heated by direct insolation. A maximum temperature difference of 10.2 C (surface-to-bottom) was observed in mid-May 1970. Dissolved oxygen (Fig. 36) was generally low, extremely so during July and August 1970 when the concentration was less than 1.0 mg/l throughout the water column. This period

TABLE 2. Observed ranges of selected chemical and physical parameters in surface (S) and bottom (B) waters.

Parameter		Lake I	II	III	IV	V	VI	Control
pH	S	2.5 - 3.2	3.0 - 3.4	3.6 - 6.4	4.5 - 7.6	6.1 - 8.2	7.4 - 8.2	7.2 - 7.7
	B	2.8 - 5.2	3.0 - 3.4	4.0 - 6.4	5.9 - 6.5	6.3 - 7.0	6.6 - 7.2	6.9 - 7.1
Temperature (°C)	S	1.4 -28.7	1.0 -31.7	5.6 -33.8	4.0 -29.9	0.8 -31.2	0.5 -28.9	7.0 -28.0
	B	1.5 -24.3	6.3 -28.5	12.6 -14.4	9.7 -11.6	9.2 -14.7	9.0 -17.2	6.6 -10.1
Dissolved oxygen (mg/l) *	S	0.2 - 4.9 (7.1)	2.8 - 9.1 (10.4)	3.9 - 9.9 (9.9)	6.2 -11.3 (12.7)	7.0 -14.6 (25.7)	7.2 -11.8 (16.8)	8.3 -11.8
	B	0.0 - 0.4	0.0 - 8.9	0.0	0.0	0.0	0.0 -11.6	0.0 -10.2
Total dissolved solids (mg/l)	S	3615-4395	2515-2745	965-1910	1140-2840	1545-2660	1200-1570	90- 95
	B	4695-5495	2570-3060	4745-5610	3290-5015	3015-3435	1830-2751	100-135

* Numbers in parentheses indicate overall oxygen maximum

TABLE 2. Continued

Parameter		Lake I	II	III	IV	V	VI	Control
Specific conductance ($K_{25} \cdot 10^6$)	S	1868-4350	2273-2778	1042-1887	781-2778	1786-2500	1250-1667	132- 145
	B	4000-4350	2273-2857	2128-4651	2941-4167	2850-3636	1786-2778	156- 213
Turbidity ($mg/l\ SiO_2$)	S	2.3 - 7.6	0.3 - 5.0	0.8 -12.0	0.8 - 7.7	1.7 -15.0	0.7 - 8.9	2.9 - 9.3
	B	12.2-60.0	0.7 - 6.9	8.6 -69.0	9.2 -20.0	4.3 -55.0	1.0 -11.0	26.0-47.0
1 percent light (m)		2.5 - 3.0+	6.0+	1.5 - 7.0	2.0 - 7.5	1.0 - 3.0	5.5 - 7.0+	2.5 - 4.0

TABLE 3. Means and standard errors of surface (S) and bottom (B) concentrations of selected ions based on six determinations (see Appendix 2).

		Lake						
Ion		I	II	III	IV	V	VI	Control
Ca^{++}	S	425.7±23.0	334.0± 9.3	172.7±15.0	273.8±37.4	299.3±19.1	163.3± 5.4	12.0± 1.0
	B	434.3±12.4	340.7±10.6	481.7± 6.5	443.0±10.1	405.3±12.2	298.7±16.4	17.0± 4.0
Mg^{++}	S	314.0±16.3	183.2± 5.1	128.3±13.0	170.5±22.8	192.3±22.2	120.7±19.1	6.50±0.71
	B	408.0±32.0	195.5± 9.7	501.2±16.2	339.2±16.8	325.0±12.6	213.0±13.3	7.00±3.00
Fe^{d}	S	81.7± 7.9	4.75 ±1.05	5.68 ±2.18	1.09 ± 0.60	0.68 ±0.31	0.14 ±0.09	0.40±0.32
	B	180.2±28.1	5.68 ±0.94	181.8±27.8	209.2±53.9	48.4 ± 8.5	1.71 ±0.74	9.25±8.25
Mn^{++}	S	50.5 ± 2.3	33.6 ± 0.6	8.78 ±0.69	5.68 ±1.04	3.73 ±1.46	0.14 ±0.08	0.28±0.03
	B	61.3 ± 0.8	33.9 ± 1.0	31.1 ± 0.7	23.9 ± 1.9	20.5 ± 2.3	8.70 ±4.04	4.10±3.90
Al^{d}	S	35.8 ± 5.6	12.9 ± 1.2	0.48 ±0.23	0.50 ±0.39	0.095±0.103	0.083±0.098	0.037±0.042
	B	32.0 ± 8.0	12.6 ± 1.3	0.54 ±0.24	0.12 ±0.17	0.10 ±0.10	0.037±0.045	1.26±0.72

d = dissolved

TABLE 3. Continued

Ion		Lake I	II	III	IV	V	VI	Control
Na^+	S	15.0 ± 1.0	44.0 ± 1.1	21.2 ± 1.5	28.0 ± 2.7	15.5 ± 1.5	48.8 ± 2.6	5.05±0.55
	B	20.7 ± 0.7	45.2 ± 1.8	36.0 ± 1.6	40.3 ± 2.2	20.5 ± 1.3	67.7 ± 2.5	5.00±0.60
K^+	S	4.65 ±0.24	5.32 ±0.15	3.90 ±0.32	4.33 ±0.35	3.88 ±0.19	4.45 ±0.16	1.70±0.50
	B	6.67 ±0.41	5.32 ±0.15	15.7 ± 3.2	15.9 ± 5.4	5.33 ±0.24	6.62 ±0.45	2.30±0.50
Zn^d	S	2.87±0.14	0.83±0.01	0.20±0.01	0.13 ±0.04	0.075±0.045	0.041±0.014	0.025±0.019
	B	2.68±0.40	0.91 ±0.01	0.33±0.06	0.083±0.016	0.060±0.015	0.050±0.012	0.025±0.019
T.H.	S	2726 ± 103	1702 ± 27	987 ± 89	1397 ± 178	1544 ± 117	912 ± 35	55.0±5.0
	B	3315 ± 166	1773 ± 65	3651 ± 69	2924 ± 159	2467 ± 65	1656 ± 35	117.5±17.5
SO_4	S	2928 ± 150	1671 ± 47	873 ± 94	1246 ± 193	1396 ± 137	798 ± 64	32.5± 2.6
	B	3408 ± 55	1775 ± 83	3221 ± 79	2365 ± 109	1996 ± 105	1267 ± 101	15.0±10.0
Cl^-	S	10.0 ± 6.1	4.67 ±1.16	17.2 ± 0.9	21.8 ± 0.1	4.67 ±0.52	3.33±0.45	2.50±1.50
	B	11.3 ± 6.0	4.67 ±1.16	9.50 ±0.76	21.7 ± 5.4	4.25 ±1.08	4.33 ±0.75	2.75±2.25

T.H. = Total hardness, the sum of Ca, Mg, Fe, Mn, Al, and Zn as $CaCO_3$.

TABLE 3. Continued

Ion		Lake I	II	III	IV	V	VI	Control
SiO_2	S	43.2 ± 2.8	27.0 ± 1.2	11.2 ± 0.6	8.17 ±0.16	10.2 ±0.70	1.88 ±0.15	5.50±2.46
	B	44.0 ± 2.2	27.0 ± 1.0	15.0 ± 1.9	14.0 ± 3.1	15.8 ± 1.1	5.95 ±0.83	7.00±0.89

TABLE 4. Known animal taxa of the Pike County lakes.

Taxon	Lake I	II	III	IV	V	VI
CILIOPHORA						
Euplotes sp.		x	x	x	x	x
PLATYHELMINTHES						
Turbellarian					x	
ROTIFERA						
Brachionus urceolaris	x	x	x	x	x	x
Keratella quadrata	x	x	x	x	x	x
Monostyla sp.	x	x	x	x	x	x
Keratella cochlearis		x	x	x	x	x
Testudinella patina		x	x	x	x	x
Filinia sp.			x	x	x	x
Hexarthra sp.			x	x	x	x
Unidentified rotifer 1			x	x	x	x
Unidentified rotifer 2			x		x	x
Chromogaster sp.			x	x		
Lecane sp.				x	x	
Brachionus angularis				x	x	x
Unidentified rotifer 3				x		
Unidentified rotifer 4				x		
Brachionus caudatus					x	x
B. calyciflorus					x	
Filinia longiseta					x	x
Asplanchna sp.					x	
Polyarthra sp.						x
Unidentified rotifer 5						x
Brachionus quadridentatus						x
ANNELIDA						
Oligochaeta			x	x		x
Hirudinea						x
CRUSTACEA						
Cyclops sp.			x	x	x	x
Calanoids			x	x		x

TABLE 4. Continued

Taxon	Lake I	II	III	IV	V	VI
Daphnia spp.	x		x	x	x	x
Ceriodaphnia sp.	x		x	x	x	x
Bosmina longirostris						x
Ostracods				x		x
Cambarus (?) sp.				x	x	x
INSECTA						
Collembola			x			
Ephemerid						x
Pantala flavescens	x					
Anax amazili		x				
Tramea lacerata		x			x	
Celithemis elisa			x	x	x	x
Libellula sp.			x	x	x	x
Gomphus consanguis			x	x	x	x
Epicordulia princeps				x		x
Erythemis sp.				x	x	
Platythemis subornata				x		
Gomphus spicatus					x	
Ladona deplanata					x	
Tetragoneuria sp.					x	
Libellula pulchella					x	x
Unidentified zygopteran		x				
Ischnura sp.			x	x		
Argia sp.			x	x	x	x
Enallagma sp.					x	x
Sigara (?) sp.	x	x	x	x	x	x
Gerrid						x
Sialis sp.		x	x	x	x	x
Unidentified trichopteran 1		x		x		x
Unidentified trichopteran 2				x		x
Unidentified trichopteran 3					x	x
Berosus sp.	x	x	x	x		
Dinetus sp.	x	x				
Peltodytes sp.		x	x	x	x	x
Laccophilus sp.		x				

TABLE 4. Continued

Taxon	Lake I	II	III	IV	V	VI
Ilybius sp.		x				
Gyrinus sp.		x				
Haliplus sp.				x		
Heleidae	x	x	x	x	x	x
Tendipes sp.	x	x	x	x	x	x
Chironomid spp.				x	x	x
Unidentified dipteran		x				
Chaoborus sp.		x	x	x	x	x
Unidentified tipulid			x	x	x	x
MOLLUSCA						
Physa sp.			x	x	x	x
Lymnaea sp.					x	
Helisoma sp.						x
Sphaerium sp.						x
VERTEBRATA						
Lepomis cyanellus			x	x	x	x
L. macrochirus				x	x	x
Chaenobryttus coronarius				x		x
Micropterus salmoides				x	x	x
Minytrema melanops				x		
Micropterus punctulatus					x	
Fundulus notatus						x
Ondatra zibethica	x	x		x	x	
Castor canadensis				x	x	
Total known taxa	12	23	32	49	49	53

TABLE 5. Mean percent volume-weighted standing crop of zooplankton organisms (individuals/m^3).

Taxon	Lake I	II	III	IV	V	VI
Rotifera	8,330	531,140	3,950	19,490	2,016,580	173,110
Cladocera	54	0	1	23	52	12,530
Copepoda	0	0	1,365	3,564	41,590	13,872
Euplotes	0	670	2,445	5,300	104,150	90
Total *	8,384	531,810	7,761	28,377	2,162,372	199,602
Percent of Lake V	0.4	24.6	0.4	1.3	100	9.2
Number of samples	40	112	147	158	90	80
Vertical series	10	17	16	14	15	10

*It is assumed for the purpose of rough comparisons that differential size is approximately compensated by a higher reproductive rate of the smaller organisms.

TABLE 6. Mean percent area-weighted standing crop of benthic organisms (mg dry weight/m^2).

	Lake I	II	III	IV	V	VI
Herbivores	551	1,373	54	74	37	508
Predators	22	43	12	21	183	255
Total	573	1,416	66	95	220	763
Percent of Lake II	40.5	100	4.7	6.7	15.5	53.9
Percent predators	3.8	2.9	18.2	22.1	83.2	33.4
Number of samples	40	120	140	130	130	110

TABLE 7. Standing crop of fish biomass.

	Lake			
	III	IV	V	VI
Total trap hours	528	498	738	180
Specimens taken	7	23	12	42
Trap-hours/specimen	75.4	21.6	61.5	4.3
Live weight (g)	848.6	1,346.4	711.6	1,399.7
g/trap-hour	1.61	2.70	0.95	7.78
$\bar{x}$ weight (g/specimen)	121.0	58.5	59.5	33.0

of extremely low oxygen was associated with high water temperature and partial overturn -- a combination that almost certainly produced a high chemical oxygen demand by upwelling of reduced solutes from the deeper anaerobic strata. The highest observed concentration of dissolved oxygen was 7.2 mg/l at a depth of 1.0 m under a 15-cm ice cover in late January 1970. This was only about 55 percent saturation at the *in situ* temperature of 3.3 C. Despite relatively high turbidity, light was probably adequate for photosynthesis throughout this shallow lake at most times. During much of 1970 light reaching the bottom equaled or exceeded 1 percent of surface illumination.

In general, the dissolved substances as indicated by total dissolved solids and conductivity (Table 2) and many individual ions (Table 3) were high in Lake I. The surface water in particular had a much greater load of solutes than the other mine lakes. This was not universally true, however, since some ions (e.g., Na^+, K^+, and Cl^-) were higher in some of the other lakes. The deep water of Lakes III and IV exceeded those of Lake I in concentrations of the major cations and, in Lake III, in total solutes.

Although it might be argued that Lake I is meromictic, it exhibited virtual surface-to-bottom uniformity of water quality (pH 2.8-2.8, temperature 20.6-20.1 C, conductivity 4350-4350 µmhos) on 29 September 1970. This lack of vertical stratification and the presence of dissolved oxygen in relatively deep water (0.4 mg/l at 2.5 m) suggests that autumnal overturn was complete although of short duration, as indicated by the stratification of physical and chemical parameters on the preceding and following sampling occasions (8 September, 14 October). On the latter date, the beginning of inverse thermal stratification was observed (surface 7.9, bottom 9.5 C). Thus Lake I is probably best regarded as having a marked tendency toward meromixis that is imperfectly realized because of its relatively shallow unprotected basin.

The biological communities of Lake I were marked by very low faunal diversity (Table 4). In the zooplankton, for example, only five taxa were recognized compared to 20 and 21 species, respectively, in Lakes V and VI. A total of 12 animal taxa were found in Lake I. Standing crop of zooplankton (Table 5) was low, Lake I ranking fifth and only slightly exceeding Lake III. In total benthic biomass, however, Lake I ranked third, with markedly greater standing crop biomass than III, IV, and V (Table 6). In both zooplankton and benthos a single species dominated. These were the rotifer Brachionus urceolaris and the midge larva Tendipes sp. which made up, respectively, about 99 percent and 85 percent of total biomass. Fish were not present in Lake I. Muskrats maintained a lodge in a stand of cattails (Typha angustifolia) at the northern end of the lake. Other aquatic vertebrates (amphibians, reptiles) were never observed, even though several species were common around the shores of Lake V a scant hundred meters distant.

Lake II differed in several ways from the other mine lakes. It was marked by relatively great uniformity of physics and chemistry both over the annual cycle and throughout the water mass. Total pH variation during the 18-month study period was 3.0 to 3.4 (Fig. 25). A weak stratification of pH (never exceeding a surface-to-bottom difference of 0.3) sometimes developed during periods of thermal stratification. Although this lake differed little from Lake I in surface pH, it was quite different from Lake I in various limnological and biological features. Many of these differences were at least partly related to stratification differences.

The thermal regime of Lake II (Fig. 31) was marked by long periods of homothermy and relatively small temperature differences during stratification (the only observations of surface-to-bottom differences greater than 5.0 C were on 3 May and 21 May 1970). The maximum observed dissolved oxygen was 10.5 mg/l (at 1.0 m under 21 cm ice in late January 1970), which, at 3.2 C, constituted approximately 80 percent saturation (Fig. 37). In midsummer dissolved oxygen values were quite low throughout the water mass (3.5 mg/l or less in July and August 1969 and again in August 1970). Thus Lake II shared with Lake I the combination of low pH, high water temperatures, and low dissolved oxygen throughout the water mass in midsummer. This environmental combination is probably strongly limiting to many species of aquatic organisms. Lake II had greater transparency than the others. Light at the bottom (6.0 m) was never less than 1 percent of surface illumination and frequently exceeded 10 percent.

The surface and bottom ranges for total dissolved solids and for conductivity were more similar than in the other lakes (Table 2). The surface concentrations of total dissolved solids and of most ions in Lake II ranked second to Lake I. In deep water, however, concentration values were exceeded by Lakes III, IV, and V and closely approached by Lake VI.

Although little different in pH, Lake II had almost twice as many animal taxa (23) as Lake I (a 92 percent increase). This increase was most striking for the insects, with 11 taxa added and but one lost. It seems likely that this greater faunal diversity is related to the lower concentrations of solutes in Lake II.

Zooplankton standing crop was high, second only to Lake V. As in Lake I, most of this biomass (over 98 percent) was due to *Brachionus urceolaris*. Lake II had the greatest standing crop of benthos, nearly twice that of second-ranked Lake VI, of which about 84 percent was *Tendipes* sp. larvae. As in Lake I, over 95 percent of the total benthic standing crop consisted of herbivores. There were no fish in Lake II even though local fishermen reported having "stocked" it with their surplus catches from time to time. Because of its clear green water, Lake II was popular locally for swimming and water skiing until the area was closed for re-mining in January 1971.

Lake III had the most complex pattern of pH variation (Fig. 26) of the six mine lakes studied. The water mass near the outlet was consistently 0.2 to 1.0 pH units lower than that near the inlet. This was the only regular horizontal difference discovered in any of the lakes. Lake III had a greater rate of flow-through than any other, and the higher "downstream" acidity was probably due to the leaching of acid-forming materials from a coal seam, mainly underwater, exposed in the old high-wall. An acid heterograde pH curve with the minimum at intermediate depth (Hutchinson 1957) was typical from July 1969 to August 1970. This type of pH curve is usually associated with meromixis. Lake III had a fairly well-marked trend toward higher pH during 1970, with no values less than 4.5 observed after April.

The pattern of temperature variation (Fig. 32) indicates the meromictic nature of Lake III very clearly. The high surface reading of 33.8 C in late May 1970 was the highest temperature measured in any of the lakes during the study. Temperature variation at the bottom encompassed the very small overall difference of 1.8 C, and the maxima and the minima lagged two to three months behind those at the surface. Dissolved oxygen was restricted to the uppermost 2 m during July and August 1969, leaving about two thirds of the water mass anaerobic (Fig. 38). This was repeated in slightly less extreme form in the summer of 1970. Even during such extreme midsummer conditions, in contrast to Lakes I and II, oxygen at the surface rarely fell below 4.0 mg/l. The highest observed concentration was 9.9 mg/l under about 2 cm ice in late December 1970 (about 87 percent saturation at 8.4 C). The deepest observed penetration of dissolved oxygen was 6.0 m during the periods of partial overturn in spring and autumn.

Turbidity values (Table 2) were generally higher in Lake III than in the other lakes, especially in deep water. This was mainly due to the precipitation of dissolved substances (as hydroxides of iron, etc.) at the interface between oxygenated and anaerobic strata. Usually, the turbidity maximum occurred at the level of this interface. During the partial overturns of spring and autumn, the surface water was colored a dark red-brown by the precipitates that resulted from an upwelling of anaerobic water with its heavy load of reduced solutes. The depth of the 1 percent level of light penetration typically approximated the depth of the oxygen interface. Thus the depth of the 1 percent level was typically 2.0-4.0 m in summer and 4.5-6.0 m in winter. A marked decrease in turbidity in May 1970 was accompanied by increased light penetration to a 1 percent level of 7.0 m. This greater transparency was maintained, except for periods of turbidity from clay particles washed in by heavy rains throughout the remainder of 1970.

The contrast between the surface and bottom concentrations of solutes in Lake III was extreme (Tables 2 and 3). Its deep water had the highest conductivity and the greatest mean concentrations of total dissolved solids, calcium, magnesium, and total hardness of all the lakes studied. The surface water, however, had the lowest observed concentration of total solids (965 mg/l in March 1970) and ranked fifth in mean total dissolved solids, calcium, magnesium, sulfate, and total hardness (exceeding but slightly the surface values of Lake VI).

Faunal diversity (Table 4) was greater in Lake III than in Lake II with nine more taxa (about a 39 percent increase) recognized. In Lake II the zooplankton and benthos were quite unequal, contributing respectively 26 percent and 70 percent of the known taxa. In Lake III, however, the two groups were nearly equal with benthos constituting 47 percent and zooplankton 50 percent. This sharp reduction in relative diversity of the benthos probably resulted from the anaerobic bottom conditions and very steep-sided basin shape of Lake III. Some major groups, including Mollusca, Annelida, and fish made their first appearance in Lake III.

The standing crop of both zooplankton and benthos was lowest in Lake III. Fish were not observed or trapped in that lake before June 1970. This may have been due to the moderation of pH and other environmental conditions as noted above. Although small (unidentified) fish were observed on two or three occasions, the only specimens taken in over 500 trap hours were seven green sunfish caught on 30 October 1970. It appears likely that colonization of Lake III by the established fish populations of Lake IV will occur if the environment remains moderate.

<u>Lake IV</u> had, with the exception of a single low surface reading (4.5 under ice cover on 26 January 1970), a quite moderate range of pH variation (Fig. 27). Apart from this unusual value, the lowest observed surface pH was 6.35. As in Lake III, the pH minimum (very rarely as low as 5.7) frequently occurred at intermediate depth.

The pattern of temperature variation (Fig. 33) was also quite similar to that in Lake III. Again there was a very slight overall annual variation at the bottom (1.9 C). Such uniformity of temperature in deep water is typical of meromictic lakes, in general, but as in the shallower lakes of this study, this may be modified by depth and transparency. Dissolved oxygen (Fig. 39) was generally greater than in the previous lakes. Even in midsummer surface values were rarely less than about 7.0 mg/l, with oxygen penetration at least 5.0 m. The maximum observed penetration was 5.6 mg/l, at 8.0 m in December 1970. The overall maximum dissolved oxygen observed was 12.7 mg/l at 1.0 m under about 1 cm of ice in December 1969, which at 9.1 C was about 110 percent saturation. The highest surface concentration (11.3 mg/l in December 1970) was about 100 percent saturation. Lake IV was the first in the series in which 100 percent saturation at the surface was usual.

Turbidity was less and transparency slightly greater in Lake IV than in Lake III. Again the 1 percent level of light penetration was often associated with the oxygen interface.

As in Lake III, the ranges of such general indicators of dissolved substances as total dissolved solids, conductivity, and total hardness were non-overlapping for the surface and bottom strata. For most of the major ions, Lake IV ranked fourth in surface concentration but third or even second in bottom concentration. It had the highest mean concentrations of dissolved iron, potassium, and chloride.

Forty-nine animal taxa were recognized in Lake IV (Table 4), an increase of 17 species or 53 percent over Lake III. There was a striking increase in the number of vertebrate species, from one each in Lakes I, II, and III to a peak of seven in Lake IV. Four more plankton species, and seven more benthic species, were found in Lake IV than in Lake III.

Zooplankton biomass (Table 5) was greater in Lake IV than in Lakes I and III but very much less than in the other three lakes. Similarly, the biomass of benthic animals (Table 6) was much less than in Lakes I, II, V, and VI and only slightly greater than in Lake III. Only Lake VI exceeded Lake IV in fish biomass.

Lake V had a range of pH variation nearly encompassing those of Lakes IV and VI. Thus a more distinct series might have been had by omitting Lake V. It has been retained in the series, however, because it is managed for sport fishing (i.e., fertilized in summer) by the Indiana Department of Natural Resources. The other lakes, in contrast, have not been disturbed since their formation except for the construction of launching ramps.

Only a moderate overall range of pH variation (Fig. 28) was observed in Lake V. The maximum vertical variation was found in late July when pH decreased from 8.2 at the surface to 6.3 at 2.0 m, then increased slightly to 6.6 at the bottom. As in Lakes III and IV, a pH minimum at intermediate depth was not unusual.

Although the overall deepwater temperature variation was greater than in Lakes III and IV (Fig. 34), Lake V must also be considered meromictic. Some partial mixing obviously occurred at the times of overturn, but the data for dissolved oxygen and conductivity (Figs. 40

and 46) and for solutes (Tables 2 and 3) indicate rather complete chemical separation of the surface and bottom water masses. Oxygen (Fig. 40) penetrated to the 4.0 m level in March 1970 but never reached the deepest (6.0 m) strata. The maximum surface value observed was 14.6 mg/l in June 1970 (about 190 percent saturation). In September 1969 a maximum concentration of 25.7 mg/l was observed at 2.0 m, about 278 percent saturation. Dissolved oxygen in excess of 20 mg/l was observed at intermediate depths on several other occasions. Surface oxygen was never observed to be less than 7.0 mg/l. In contrast to the previous lakes, the highest dissolved oxygen concentrations in Lake V occurred during the warmest part of the year (April through October), probably because of massive algal blooms that were apparently a response to the fertilization of the lake.

Such blooms and the accompanying large populations of zooplankton were, in part, responsible for the high turbidity and restricted light penetration characteristic of Lake V (Table 2). There was, also, a marked turbidity maximum at the lower limit of dissolved oxygen as in Lakes III and IV. It was usual for the 1 percent level of light penetration to occur within that boundary zone.

Again in Lake V, the general indicators of dissolved substances (total dissolved solids, conductivity, total hardness) had non-overlapping ranges for the surface and bottom water masses (Tables 2 and 3). The dichotomy is less well-marked than in Lakes III and IV, primarily due to higher surface concentrations of major ions (Ca, Mg, SO_4) in Lake V.

Although the total number of animal taxa known in Lake V is the same as in IV (Table 4), there are marked differences in fauna between the two. Of the 15 taxa present in Lake IV but not in Lake V, only one was replaced by a taxon found in one of the previous lakes in the series (an unidentified rotifer species also found in Lake III). Four species of fish were taken in Lake V compared to five each in Lakes IV and VI.

The standing crop of zooplankton in Lake V (Table 5) greatly exceeded that of any other lake. The weighted mean value of more than two million individuals per m^3 indicates a quite impressive level of production. In contrast to plankton, benthic biomass (Table 6) was relatively low in Lake V. Here, again, extensive areas of the bottom are anaerobic throughout most or all of the annual cycle. One curious feature of the benthos in Lake V is the apparent imbalance between the herbivores and the predators. Usually, the generalization is made that each trophic level is exceeded by the previous one upon which it feeds by a factor of about 10. This will be reflected in the biomass unless a marked difference exists in the rate of production. Since there is no very good reason to think that the herbivore and predator benthos in these lakes differ greatly in their rates of productivity (typically one generation annually), the biomass of herbivores is expected to be roughly ten times that of predators. It can, of course, be many times greater. This expectation was reasonably well fulfilled in all the lakes except Lake V, where the predators were about five times greater in biomass than the herbivores. It seems likely that these predators, mainly immature Odonata, feed on the abundant small fish that feed in turn on the heavy crop of plankton and seek shelter in the same beds of dead leaves where the dragonfly naiads are most common. Many small (2-5 cm) specimens of Lepomis and Micropterus were taken in the benthic samples along with the dragonflies.

Fish biomass (Table 7) was quite low in Lake V. No very satisfactory explanation for this has been found. The plankton populations could certainly support very large numbers of small fish adequately. In fact, large samples of immature fish were seined easily in shallow water. It may be that the physical and chemical conditions, especially in summer when oxygen is restricted to the upper 2 m, limit the survival of more mature fish.

Lake VI had relatively little pH variation throughout the annual cycle (Fig. 29). The surface water remained slightly alkaline, and there was no overlap in pH ranges for the surface and bottom water masses (Table 2). Temperature variation (Fig. 35) resembled the pattern found in Lakes III-V, but was less extreme. A relatively wide temperature range (8.6 C) was measured in deep water. Dissolved oxygen (Fig. 41) varied moderately in the surface waters. The deepest stratum (below 6.0 m) was essentially anaerobic from late August to mid-October 1970, but had reasonable oxygen concentrations during most of the remainder of the year. The maximum observed concentration was 16.8 mg/l at 5.0 m in September 1970 (about 205 percent saturation). This high concentration at intermediate depth was due to photosynthetic oxygen production by the dense growth of Potamogeton that carpeted Lake VI at all depths from about 1.0 to 6.0 m in summer and early autumn. The greatest observed open surface concentration was 11.8 mg/l in December 1970 constituting about 110 percent saturation. In general, Lake VI had lower turbidity and greater light penetration than any other except Lake II. Light intensity at the bottom frequently equalled or exceeded 1 percent of surface illumination, except that in late summer and autumn the plant growth mentioned above shaded out the deepest meter or two.

Solute concentrations in Lake VI, especially in deep water, were noticeably less than in the other lakes. This was true for total dissolved solids, conductivity, and most ions (Tables 2 and 3). The observed ranges of surface and bottom concentrations, however, were mostly non-overlapping, indicating rather rigid chemical stratification. Lake VI was meromictic during 1970, but the monimolimnion was essentially limited to the deepest meter. The stability of this stratification was probably much less than in Lakes III-V.

