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Original: Fish Division
cc: Education-Game
Inst. for Fish. Res.
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COOPERATING WITH THE
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UNIVERSITY MUSEUMS ANNEX
ANN ARBOR, MICHIGAN

July 27, 1955

Report No. 1454

SOME CHEMICAL AND MORPHOMETRIC CHARACTERISTICS OF SOUTHERN MICHIGAN LAKES

By

Frank F. Hooper

Abstract

A study was made of the morphometric features and chemical properties of the waters of 8 special regulation lakes in southern Michigan. Four of the lakes (Birch, Bear, Big Portage and Duck) are similar in having (1) a steep slope of the lake basin between the 5- and 20-foot contours, (2) an epilimnion of small volume as compared with total lake volume, (3) littoral soils primarily of marl, and (4) a comparatively small percentage of the lake bottom with submerged rooted aquatic plants. These lakes are also similar in certain chemical properties; all are high in methyl orange alkalinity, conductivity and calcium, and show large seasonal fluctuations in these chemical qualities. Three of the stratified lakes (Fine, Whitmore and Minnewaukon) and the one unstratified lake (Sugarloaf) all have a gently sloping littoral zone, a high ratio of epilimnion volume to total volume, littoral soils of peat and an abundance of rooted vegetation. These lakes were lower in calcium, alkalinity and conductivity and showed smaller seasonal fluctuations in these chemical properties than the first group of lakes.

Lakes having a high total phosphorus content tended to be high in total hitrogen butthere was little apparent correlation between average phosphorus and nitrogen content and the quanity of other chemicals present. The average

total phosphorus content of the 8 lakes appeared to be considerably below similar averages for Minnesota lakes and slightly below averages for northeastern Wisconsin lakes. Michigan lakes, however, appeared to be somewhat higher in total nitrogen than the Minnesota and Wisconsin lakes.

In 27 stratified lakes in Oakland County, there was a high positive correlation (0.74) between methyl orange alkalinity and mean slope of the lake basin between the 5- and 20-foot contours. In this group of lakes there was a high negative correlation between alkalinity and the ratio of eplimnion volume to total volume. These interrelationships between alkalinity and morphometric features appear to be due to increased deposition of marl in lakes of progressively higher alkalinity. The scatter of points obtained when methyl orange alkalinity was plotted against basin slope for the Oakland County lakes suggested that marl deposits begin to influence the basin shape when the alkalinity exceeds a value of approximately 105 p.p.m. This alkalinity value appears to be a natural point of separate categories of lakes classified on a hardness basis.

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By

Frank F. Hooper

In the course of recent studies of the chemical properties of a group of eight lakes in southern Michigan, it was found that a correlation existed between the shape of the basins of these lakes and certain chemical properties of the lake waters. This paper gives the results of these studies and also presents related and unpublished records dealing with the regional limnology of southern Michigan.

In an admirable appraisal of Michigan's inland waters, Welch (1950) points out that there is a shortage of factual data. Although many studies of southern Michigan lakes have focused attention upon interrelationships within the ecosystem of a single lake (Hankinson, 1908; Eggleton, 1931; Raymond, 1937; Ball, 1948; Newcomb and Slater, 1950), none has dealt with the regional characteristics of these waters. The numerous contributions of E. A. Birge and C. Juday have defined the properties of lakes in southern and northeastern Wisconsin. Similarly, many limnological characteristics or regions in North America have been described: Minnesota (Moyle, 1949), Connecticut (Deevey, 1940), the Canadian Rockies (Rawson, 1942), southern Saskatchewan (Rawson and Moore, 1944), and northern Colorado (Pennak, 1945).