Animal diversity was greatest in Lake VI, although habitat diversity appeared to be no greater than, for example, in Lake IV. Four more taxa were found than in Lakes IV and V. The fauna of Lake VI was reasonably well balanced with 22 taxa of zooplankton, 25 of benthos, and 5 of fish. Beavers and muskrats, which occurred in Lakes IV and V, were never observed in Lake VI.

The standing crop of zooplankton in Lake VI (Table 5) ranked third, about 9 percent of that in Lake V. The weighted mean total of nearly 200,000 individuals per m^3 was much greater than those of Lakes I, III, and IV. In benthic biomass (Table 6), Lake VI ranked second to Lake II. Although the standing crop was only about half as great, benthic production in Lake VI may have actually been even higher assuming fairly heavy predation by its relatively large fish populations. The biomass of fish in Lake VI (Table 7) was about three times that in second-ranked Lake IV. The average weight of individuals caught, however, was markedly less than in Lakes III, IV, and V.

The Control Lake had an observed pH range of 6.9-7.7, within the ranges of both Lakes V and VI. It must be noted, however, that this and the other data for the control (Tables 2 and 3) are based on only two complete series of samples (June and December 1970). In June, the lake was thermally stratified and anaerobic below 4.0 m. In December, it was virtually homothermal (7.0 C at the surface gradually shading to 6.6 at the bottom) with 10.0 mg/l or more dissolved oxygen throughout. This lake probably follows the temperature regime typical of small ponds and lakes in southern Indiana. If so, it circulates twice annually in spring and autumn, with the possibility of prolonged circulation in years of mild winters with no ice cover.

Turbidity (Table 2) was higher in the control lake than in several of the stripmine lakes. This turbidity was partly due to very dense plankton concentrations on both sampling dates. The 1 percent level of light penetration was at 2.5 m in June and 4.0 in December.

The most striking limnological difference between the control and the stripmine lakes was, of course, its very much lower concentrations of dissolved substances (Tables 2 and 3). Even Lake VI exceeded the control by a factor greater than ten in total dissolved solids and conductivity. The control did have, however, higher concentrations of certain ions (notably Fe, Al, and SiO_2) than Lake VI.

Because of the difficulty of access (it was necessary for the landowner to hitch my boat trailer to his tractor and tow it to the lake and back through his pasture) and limitations of time, extensive quantitative sampling of the fauna was not undertaken. No absolute statements about either the diversity or standing crop of animals are possible for the control. A few general statements based on limited sampling and informal observation can be made. There is no reasonable doubt that the diversity of most ecological groups was greater than in any of the stripmine lakes. A rapid survey of the plankton samples taken in June and December revealed not fewer than 25 taxa of zooplankton, more than were found by careful enumeration of 100 or more samples each (including qualitative samples) taken at all seasons in any mine lake. In the few quantitative samples taken, the number of individuals (total) was higher than in even those from Lake V. The benthic fauna appeared not to exceed Lake VI in biomass, but was probably more diverse. Fish were taken in the control lake by angling with rod and reel on several occasions. From personal experience and the success of other anglers, it is clear that the several species introduced have become well established.

B. Patterns between the lakes

The lakes were originally arranged on the basis of increasing pH but, as previously noted, that simple series was unexpectedly complicated by the meromictic nature of some of the lakes. Although the two factors are superimposed in nature, an attempt has been made to distinguish between the influences on the ecosystems of pH and of meromixis. The very interesting patterns of environmental stratification that often develop in a meromictic lake, illustrated by the following example drawn from Lake III, can have pronounced effects on the biocoenosis of the lake ecosystem.

1. The influence of meromixis. On the morning of 15 July 1970 the weather was pleasant (27 C, overcast, light variable breeze) at Lake III, and the green water was unusually transparent for that Lake (1% = 6.5 m). There was, in fact, no visible surface evidence of the remarkable complexity that existed in the subsurface environment (Fig. 7). The metalimnion was shallow (1-3 m), and the curve of dissolved oxygen closely paralleled that of temperature, with anaerobic conditions below 3.0 m. The vertical distribution of pH was quite complex with minima at 2-3 m and 6-7 m and maxima at 0-1, 4-5, and 8 m. Turbidity increased abruptly from 6.6 mg/l at the surface to 19 mg/l at 3 m. Dissolved substances, as indicated by conductivity, increased stepwise with major steps (chemoclines) at 5-6 and 7-8 m. Thus even by these rather crude measures, environmental stratification was indeed complex.

The influence of this kind of stratification on the benthic fauna is evident in Table 8, which summarizes the results of bottom fauna samples taken on the day in question. This particular example was chosen partly because the benthic grab samples included a greater range of depths than was usual in Lake III. At this time, only about 24 percent of the bottom area was within the aerobic zone (shallower than 3 m).

Two kinds of benthic animals were taken, both of them immature stages of Diptera. These two groups (the "true midges" of the family Chironomidae and the "biting midges" or "no-see-ums" of the family Heleidae) occurred in the benthos of all six lakes. Four of the six samples taken above the lower limit of dissolved oxygen (3.0 m) had at least one organism, while none of the four samples taken deeper had any macroscopic benthic animals. Densities of approximately 100 larvae per grab sample (as in samples 3 and 4) indicate a density in the lake bottom sediments on the order of 2,000 larvae per m^2. This was quite high for Lake III, but would be only a moderate density for Lake II.

Nine taxa of zooplankton organisms were taken on 15 July 1970. Most of these occurred at all depths, with greatest density at 2 m and least at 7-8 m. Total rotifers, for example, decreased from 10,000 individuals

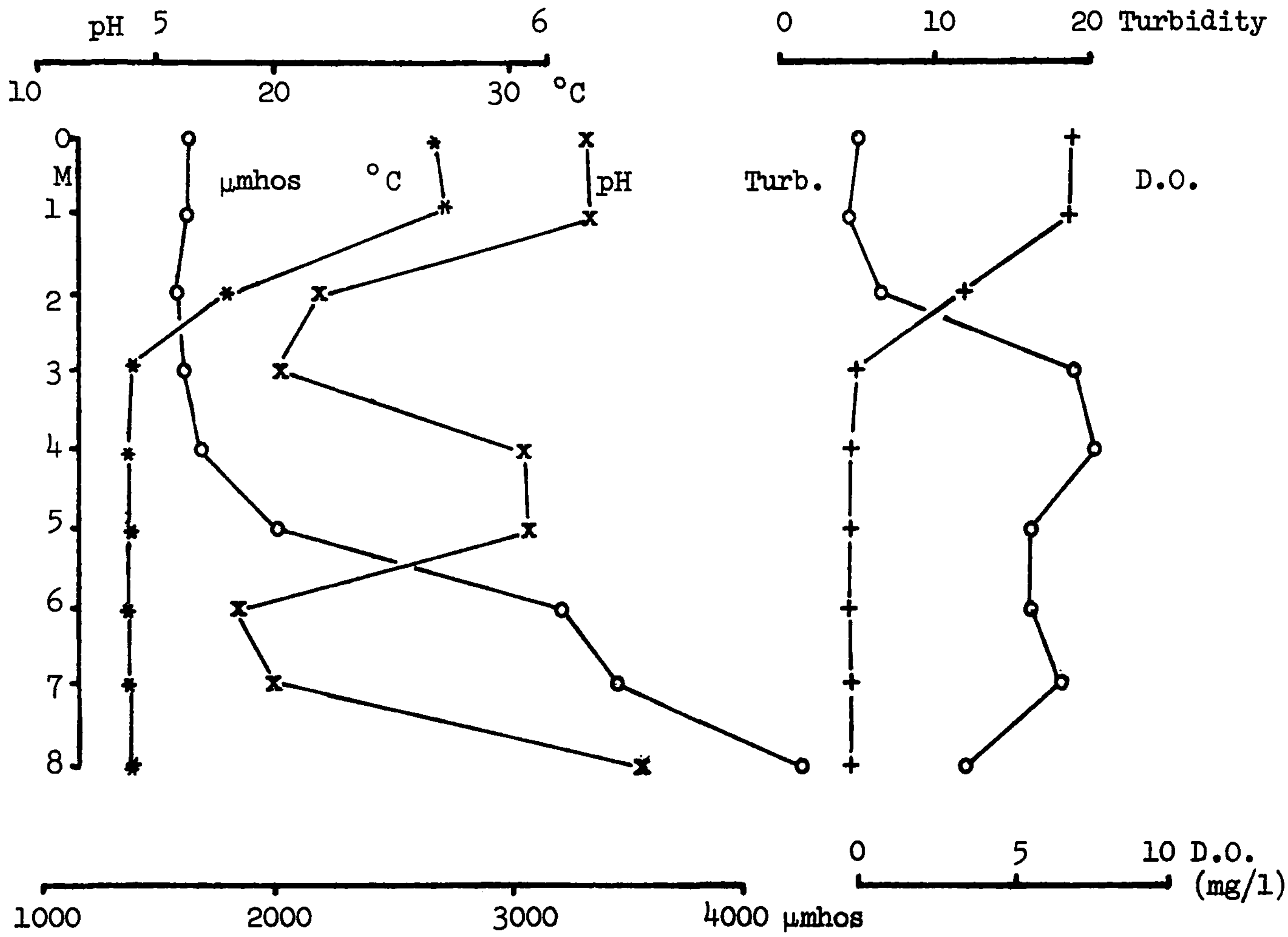


FIG. 7. Complex stratification in Lake III, 15 July 1970.

per m^3 at 2 m to 2300 per m^3 at 8 m. In contrast, one rotifer (*Hexarthra* sp.) was most numerous at 8 m. Plankton animals are better able to tolerate anaerobic conditions than benthos, or so it seems from these results. The zooplankters in the deepest stratum can reach oxygen by swimming or floating vertically upward a distance of a few meters. Benthic animals, on the other hand, would have to crawl much longer distances horizontally (assuming they do not swim very readily). In fact, however, the chironomid and heleid larvae were faculatively pelagic in Lakes I, II, and III, occurring sporadically in plankton samples at various depths and times without apparent relationship to any of the environmental parameters measured. Nevertheless, these larvae were recovered from only about 9.5 percent of the bottom samples taken at anaerobic depths, always in relatively low densities. Thus meromixis appears to have a much more limiting effect on bottom fauna than on zooplankton (see p. 68-74).

It is not known how common meromixis is in coal stripmine lakes. Campbell *et al*. (1965a) presented evidence for meromixis in their shallow acid Lake A_1 (pH 2.0-2.9, maximum depth 2.0 m) in central Missouri. Even

TABLE 8. Results of benthos sampling in Lake III, 15 July 1970.

Grab sample number	Depth (m)	Benthic animals collected	Number
1	0.3	Chironomid larvae Heleid larvae	6 1
2	0.5	None	0
3	1.0	Chironomid larvae Heleid larvae	91 1
4	1.5	Chironomid larvae	99
5	2.0	None	0
6	2.5	Heleid larvae	1
7	4.0	None	0
8	5.0	None	0
9	5.0	None	0
10	8.0	None	0

when this lake was "thoroughly mixed" with an outboard motor boat, it reverted within 24 hours to an extremely stratified condition (Campbell, personal communication). Lake A_1 is not a typical stripmine lake but rather a shallow abandoned mine "tipple," that is, an artificial lake constructed for the purpose of washing coal. It differs from a final-cut lake in having a saucer-shaped basin and also in having a bottom composed of fragments of coal and shale (from fine powder to fairly large chunks) to a depth of perhaps a meter or more. The other lakes studied by Campbell's group showed no tendency toward meromixis, but rather exhibited only limited and transient stratification (Crawford 1942, Heaton 1951).

The stripmine ponds in southern Illinois studied by Lewis and Peters (1955) were generally stratified in summer, but circulated throughout the rest of the year. Similarly, Parsons (1964) found stratification to be absent or limited to summer in six acid mine lakes in Missouri. Simpson (1961) found no thermal stratification in three stripmine lakes in southeastern Kansas. Two other sets of Kansas mine lakes studied by Stockinger and Hays (1960) and by Maupin et al. (1964) exhibited only moderate summer stratification and circulated during the remainder of the year. Riley's (1965) incomplete data indicate rather weak and impermanent stratification in the stripmine lakes he studied in southern Ohio. Finally, the three-year study of six lakes in Kansas (Waller 1967, Gash 1968, Tobaben 1969) disclosed no evidence of meromixis. On the contrary, some of these lakes exhibited only brief or incomplete stratification before treatment with lime, and typical stratification after treatment.

Thus meromixis would seem to be somewhat uncommon in coal stripmine lakes; the present study being the first to document prolonged stratification in such lakes of moderate pH and depth. Had this situation been anticipated, the meromictic lakes might have been avoided because of their obscuring effect on the pH series.

Certain characteristics of stripmine lakes seemingly predispose them to behave in meromictic fashion. The water typically has a heavy load of dissolved substances. During summer thermal stratification, the concentration of solutes in the surface water can be decreased by dilution with rain water and the precipitation of reduced solutes by oxygen. At the same time, the dissolved substances in deep water can be increased by the addition of water with a very high concentration of solutes (leached from the cast overburden or from exposures of coal and shale in the highwall by surface and subsurface drainage) which flows downward to its density level. Further, solubility is higher for some substances in deep water due to anaerobic conditions, and thus some precipitates (e.g., hydroxides of iron and manganese) can be redissolved when they settle below the lower limit of oxygen. If the density difference resulting from these processes becomes greater than that caused by cooling of the surface water in autumn, the chemical stratification will be perpetuated through the winter months. Inverse thermal stratification will exist until the following spring when partial overturn returns the lake to summer thermal stratification. The narrow deep basin shape (small surface area) of typical stripmine lakes and the sheltering spoil banks and highwalls combine to reduce the effect of wind mixing to a minimum. Thus even a relatively small density difference can be perpetuated. The processes noted above (dilution, precipitation and resolution, leaching) are in operation throughout the year, continually increasing the density difference between surface and bottom strata. The stability of stratification is directly related to this difference and may be great as in Lake III, or relatively little as in Lake VI. In greater or lesser degree, however, it is clear that meromixis is not directly related to pH and therefore disturbs the simple pattern of increasing pH in the series. Hence the influence of meromixis must be taken into account in the analysis of trends that follows.

2. Other stripmine lake studies: Missouri. It is desirable to compare trends in the Indiana lakes with those found in other stripmine lake studies. The Missouri series studied by Campbell and others is the only group of lakes with sufficient information available for detailed comparisons. Table 9 includes morphometric and environmental data for the Missouri series.

TABLE 9. Morphometry and physiochemical data of the five stripmine lakes in Missouri studied by Campbell et al. (1965a, 1965b)*.

Lake	A_1	A_2	A_3	B	D
Area (m^2)	1,300	6,830	2,160	6,490	3,885
Max. depth (m)	1.8	1.2	4.2	5.1	3.9
Mean depth (m)	1.1	1.1	3.0	3.0	2.5
Volume (m^3)	1,430	7,500	6,480	19,470	9,700
pH	2.0-2.9	2.8-3.2	3.4-4.1	6.4-7.6	6.3-7.9
Conductance (μmphos)	2,000-13,600	1,200-3,990	320-560	340-500	110-220
Total solids (120 C)	1,098-12,220	1,290-5,350	211-815	281-520	120-360
Turbidity (ppm)	10-28	<7-22	<7-9	<7-19	10-24
Secchi disc (m)	0.5-1.1	0.5-1.1	0.6-4.0	0.8-3.5	0.5-1.5
Calcium (ppm)	63-45	9-79	29-131	10-105	10-46
Magnesium (ppm)	31-232	59-159	10-22	17-25	6-16
Ferric iron	73-1040	28-35	0.9-1.6	0.02-0.3	0.03-0.4
Ferrous iron	0-2580	0.5-2.2	0-0.2	0.0	0.0
Total iron (ppm)	86-2730	28-42	0.9-1.7	0.02-0.3	0.005-0.5
Manganese (ppm)	3.9-95	7.7-17.2	1.0-3.5	0.0-8.9	0.0-6.8
Aluminum (ppm)	228-475	71-244	0.5-1.7	0.01-0.05	0.008-0.07
Sodium (ppm)	4.6-28.2	5.1-9.9	2.4-4.5	5.7-8.7	2.9-7.2
Potassium (ppm)	0.06-1.6	0.75-1.5	5.3-9.2	3.9-6.3	3.8-5.3
Zinc (ppm)	6.5-100	0.8-2.3	0.6-2.5	0.0-0.1	0.0-0.1
Sulfate (ppm)	777-7600	499-1367	143-339	75-336	1.8-155

TABLE 9. Continued

Lake	A_1	A_2	A_3	B	D
Silica (ppm SiO_2)	5.2-92.5	14.8	7.9-27.5	0.3-4.5	1.0-6.2
Phosphate (ppm)	0.0-0.01	0.15-0.5	0.0-0.9	0.0-0.59	0.0-0.47

*Morphometry converted to metric system

It is evident from a comparison of Tables 1 and 9 that as a group the Missouri lakes were much smaller and shallower than those of the present study. The Indiana lakes had about 10 times the area, twice the depth, and 20 times the volume (mean values) as the Missouri lakes (Table 10).

A second significant difference between the two series is that the pH spectra represented were not identical. The overall range covered by the Missouri series (2.0-7.9) was slightly greater and slightly lower on the pH scale than that of the Indiana series (2.5-8.2). Neither group of lakes was uniformly distributed within its range and there was, unfortunately, no Missouri lake in the middle range (about 4.0-6.5). The surface pH ranges and medians are indicated for the two series in Fig. 8.

These two basic differences between the Indiana and Missouri lakes must be borne in mind, as comparisons between the two groups are made in the following sections.

TABLE 10. Morphometric differences between the Missouri and Indiana lake series.

Mean of series	Missouri	Indiana
Area (m^2)	4,100	43,400
Mean depth (m)	2.1	4.1
Maximum depth (m)	3.2	6.7
Volume	8,900	187,000

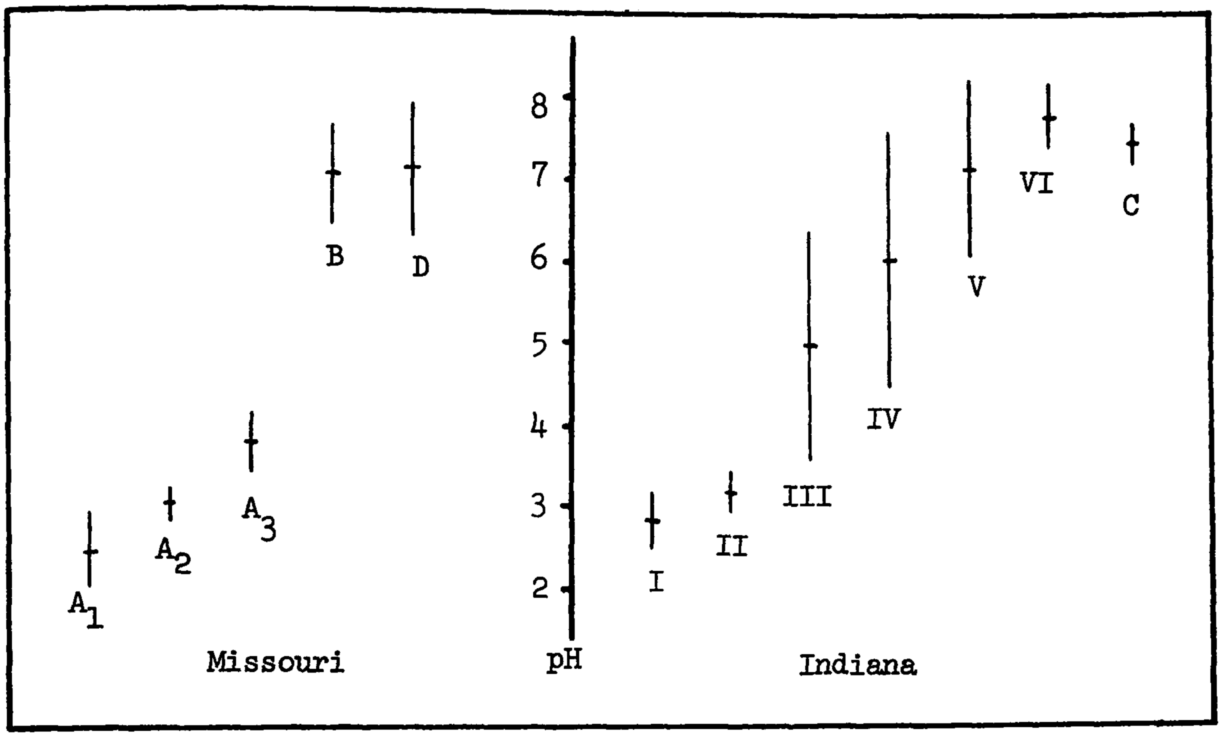


FIG. 8. Ranges and medians of surface pH for the Missouri and Indiana stripmine lakes.

3. Environmental patterns

a. pH. Although the original selection of the lakes and their arrangement into a series of increasing pH was based on relatively few samples, the series remained valid after 18 months of study. In view of the wide and overlapping ranges of pH in some of the lakes this was, perhaps, primarily due to good fortune. The most striking differences between the annual cycles of pH in the six lakes (Figs. 24-29) were in the vertical stratification and in the magnitude of variation with time. Vertical stratification of pH persisted throughout the period of study in the four meromictic lakes (III-VI). These vertical pH differences were greatest during summer thermal stratification, at which times Lakes I and II also exhibited pH stratification. Lakes III, IV, and V had the greatest overall surface pH variation and Lakes I and II, the greatest overall bottom variation. The magnitude of pH variation with time, like that of vertical stratification, appeared to be related more to meromixis than to relative placement on the pH scale.

None of the Missouri lakes studied by Campbell *et al.* (1965a) had a reported overall range of pH variation as great as those of Indiana Lakes I, III, IV, and V. Information regarding vertical stratification and patterns of annual variation in the Missouri lakes is not available (except for Lakes A_3, B, and D when studied by Crawford and by Heaton, at which times their other characteristics were different).

b. Temperature. The most obvious difference between the patterns of temperature variation in the study lakes (Figs. 30-35) was that between Lake II, with its prolonged periods of homothermy and complete circulation, and the other five more or less permanently stratified lakes. Lake I, while thermally stratified throughout most of 1970, was essentially homothermous in mid-August and late September. This lake is probably best regarded as transitional between typical holomictic lakes (e.g., Lake II and Control) and the meromictic lakes. The overall temperature differences in the bottom strata (Table 11) provide a good indication of these differences in thermal patterns.

Certain anomalous thermal patterns usually associated with meromixis were observed in the study lakes. For example, dichothermous temperature distributions (the minimum temperature occuring at intermediate depth; see Hutchinson 1957) occurred in Lakes I and II in March 1970, in Lake III from February through June 1970, in Lake IV from February to early August 1970, and in Lake VI during March and April 1970. Mesothermy (maximum temperature at intermediate depth) was observed in Lake I in August 1970, Lake IV in early November 1969 and 1970, and Lake V in April 1970. The complex temperature distribution in which one or more maxima and one or more minima occur at intermediate depth is known as poikilothermy and, according to Hutchinson (1957), is very rare. Poikilothermous curves were observed in Lake III throughout November and early December 1969, and in Lake V in late October of 1969 and 1970.

As previously noted, in the Missouri series only Lake A_1 was meromictic, while the other lakes exhibited limited stratification or none. The holomictic nature of Lakes A_3, B, and D is almost certainly due to their relatively (as compared with the Indiana mine lakes) low total solute concentrations (Table 9). Missouri Lake A_2, like Indiana Lake II, was holomictic. In both cases the reasons for the failure of meromixis to develop are unknown (see p. 55).

c. Dissolved oxygen. In the six lakes studied, both the level of dissolved oxygen and the percentage saturation increased with increasing pH (Fig. 9). This relationship was modified by meromixis in that, with the exception of Lake VI, the deep waters of the chemically stratified lakes remained anaerobic throughout the period of study (Figs. 36-44). Only Lakes II and VI had appreciable amounts of dissolved oxygen in deep water during a significant part of the annual cycle. The only lake that did not fit into the trend of increasing oxygen with increase in pH was Lake V which had unusually high levels of dissolved oxygen and also very high relative saturation. The fact that the peak occurred in Lake V (rather than Lake VI) probably resulted from the photosynthetic oxygen production by massive blooms of algae that occurred in Lake V in response to the fertilization program mentioned previously.

Thus the differences between the various patterns of dissolved oxygen variation observed in these lakes can be attributed, at least in part, to the different pH levels, to meromixis vs. holomixis, and to differences

TABLE 11. Observed annual ranges of bottom temperatures in the Pike County study lakes.

Lake	Annual temperature range (°C)	Temperature difference (°C)
I	9.5 - 24.3	14.8
II	6.3 - 28.5	22.2
III	12.6 - 14.4	1.8
IV	9.7 - 11.6	1.9
V	9.2 - 14.7	5.5
VI	9.0 - 17.2	8.2

in photosynthetic activity. pH probably acts indirectly, acidity increasing the total solutes (because many substances are more soluble at low pH) and leading, in turn, to increased oxygen demand by the reduced solutes.

Oxygen variation in the Missouri lakes was not discussed by Campbell et al. (1965a). The earlier studies of Crawford (1942) and Heaton (1951), however, indicated reasonably high levels of dissolved oxygen at all depths in all three lakes then under study (not including Lakes A_1 and A_2, which were added to the series later). On rare occasions during thermal stratification, anaerobic conditions existed briefly in the deepest strata. Even during mid-summer the dissolved oxygen levels in the Missouri acid Lake A_3 (Crawford 1942, Heaton 1951) did not approach the very low values observed in Lakes I and II of this study. Lake A_3 had much lower solute concentrations than Missouri Lakes A_1 and A_2 or than all of the Indiana stripmine lakes, and therefore it probably had a correspondingly much lower chemical oxygen demand.

d. Optical properties. Turbidity and transparency (Table 2) did not appear to be related directly to pH, but were influenced by the stratification patterns. As discussed previously (p. 39), high turbidity was frequently observed in a stratum of water corresponding in depth to the lower limit of oxygen in the meromictic lakes (except VI). The two lakes with oxygen in deep water during the greater part of the annual cycle (Lakes II and VI) had strikingly lower turbidity, especially at the bottom. The control lake had quite high turbidity on the two days that it was measured. Transparency, as indicated by the 1 percent level, was approximately inversely related to turbidity. Lakes II and

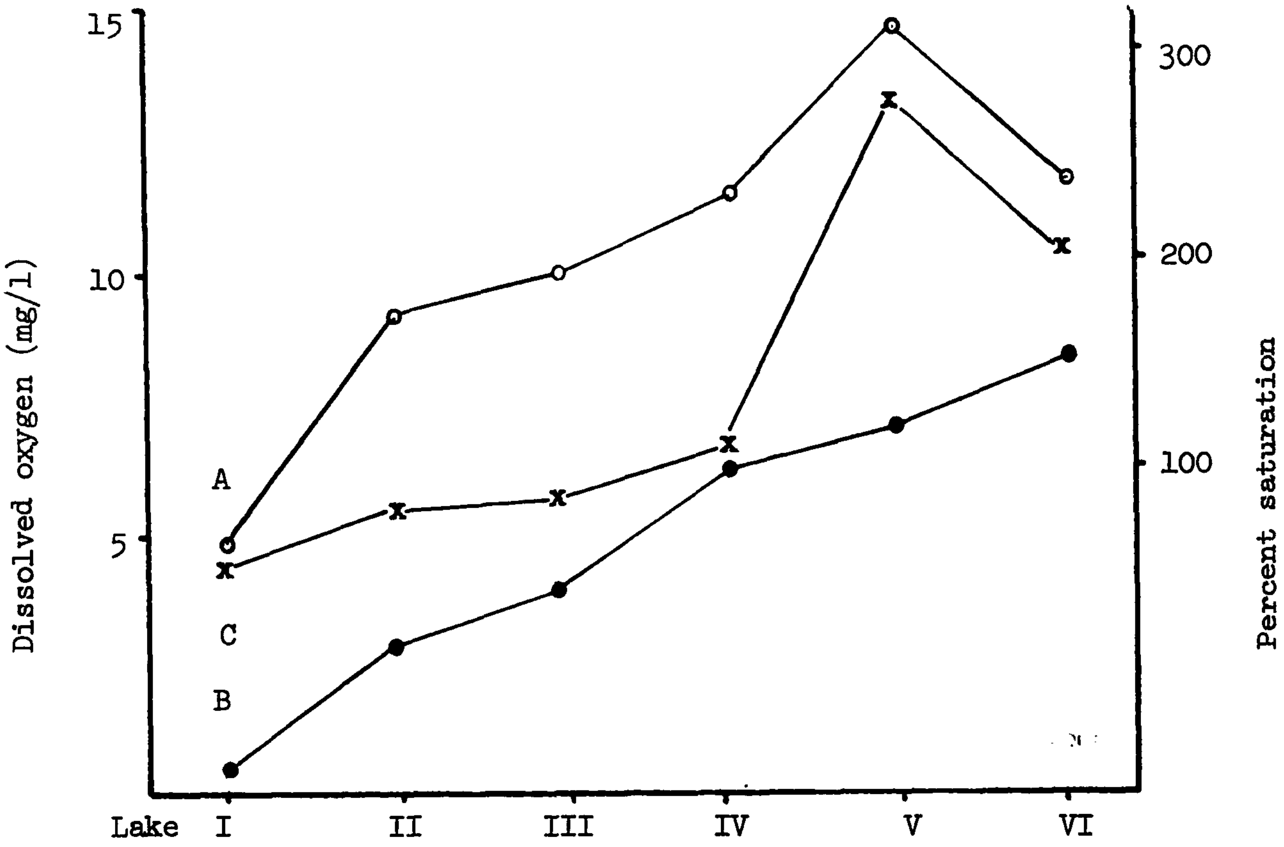


FIG. 9. Maximum (A) and minimum (B) open surface (no ice cover) dissolved oxygen; and percent saturation (C) at overall maximums (any depth, ice present or absent) in Pike County lakes.