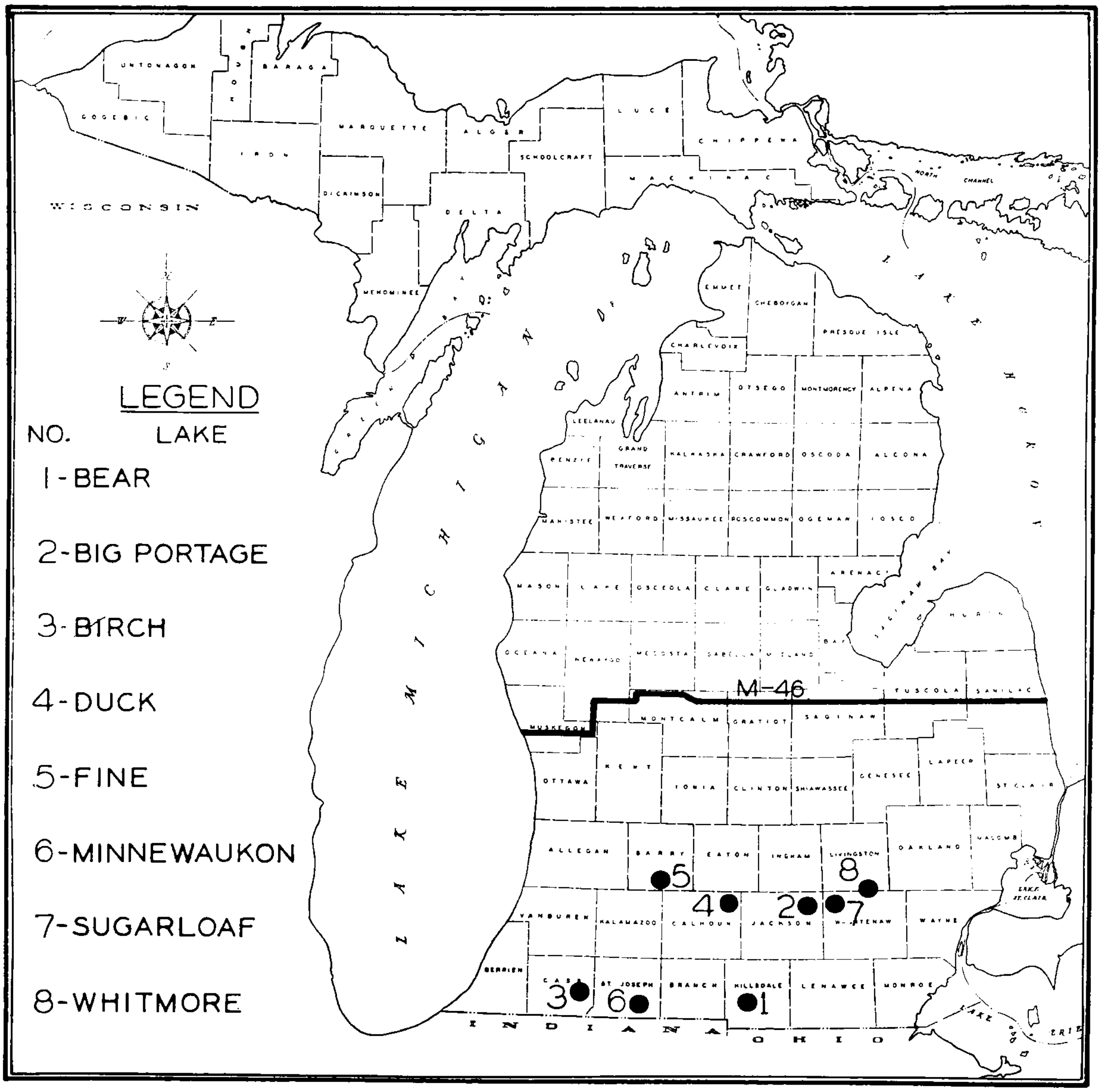
Data presented in this paper are from two sources: first, the physical and chemical records for one year of eight lakes in southern Michigan, and, second, the lake-inventory records of the Institute for Fisheries Research of the Michigan Department of Conservation, Ann Arbor. The Institute's records cover a period of twenty-four years and include the following: (1) a hydrographic map showing the submerged contours, the types of botton soil and location of beds of aquatic vegetation; (2) measurements of temperature, oxygen, alkalinity, carbon dioxide and pH, made at one or more locations in each lake, and (3) qualitative lists of the aquatic plants and fish present.

Physiography and Geology

These lakes are all located within glacial deposits associated with the Mankato substage of the Wisconsin period. All are within the three southernmost tiers of counties and are south of Highway M-46, a highway frequently used as the dividing line between the northern and southern portions of the Lower Peninsula. The physiography of the area south of M-46, except for narrow strips adjoining the Great Lakes, is classified by Veatch (1953) as the southern upland region. These lakes are located in three subdivisions of the southern upland: (1) the Hillsdale-Lapeer Highland, a northeast, southwest band of relatively high land in southeastern Michigan characterized by pitted plains, lakes, swamps, and land of locally strong relief, (2) the Barry-Hillsdale Highland, a similar area of strong relief in south-central Michigan, and (3) the Cass-Kalamazoo Plain, an area of low relief characterized by sandy drift, lakes and swamps.

The drainage basins of the 8 lakes have soils belonging to three soil associations (Veatch, 1953). These are: (1) the Miami-Hillsdale-Conover Association, which is a loam soil that is characteristic of rolling till plain and subdued clayey moraine, (2) the Bellefontaine-Hillsdale-Coloma Association, a sandy loam soil characteristic of rolling moraine and high land, and (3) the Fox-Osthemo-Plainfield Association, which is typical of outwash plains of low

Fig. 1. Location of "special regulation" lakes.


LEGEND
NO. LAKE
1-BEAR
2-BIG PORTAGE
3-BIRCH
4-DUCK
5-FINE
6-MINNEWAUKON
7-SUGARLOAF
8-WHITMORE
M-46
WISCONSIN
LAKE MICHIGAN
LAKE HURON
INDIANA
OHIO

relief and made up chiefly of sandy and sandy loam soils. The latter two soil types characterize regions in which lakes are abundant.