VI were the most transparent, Lakes III and V least transparent. Lake I had greater transparency (as indicated by the shallowest observed 1 percent level) than expected on the basis of turbidity.

The methods for turbidity (platinum wire) and for transparency (secchi disc) used by Campbell et al. (1965a) were not strictly comparable to those used in this study. Unfortunately, the platinum wire turbidity method lacks accuracy at low values (below 7 ppm). Missouri Lake A_3 was similar to Indiana Lake II in pH. These two relatively transparent lakes may both be examples of Parsons' (1964) Type III: Blue Lakes (pH 3.0-4.0, no turbidity, no thermal stratification, iron less than 30 mg/l). Parsons' classification scheme for stripmine lakes is compared with the Indiana and Missouri lakes in a later section. Missouri Lakes A_1, A_2, B, and D had turbidity levels that were generally in the middle range of the Indiana lakes. None had the very high upper limits observed in the deep waters of Lakes I, III, and V. Relative turbidity and transparency within the Missouri series (Fig. 10) had an interesting relationship to pH. Turbidity was lowest in Lake A_3, the middle lake in pH, and increased with both increasing and decreasing pH. A similar relationship was present in the Indiana series (Fig. 11), turbidity increasing both above and below Lake II on the pH scale. In the latter series, however, this relationship was obscured by meromixis and the attendant precipitates. It seems reasonable that stripmine lakes of about pH 3.0-4.0 may be lowest in turbidity because below about pH 3 the solubility of iron increases abruptly (leading to turbidity from precipitates), and above that pH 4 organic turbidity of various sorts (plankton, increased decomposition, etc.) increases.

e. Dissolved substances. According to Hutchinson (1957, p. 552) "Normal fresh waters are dilute solutions of alkali and alkaline earth bicarbonate and carbonate, sulfate, and chloride, with a variable quantity of largely undissociated silicic acid ... which is often present in excess of sulfate and chloride." In addition, there may be a number of other ions (some quite significant biologically) and certain organic and inorganic colloids. The stripmine lakes of this study cannot, of course, be considered "normal" fresh waters. In most natural fresh-water lakes the major cations are Ca^{++}, Mg^{++}, Na^{+}, and K^{+} and the major anions are HCO_3^{-}, SO_4^{-}, and CO_3^{--} in order of decreasing concentration. The proportions are much less constant than is the case in oceanic sea-water.

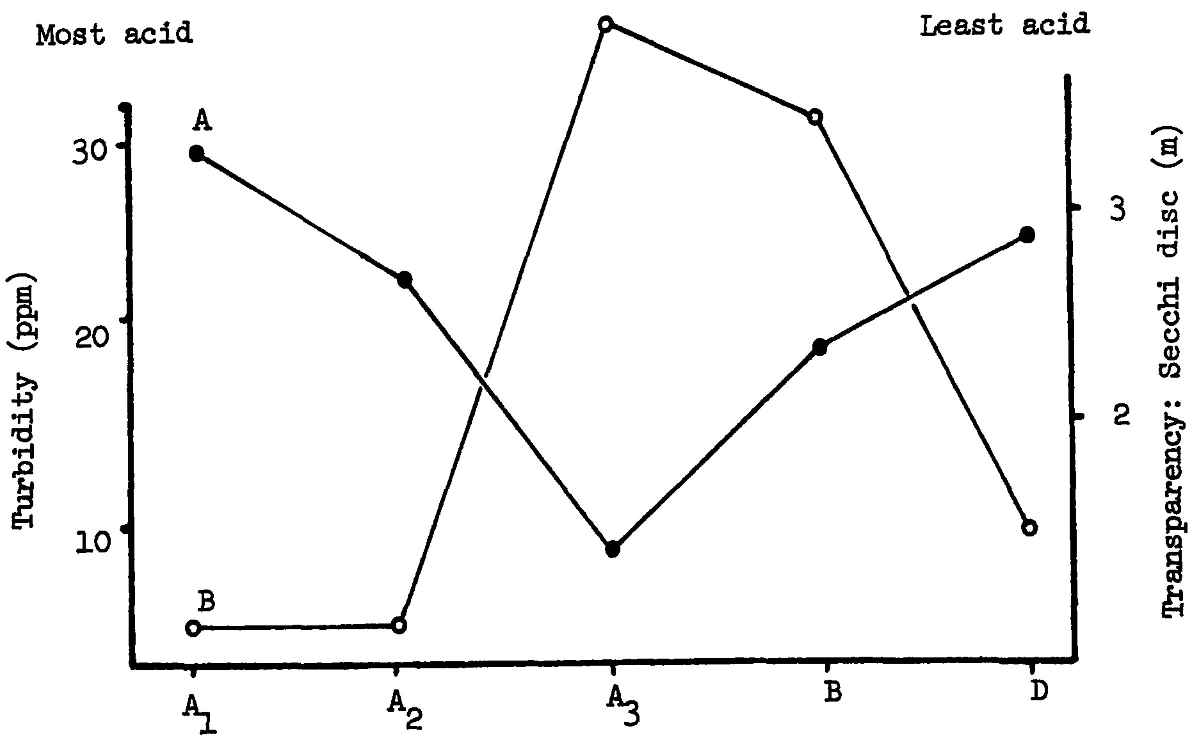


FIG. 10. Maximum turbidity (A) and transparency (B) in the Missouri lakes.

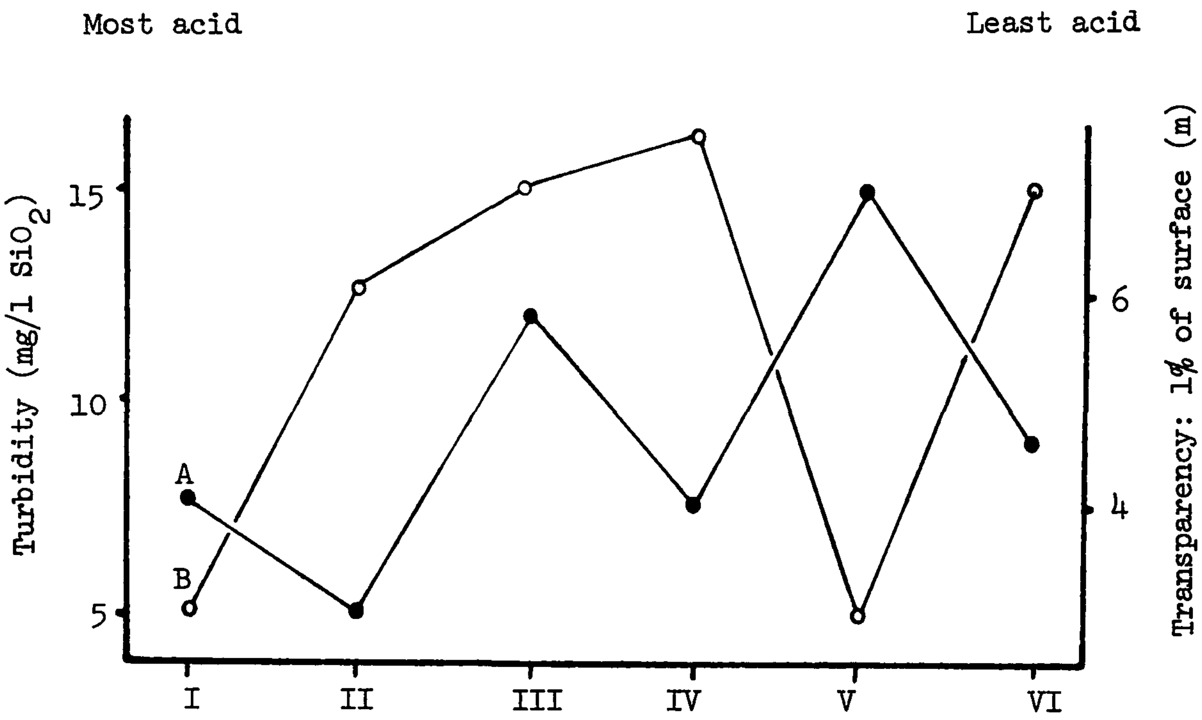


FIG. 11. Maximum surface turbidity (A) and transparency (B) in the Pike County lakes.

Perhaps the most straightforward measure of ionization in a liquid is electrical conductivity adjusted to a standard temperature, generally 25 C in North America. Results are reported in reciprocal meghoms or micromhos. Since most of the substances dissolved in water ionize to some degree, the values for conductivity vary with those for dissolved solids (Tables 2 and 10). Overall variation in conductivity or specific conductance ($K_{25} \cdot 10^6$) for the Indiana lakes is shown in Figs. 42-46.

The range of conductivity values reported for freshwater lakes is about 9-400 micromhos (Hutchinson 1957, Reid 1961), but some saline lakes may exceed 60,000 micromhos, and certain industrial effluents are much higher. The range reported for the Missouri lakes (Table 9) was 110-13,600 µmhos, probably approaching the extreme to be found in coal stripmine lakes. The overall variation in conductivity in the lakes of this study was much less than that of the Missouri lakes (Fig. 12). The curves for the Indiana and Missouri lakes corresponded in conductivity only in the region of pH 3. The very acid Lake A_1 had remarkably high conductivity, which may have been due, at least in part, to the extensive areas of coal and shale fragments in its basin. In both series, the surface conductivity values tended to stabilize at pH values higher than 3.5 although at different levels. These might be controlled by geological differences (i.e., differences in the composition of the coal or associated materials) or in part by differences in age. The latter seems unlikely, however, since the pH and conductivity were not well correlated with age in either series. For example, at the time of the study (Campbell *et al.*

1965a) Lakes A_1 and A_2 were about 30 years old, and Lakes A_3, B, and D were about 45 years old. Yet Lakes A_1 and A_2 with similar pH differed greatly in conductivity, while A_3 was much more acid than B and D but relatively similar in conductivity. Indiana Lakes I and V are, literally, but a stone's throw apart and were formed by the same mining operation in 1940, yet were markedly different in pH and to a lesser degree in conductivity. Thus in both the Indiana and Missouri series, there is a progressive but irregular decrease in dissolved substances with increasing pH.

The overall difference in total solutes between the surface and bottom strata of meromictic Lakes III-VI is apparent in Figs. 44-47. The difference was especially great in Lake III, accounting for its relatively great stability of meromictic stratification. Holomictic Lake II also had slightly higher maximum conductivity at the bottom, but Lake I had identical maximum conductivities for the surface and bottom waters.

f. Major ions. Unfortunately, there is no comprehensive and universally accepted system of classifying lakes in terms of their chemical nature. Of the various classificational or organizational schemes proposed (reviewed by Hutchinson 1957), perhaps the most useful is the system of ionic diagrams proposed by Maucha (1932). This system would be too complex in the present context, and hence I prefer to discuss each of the major ions briefly. The data are summarized in Table 3 and presented in detail in Appendix 2.

Ca^{++}. In the lakes of the present study calcium varied from about 120 to 500 mg/l. The highest concentrations were found in Lake I and the deep waters of Lakes III, IV, and V, and the lowest in the surface waters of Lakes III and VI. Calcium in the Missouri lakes (Table 9) was generally lower, but Lake A_1 had a maximum of 455 mg/l. The range in natural surface waters is from 0.13 or less to about 10,000 mg/l (Dead Sea), but most freshwater lakes contain 2.5-60 mg/l (Hutchinson 1957). The control lake, with an observed range of 11-21 mg/l, was well within these limits.

Mg^{++}. The overall range of magnesium concentration observed was from 85 mg/l in the surface waters of Lake III to 537 mg/l in the deep waters of that lake. This range was much higher than that for natural freshwater lakes (0.4-9.9 mg/l), but much lower than typical values for natural saline lakes (e.g., 5,600 mg/l in Great Salt Lake and 38,000 mg/l in the Dead Sea) according to Hutchinson (1957). Magnesium concentrations in the Missouri lakes (Table 9) were well below those of the Indiana lakes of similar pH. The control lake although having a maximum observed value of 10 mg/l in deep water during summer stratification may reasonably be regarded as within the range for natural freshwater lakes.

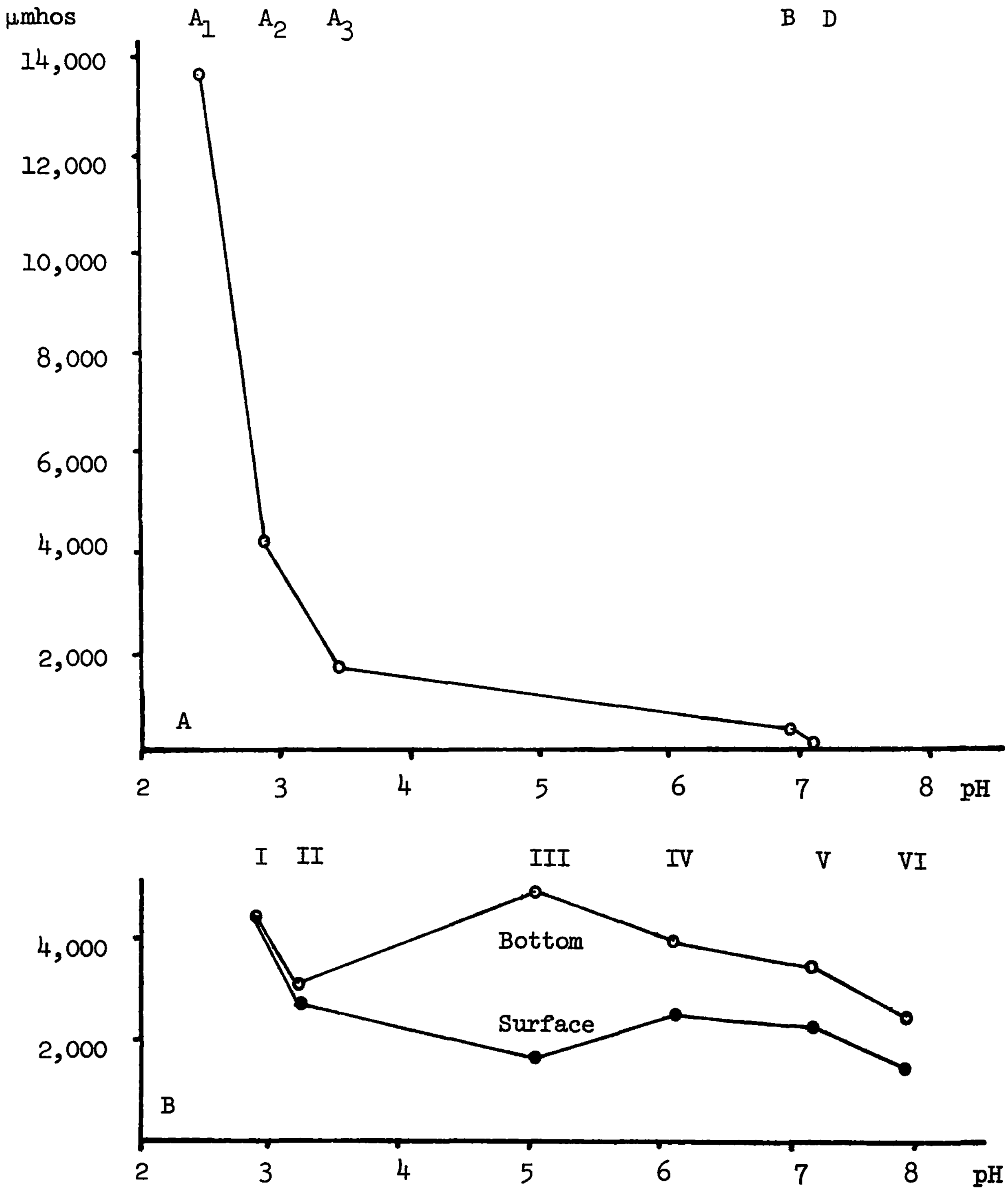


FIG. 12. Maximum conductivity in relation to median surface pH in the Missouri (A) and Pike County (B) lakes.

Dissolved iron. In this section I have dealt with the total dissolved iron without attempting to sort out the various ionic forms (Fe^{++}, Fe^{+++}, $FeOH^{++}$, $H_2FeO_3^-$, etc.) that may be present. Hutchinson (1957) gives the iron concentration for the upper circulating waters of lakes as ranging from undetectable to 19.2 mg/l. The upper value is from a volcanic lake with a high content of sulfuric acid and a pH of about 1.8. A much higher value of 50 mg/l was reported from a bog of pH 4.0 near Moscow, USSR. Iron in the surface waters of the study lakes (Table 3) had the familiar inverse relationship to pH. The total range was from <0.05-0.55 mg/l in Lake VI to 60-105 mg/l in Lake I. Missouri acid Lakes A_1 and A_2 markedly exceeded Indiana lakes which had much higher iron concentrations, especially in deep water. The control lake exceeded Lake VI in iron, especially in deep water during stratification.

Ferrous iron accumulates in the deep anaerobic waters of lakes during stratification. Under such conditions, ferrous and manganous bicarbonates in the deepest strata of the monimolimnion of a meromictic lake or the hypolimnion of a thermally stratified lake can have a buffering action, resulting in an acid heterograde curve of pH distribution with a minimum value in the upper part of the anaerobic zone (Hutchinson 1957). During summer stratification, meromictic lakes have four major layers including the usual three (epilimnion, metalimnion, hypolimnion) and the monimolimnion. At such times, a sort of double acid heterograde curve of pH distribution was observed in Lakes III, IV, and V (Fig. 13) but not in Lake VI, which had oxygen in deep water during most of 1970.

Manganese. Like iron, manganese may exist in either a reduced or oxidized form or both, depending on pH and redox potential. The total manganese in the study lakes was clearly inversely proportional to pH. The lowest values (<0.05-26.0 mg/l) occurred in Lake VI and the highest (40.0-64.0 mg/l) in Lake I. Moderately high values also occurred in deep water during stratification. The control lake was well within the range of <0.005-15.0 mg/l found in natural freshwater lakes (Hutchinson 1957). Values of manganese reported for the Missouri lakes were generally comparable to those of the Indiana lakes of similar pH.

Aluminum. According to Hutchinson (1957), aluminum in natural lakes ranges from undetectable to about 97 mg/l (in a shallow saline lake in a closed basin). In the present study a range of from 0.05 to 44.0 mg/l was found. The maximum (from Lake I) was rather low for an acid mine lake. Missouri Lakes A_1 and A_2 were both much higher. Aluminum, too, is much more soluble in acid waters (and also above pH 8). Meromixis had little, if any, influence on aluminum concentration in the monimolimnion as compared with the mixolimnion. In the control lake the concentration in deep waters during summer stratification was fifty times that in the surface waters (Appendix 2).

Na^+. In naturally occurring salt lakes sodium may reach very high values (e.g., 67,500 mg/l in Great Salt Lake, Utah). In most natural lakes, however, typical values range between 0.13 and 16.6 mg/l

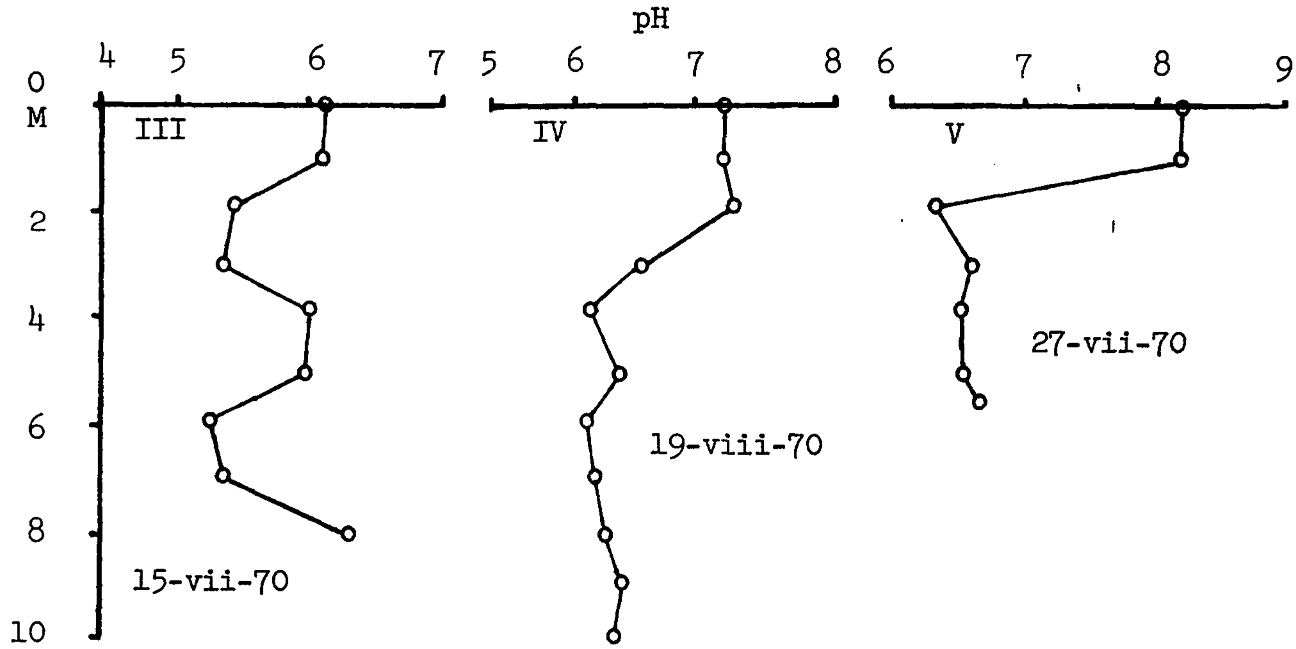


FIG. 13. Double heterograde pH curves associated with maximum summer stratification in meromictic Lakes III, IV, and V.

(Hutchinson 1957). The range in this study was from 11 mg/1 in the surface waters of Lakes I and V to 75 mg/1 in the deep waters of Lake VI. Thus the lakes of this study were moderately higher than "typical" freshwater lakes, but did not approach the natural saline lakes in sodium concentration. Concentrations were only slightly higher in the monimolimnion of the meromictic lakes than in the surface waters, and showed little or no systematic variation with pH. The control lake was moderate, and the Missouri lakes were generally somewhat lower in sodium than the Indiana lakes of similar pH.

K^+. The surface waters of the study lakes were all quite similar in potassium concentration, varying from 2.5 to 5.5 mg/1. This is generally within the range to be found in natural freshwater lakes (Hutchinson 1957). Saline lakes may contain much higher amounts. In the deep waters of Lakes III and IV potassium reached 25 mg/1 during intense summer thermal stratification. This, together with a similar but less dramatic increase in magnesium, suggests a possible biogenic element in the meromixis of these lakes. The control lake had lower potassium than any mine lake, and the Missouri lakes were generally lower than the Indiana series.

Zinc. According to Hutchinson (1957), the occurrence of zinc in natural waters has received little attention. Reported values range from 0.0013 to 0.65 mg/1, the latter reputedly toxic to Cladocera. In the lakes of this study zinc concentration was inversely related to pH, varying from

0.1 mg/l or less in Lake VI to as high as 4.0 mg/l in Lake I. The latter concentration is probably toxic to many aquatic organisms. There was no consistent difference between surface and bottom waters. Missouri Lake A_1 had as much as 100 mg/l, but the other lakes in that series were similar to the Indiana lakes. The control lake had moderate zinc concentrations.

$SO_4^{=}$. Sulfate is by far the dominant anion in coal stripmine lakes. In natural freshwater lakes the range encountered is about 6.2-20.5 mg/l, but values in excess of 60,000 mg/l have been reported (Hutchinson 1957). The overall range found in this study was from 510 mg/l (surface of Lake III) to 3650 (bottom of Lake I). Values in the surface waters were only moderately influenced by pH, and significantly higher values were encountered in the monimolimnion of the meromictic lakes. The control lake had a very much lower concentration than any mine lake, but well within the upper part of the range for natural freshwater lakes. The maximum value for Missouri Lake A_1 was quite high (7600 mg/l), but the other lakes in that series had lower values than the Indiana lakes of similar pH.

Cl^-. Chloride in the study lakes ranged from less than 1.0 to about 40.0 mg/l. In general Lakes III and IV had the highest values, Lakes II, V, and VI the lowest. These levels of chloride were somewhat high, but were well within the range for natural lakes (Hutchinson 1957). The control lake had relatively low chloride. Chloride was not reported for the Missouri lakes by Campbell *et al*. (1965a).

HCO_3^-. Bicarbonate occurred in Lakes III through VI in increasing amounts. The overall range was from 24 to 296 mg/l (in the surface waters of Lake III and bottom waters of Lake VI, respectively). This was well within the range for natural freshwater lakes. The very low ratio of bicarbonate to sulfate (from .03 in Lake III to .21 in Lake VI) is probably met with, in nature, only in such uncommon situations as volcanic lakes and peat bogs.

Other ions (nitrate, phosphate, and the forms of silica) of biological significance were also measured. Silica varied inversely with pH, but nitrate and phosphate were rather uniformly low. One doubts that low levels of these substances are ever limiting factors in the mine lakes because of other overriding chemical conditions.

Thus in the stripmine lakes of this study, the ionic situation is complex. In typical freshwater lakes the dominant cations are considered to be Ca^{++}, Mg^{++}, Na^+, and K^+ in that order. In the acid mine lakes, iron, manganese, and aluminum tend to exceed sodium and potassium. Iron and manganese are also high in the monimolimnion of the meromictic lakes. In the surface waters of the less acid or slightly alkaline mine lakes, the usual situation (sodium and potassium in third and fourth rank) prevails. In "normal" lakes the dominant anions are HCO_3^-, $SO_4^{=}$, Cl^-, and $CO_3^{=}$ in decreasing order of abundance. The same ions, but in different order of abundance, occur in the mine lakes, with carbonate excluded at low pH values (less than 8.4).

In summary, certain trends in the ionic composition of the study lakes may be noted. pH influenced the concentration of several ions. Calcium, magnesium, iron, manganese, aluminum, zinc, sulfate, and chloride varied inversely with pH. Sodium and bicarbonate were directly related to pH. Ions that were markedly higher in the monimolimnion of meromictic lakes (probably due primarily to the redox situation) included calcium, magnesium, iron, manganese, sodium, sulfate, and bicarbonate. Some ions including calcium, magnesium, iron, manganese, sodium, zinc, and sulfate, were much higher than in natural freshwater lakes.

The magnitude of seasonal variation in concentrations for most of the ions measured was relatively small. The most prominent kind of trend found was an increase in concentration--especially in deep water--during maximum summer stratification. Such a pattern was observed for calcium, magnesium, iron, sodium, potassium, manganese, silica, and sulfate in at least some of the lakes, although not in Lakes I and II. No other marked seasonal trends were observed.

The control lake had consistently lower values for nearly all ions than any of the mine lakes. This lake fell well within the range of water chemistry for natural freshwater lakes and it is probably representative of "natural" (i.e., nonstripmine) ponds and small lakes of the region.

The most striking differences between the Missouri lakes and those of the present study were (1) the much higher concentrations of several ions in Lake A_1 than in any Indiana lake and (2) the relatively low total solute concentrations in Missouri Lakes A_3, B, and D. These differences may be related to the origin of Lake A_1 as a coal-washing basin and to regional differences in geology and weather.

g. Lake types. Parsons (1964) has suggested a classification of stripmine lakes on the basis of certain physical and chemical characteristics. The successive types in this series are thought to represent sequential stages in the recovery of a mine lake from acid pollution. The criteria upon which these types are based have been arranged as Table 12. In this series acidity and iron decrease, alkalinity increases, and turbidity and thermal stratification increase initially and later decrease.

The lakes of this study do not, for the most part, fit very well into this classification. On the basis of pH Lake I would be a Type II lake, but it had greater iron, turbidity, and thermal stratification, and did not show the seasonal variation suggested for that type. Lake II, as previously noted, meets the specifications for Type III except that it did have measurable turbidity and a limited degree of thermal stratification. The remaining four lakes would all be Type IV on the basis of pH, but all had prolonged stratification, high upper limits of turbidity, and (except Lake VI) moderate to high dissolved substances including iron.

The Missouri lakes fit the scheme better than the Indiana series, probably because Parsons' lake types were formulated mainly on the basis of data from the same region. The striking differences between the combinations of conditions found in the Indiana lakes of this study and those of the Missouri lakes may, as noted below, reflect basic differences in the geology and climate of the two areas.

Campbell et al. (1965a) arranged the five Missouri lakes into three successional stages: youthful (A_1), early recovery (A_2, A_3), and late recovery (B, D), which they characterized in terms of acidity, solutes, transparency, thermal stratification, and biological diversity. The same general problem is encountered when trying to fit the Indiana lakes into this scheme as with Parsons' types (i.e., the sets of conditions present in the individual lakes are not the same). Thus a given Indiana lake might rank as youthful in terms of stratification, early recovery as to solutes and turbidity, and late recovery as to pH and color (as in fact Lake VI does). Lake II was once again the only Indiana lake that matched one of the categories (early recovery) reasonably well.

TABLE 12. Coal stripmine lake types proposed by Parsons (1964).

	Type I: Red lakes	Type II: Transitional	Type III: Blue lakes	Type IV: Grey lakes
pH	1.2-2.5	2.5-3.5	3.0-4.0	$\geq$ 4.0
Titratable acid (mg/l H_2SO_4)	5500	3500	$\leq$ 3000	Low
Turbidity (ppm)	All seasons, due to iron hydroxides	Spring only, due to iron hydroxides	None	Low to normal; organic and inorganic
Iron (mg/l)	High ($\geq$ 65)	High (130) in spring, low (15) other seasons	Low (< 30)	Low
Thermal stratification	Present in summer	None	None	Little to normal
Alkalinity (mg/l as $CaCO_3$)	None	None	None	$\geq$ 30

No doubt a valid series of limnological stages through which all coal stripmine lakes pass during recovery from acid pollution could be formulated. To have general application, such a scheme would have to be based on data from lakes in the various regions in which coal stripmining is carried out and would probably have to be based on more (perhaps different) criteria than those considered above. The formulation of such a general successional scheme for stripmine lakes is not an objective of this paper.

4. Biological patterns

a. Diversity. There was clearly an increase in overall faunal diversity with increasing pH in the lakes of this study (Table 4). The rate of increase, however, was not uniform either for the total fauna or for the ecological subgroups (Fig. 14). The overall rate of increase was greater at low pH (Lakes I-IV) than at higher pH (Lakes IV-VI). This was generally true of both zooplankton and benthos, and vertebrates were most diverse in Lake IV. The increase in benthic taxa between Lakes I and II was as great as the total additional increase from Lake II to Lake VI. This may reflect the influence of meromixis in Lakes III-VI on the conditions of life for the bottom fauna. Similarly, the greatest increase in number of zooplankton taxa occurred between Lakes II and III (nine taxa added of the total increase of 16 from Lake I to Lake VI).

It is of some interest to consider the relative importance of addition and substitution in the faunal changes that occurred through the lake series (Table 13). The number of taxa carried over from one lake to the next at each step was typically about 75 percent, but only about half (56 percent) were carried over from Lake II to Lake III and nearly all (94 percent) from Lake III to Lake IV. The increase in faunal diversity may reasonably be regarded as primarily a result of addition of taxa. The total change from Lake I to Lake VI was from 12 to 53 taxa or an overall increase of 41 (342 percent). Eight of the 12 taxa found in Lake I were also present in Lake VI. These groups must be regarded as quite eurytopic with regard to pH, solutes, etc.

The Missouri lakes (Campbell et al. 1965a) had more animal taxa at high pH and fewer at low pH than the Indiana lakes (Fig. 15). This may be related to the relatively lower solutes in the high pH Missouri lakes. Another contributing factor is the longer period of study (almost 30 years) and greater number of investigators of the Missouri lakes. This does not, of course, explain the greater number of taxa found in the Indiana lakes of low pH. It has been noted previously that Missouri Lake A_2 and Indiana Lake II are environmentally quite similar, and it is therefore surprising that Lake II had nearly four times as many animal taxa (23 vs. 6) as Lake A_2.

b. Standing crop. Two general features of the overall mean biomass (Table 14) are of interest. First, the rank order of the lakes was different for each of the three faunal categories, no single lake

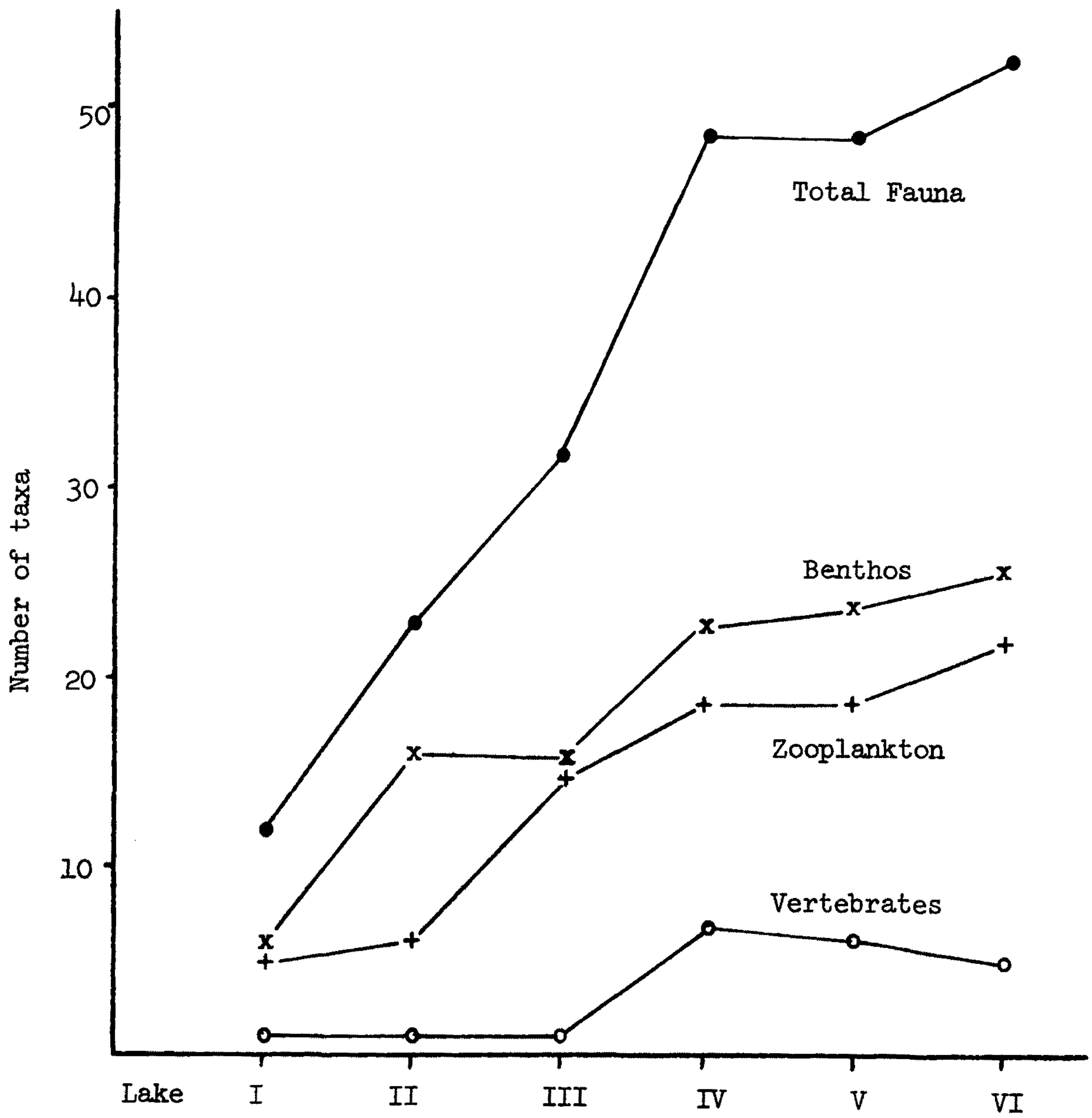


FIG. 14. Number of animal taxa recognized in the Pike County lakes.

dominating all others. In general Lakes II and VI were high, Lakes III and IV low, and Lakes I and V variable. Second, the magnitude of the differences between lakes was generally large, the highest exceeding the lowest by factors of approximately 8, 20, and 285 (fish, benthos, and zooplankton).

The total percentage standing crop can be calculated (Table 15) for purposes of comparison between lakes. The apparent fallacy that results from combining data based on numbers and weight--"adding apples and oranges"--can be avoided simply by regarding the total percentages

TABLE 13. Faunal changes in the Pike County lakes.

Lake interval	Taxa maintained No.	Taxa maintained %	Taxa added No.	Taxa added %	Taxa lost No.	Taxa lost %	Net change No.	Net change %
I-II	9	75	14	117	3	25	+11	+92
II-III	13	56	19	83	10	44	+ 9	+ 39
III-IV	30	94	19	59	2	6	+17	+ 53
IV-V	35	71	14	29	14	29	0	-
V-VI	37	76	16	33	12	24	+ 4	+ 8
I-VI	8	67	45	375	4	33	+41	+342

TABLE 14. Overall mean animal standing crop in the Pike County lakes.

Zooplankton Lake	Zooplankton Number/m^3	Benthos Lake	Benthos mg/m^2	Fish Lake	Fish g/trap-hour
V	2,162,372	II	1,416	VI	7.78
II	531,810	VI	763	IV	2.70
VI	199,602	I	573	III	1.61
IV	28,377	V	220	V	0.95
I	8,384	IV	95		
III	7,761	III	66		

as "fruit." On this basis, it appears that there was a trend toward increasing biomass with increasing pH. This was not so straightforward, however, as was the case with diversity. Lake II was much higher and Lakes III and IV lower than would have been expected on the basis of pH alone. The differences between lakes in the patterns of circulation are probably responsible, at least in part, for this lack of agreement between pH and biomass.

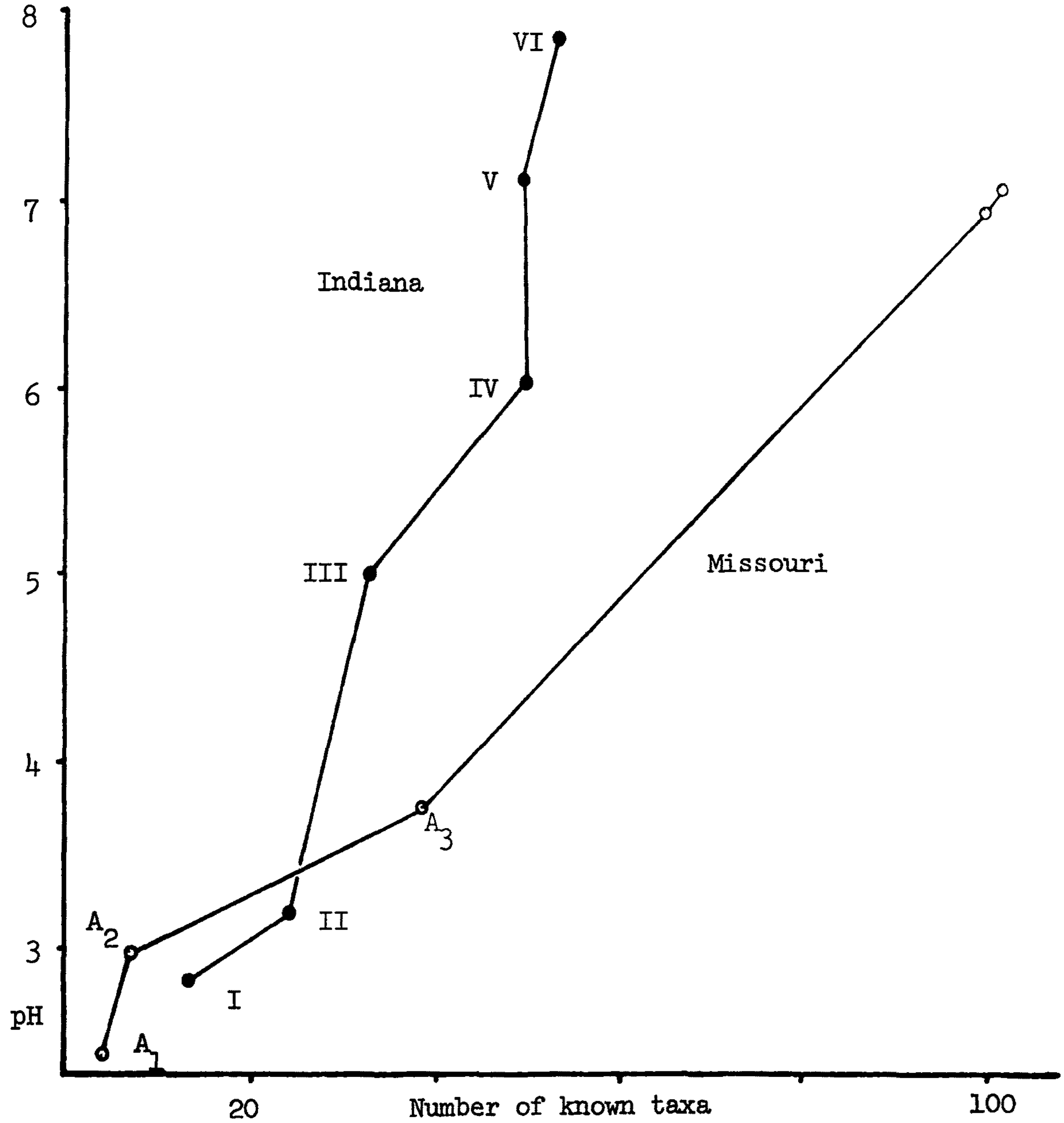


FIG. 15. Animal diversity and pH in the Missouri and Indiana lake series.

It is possible to construct a simple index of environmental stress by assigning arbitrary values to the different levels of stress of the various environmental factors. This has been done for the study lakes using pH, dissolved oxygen, total solutes (as indicated by conductivity), and intensity of stratification (as indicated by surface-to-bottom temperature differences). For each factor, the lakes were simply ranked in order of increasing stress and assigned numbers from one to six (Table 16). The total for each lake constitutes its index of environmental stress. On this basis, Lake III was the most successful and Lake VI the least so. The index of stress was inversely

TABLE 15. Percent of total standing crop in the Pike County lakes.

	Lake					
	I	II	III	IV	V	VI
Zooplankton	0.3	18.1	0.3	1.0	73.6	6.7
Benthos	18.3	45.2	2.1	3.0	7.0	24.4
Fish	0	0	12.3	20.7	7.3	59.6
Total	18.6	63.3	14.7	24.7	87.9	90.7

TABLE 16. Index of environmental stress in Pike County lakes.

	Lake					
Factor	I	II	III	IV	V	VI
pH	6	5	4	3	2	1
Temperature difference	2	1	6	5	4	3
Maximum conductivity	5	2	6	4	3	1
Dissolved oxygen	6	5	4	3	1	2
Index of stress	19	13	20	15	10	7

related to overall standing crop (Fig. 16), indicating that a combination of factors influenced animal biomass rather than mainly pH as seemed true for diversity.

The influence of meromixis can be assessed by considering the distribution of biomass with depth (Tables 17 and 18). These data, however, reflect the influence of relative area and volume. It is, therefore,

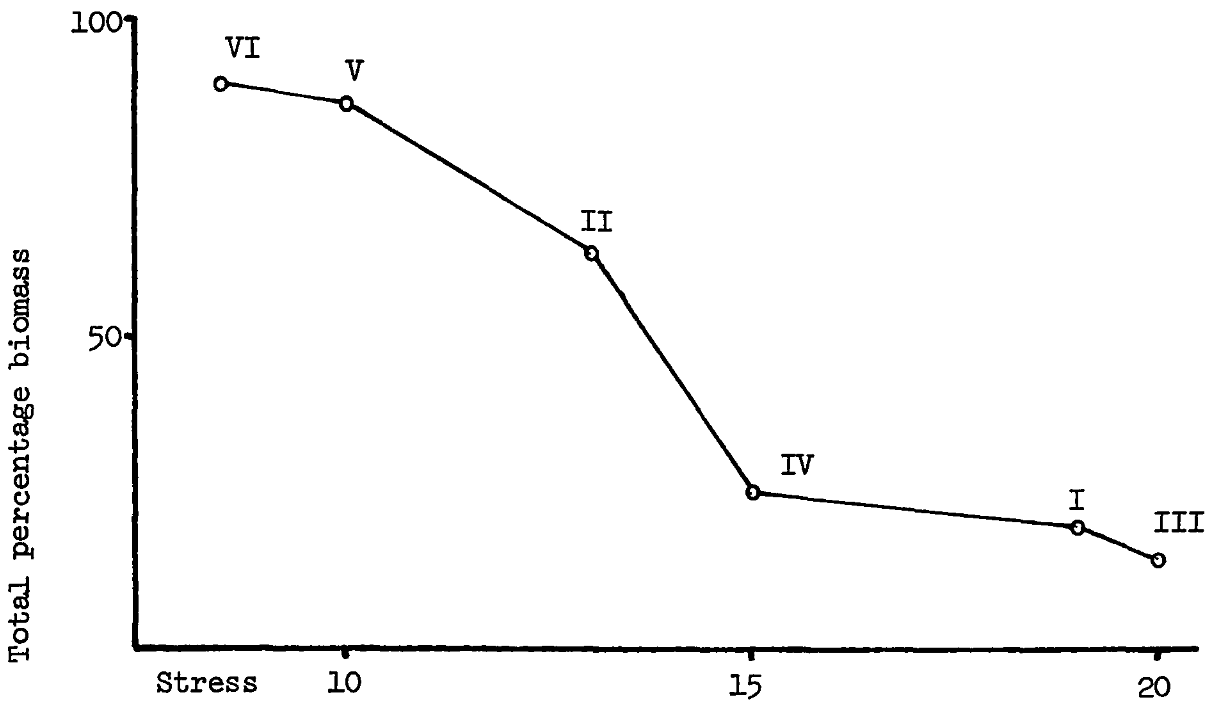


FIG. 16. Biomass and environmental stress in the Pike County lakes.

more appropriate to use the original non-weighted values which have been plotted as percentages of the total for each lake in Figures 17 and 18.

Clearly, the depth distribution of zooplankton was less influenced by differences in stratification patterns than that of benthos. With the single exception of Lake I, the zooplankton was distributed remarkably uniformly throughout the water column. In Lake I the zooplankton was concentrated near the bottom for unknown reasons. Benthic biomass, on the contrary, had three distinct patterns of distribution with depth. The biomass tended to be greatest in deep water in Lake II, in the shallow regions of Lakes I, III, V, and VI, and at the surface and intermediate depths in Lake IV. More than half the total benthic biomass in Lake II was concentrated in the two deepest 1-m depth intervals, while Lakes I and VI had relatively little, and Lakes III, IV, and V no benthos in their deepest areas. The benthic maximum between 5 and 6 m in Lake IV may have been partially due to the presence of a moderate shelf between 5 and 8 m. However, it is probably correct to view the lower limit of dissolved oxygen during maximum summer stratification as very important in restricting benthos to the shallower parts of these lakes. Thus it is not surprising to find virtually no benthic production in the deepest areas of Lakes III, IV, and V. Less readily accounted for is the low biomass below 4 m in Lake VI where dissolved oxygen was always adequate to 6 m and usually to 7 m.

TABLE 17. Depth distribution of mean percent area-weighted total benthos biomass (mg/m^2).

	Lake					
Depth (m)	I	II	III	IV	V	VI
0-1	405	140	23	27	162	328
1-2	130	117	29	6	52	109
2-3	38	160	6	3	5	116
3-4		127	4	3	0	101
4-5		663	3	3	1	22
5-6		209	1	51	0	49
6-7			0	2		38
7-8			0	0		
8-9				0		
9-10.5				0		
Total	573	1,416	66	95	220	763

The lower boundary of dissolved oxygen was also apparently important in the distribution of the planktonic ciliate *Euplotes* (Fig. 19). Although most of the zooplankton organisms were distributed more or less uniformly as was the total, *Euplotes* tended to be concentrated at, or just below, the lower limit of oxygen where it presumably fed on the bacteria associated with that chemical boundary zone.

The mean biomass data plotted on a monthly basis (Figs. 20 and 21) provide a rough outline of the patterns of seasonal change. These data are admittedly limited, especially for Lakes I and VI. The benthos data for Lake I are inadequate for this purpose and have been omitted.

Zooplankton abundance (Fig. 20) was generally greatest in autumn and in spring or early summer, least in midwinter and midsummer. There were, however, exceptions such as the midsummer peaks of abundance in Lakes III and V. The zooplankton biomass in Lake V fluctuated greatly during

TABLE 18. Depth distribution of mean percent volume-weighted total zooplankton biomass (ind./m^3).

Depth (m)	Lake I	II	III	IV	V	VI
0 -0.5	1,340	56,450	445	590	114,290	8,680
0.5-1.5	1,660	85,050	730	1,540	866,950	41,480
1.5-2.5	4,580	84,700	1,060	1,210	599,400	50,320
2.5-3.5	800	108,280	975	2,600	447,120	31,490
3.5-4.5		94,060	1,705	3,890	98,250	25,860
4.5-5.5		70,070	1,550	4,830	36,360	22,390
5.5-6.5		33,200	650	3,770		14,540
6.5-7.5			425	5,080		4,840
7.5-8.5			220	3,070		
8.5-9.5				1,290		
9.5-10.5				510		
Total	8,380	531,810	7,760	28,380	2,162,370	199,600

summer of 1970, perhaps in response to changing phytoplankton abundance resulting from the artificial fertilization program. No other lake had such pronounced short-term oscillations in biomass.

Benthic biomass in all of the lakes increased through the autumn to a peak in November-December, then decreased abruptly to a low level in March (Fig. 21). In Lakes II, III, and V the benthos remained low during the summer, but in Lakes IV and VI a secondary peak occurred in May-June. The rapid decrease in the benthic biomass in spring was associated with the emergence of insects whose aquatic larvae constituted the bulk of the benthos in all of the lakes except Lake VI (where gastropods made up over 50 percent).

The meromictic lakes did not have any characteristic pattern of seasonal changes in biomass distinct from that of the nonmeromictic lakes. The seasonal patterns do not appear to differ from those

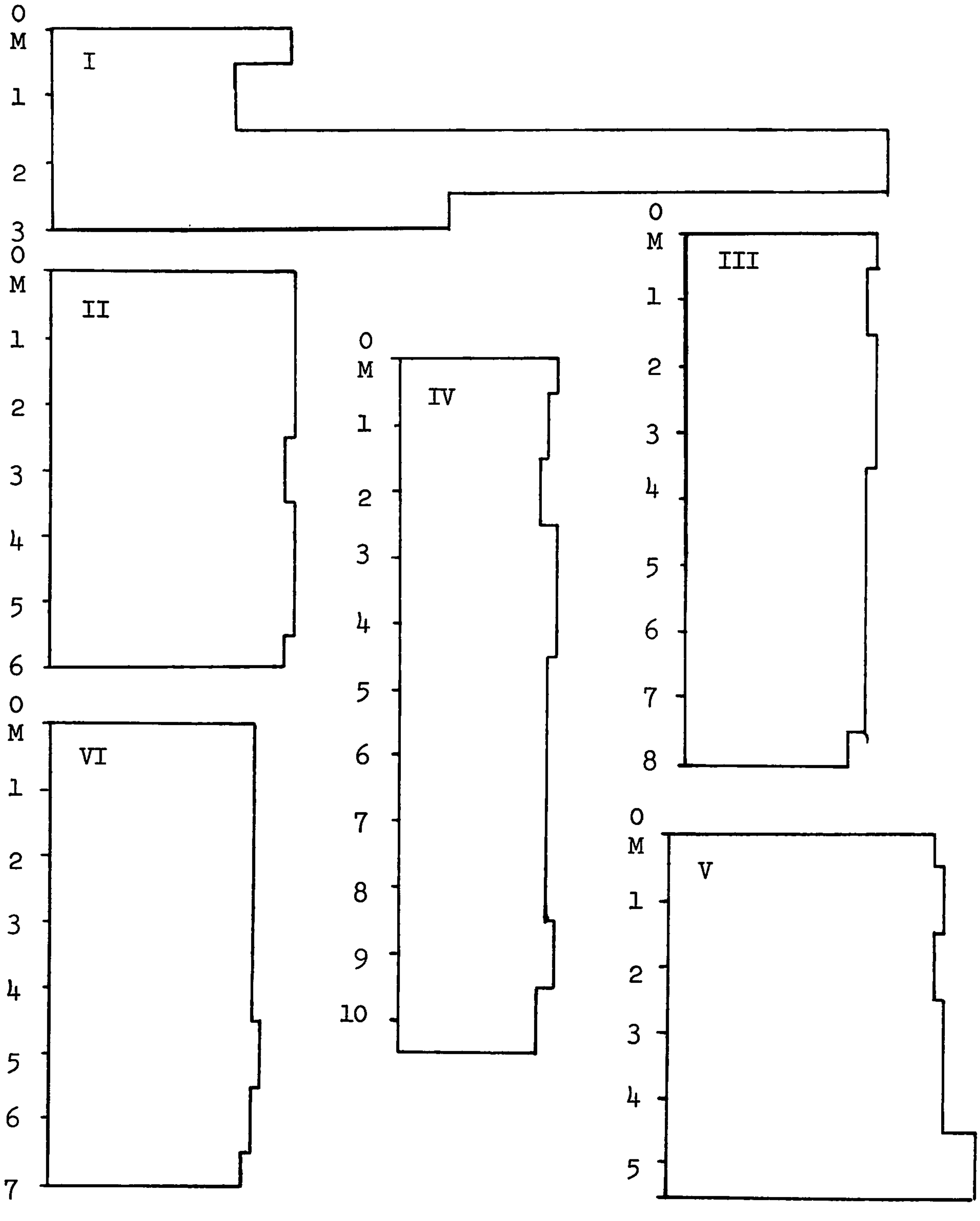


FIG. 17. Depth distribution of unweighted total mean zooplankton standing crop (individuals/m^3).

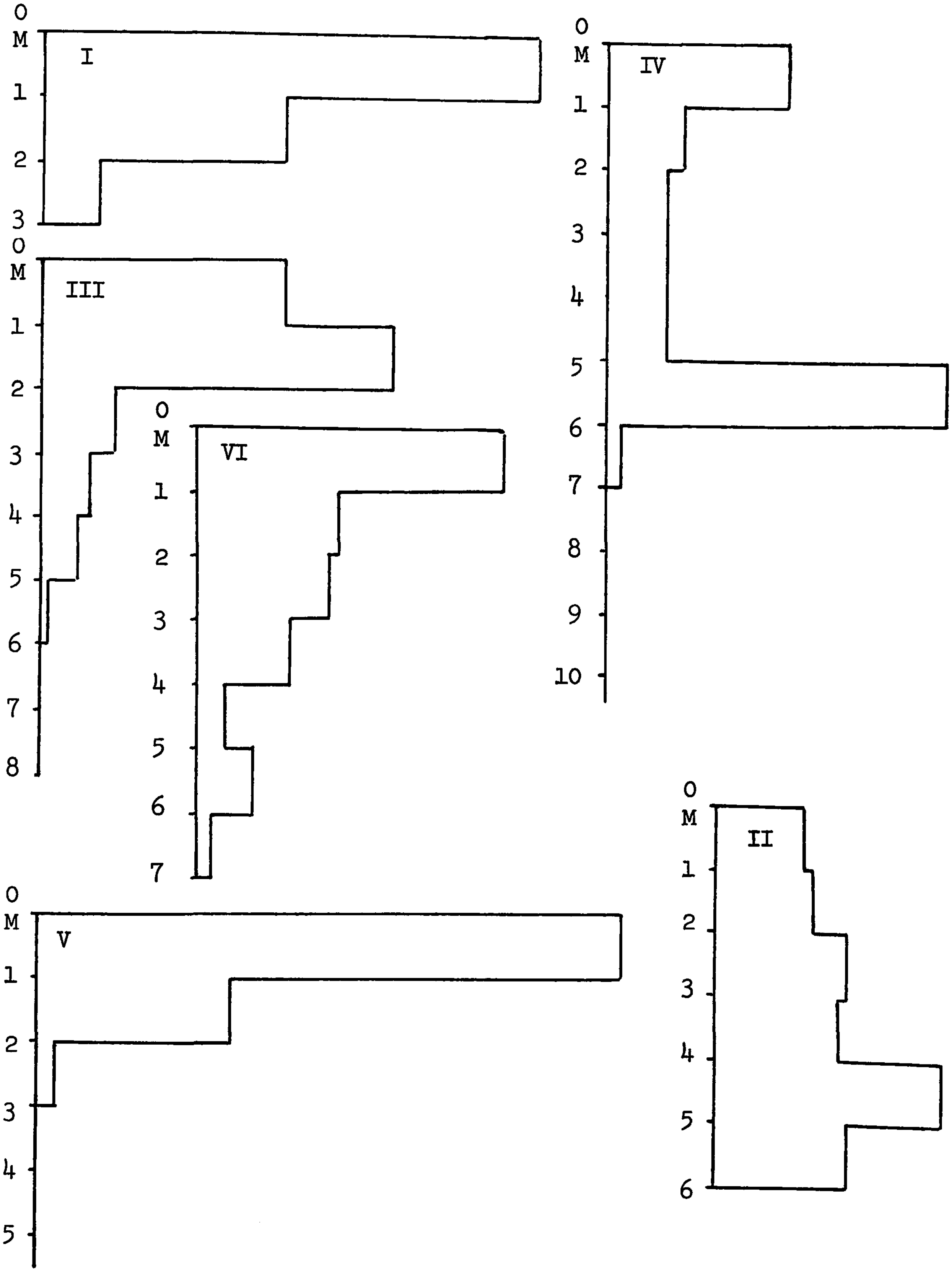


FIG. 18. Depth distribution of unweighted total mean benthic standing crop (mg/m^2).