Bear Lake, Hillsdale County, T. 7 S., R. 3 W., Sec. 8, 17

Bear Lake has an area of 117 acres. It is located approximately 4 miles southwest of Hillsdale and is surrounded by flat agricultural uplands. Soils of its drainage basin are of the Fox-Osthemo-Plainfield Association. The lake is fed by spring seepage and by a stream entering from an adjoining small lake. It has a large shallow marl shoal region and an abrupt drop-off to deep water. Submerged rooted vegetation is limited to a narrow bandalong the drop-off.

Big Portage Lake, Jackson County, T. 1-2 S., R. 1-2 E,
Sec. 25, 36, 30, 31, 32, 5, 6

This lake is located about 14 miles east of Jackson. It has an area of 360 acres. A marshy lowland surrounds much of the lake while the adjacent upland is rolling and partially wooded. Soils of the drainage basin are of the Bellefontaine-Hillsdale-Coloma Association. The lake is fed by two small creeks and by spring seepage. Its outlet is a tributary of the Grand River. The lake basin is similar to that of Bear Lake in that it has extensive shallow marl shoals and an abrupt slope to deep water. Submerged rooted aquatic plants are to be found chiefly in a narrow band along the drop-off.

Birch Lake, Cass County, T. 7 S., R. 15 W., Sec. 5, 6, 7, 8

Birch Lake has a surface area of 295 acres. It is surrounded by rolling and wooded upland. Soils of the drainage basin are of the Fox-Osthemo-Plainfield Association. The lake is fed by springs and one small drain. The outlet is a tributary of the St. Joseph River. It has a narrow marl shoal, an abrupt slope at the drop-off and an extensive deep water zone.

Duck Lake, Calhoun County, T. 1 S., R. 4 W., Sec. 9, 6, 21

This lake has an area of 629 acres. It is located about 10 miles north of Albion. The surrounding land is gently rolling and partly wooded and has soils of the Miami-Hillsdale-Conover Association. The lake has no active inlet but receives seepage from an adjacent marsh. The outlet is intermittent. At the northeastern end of the lake there is an extensive shallow marl shoal. The drop-off to deep water is abrupt and the areas of stands of submerged aquatic plants are small.

Fine Lake, Barry County, T. 1 N., R. 8 W., Sec. 19, 29, 20, 30

Fine Lake has an area of 320 acres. It is located 10 miles northwest of Battle Creek. The lake has no inlet. Its outlet is intermittent and is a tributary of the Thornapple River. It has extensive shoals of sand and organic soils which are covered with dense stands of rooted aquatic vegetation. Soils of the surrounding rolling moraines are of the Bellefontaine-Hillsdale-Coloma Association.

Sugarloaf Lake, Washtenaw County, T. 1 S., R. 3 E., Sec. 31, 32

The lake is located 7 miles northwest of Chelsea. It has an area of 180 acres. The surrounding rolling, wooded moraine consists of soils of the Bellefontaine-Hillsdale-Coloma Association. Approximately 90 per cent of the lake is less than 5 feet deep. The bottom is a mixture of marl and organic matter and is covered by submerged aquatic plants, chiefly <u>Chara</u>.

Whitmore Lake, Washtenaw and Livingston Counties, T. 1 N., R. 6 E., Sec. 32

The lake, located 12 miles north of Ann Arbor, has an area of 677 acres. It is surrounded by gently rolling farm land, and has no inlet nor natural outlet. An artificial drain has been constructed which connects this lake with Horseshoe Lake to the south. It has an extensive shallow water region of sand and peat which is well covered with rooted aquatic vegetation. The surrounding soils are of the Miami-Hillsdale-Conover Association.

Minnewaukon Lake, St. Joseph County, T. 7 S., R. 10 W., Sec. 34, 35

Minnewaukon Lake, is located 2 miles northwest of the town of Sturgis. The lake has an area of approximately 126 acres. It has no inlet nor outlet, and is surrounded by flat or gently rolling farm land. It is comparatively shallow; the maximum depth is only 25 feet. Bottom soils are peat and rooted plants cover almost the entire basin.

METHODS

Water samples were collected for chemical analyses from the 8 lakes at approximately monthly intervals from February 1953 to February 1954. Samples were taken at the surface and at the maximum depth. During months in which the lake was straitfied, a third sample was collected at the lower limit of the epilimnion. At the same time, temperature readings were made at 2-foot intervals from the surface to the maximum depth. Two-quart fruit jars were used to collect water samples for the first four months. At that time it was found that the glass of the jars increased the sodium content of the samples. Thereafter polyethlene bottles of 1-liter capacity were substituted. When it was necessary to store water samples longer than 24 hours, chloroform was added as a preservative. Chemical procedures used, unless otherwise indicated, were taken from Standard Methods for the Examination of Water and Sewage (American Public Health Association, 1946). Ammonia was measured by distillation and nesslerization, and organic nitrogen was determined by the Kjeldahl method. Iron was analyzed with bipyridine (dipridyl), and sulfate was determined by the benzidine method. The procedures used for measuring total phosphorus are those given by Ellis, Westfall, and Ellis (1946). Calcium and sodium were measured with a Beckman flame photometer. Conductivity readings were taken with a portable battery-operated conductivity bridge.

The procedures employed in lake mapping by field parties of the Institute for Fisheries Research have been described by Brown and Clark (1939). An example of the data that were collected has been published by Brown (1942). Measurements of lake maps were made with a polar planimeter. The methods used in calculating the volumes, mean depths, and mean slopes are those given by Welch (1948).

The assistance of Mr. K. E. Christensen, of the Institute for Fisheries Research, and of the creel-census clerks working under his direction in collecting water samples is acknowledged. Dr. Stanford H. Smith, of the United States Fish and Wildlife Service, made available the flame photometer used in the sodium and calcium analyses.

MORPHOMETRIC CHARACTERISTICS

Hydrographic maps of all the lakes except Birch have been published recently (Christensen, 1953). A classification of these lakes and a selected group of their morphometric characteristics appear in Table I. This system of classification, given by Pennak (1945), groups lakes according to their drainage relationships. Those with inlets and outlets that are active throughout the year are classed as drainage lakes. Those whose inlets and outlets function intermittently are termed semidrainage lakes, and those without inlets or outlets (landlocked lakes) are termed seepage lakes. Presumably, this classification reflects the rate at which water moves through the lake and the rate of influx of dissolved salts from the watershed. This rate is believed to be highest in lakes connected with large streams and lowest in lakes whose level is maintained by the slow seepage of ground water.

A morphometric index of ecological significance is the mean slope of the basin between the 5- and 20-foot contours. This index was calculated using the

Table I

Morphometric characteristics of eight southern Michigan lakes

Lake	Drainage classification**	Area, in acres	Maximum depth, in feet	Mean depth, in feet	Volume development index	Ratio of volume of epilimnion to total volume	Mean slope of basin between 5- and 20-foot contours (per cent)	Per cent of bottom supporting submerged plants	Predominant soil type of littoral zone
Birch	Drainage	295	95	43.0	1.37	0.37	38.7	11.5	Sand-marl
Bear	Drainage	117	53	17.0	0.97	0.55	17.5	6.6	Marl
Big Portage	Drainage	360	40	10.7	0.81	0.78	8.2	7.3	Marl
Duck	Semi-drainage	629	51	14.2	0.83	0.76	9.7	10.5	Marl-sand
Fine	Semi-drainage	320	48	10.5	0.66	0.96	3.4	60.0	Sand-peat
Sugarloaf	Drainage	180	18	3.7	0.55	0.99	*	97.0	Marl-peat
Whitmore	Seepage	677	69	14.2	0.62	0.83	3.5	74.0	Sand-peat
Minnewaukon	Seepage	96	25	7.9	0.95	0.88	5.2	98.0	Peat

*Maximum depth less than 20 feet.

**For explanation of this classification see text.

formula $S = \frac{C_1 + C_2}{2} \cdot \frac{I}{A}$ where S is the slope in per cent between the two contours; C_1 and C_2 are the lengths of the contours involved; I is the vertical distance between the two contours and A is the area of the lake bottom included between the two contours. The 5-20 foot depth range was selected to obtain an index of the slope of the littoral zone beyond the depths which are influenced by water level fluctuations or strong wave action. Although the depth range selected was arbitrary and admittedly includes slightly different habitats depending upon the size and shape of the lake, it nevertheless includes the most productive benthis zone and most of the lake bottom where submerged rooted aquatic plants grow in these lakes. The percentage of lake bottom with stands of submerged plants was calculated from the areas of vegetation outlined on the lake inventory maps. Checks made on these lakes during the summers of 1953 and 1954 indicated that these beds had been located accurately. Calculation of the ratio of the volume of epilmnion to the total lake volume was made from the temperature data of August 1953.

Inspection of these morphometric indices (Table I) suggests certain trends and similarities between lakes. The two drainage lakes of moderate depth, Birch and Bear, have a more abrupt slope, a smaller percentage of the bottom covered with submerged plants, and a smaller ratio of epilimnion volume to total volume than either the two seepage lakes (Whitmore and Minnewaukon) or one of the semidrainage lakes (Fine Lake). Big Portage, a drainage lake, and Duck, a semidrainage lake, are intermediate in these three characteristics. The basin slope of Sugarloaf Lake connot be compared with the other lakes in this series because of its shallowness. It is significant that lakes having an abrupt slope of the littoral zone have predominantly marl soils. Soils of lakes with gently sloping basins (Fine, Minnewaukon, and Whitmore) are peaty. Varying amounts of sand occur in both types. These interrelated characteristics of soil type, slope, and amount of vegetation appear to be independent of the area and the maximum depth of these lakes. Mean depth and the volume-development index are not so well correlated with these characteristics as is slope because these indices are influenced strongly by the size of that portion of a lake basin outside the five-foot contour.