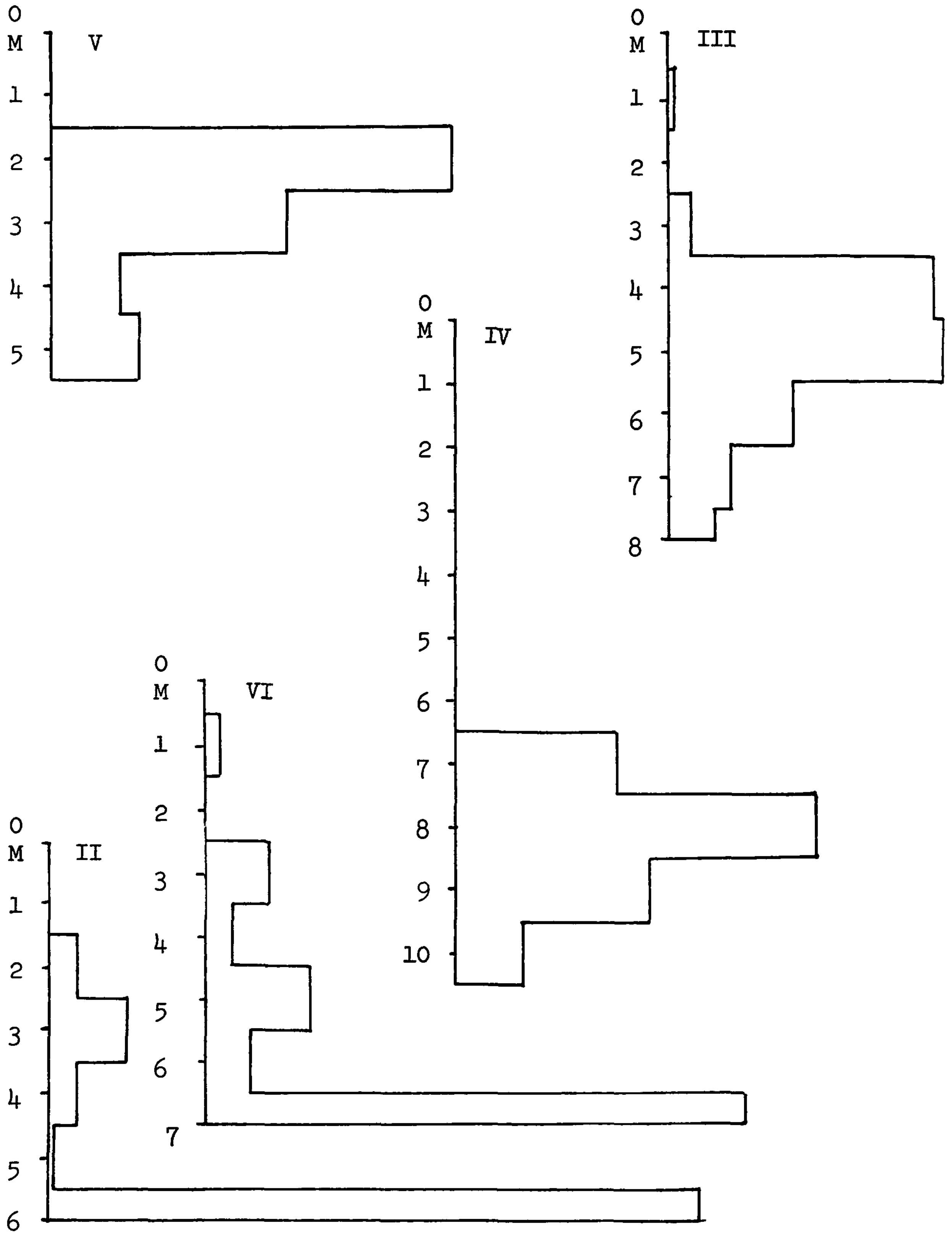


FIG. 19. Depth distribution of unweighted mean Euplotes standing crop (individuals/m^3).

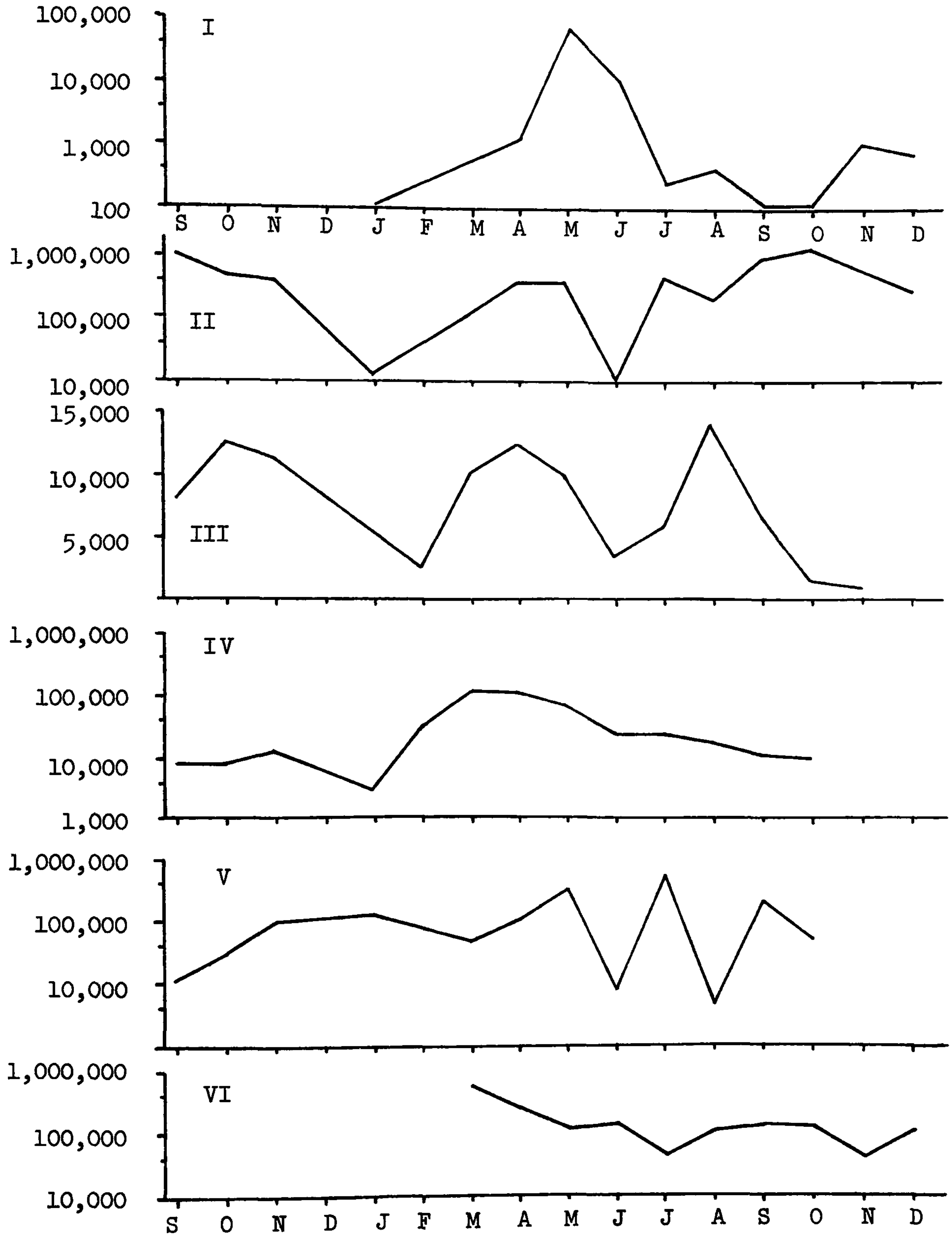


FIG. 20. Seasonal cycles of total zooplankton standing crop (individuals/m^3), September 1969 to December 1970.

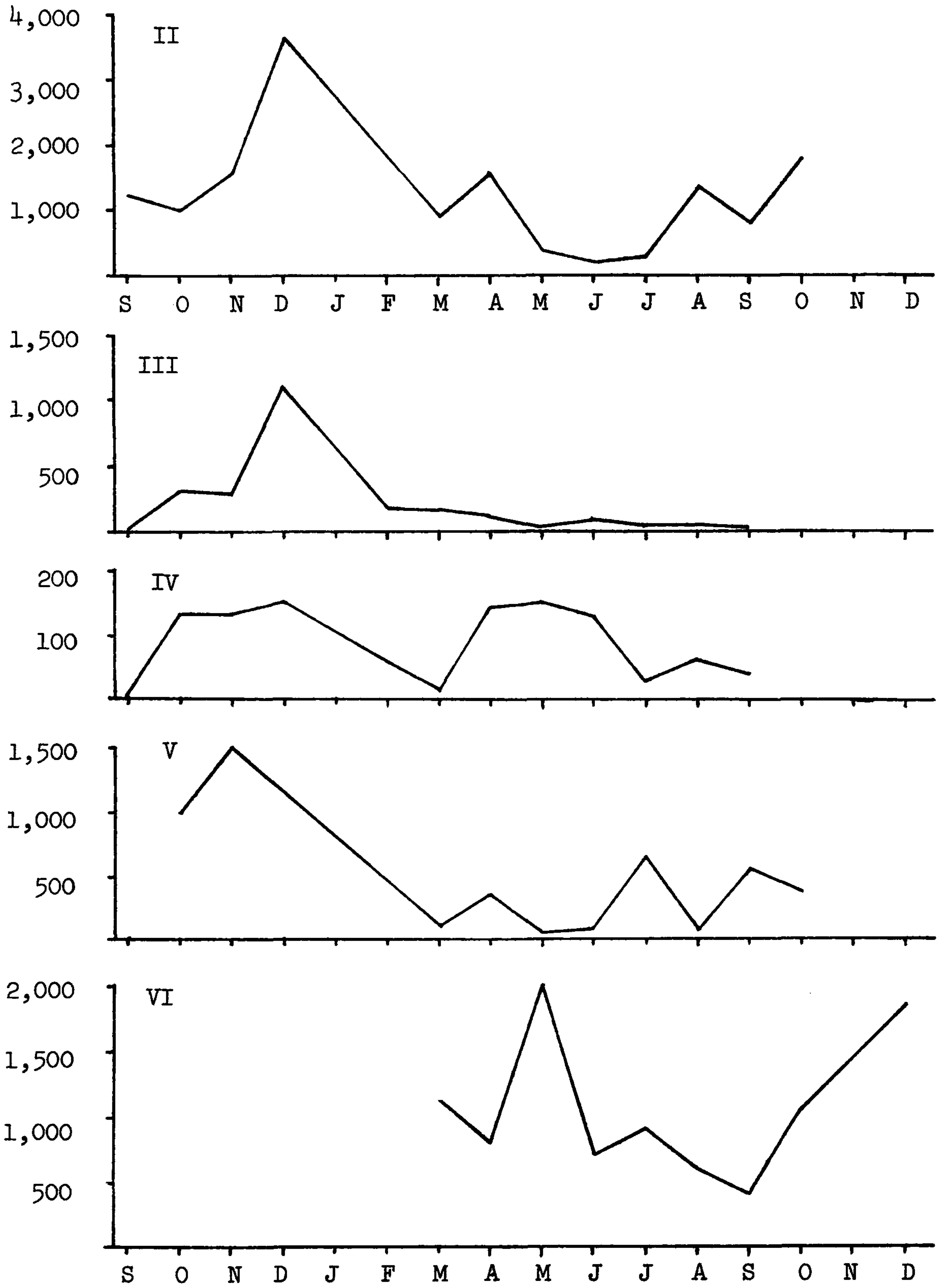


FIG. 21. Seasonal cycles of total benthos standing crop (mg/m2), September 1969 to December 1970.

commonly observed in other kinds of lakes and ponds. Unfortunately, no data are available regarding the relative biomass of the Missouri lakes.

C. Patterns of ecosystem organization

1. The ecosystem concept. The term "ecosystem" was coined by Tansley (1935) to designate a group of interacting organisms together with their nonliving environment. The term embodies the idea that the organisms and their surroundings constitute a functional as well as a structural unit. This idea was eloquently stated and developed by Forbes (1887) in his remarkable essay on the interconnectedness of life within the microcosm of a lake.

When used without qualification, "ecosystem" designates any organism-environment complex from a very small and impermanent unit, such as a fallen log in a forest or a rain puddle on the prairie, to the entire biosphere. In ordinary use, however, only those systems that have at least moderate extension in space and time are intended. Hutchinson (1967) has addressed himself to this problem and for him an ecosystem is "... the entire contents of a biotope." A biotope in turn is "... any segment of the biosphere with convenient upper and lower boundaries, which is homogeneously diverse relative to the larger motile organisms within it ...." The phrase "homogeneously diverse" means that "... the relevant mosaic elements of the environment (sand grains, chemical gradients, etc.) "are small compared with the normal ranges of individuals of species S." If the mosaic elements are large compared to these ranges, the area is "heterogeneously diverse." Thus "The littoral of a lake will be heterogeneously diverse in relation to a natommatid rotifer, homogeneously diverse in relation to a sun fish" (Hutchinson 1967, p. 229).

As I conceive and use the term, an ecosystem ought to have enough size and enough organizational stability (feedback mechanisms, alternate energy and material pathways, etc.) to ensure its integrity over periods of time measured in years (rather than in weeks or months) in the absence of external catastrophe. Obviously, some ecosystems (e.g., temporary ponds) have seasonal cycles of activity.

No ecosystem on earth stands entirely alone. All life on the planet depends ultimately for energy on solar radiation. The earth's larger ecosystems such as the sea, the North African desert, the Taiga, and the Tundra (sometimes distinguished by the term "Biomes") are all linked by biogeochemical cycles, by the common atmosphere, water supply, and store of chemical elements. In general the smaller an ecosystem is, the greater will be the influence of neighboring systems upon it.

Small aquatic ecosystems, like oceanic islands are convenient to study because it is relatively easy to define their spatial limits. The small lakes of the present study were chosen partly for that reason. They were also small enough to treat in a reasonably thorough manner, yet large enough to satisfy the criteria mentioned above. As Forbes wrote (1887), "Nowhere can one see more clearly illustrated than in a lake what may be called the sensibility of such an organic complex (i.e., ecosystem), expressed by the fact that whatever effects any species belonging to it, must have its influence of some sort upon the whole assemblage."

2. Some hypotheses of ecological succession. This enquiry began with the idea that a series of coal stripmine lakes at different stages of recovery from acid pollution could be regarded as a series of stages in the primary succession of a single such lake. It was further suggested that such a set of lakes could be used as an analogue to test hypotheses about ecological succession in general. Odum (1963) suggested that ecological succession has the following attributes: (1) It is an orderly process of directional, and therfore predictable, community changes; (2) It results from modification of the environment by the community; (3) It culminates in the establishment of the maximum possible ecosystem stability. Odum emphasized that the biological community (the "biocoenosis" of Hutchinson 1967) controls ecological succession and that the physical environment "determines the pattern of succession but does not cause it" (Odum 1963, p. 78).

Certain kinds of changes are regarded as generally characteristic of the process of ecological succession (Odum 1959, 1963, Hutchinson 1959, Margalef 1963). These are here set forth in their simplest form: (1) The kinds of organisms present change continuously throughout succession; (2) The number of taxa present increases initially, then stabilizes or declines; (3) Total biomass increases; (4) Net production decreases as a result of an increase in community respiration; and (5) Complexity of organization increases or, in Margalef's terms, total information increases. All these changes are in the direction of increased homeostasis. This pattern occurs only in the context of a relatively stable environment. If the environment is unstable, an ecosystem will be selected that is composed of species with high reproductive potentials and broad environmental tolerances (Margalef 1963).

Before considering the data in this context, one must recall that at least three factors besides pH almost certainly have a strong influence on the stripmine lake ecosystems. The first is morphometry. Deevey (1941) failed to find a good correlation between mean depth and bottom fauna in small lakes in New England. On the other hand, Rawson (1955) and Rounsefell (1964) have demonstrated a correlation between relative extent of the shallow littoral zone and productivity of bottom fauna and fish. Several authors including Burner and Leist (1953), Arata (1959) and Klimstra (1959) have suggested that the very restricted area of the shallow shore zone in most stripmine lakes may be an important factor limiting production of benthic organisms and organic production in general. Prospective spawning sites are, also, thus limited. Verts (1956) observed that muskrats living in stripmine ponds were forced to burrow into the banks, because the restricted littoral areas were too small to permit house building.

The second factor, meromixis, is related to morphometry in two ways. The narrow deep basin shape undoubtedly predisposes these lakes to incomplete turnover. In addition, such narrow deep lakes necessarily have a relatively small proportion of their volume in the upper circulating mixolimnion.

The third factor is the relatively low habitat diversity present in the mine lakes. Substrates present are limited almost entirely to clay, fallen leaves, and in some cases tree branches. In the two lakes where they occur in significant volume (IV and VI), rooted aquatic plants provide a substrate for some organisms.

All three factors probably depress both production and diversity in the study lakes. However, the first affects all the study lakes except I, and the third affects all six. Only meromixis has a pronounced differential occurrence--affecting primarily Lakes III, IV, and V (since the monimolimnion of Lake VI is limited to the 6-7 m stratum and dissolved oxygen is usually available at all depths).

The rate of ecological succession is highly variable, depending on regional climate and geomorphology, kind of ecosystem, stage of the evolutionary process, and many other factors. Generally change is slow at first, then accelerated and finally slowed again in the late stages.

3. Some evidence: system changes in the Indiana lakes. If the six stripmine lakes do in fact represent a series of stages in the successional development of an ecosystem, then some or all of the trends listed above should be present in the series. In this section the data are considered in relation to these hypothetical patterns of directional change.

(1) The composition of the biocoenosis changes continuously throughout succession. This was certainly true of the fauna (Table 13). Considerable change occurred at each step in the series including that from Lake IV to Lake V at which 14 taxa were replaced with no net change in number of taxa. Generally, the overall change in composition of the fauna was greater in the earlier stages of the series.

(2) The number of taxa increases, especially in the early stages of succession. This, too, was generally true for the fauna. The data (Tables 4 and 13, Fig. 14) show a progressive increase in number of animal taxa except in Lake V. The rate of increase was greater in the early stages (i.e., acid lakes) than in the later ones. Hall *et al.* (1970) reported that predation by bluegills (*Lepomis macrochirus*) in a series of artificial ponds increased diversity of prey species (zooplankton and benthos), presumably by reducing competition between the prey species. This kind of effect might account for the relatively great increase in diversity from Lake III to Lake IV in the present work.

(3) Biomass increases during the course of succession. This was true only in a very general sense. A review of the data (Tables 14 and 16, Fig. 16) will show that faunal biomass was not well correlated with pH. Other factors, especially those associated with meromixis, were also important.

(4) Net productivity decreases during the course of successions. An increasingly greater fraction of the gross productivity is used within the ecosystem as it matures leading to longer food chains and a greater standing crop of secondary, tertiary, and higher order consumers. The general increase in the proportion of predators among the benthos (Table 6) suggests an increase in net productivity, as does the increase in fish (Table 7) which are the top carnivores in those lakes where they occur. In Lake V, the increase in net productivity was apparently translated into a relatively very high biomass of benthic predators at the expense of the fish population (or perhaps a more correct view would be that other factors limited the fish and thus allowed invertebrate predators to increase). The overall increase in the relative importance of higher order consumers is illustrated by the combined data (as percent of maximum) for fish and benthic predators (Fig. 22).

(5) Ecosystem organizational complexity increases during succession. This hypothesis implies such factors as increase in diversity of pigments and other biochemicals, increase in ecosystem compartments and alternative pathways, greater habitat diversity, and increase in the total amount of information in the system. One historical approach to assessing this aspect of ecosystems has been the study of the relationship between the number of taxa ("biotic diversity") and the size of the area studied (mainly plant studies) or the number of individuals (mainly animal studies).

A much more comprehensive approach to the study of ecosystem complexity is that of systems ecology. Among others, Van Dyne (1966) and Patten (1966) have discussed the frame of reference and chief goals of what might be called the "mainstream" of systems ecology in the U.S. In general, a systems analysis includes the identification and quantification of compartments (variables of habitat, resources, and biocoenosis) and their interconnecting pathways of material and energy transfer. An increase in the number of compartments implies more pathways, greater redundancy, increased feedback, and hence increased homeostasis and stability. In the lakes of this study, the only really significant differences in compartments appeared to be those of the biocoenosis. That is, the environmental (habitat and resource) variables did not differ appreciably. From this it follows that the observed increase in biological compartments at various levels (i.e., the addition of major taxa such as rooted plants and fish, or of minor taxa such as additional species of rotifers or insect larvae) implies a corresponding increase in organizational complexity.

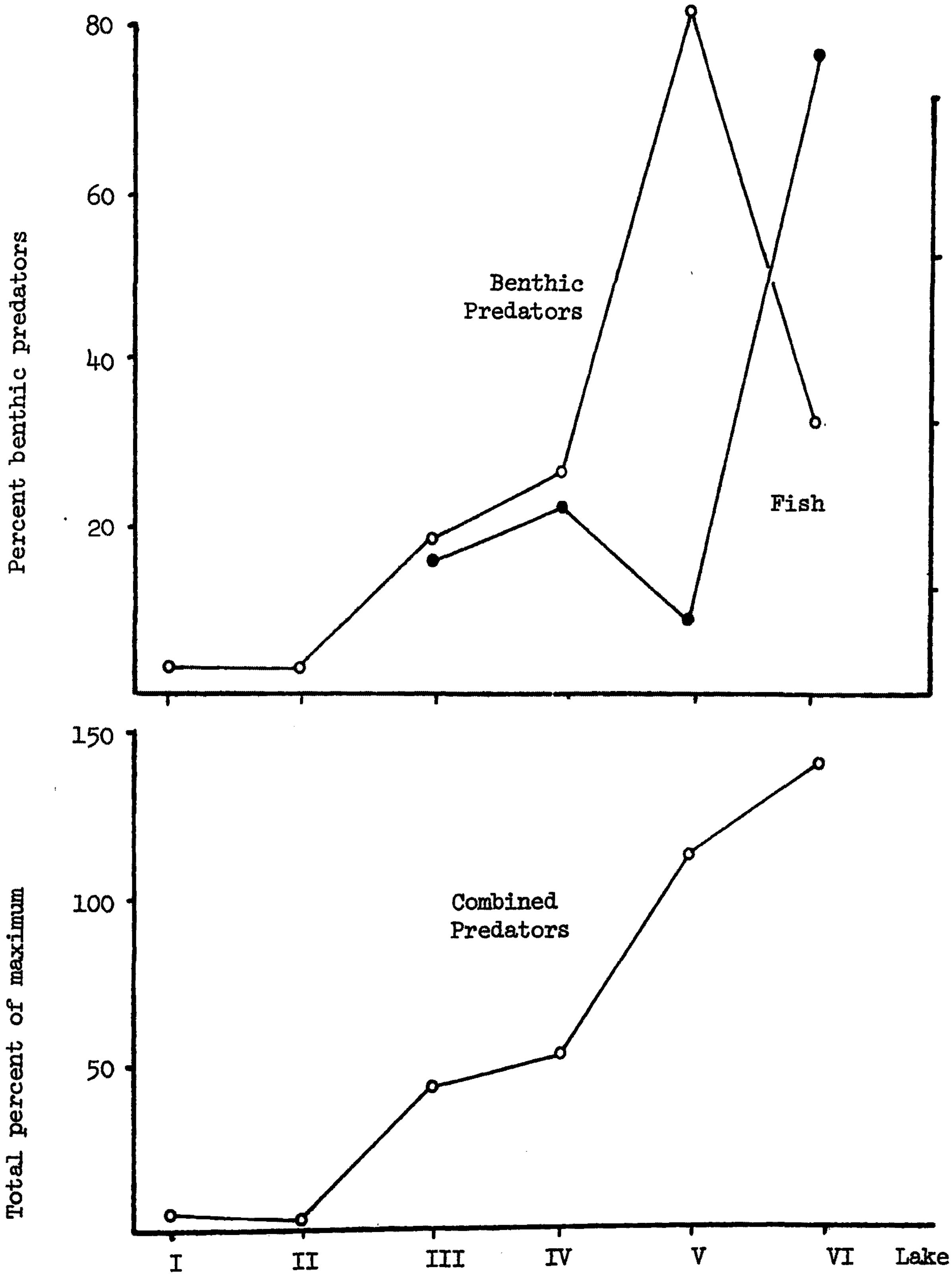


FIG. 22. Increase of fish, benthic predators, and combined higher consumers in Indiana lake series.

One line of evidence that bears upon this question is that of seasonal changes in biomass. If it is true that homeostasis, and hence stability, increase with increasing pH in the six lakes, then this should be "expressed" in terms of a sequential damping of the seasonal oscillations. An examination of the curves for zooplankton (Fig. 20) suggests that the more "mature" systems (Lakes IV through VI) do, in fact, have seasonal variations of somewhat less dramatic magnitude than the less mature Lakes I and II. As noted previously, the fertilization of Lake V in summer apparently resulted in dramatic oscillations between May and September 1970. The bottom fauna cycles (Fig. 21) are expected to be more oscillatory because of the emergence of aquatic insects at certain seasons. It appears, however, that Lake VI had much higher minima than the others.

Thus it would seem that the hypothesis of increasing organizational stability is supported, in a somewhat limited way, by the data.

D. Alternative patterns of stripland utilization

1. General utilization. The general question of the best use for abandoned coal stripmine areas has been much discussed (Arata 1957, Birkenholz 1958, Bowden 1961, Burner 1956, Burner and Schoonover 1953, Funk 1962, Hall 1940, Harman 1957, Holmes 1944, Lewis and Nickum 1964, Limstrom 1948, Limstrom and Merz 1949, Roseberry 1963, Riley 1947, 1954, 1957, Sawyer 1949, Touenges 1939, USDI 1967, Wells 1953, Yeager 1940 and many others). A rather large percentage of the abandoned coal striplands in southern Indiana and Illinois and in central Missouri that I have visited are not presently utilized in any fashion, but rather ignored beyond nominal replanting. Of the many possible uses for old coal stripmine areas, the following would seem to be among the most practical.

a. Wildlife habitat. Some areas of old stripmine land in the Patoka Fish and Game Area have been designated as wildlife areas. Even with rather extensive planting of food plots, the density of most species is extremely low. Perhaps improvements in reclamation procedures leading to increased plant growth, and hence in improved cover and food supply, would increase wildlife populations.

b. Farmlands. In many areas, including some of southwestern Indiana, the land stripped for coal was never very good farmland. Thus even if sources of acid pollution were covered and the topsoil restored to the surface, it would be suitable for little more than rangeland or pasture. In some areas old striplands have been restored to satisfactory crop production (see USDI 1967). Recently, sludge from Chicago's treatment plants has been used to fertilize old stripland in Fulton County, Illinois, with striking results (Anonymous 1971).

c. Residential. Abandoned stripmine lands can provide space for human habitation, either in the form of single-family dwellings or as multiple-dwelling complexes. This use is compatible with a and b above. While some very attractive farm homes, summer cabins, and permanent residences have been observed by the writer on abandoned striplands in Indiana, much greater utilization would be possible without overcrowding or "despoilation" of the landscape.

d. Recreational areas. Some very attractive recreational sites have been developed on old stripmine areas. Such areas may include golf courses, camping and picnicking facilities, water sports areas, etc. (see USDI 1967). Again, the potential for this sort of development on abandoned striplands has been little realized.

2. Sport fishing in the final cut lakes is quite compatible with all of these uses. In the course of numerous conversations with local anglers, it has become apparent to the writer that even the nonacid stripmine lakes in the study area do not usually provide very good fishing success. Some results of this study having implications for the formulation of management techniques that could improve fish production in such lakes are here briefly discussed.

a. Meromixis in these lakes has several implications for their successful management. Therefore, a regular schedule of limnological sampling should be undertaken on any lakes to be manipulated for sport fishing. Such a program should, at a minimum, include depth series for temperature, dissolved oxygen, pH, conductivity, and transparency. These data would indicate the presence or absence of meromixis and the gross effects of any management procedures undertaken. The two main direct effects of meromixis are: (1) Solutes become "trapped" in the monimolimnion. This might be desirable in the case of high concentrations of inorganic ions, but unfortunate in that of essential nutrients. (2) Dissolved oxygen is usually not present in the monimolimnion at any time of the annual cycle. Further, during summer thermal stratification the oxygenated epilimnion may be shallower than if the lake were holomictic. This confines many groups of animals to the surface strata where other factors (e.g., temperature) may be suboptimal.