CHEMICAL CHARACTERISTICS

Methyl orange alkalinity and conductivity

The mean annual methyl orange alkalinity of the eight lakes ranges from 73 p.p.m. to 151 p.p.m. and the alkalinity of over 60 per cent of the lakes of southern Michigan that have been inventoried by the Institute for Fisheries Research falls within these limits. Minnewaukon Lake is rated among those with the softest water (73 p.p.m.) and Bear Lake among those in the upper 30 per cent in hardness. As in other areas (cf. Pennak, 1945, and Juday, Birge, and Meloche, 1935), drainage lakes are higher in alkalinity than seepage and semidrainage lakes. There are indications of correlation between the mean alkalinity and the group of associated morphometric characteristics discussed above (mean slope, ratio of volume of epilimnion to total volume, and area of submerged vegetation). Lakes having a high alkalinity also have a high average slope of the littoral zone and a small area of vegetation, while lakes having a low alkalinity have a low average slope (Whitmore, Fine and Minnewaukon). The ratio of bicarbonate to total salt (Table II) was calculated by determining the conductivity of a bicarbonate solution equivalent to the mean annual alkalinity value for each lake and dividing by the mean annual conductivity. Most of the lakes have ratios close to the usual ratio of 0.90 (Ruttner, 1953). Whitmore Lake, however, is considerably below this ratio (0.68), thus the presence of a high concentration of salts other than bicarbonate is indicated.

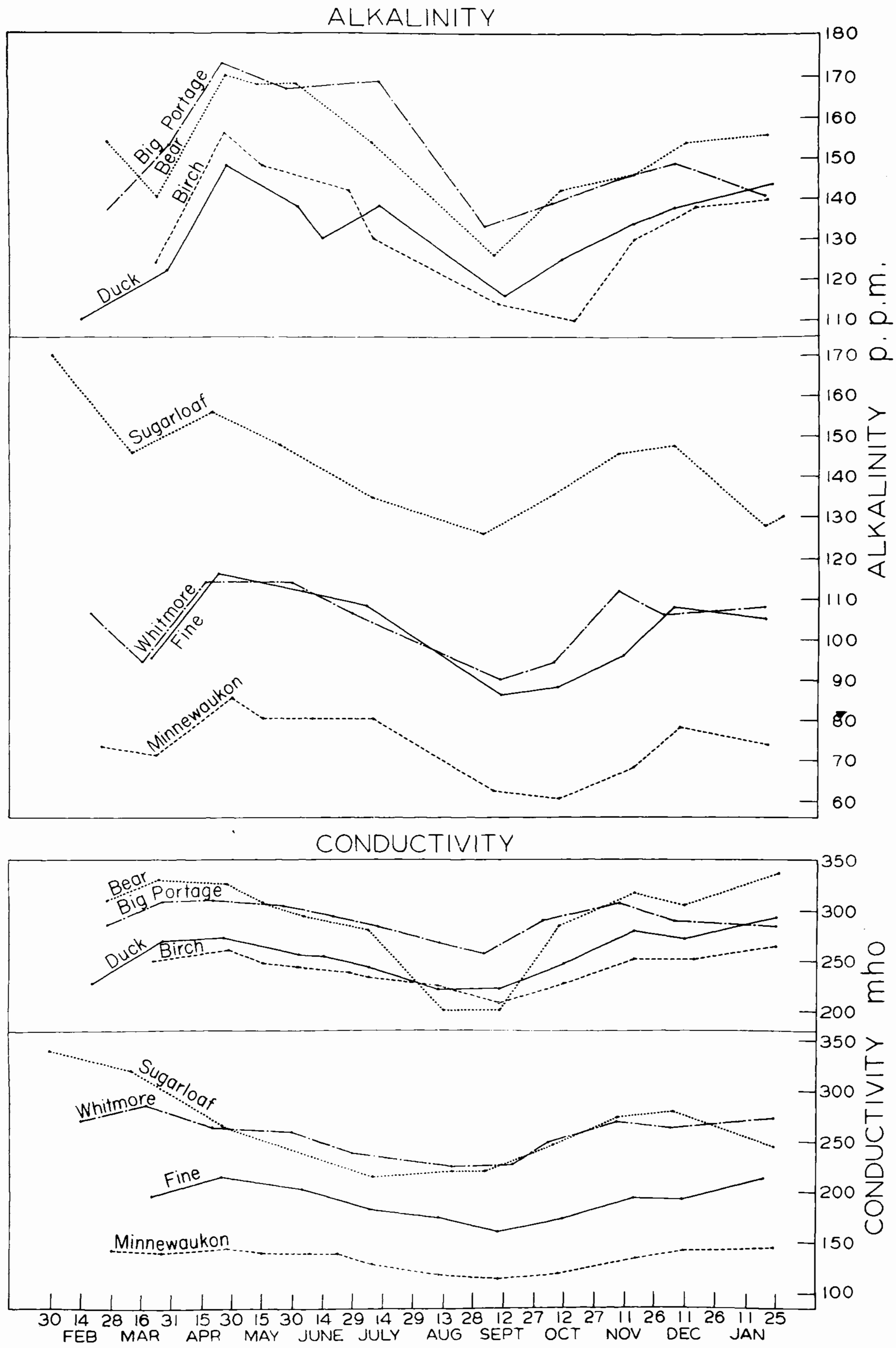
Table II

Chemical properties of surface water of eight southern Michigan lakes from February 1953 to February 1954

(12 monthly samples unless otherwise indicated)

Lake	Calcium, p.p.m.		Methyl orange alkalinity, p.p.m.		Conductivity in reciprocal megohms		Ratio bicarbonate to total salt	Sodium, p.p.m. (7 samples)		Total phosphorus, in micrograms per liter		Total nitrogen, p.p.m.		Sulphate, p.p.m. (3 samples)	Iron, p.p.m. (3 samples)
	Range	Mean	Range	Mean	Range	Mean		Range	Mean	Range	Mean	Range	Mean	Mean	Mean
Bear	28-41	37	126-170	151	260-330	299	0.82	3.2-3.8	3.4	7-24	13	0.37-1.1	0.77	35	0.009
Big Portage	20-40	33	132-174	151	258-310	290	0.85	2.6-3.5	3.1	6-15	10	0.30-1.5	0.55	28	0.014
Duck	21-34	28	112-148	130	224-293	259	0.82	3.0-3.8	3.3	10-23	16	0.50-2.8	0.89	19	0.008
Birch	16-33	24	115-156	131	214-266	242	0.89	2.4-3.6	2.7	9-23	14	0.24-1.4	0.57	13	0.014
Sugarloaf	23-31	27	127-170	141	215-340	256	0.90	2.7-3.3	2.9	8-18	11	0.30-1.5	0.65	13	0.016
Whitmore	20-28	25	90-114	106	225-284	256	0.68	6.0-6.1	6.0	10-41	19	0.40-1.6	0.95	28	0.004
Fine	18-28	23	86-115	102	162-212	190	0.88	2.2-2.9	2.6	9-18	13	0.30-1.9	0.71	13	0.017
Minnewaukon	13-22	17	60-85	73	113-145	133	0.95	0.9-1.6	1.1	8-22	14	0.48-1.7	0.64	7	0.013

Fig. 2. Methyl orange alkalinity and conductivity of the surface water of 8 southern Michigan lakes, 1953-1954.


ALKALINITY
Big Portage
Bear
Birch
Duck
Sugarloaf
Whitmore
Fine
Minnewaukon
180
170
160
150
140
130
120
110
170
160
150
140
130
120
110
100
90
80
70
60
ALKALINITY p.p.m.
CONDUCTIVITY
Bear
Big Portage
Duck
Birch
Sugarloaf
Whitmore
Fine
Minnewaukon
350
300
250
200
350
300
250
200
150
100
CONDUCTIVITY mho
30 14 28 16 31 15 30 15 30 14 29 14 29 13 28 12 27 12 27 11 26 11 26 11 25
FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC JAN

Seasonal maxima and minima in alkalinity and conductivity occur at approximately the same time in all lakes (Fig. 2). The highest values in alkalinity of surface water occur near the close of the spring circulation period. Lowest values occur during late summer before the fall circulation begins. A second high occurs before the ice forms in late fall. Under the ice, alkalinity may drop below the late summer minimum. Although spring maxima and summer minima occur at approximately the same time in all these lakes, there are differences in the amplitude of seasonal fluctuations and in the time of the fall maxima. Two patterns appear; in Birch, Bear, Duck and Big Portage lakes, the seasonal change is large (36-49 p.p.m.) and the fall maximum occurs late in the season; the seepage and semi-drainage lakes of lower alkalinity (Fine, Minnewaukon and Whitmore) change less (25-29 p.p.m.), reach a fall maximum somewhat earlier, and do not show the small fluctuations characteristic of the high alkalinity group.