Under some circumstances it would probably be possible to convert meromictic stripmine lakes to holomixis by pumping deep water up to the surface, most effectively at the time of partial overturn. If all sources of excess solutes could be stopped, a permanent change should be possible.

b. Basin shape is quite important to the production of benthic animals, which are, in turn, an important food source of some medium- and large-size game fishes. In the stripmine lakes, the steep-sided form of the basin restricts the shallow area of greatest benthic production. This effect, as we have seen for Lake III (pp. 55-56), can be compounded by meromixis. A comparison of bottom fauna distributions with area and depth (Fig. 23) illustrates this relationship in the lakes of the present study. The concentration of bottom fauna in the shallows was especially marked in Lakes III and V, but only in Lake II was the distribution very uniform.

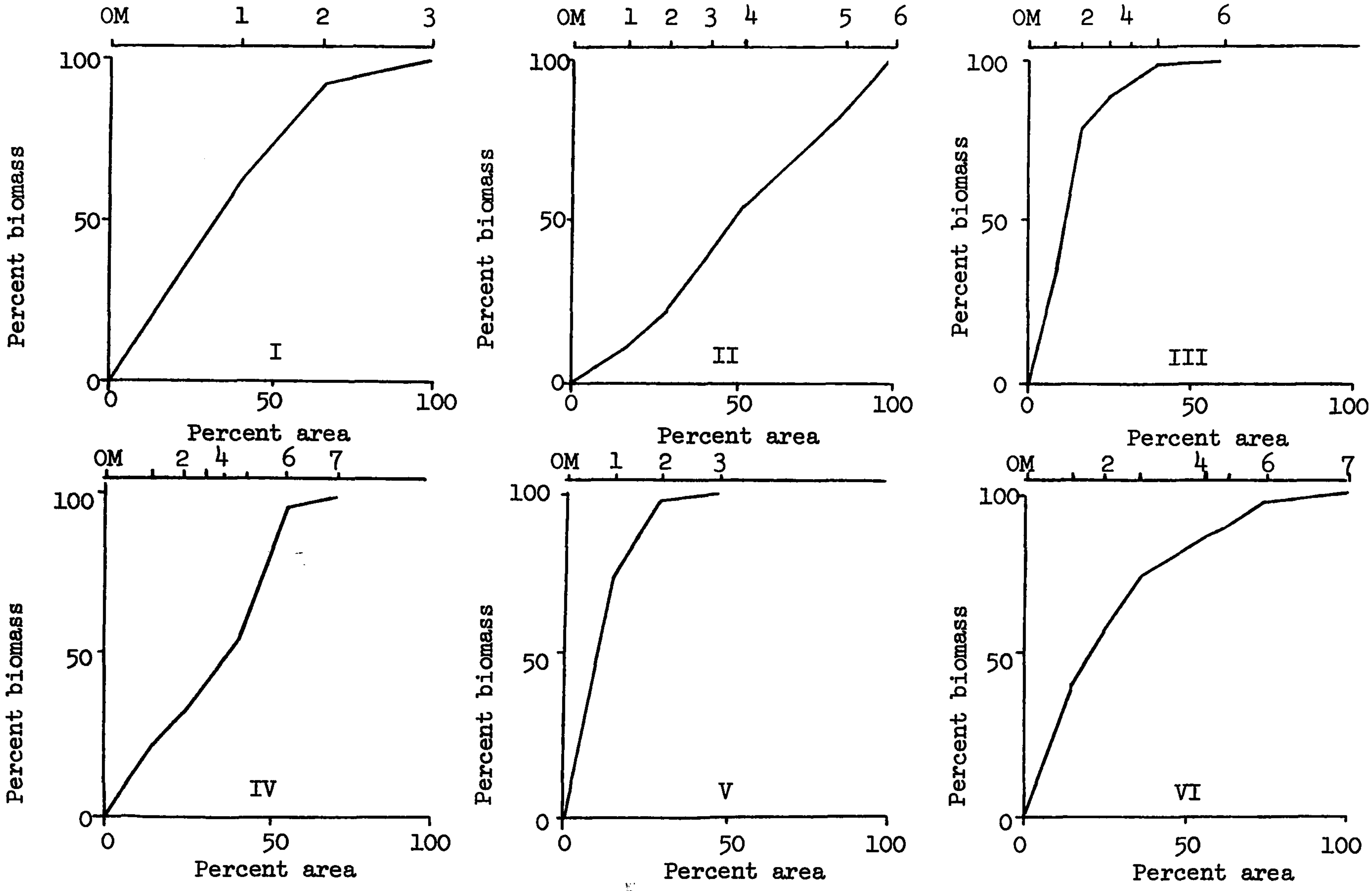


FIG. 23. Distribution of benthic biomass with depth and area in the Pike County lakes.

Thus one obvious way to improve bottom fauna production in such lakes would be to increase the extent of the shallow littoral zone. The stripmine lake most productive of fish in the Patoka Fish and Game Area is one in which the littoral was extended in the mid-1960's by construction of a low earth-fill dam. It is apparently the only stripmine lake in the region that supports fish populations approaching those of typical local nonstripmine ponds. Whenever feasible, the use of this technique should materially improve fish production in stripmine lakes.

c. Fertilization, if practiced, would require careful monitoring and regulation. The resultant high algal production, such as observed in Lake V, can lead to heavy mortality among fishes and other animals because of (1) oxygen depletion during the dark period (or even on cloudy days) resulting from algal decomposition and the respiration of both algae and the dense zooplankton populations that accompany such blooms, and (2) toxic substances released by decomposing algal masses. Excessive algal production can also reinforce meromixis by adding a biogenic component to the crenogenic element already present. One intentional effect of lake fertilization is the "shading out" of rooted aquatic plants (Bass 1964). While excessive growth of the macrophytes may be undesirable, their complete and lasting eradication (as has been accomplished in Lake V) seriously reduces habitat diversity, which is already quite low in stripmine lakes. The rooted plants provide food as well as shelter for benthic animals, and are important in recycling nutrients from the bottom sediments.

SECTION VII

APPENDICES

<u>Appendix 1.</u> <u>Time-depth diagrams</u>

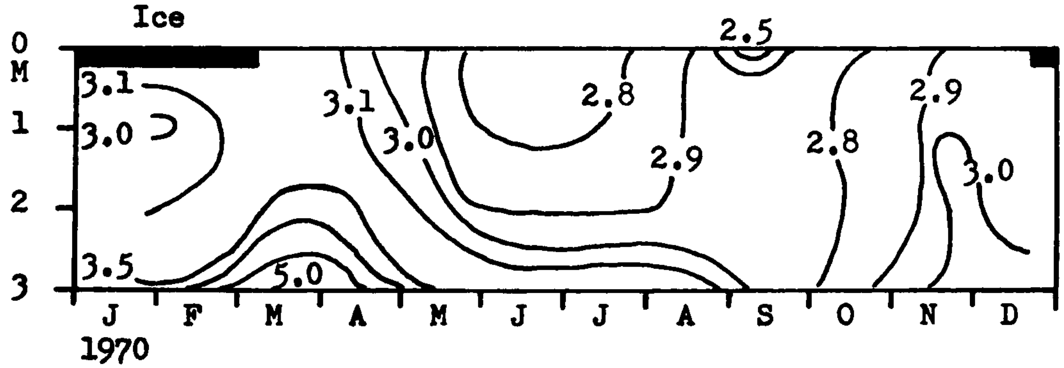


FIG. 24. Time-depth diagram of pH variation in Lake I.

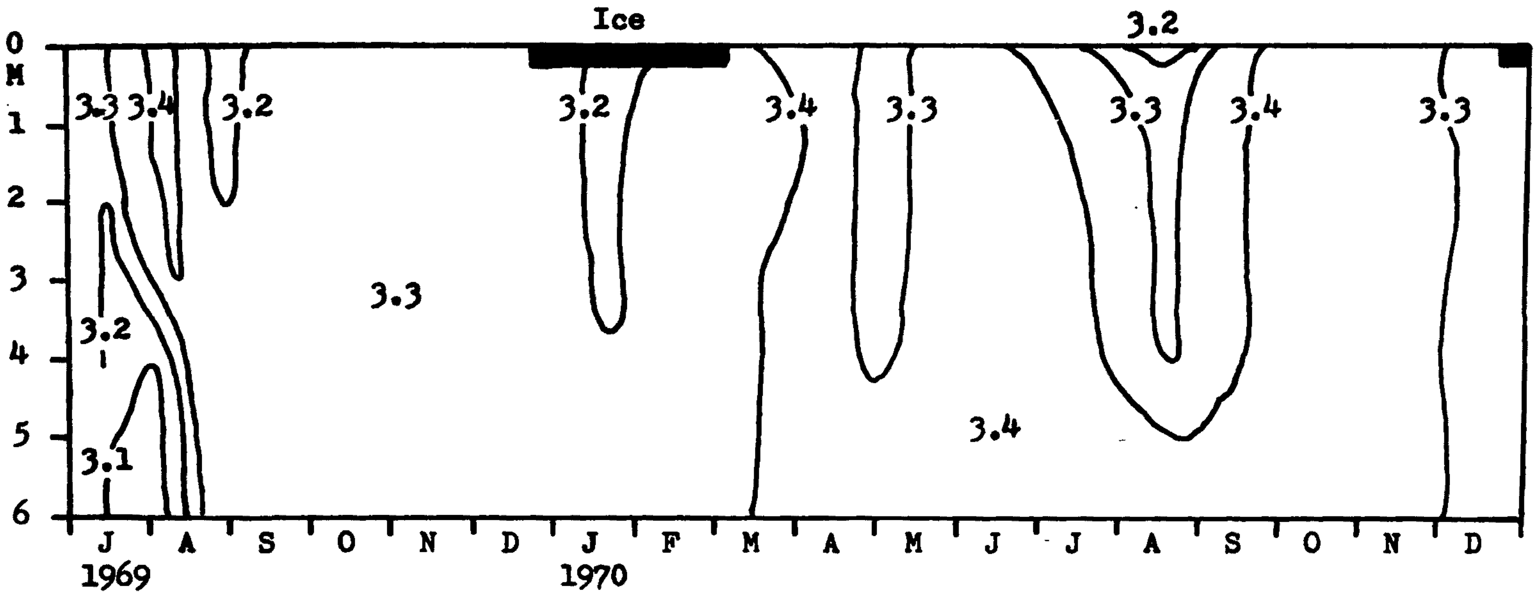


FIG. 25. Time-depth diagram of pH variation in Lake II.

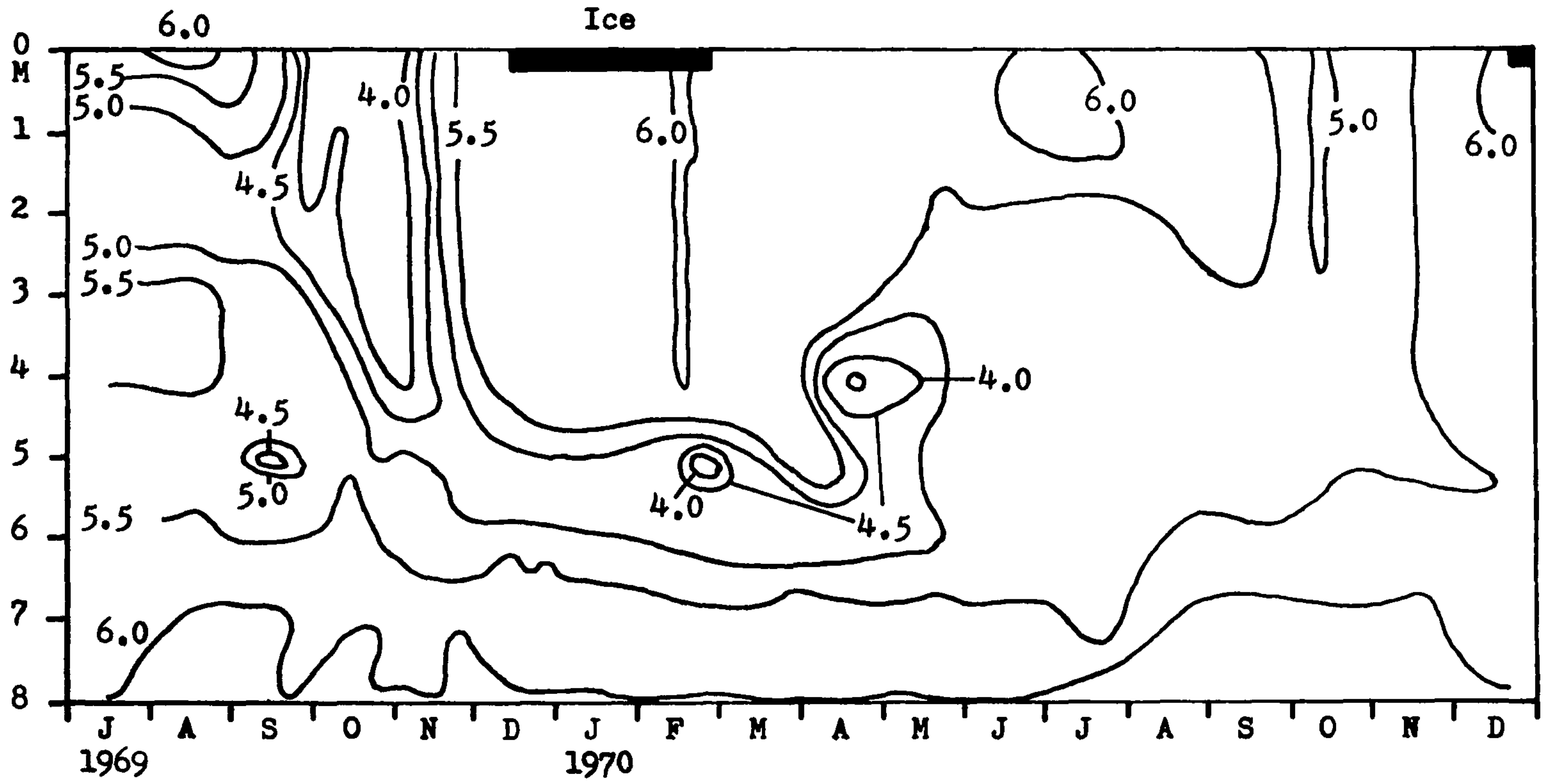


FIG. 26. Time-depth diagram of pH variation in Lake III.

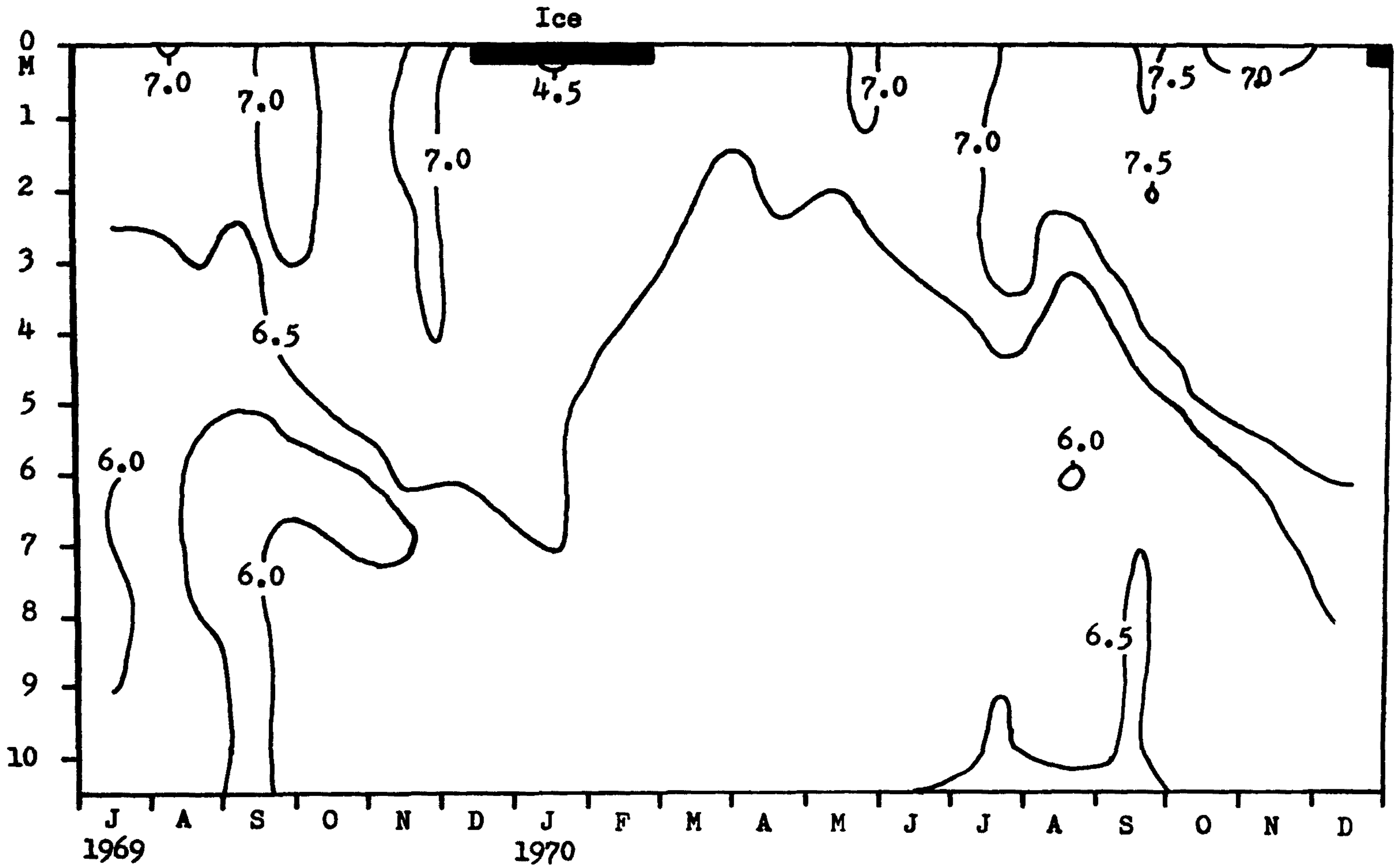


FIG. 27. Time-depth diagram of pH variation in Lake IV.

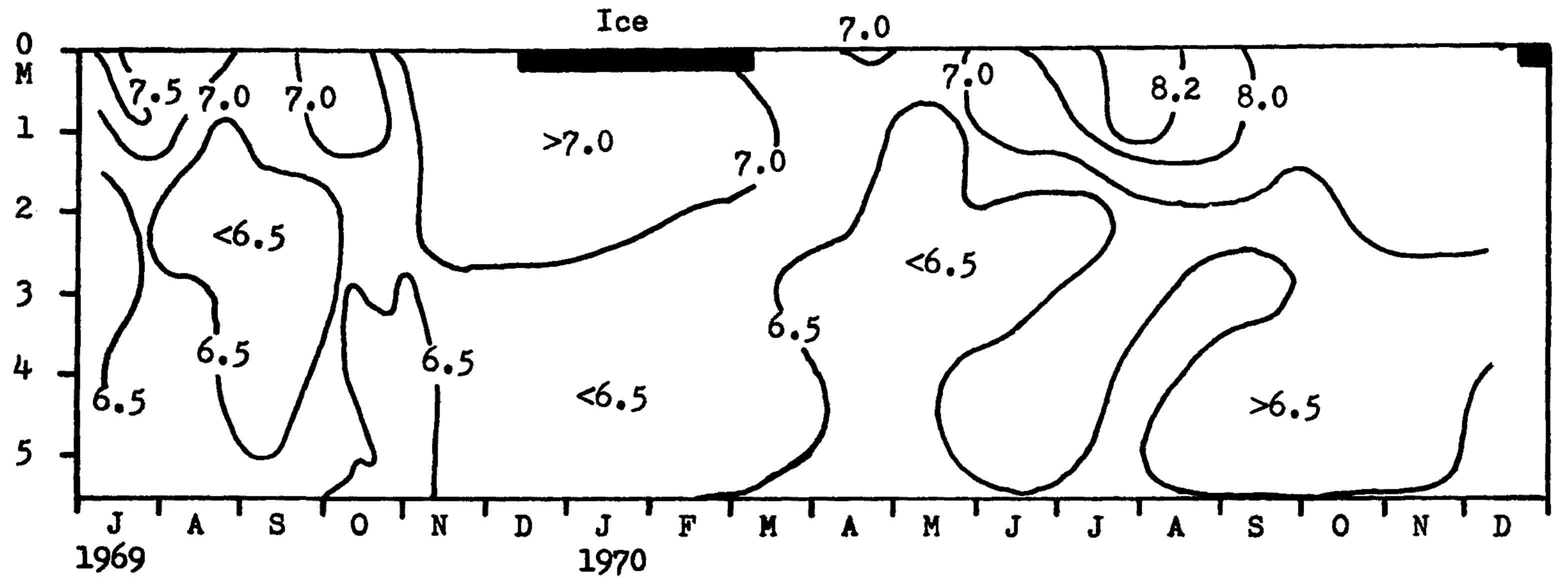


FIG. 28. Time-depth diagram of pH variation in Lake V.

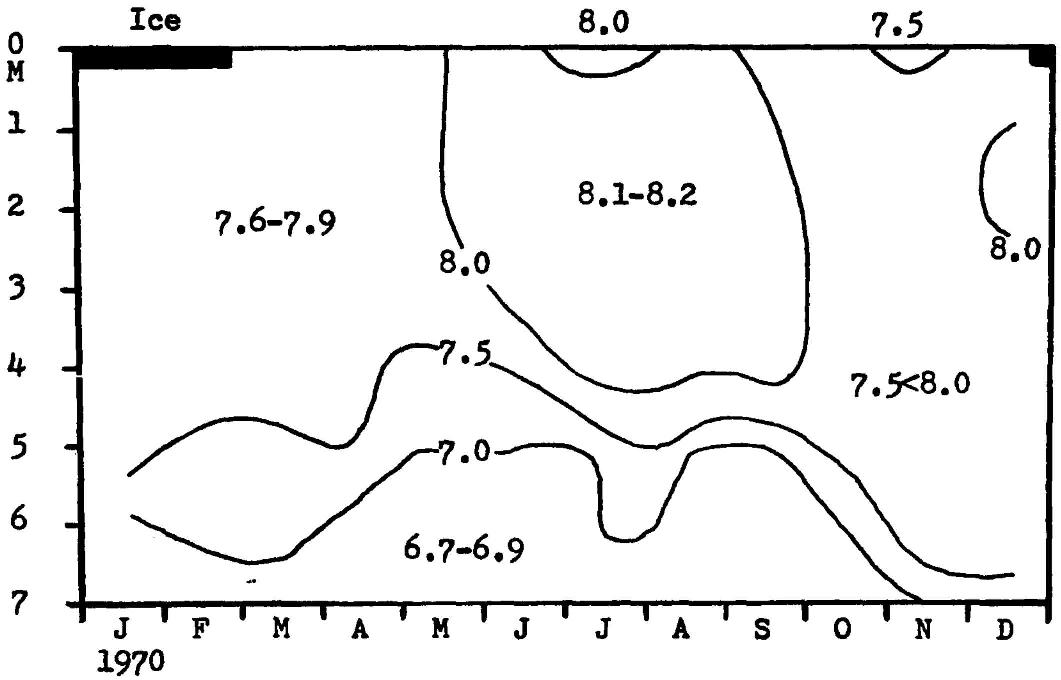


FIG. 29. Time-depth diagram of pH variation in Lake VI.

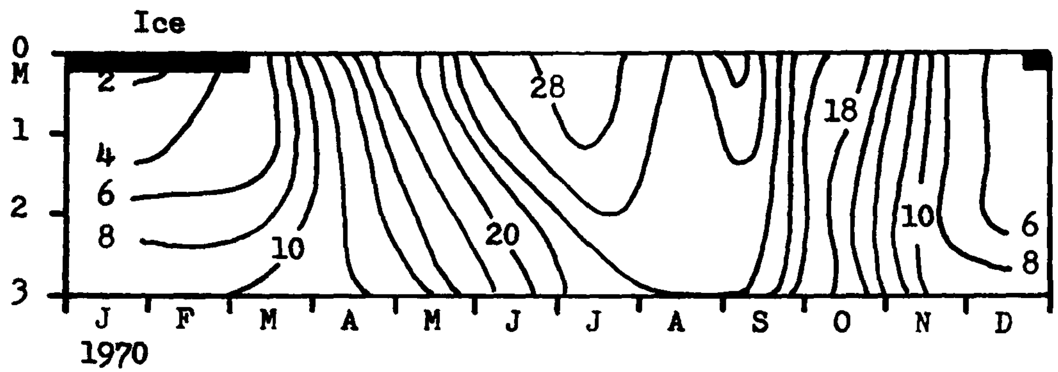


FIG. 30. Time-depth diagram of temperature variation (°C) in Lake I.

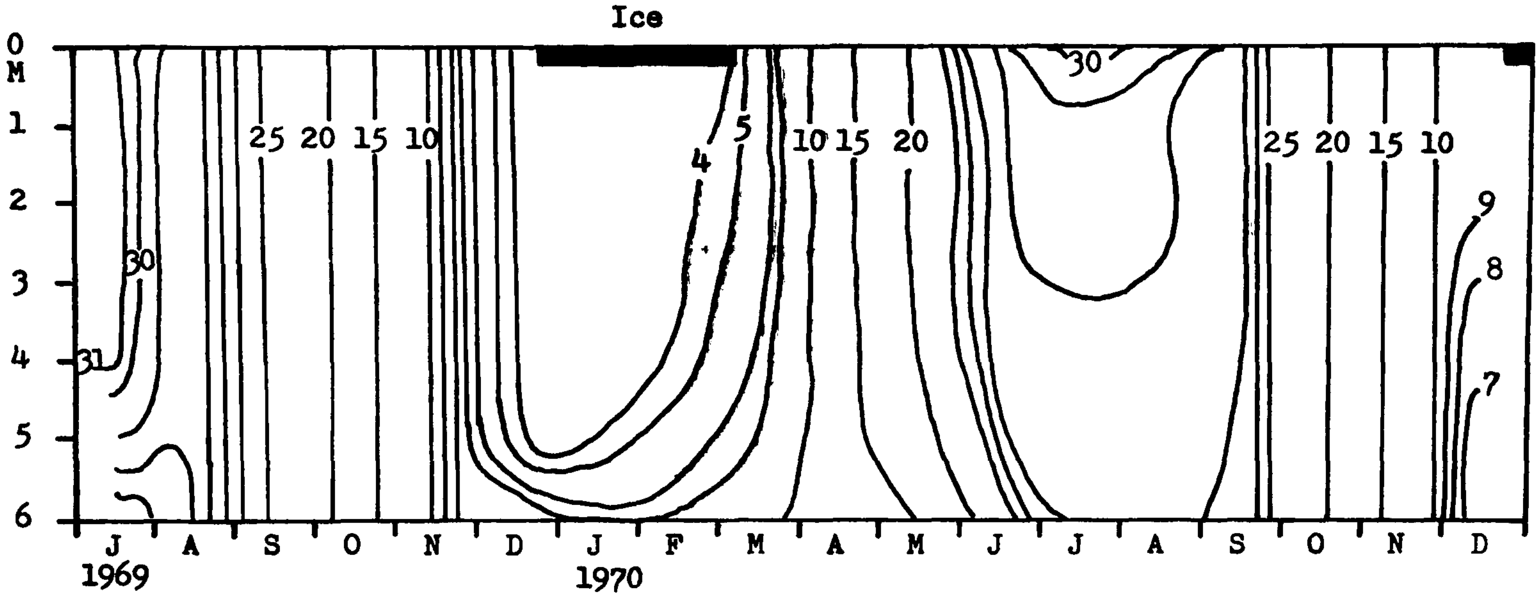


FIG. 31. Time-depth diagram of temperature variation (^{o}C) in Lake II.