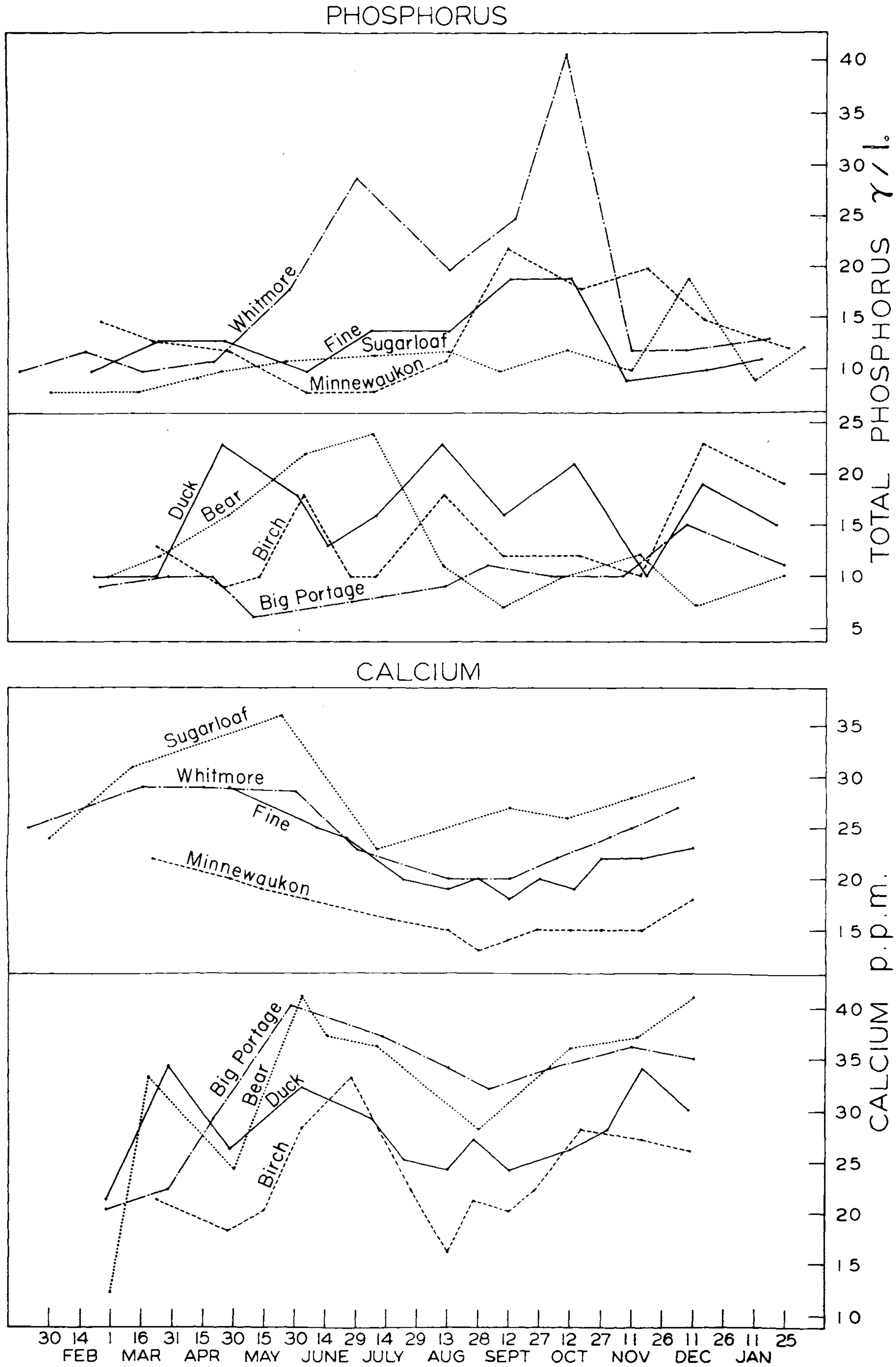
Calcium

The average calcium content of these lakes varies less than does the alkalinity (see Table II). Minnewaukon and Fine lakes contain only slightly less calcium than do Birch, Sugarloaf, and Duck lakes. Seasonal fluctuations in calcium content (Fig. 3) follow the same general pattern as alkalinity and conductivity, except that the spring calcium maximum is later than the spring alkalinity maximum in Birch, Bear, and Big Portage lakes.

Sodium

The sodium data cover only the period from July 1953 to February 1954. During this period there was little difference in the sodium content of the lakes and in none of them was there much seasonal variation. Minnewaukon is

Fig. 3. Total phosphorus and calcium in the surface water of 8 southern Michigan lakes, 1953-1954.


PHOSPHORUS
Whitmore
Fine
Sugarloaf
Minnewaukon
Duck
Bear
Birch
Big Portage
TOTAL PHOSPHORUS γ / l.
40
35
30
25
20
15
10
25
20
15
10
5
CALCIUM
Sugarloaf
Whitmore
Fine
Minnewaukon
Big Portage
Bear
Duck
Birch
CALCIUM p.p.m.
35
30
25
20
15
40
35
30
25
20
15
10
30 14 1 16 31 15 30 15 30 14 29 14 29 13 28 12 27 12 27 11 26 11 26 11 25
FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC JAN

slightly below the other lakes, and Whitmore has an average almost double that of the others (see Table II). The high sodium content of Whitmore Lake and the low ratio of bicarbonate to total salt are indications of pollution from domestic drainage.