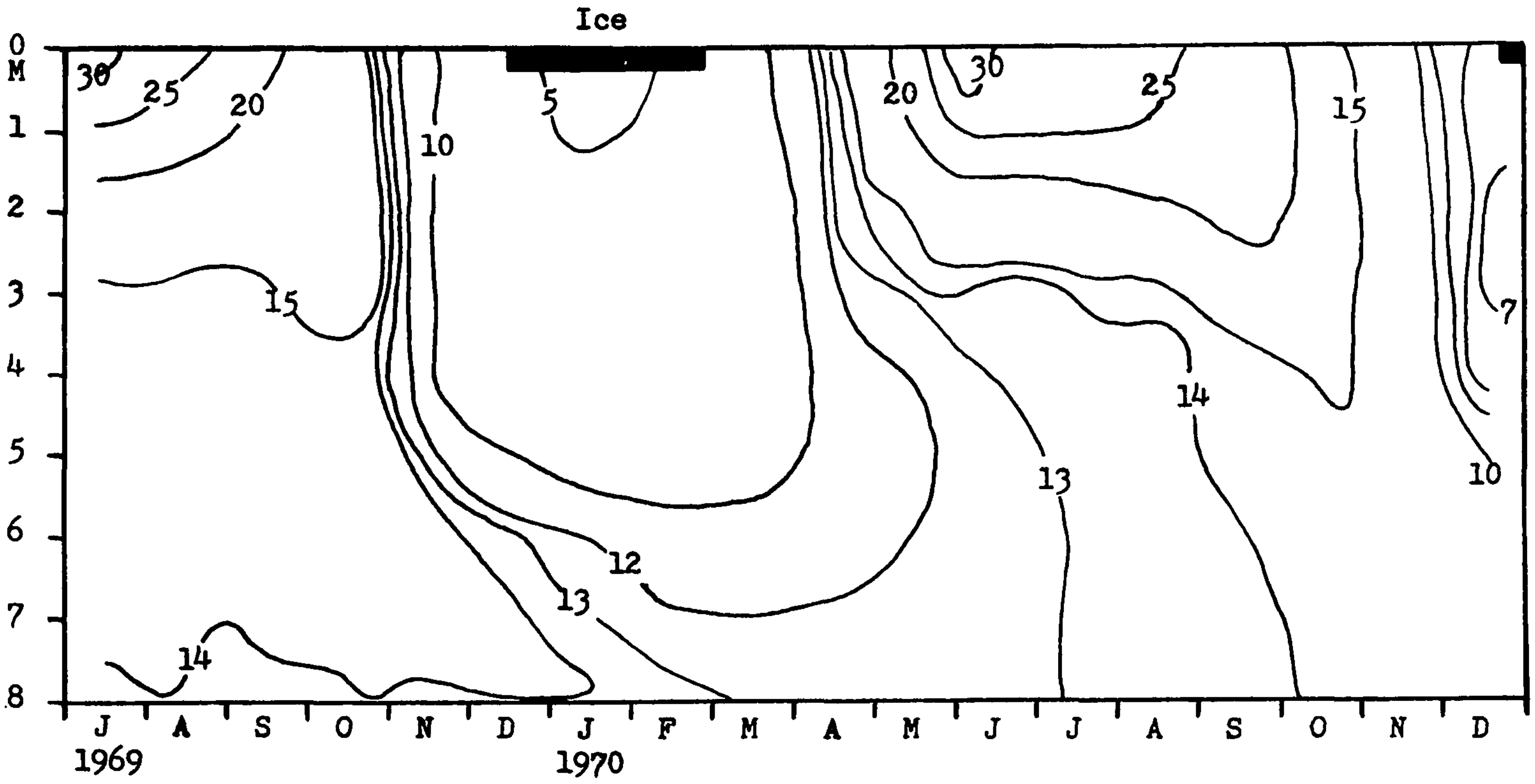


FIG. 32. <u>Time-depth diagram of temperature variation (°C) in Lake III</u>.

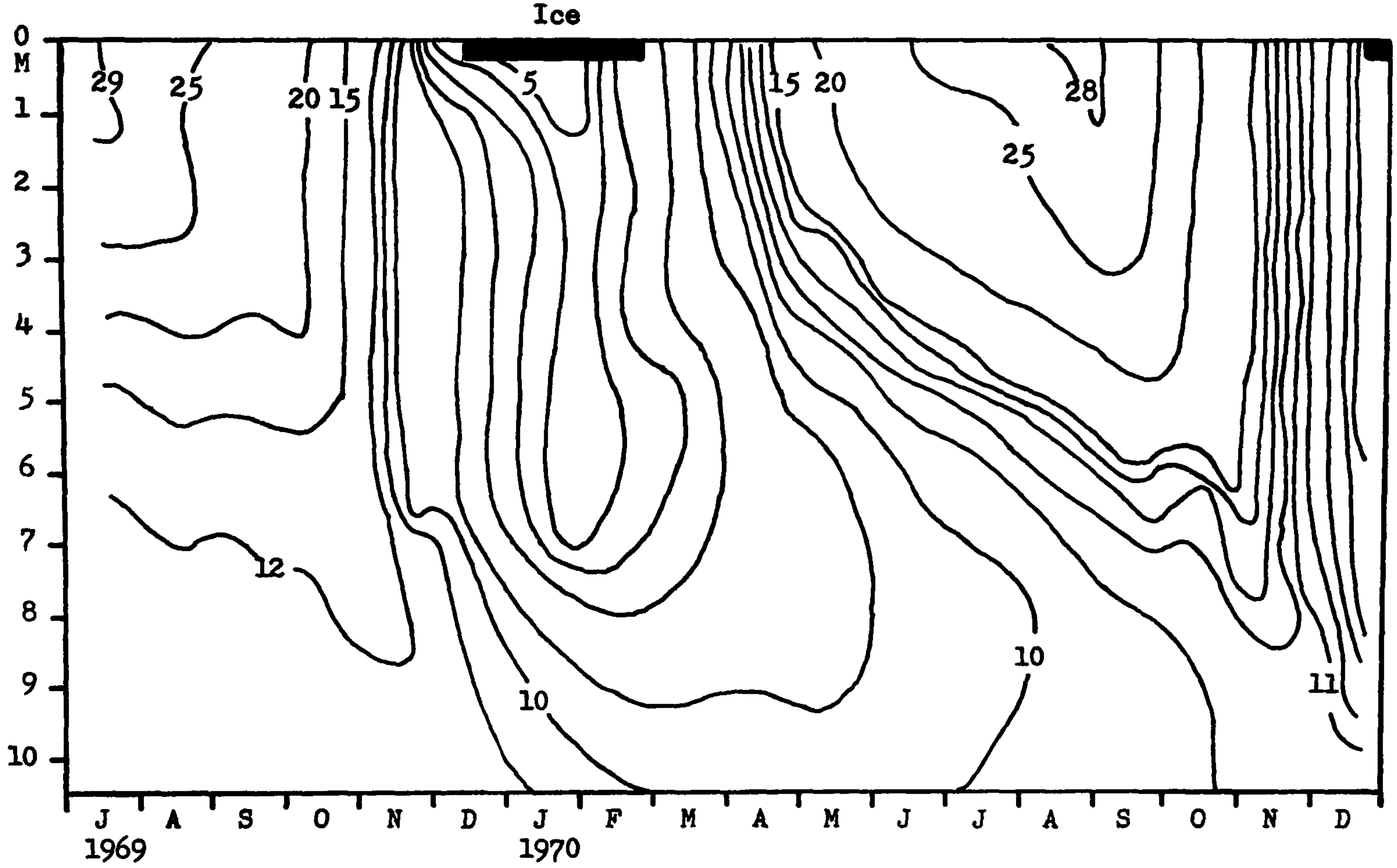


FIG. 33. Time-depth diagram of temperature variation (°C) in Lake IV.

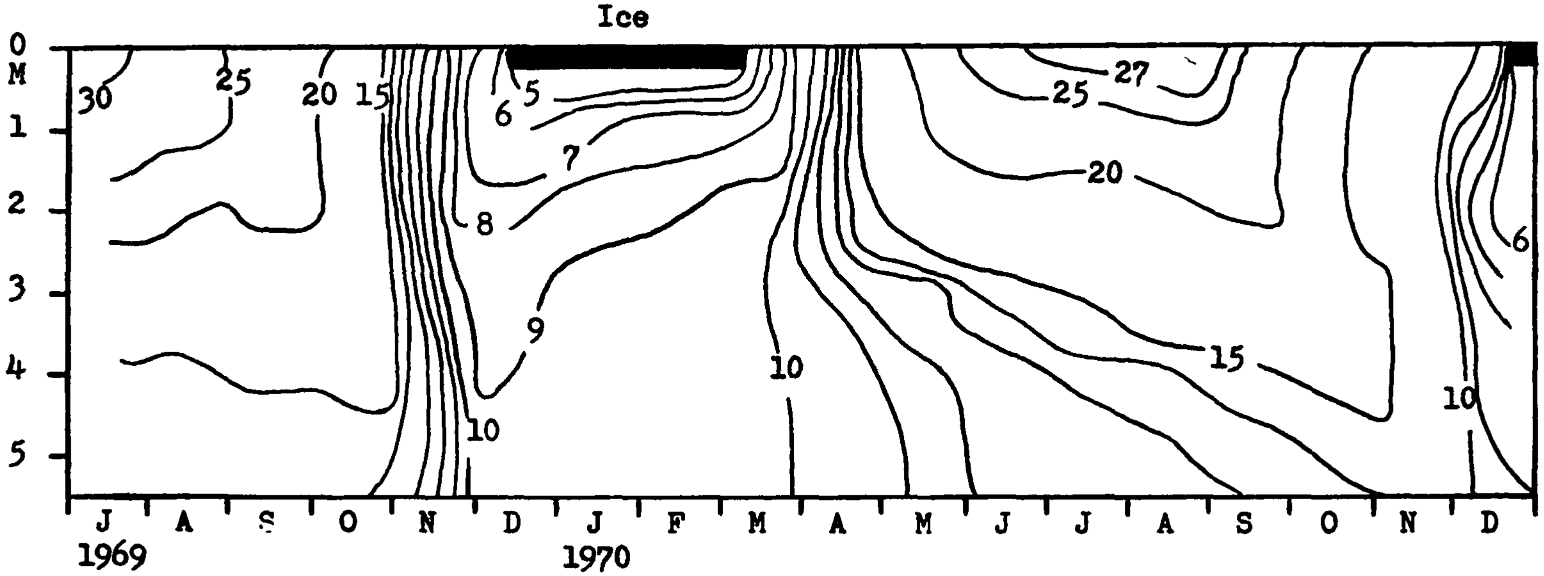


FIG. 34. Time-depth diagram of temperature variation (°C) in Lake V.

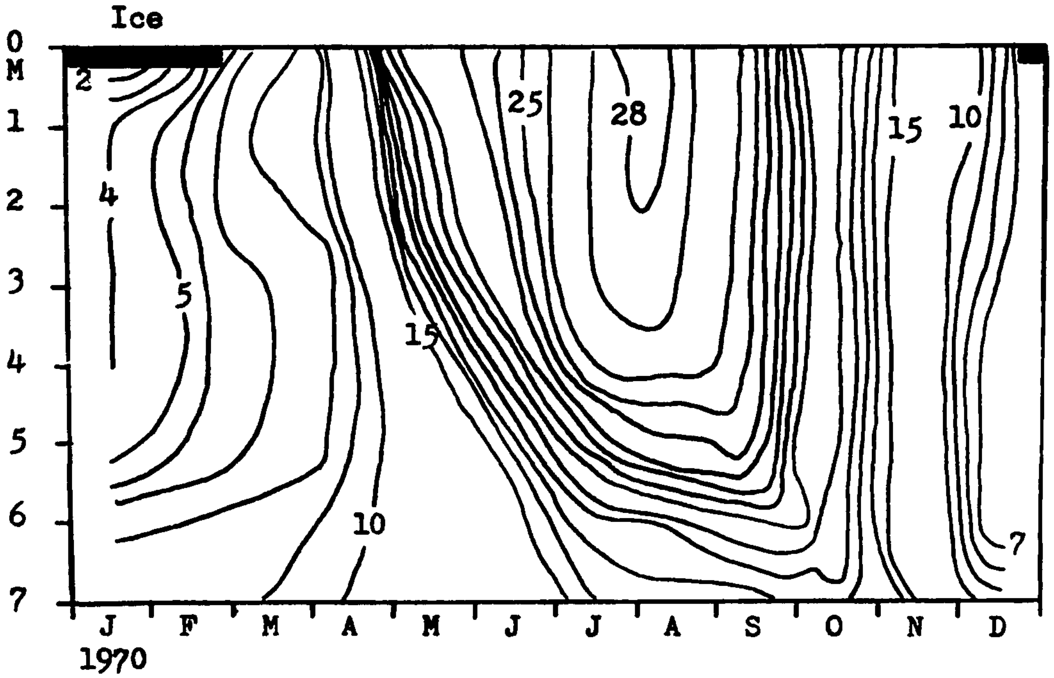


FIG. 35. Time-depth diagram of temperature variation (°C) in Lake VI.

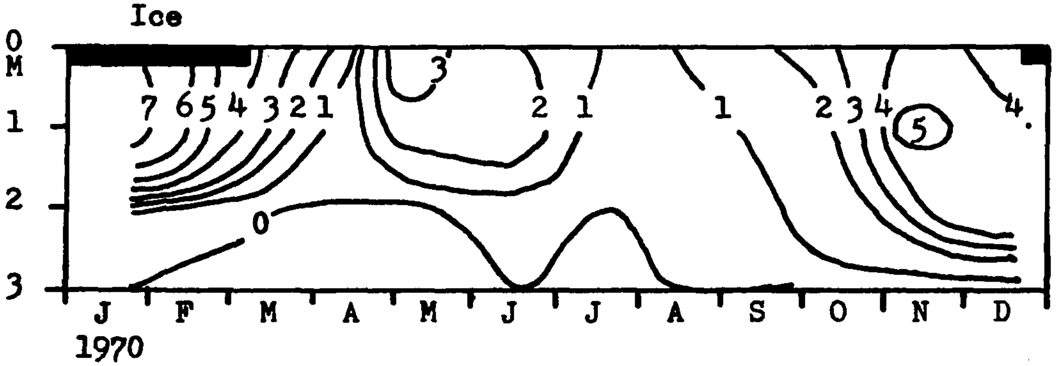


FIG. 36. Time-depth diagram of dissolved oxygen variation (mg/l) in Lake I.

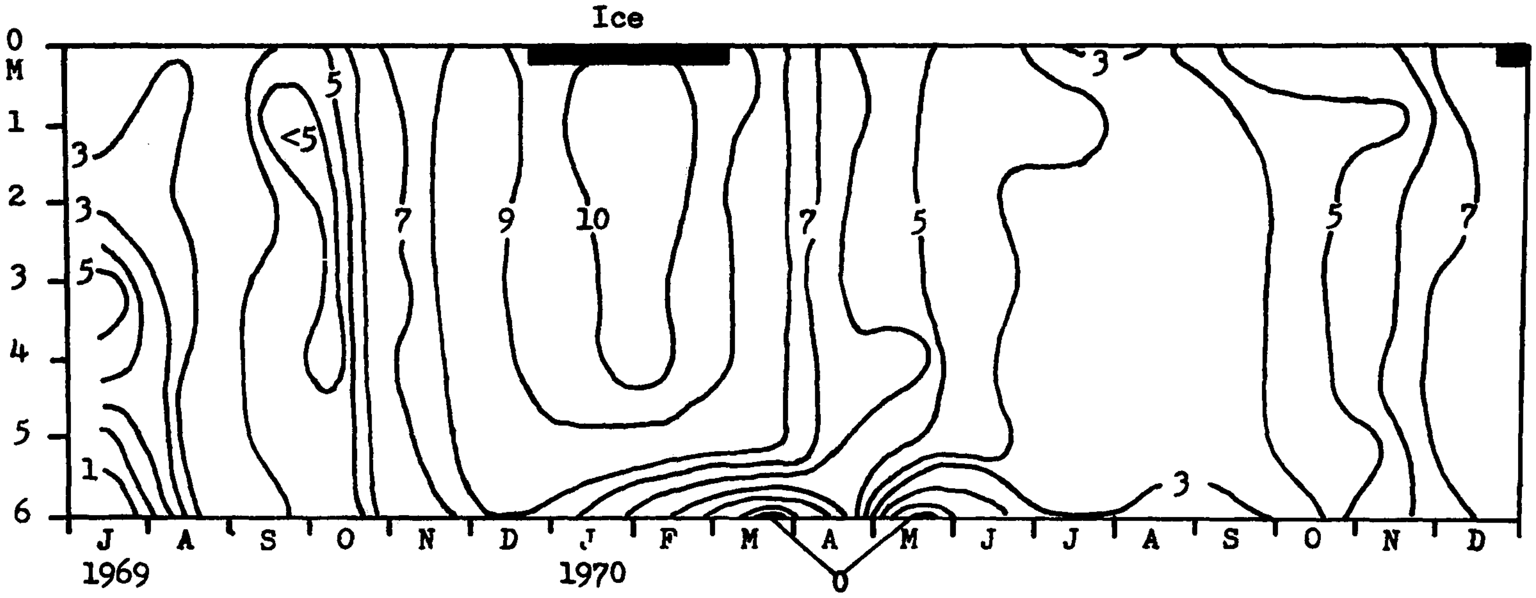
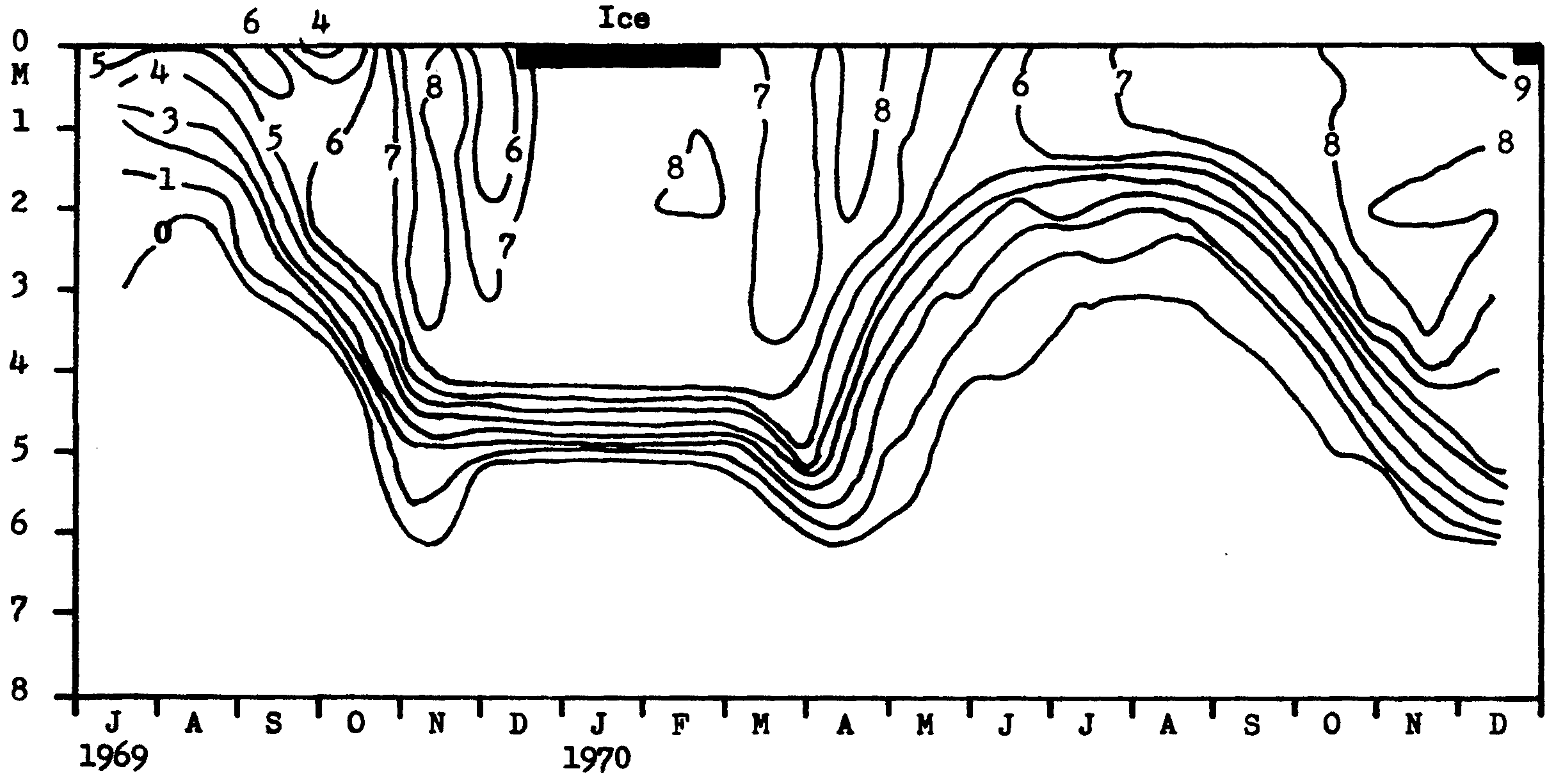


FIG. 37. Time-depth diagram of dissolved oxygen variation (mg/l) in Lake II.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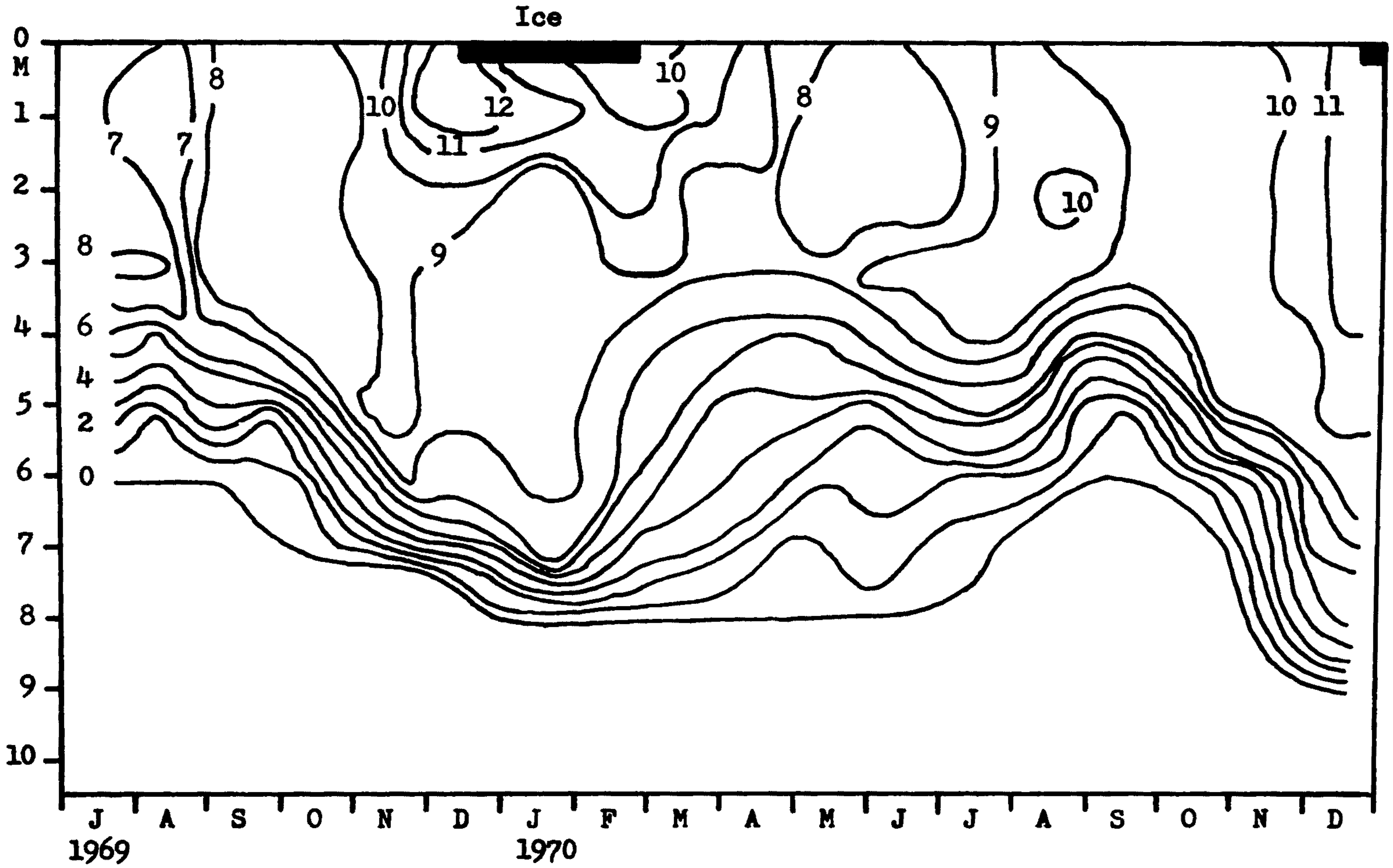

FIG. 39. Time-depth diagram of dissolved oxygen (mg/l) in Lake IV.

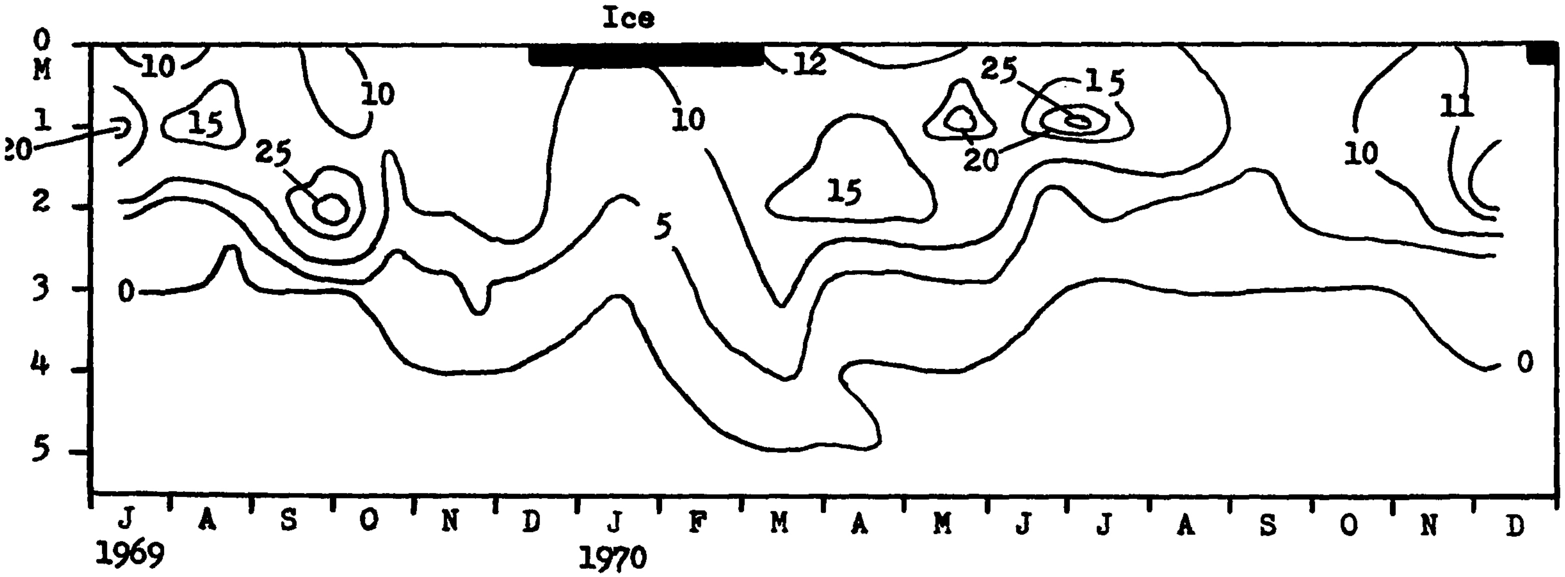

FIG. 40. Time-depth diagram of dissolved oxygen variation (mg/l) in Lake V.

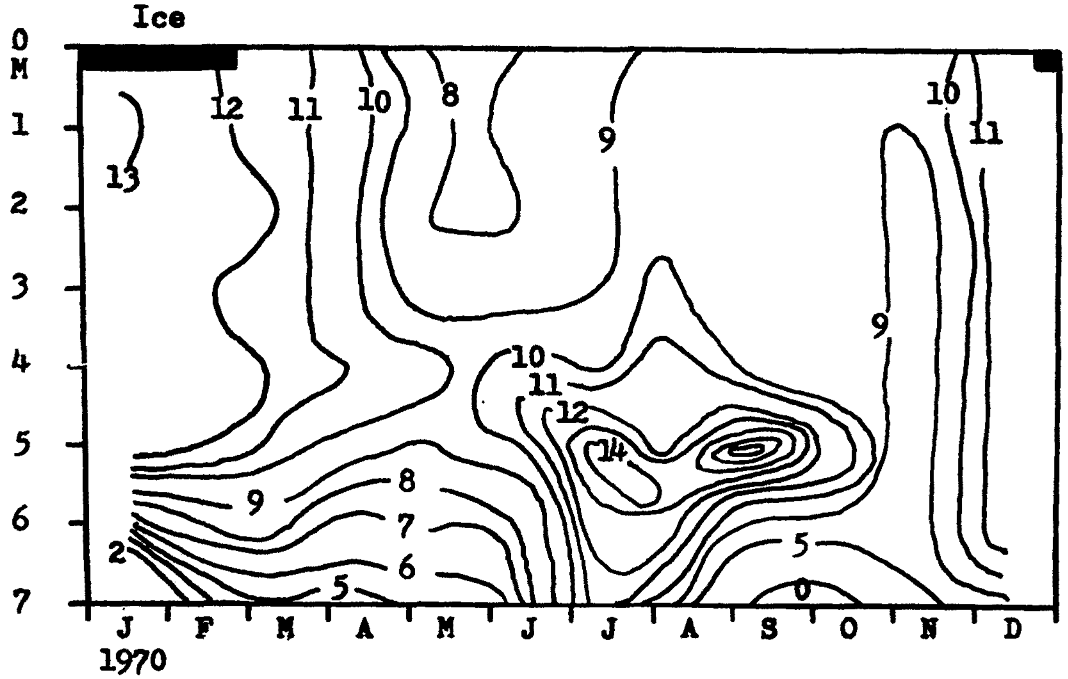

FIG. 41. Time-depth diagram of dissolved oxygen variation (mg/l) in Lake VI.

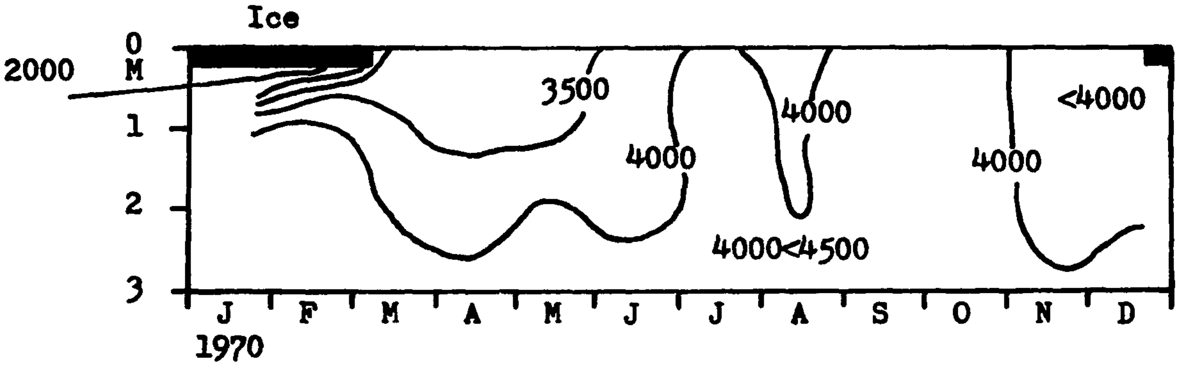

FIG. 42. Time-depth diagram of specific conductance ($K_{25} \cdot 10^6$) in Lake I.

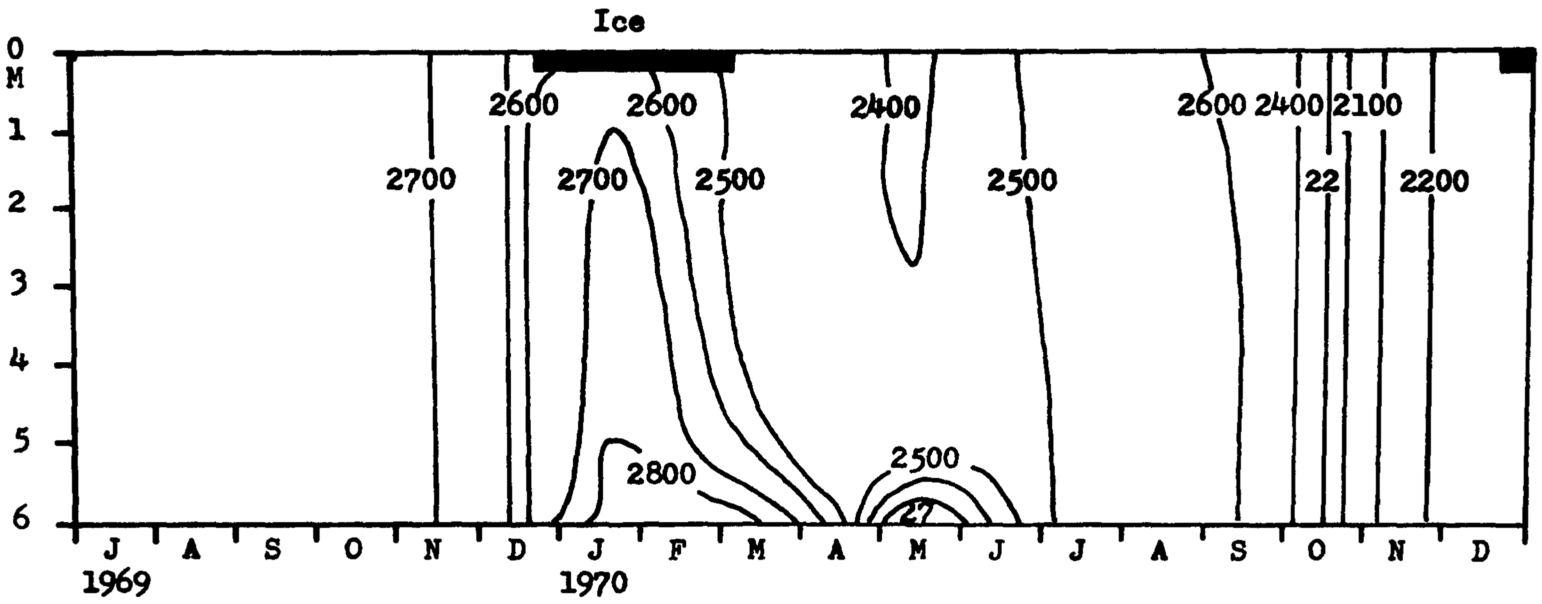

FIG. 43. Time-depth diagram of specific conductance ($K_{25}\cdot 10^6$) in Lake II.

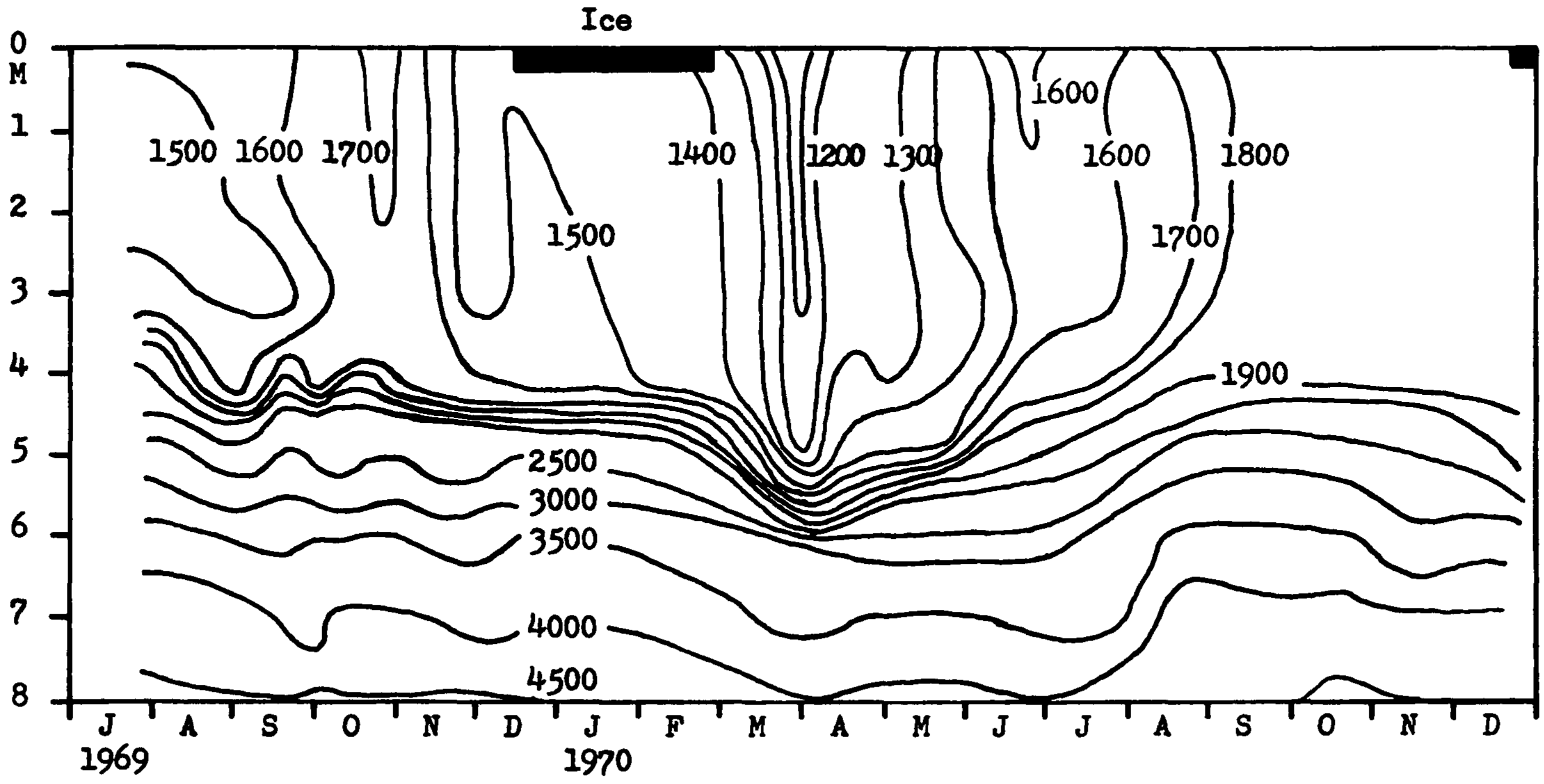

FIG. 44. Time-depth diagram of specific conductance ($K_{25} \cdot 10^6$) in Lake III.

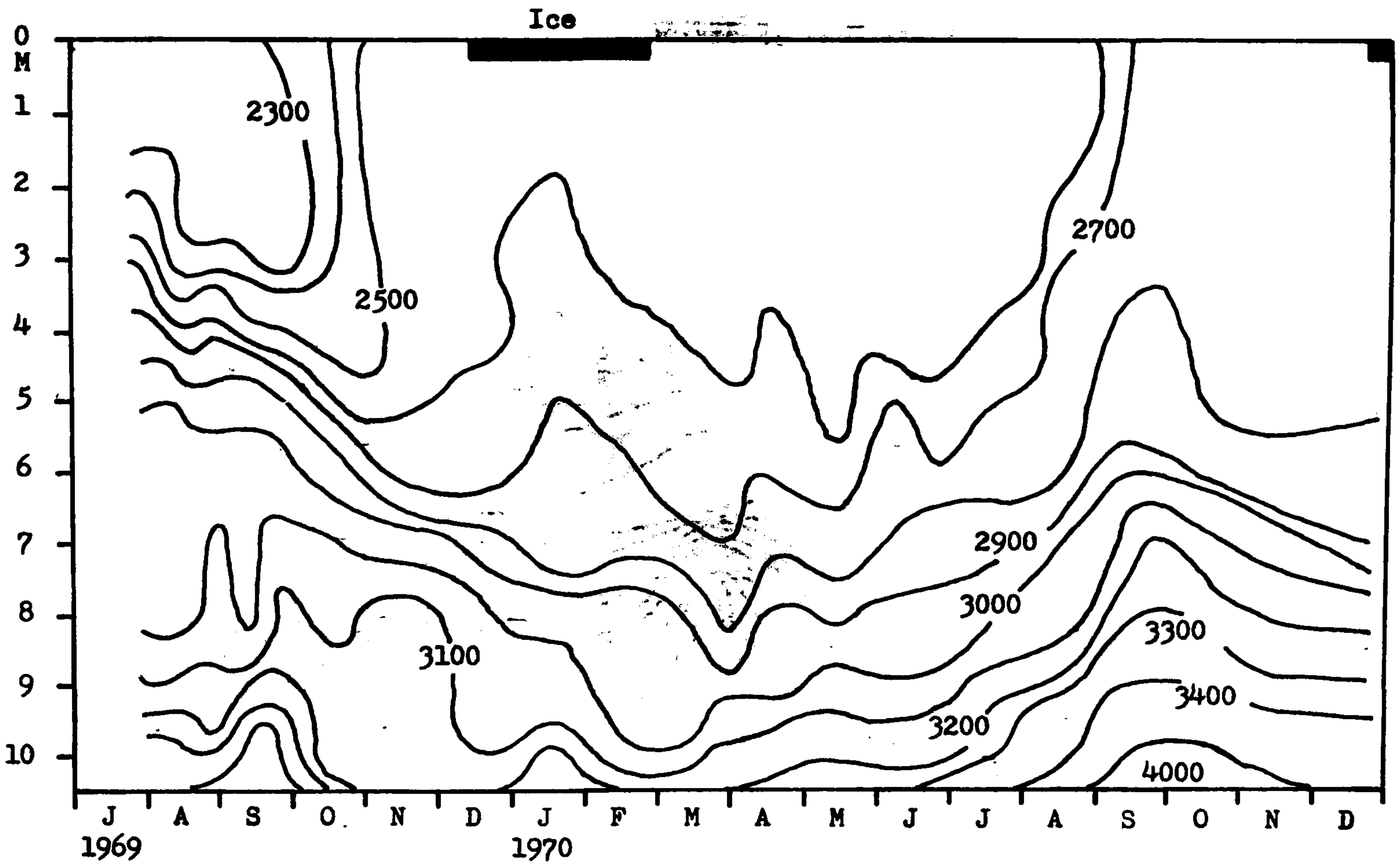

FIG. 45. Time-depth diagram of specific conductance ($K_{25} \cdot 10^{6}$) in Lake IV.

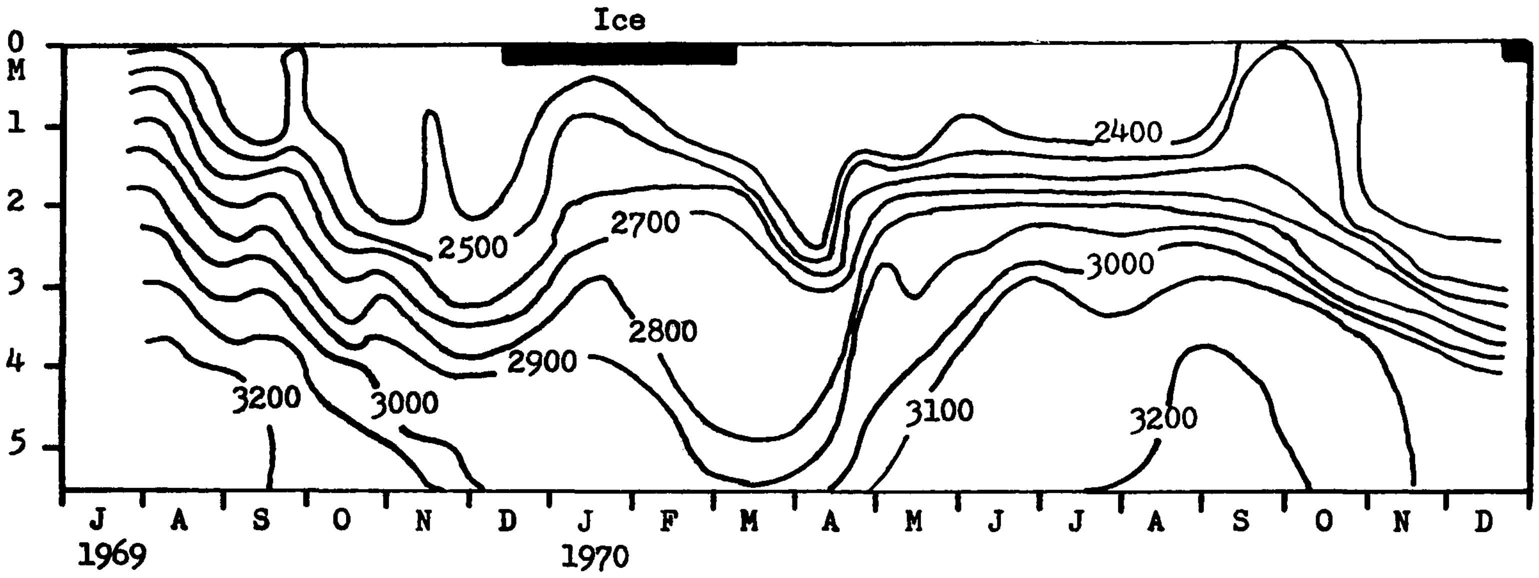

FIG. 46. Time-depth diagram of specific conductance $(K_{25} \cdot 10^6)$ in Lake V.

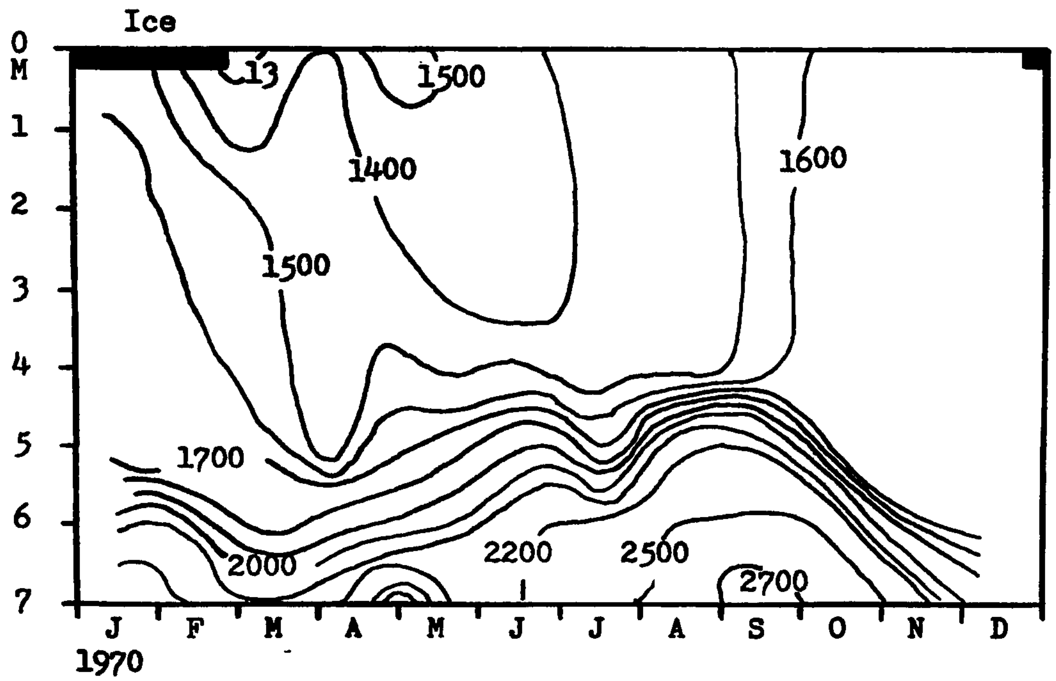

FIG. 47. Time-depth diagram of specific conductance ($K_{25}\cdot 10^6$) in Lake VI.

APPENDIX 2. Seasonal variation in surface (S) and bottom (B) concentrations of selected ions (mg/l).

Lake		I	II	III	IV	V	VI	Control
		29 Jan	28 Jan	19 Feb	26 Jan	28 Jan	28 Jan	
Sampling		27 Mar	4 Apr	31 Mar	31 Mar	31 Mar	4 Apr	
Dates		12 June	4 June	3 June	3 June	3 June	4 June	10 June
(1970)		11 Aug	18 Aug	17 Aug	17 Aug	11 Aug	15 Aug	
		14 Oct	27 Oct	12 Oct	12 Oct	12 Oct	13 Oct	
		17 Dec	2 Dec	24 Dec	24 Dec	14 Dec	9 Dec	9 Dec
Calcium	S	520	380	148	196	320	160	
		392	320	120	144	204	164	
		460	320	160	268	312	148	11
		424	328	212	368	320	152	
		368	328	212	372	320	172	
		390	328	184	295	320	184	13
	B	480	390	500	432	392	236	
		448	328	490	490	400	284	
		440	324	488	416	360	300	21
		432	322	488	440	448	336	
		416	348	464	440	424	348	
		390	332	460	440	408	288	13
Magnesium	S	340	178	110	144	105	122	
		284	190	85	100	146	117	
		317	189	122	193	210	104	6

APPENDIX 2. Continued

		356	200	163	224	220	117	
		337	164	168	237	239	134	
		250	178	122	125	234	130	7
	B	380	240	525	322	298	164	
		468	198	450	300	293	195	
		451	190	527	307	378	207	10
		488	194	537	403	327	234	
		386	173	517	376	337	258	
		275	178	451	327	317	220	4
Iron	S	105	5.1	10.0	4.0	2.0	<0.05	
(Dissolved)		77	8.8	6.4	1.0	1.1	0.55	
		65	3.5	0.65	0.3	0.2	<0.05	0.3
		60	3.7	0.9	0.2	0.05	0.05	
		78	3.5	2.4	0.25	0.05	0.10	
		105	3.9	13.7	0.8	0.65	0.10	0.5
	B	240	4.4	130	100	51	0.05	
		244	9.8	122	80	11.5	0.5	
		240	6.9	135	93	70	3.6	17.5
		130	5.0	170	350	63	0.1	
		90	3.8	270	350	55	4.2	
		137	4.2	264	282	40	1.8	1.0
Manganese	S	52	34	8.5	5.9	-	0.1	
		40	33	5.8	5.5	8.2	0.55	
		50	32	9.5	10.5	5.8	<0.05	0.35

APPENDIX 2. Continued

		52	32.5	9.7	4.8	0.05	<0.05	
		52	36	10.7	3.3	1.7	0.05	
		57	34	8.5	4.1	2.9	0.1	0.2
	B	60	38	34	21.5	-	4.0	
		63	34	29	19.5	13.5	6.5	
		64	31	32	18.5	16.5	5.3	8.0
		60	32.5	30	29	21	0.4	
		62	35	31.5	29	24	26	
		59	33	30	26	27.5	10	0.2
Aluminum	S	36	15	0.5	1.1	-	<0.05	
		25	13.8	0.7	0.4	0.3	0.3	
		34	12.4	0.7	0.05	0.05	0.05	0.05
		37	11.5	0.05	0.05	0.05	0.05	
		40	11.8	0.5	0.5	0.05	0.05	
		43	12.8	0.4	0.9	<0.05	<0.05	<0.05
	B	27	15	0.7	<0.05	-	0.05	
		25	13	0.6	0.05	0.1	0.05	
		23	11.4	0.8	0.05	<0.05	0.05	2.5
		32	11.2	0.6	0.05	0.3	<0.05	
		44	12.1	0.5	0.5	0.05	0.05	
		41	12.8	0.05	0.05	<0.05	<0.05	<0.05
Sodium	S	17	47	23	24	15	47	
		11	41	16	20	11	45	
		13	41	19	28	14	40	4.5

APPENDIX 2. Continued

		16	45	24	35	15	49	
		17	47	26	37	19	54	
		16	43	19	24	19	58	5.6
	B	24	53	37	38	20	60	
		20	41	32	35	16	65	
		19	41	31	34	18	62	4.4
		23	45	36	45	21	75	
		19	46	40	45	24	73	
		19	45	40	45	24	71	5.6
Potassium	S	4.4	5.5	4.1	4.0	3.5	4.2	
		3.7	5.2	3.5	3.2	3.2	4.6	
		4.5	4.8	2.5	3.7	4.0	3.9	1.2
		5.3	-	4.5	4.9	3.9	4.3	
		5.2	5.5	4.5	5.5	4.5	4.7	
		4.8	5.6	4.3	4.7	4.2	5.0	2.2
	B	6.3	5.6	11.0	9.0	4.7	5.9	
		7.1	5.2	9.0	8.4	4.6	6.9	
		7.1	4.8	9.4	8.7	5.5	6.8	2.3
		8.2	-	14	22	5.9	7.8	
		5.7	5.5	25	25	6.0	5.0	
		5.6	5.5	26	22	5.3	7.3	2.3
Zinc	S	3.0	0.75	0.15	0.20	-	0.10	
		2.2	0.95	0.20	0.25	0.25	0.05	
		2.9	0.80	0.20	0.05	0.05	<0.05	<0.05

APPENDIX 2. Continued

		3.0	0.80	0.25	0.10	<0.05	<0.05	
		3.1	0.90	0.20	0.05	<0.05	<0.05	
		3.0	0.80	0.20	0.05	<0.05	<0.05	<0.05
	B	2.2	0.80	0.35	0.05	-	0.10	
		1.4	1.00	0.50	0.05	0.10	0.05	
		2.0	0.95	0.40	0.10	<0.05	<0.05	<0.05
		3.0	0.85	0.40	0.15	0.10	0.05	
		4.0	0.95	0.20	0.10	0.05	0.05	
		3.5	0.90	0.10	0.05	<0.05	<0.05	<0.05
Total	S	3105	1805	860	1100	1235	900	
Hardness		2450	1710	675	785	1130	890	
(Ca, Mg,		2790	1690	920	1480	1650	800	50
Fe, Mn, Al,		2865	1730	1220	1850	1700	860	
and Zn as		2690	1610	1245	1900	1785	980	
$CaCO_3$)		2455	1665	1000	1265	1765	1040	60
	B	3400	2095	3705	2615	2315	1270	
		3685	1760	3375	2680	2245	1525	
		3585	1700	3685	2500	2605	1615	135
		3545	1710	3785	3435	2610	1900	
		3065	1700	3825	3325	2585	1985	
		2610	1675	3530	2990	2440	1640	100
Sulfate	S	2750	1650	750	925	1250	750	
		2365	1550	510	600	775	750	
		3450	1700	875	1300	1600	675	35

		2900	1675	1075	1625	1500	640	
		3150	1575	1150	1900	1650	1050	
		2950	1875	875	1125	1600	925	30
	B	3650	2125	2850	2050	2250	1000	
		3400	1550	3200	2150	1550	1025	
		3450	1850	3275	2190	2200	1250	5
		3350	1700	3300	2500	1875	1350	
		3350	1625	3300	2650	2000	1675	
		3250	1800	3400	2650	2100	1300	25
Chloride	S	8	4	19	18	5	3	
		3	5	15	21	4	3	
		4	4	16	23	6	2	1
		3	6	18	26	3	3	
		40	5	20	25	6	5	
		2	4	15	18	4	4	4
	B	14	4	8	15	8	3	
		3	5	10	22	3	4	
		5	4	8	19	3	3	<1
		3	6	9	37	<1	4	
		40	5	13	18	6	8	
		3	4	9	19	5	4	5
Bicarbonate	S	0	0	24	51	114	160	
		-	-	-	-	-	-	
		-	-	-	-	-	-	-

APPENDIX 2. Continued

		-	-	-	-	-	-	
		-	-	-	-	-	-	
		0	0	8	71	181	213	47
	B	0	0	233	177	284	296	
		-	-	-	-	-	-	
		-	-	-	-	-	-	-
		-	-	-	-	-	-	
		-	-	-	-	-	-	
		0	0	0	-	366	528	45
Silica	S	39	32	10	8	12	2.1	
(SiO_2)		39	25	9	8	11	2.4	
		38	23	12	8	12	1.6	6
		50	27	13	9	9	1.4	
		45	27	12	8	9	1.7	
		48	28	11	8	8	2.1	5
	B	47	31	13	12	15	4.5	
		43	25	12	9.2	14	5.0	
		36	24	17.1	11.5	14	4.2	9
		43	28	23	29	21	5.0	
		52	27	15	12	15	9.0	
		43	27	10	10	16	8	5
Nitrate	S	<5	5	5	<5	<5	<5	
		5	<5	<5	<5	<5	<5	
		<5	<5	<5	<5	<5	<5	<5

		10	<5	<5	<5	<5	<5	
		<5	<5	<5	<5	<5	5	
		<5	<5	<5	<5	<5	<5	<5
	B	5	5	<5	<5	<5	5	
		5	<5	<5	<5	<5	<5	
		<5	<5	<5	<5	<5	<5	<5
		10	<5	5	<5	<5	20	
		<5	<5	<5	<5	<5	<5	
		<5	<5	<5	<5	<5	<5	<5
Total	S	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	
Phosphate		<0.1	0.1	<0.1	<0.1	<0.1	0.3	
		<0.1	0.2	0.1	<0.1	0.1	<0.1	<0.1
		<0.1	0.1	0.1	0.2	3.7	0.2	
		0.1	1.0	0.1	-	0.2	0.1	
		<0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1
	B	0.1	0.1	<0.1	<0.1	<0.1	0.2	
		<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	
		<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1
		<0.1	0.1	0.1	0.1	<0.1	0.1	
		0.1	4.0	<0.1	<0.1	0.2	0.2	
		<0.1	0.1	0.15	0.15	<0.1	0.1	<0.1

SECTION VII

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SECTION IX

LIST OF APPENDICES

1 Accession Number	2 Subject Field & Group	
	Acid-Mine Pollution Lake Biology	**SELECTED WATER RESOURCES ABSTRACTS** INPUT TRANSACTION FORM

5 *Organization*

Indiana University Foundation
Indiana University, Bloomington, Indiana 47401

6 *Title*

"Acid Mine Pollution Effects on Lake Biology"

10 *Author(s)*

Smith, Ronald W.
Frey, David G.

16 *Project Designation*

EPA WQO Contract No. 53-342-26
Project No. 18050-EEC

21 *Note*

22 *Citation*

23 *Descriptors (Starred First)*

*acidic water
*strip-mine lakes
benthic fauna
plankton
aquatic productivity
ecosystems
limnology
water properties

25 *Identifiers (Starred First)*

02. Water cycle
2H. lakes
2K. chemical processes
05. Water quality management & protection
*5C. effects of pollution

27 *Abstract*

Six coal stripmine lakes in southern Indiana encompassing a pH range of 2.5 to 8.2 were studied from July 1969 to December 1970. Generally, differences between the lakes indicated successional trends with increasing pH. Environmental trends in the surface waters included increasing levels of dissolved oxygen and decreasing concentrations of dissolved substances. These tendencies were somewhat obscured by differences in the annual cycles of stratification, four of the lakes proving to be unexpectedly meromictic. Biological changes associated with increasing pH included increasing diversity and increasing homeostasis. Biomass was influenced by both pH and circulation patterns (meromixis vs. holomixis), and bottom fauna was further limited by the steep-sided basin form. All the stripmine lakes had much higher solute concentrations and lower biological diversity than a small local non-stripmine reservoir studied as a control. A fertilization program in one lake has apparently produced elimination of all rooted aquatic plants, violent oscillations of plankton, and low fish populations. It is suggested that sport fishing in stripmine lakes, not presently very satisfactory, could be improved by management techniques adapted to their unique limnological nature.

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