Nitrogen and phosphorus

The variation in total phosphorus content is small between lakes. The range of mean annual phosphorus is from 10 to 19 micrograms (g.) per liter, and the average for the eight lakes is 14 micrograms per liter. Compared with other waters, the lakes appear to be poor in phosphorus. Moyle (1949) found an average total of 47 micrograms per liter in forty-five Minnesota lakes. The eight Michigan lakes all fall into Moyle's lowest category of phosphorus fertility. Moyle's state average is based upon one or more analyses during the summer for each of the forty-five lakes, but the Michigan averages are a yearly mean. However, all of the Michigan lakes except Whitmore would still fall into the low category for Minnesota lakes if the summer average instead of a yearly average were used. The Michigan averages are also below the average of 23 micrograms per liter for the 479 lakes in northeastern Wisconsin that were studied by Juday and Birge (1931).

The average total nitrogen content for the eight lakes was 0.71 p.p.m., and the range was between 0.55 and 0.95 p.p.m. This average is somewhat above that given by Moyle (1949) for forty-five Minnesota lakes (0.42 p.p.m.). Although the summer average for the eight Michigan lakes (0.66) is lower than the yearly average, it, to, is above the Minnesota average. These averages can also be compared with an average of 0.457 p.p.m. for 529 lakes in northeastern Wisconsin (Birge and Juday, 1934).

Lakes tending to be high in total phosphorus (e.g., Whitmore) tended to be high in total nitrogen. There was, however, little correlation between nitrogen and phosphorus content and other chemical variables (alkalinity and calcium) or other factors (drainage type, amount of vegetation, and basin slope). Seasonal trends in the amount of phosphorus present are indicated in Whitmore, Fine and Minnewaukon lakes (see Fig. 3). In them the maximum amount of phosphorus was found in the middle or late summer, near the time of the alkalinity minimum and before the fall overturn. The phosphorus content of the other lakes was highly variable and showed no well-defined seasonal trends.

Sulfate and iron

With the exception of Whitmore, the lakes rank about the same in sulfate content as in calcium. The high-calcium drainage lakes (Bear and Big Portage) are also high in sulfate. Those lowest in calcium (Fine and Minnewaukon) are lowest in sulfate. Whitmore Lake again is somewhat anomalous. All of the 8 Michigan lakes studied had a concentration of sulfate below the high range Moyle (1949) found in southwestern and western Minnesota. All of the lakes, except Minnewaukon, have a greater sulfate content than lakes in northeastern Wisconsin (Juday, Birge and Meloche, 1938).

The variation in iron content was from 4 to 17 micrograms per liter. Whitmore Lake was lowest in iron and Fine Lake was highest. There was little apparent correlation between the iron content of these lakes and the quantity of other minerals present.

Relation of alkalinity to the slope of the lake basin

The indication that there was a basic relationship between alkalinity of the water and the slope of the lake basin between the 5- and 20-foot contours in the 8 southern Michigan lakes suggested the need for further studies to determine whether or not such a relationship could be demonstrated in a larger number of lakes. The lakes of Oakland County were selected for this analysis because (1) more lakes have been mapped in this county than in any other southern Michigan county, and (2) most of the alkalinity measurements were made in mid-summer of 1946 by a single survey party and therefore can be compared with more confidence than data from other counties which in most cases were collected by a variety of parties over a span of years. To compare lake basin slopes between the 5- and 20-foot contours, it is necessary for all lakes to be deeper than 20 feet. This eliminates lakes in which the slope at the 20-foot contour is influenced strongly by its proximity to flat areas at the maximum depth. All of the lakes used in this analysis had maximum depths of at least 30 feet and are thermally stratified during the summer. Similarly, basin slope is influenced by surface area. Lakes whose surface area is small compared to the maximum depth always have a high slope regardless of alkalinity. All of the lakes selected for this analysis had a surface area of at least 20 acres. In very large lakes, much of the bottom between the 5- and 10-foot contour falls within the zone of strong wave action where the slope is gradual and is determined by purely physical processes. To avoid such cases, all Oakland County lakes with surface area over 1,000 acres were not considered in the analysis.

Plotting slope of lakes against their alkalinity (Fig. 4) gives a scatter of points around a line sloping at a rate of approximately 10 per cent basin slope for an alkalinity change of 40 p.p.m. in the upper range of alkalinities. Below alkalinities of approximately 105 p.p.m., the scatter of points appears to be almost parallel to the alkalinity axis, which suggests that a lower values slope is not influenced by alkalinity (Fig. 4). The seepage lakes and semi-drainage lakes all have slopes between 3.5 and 12.6 per cent while the drainage lakes, with one exception, have slopes greater than 12 per cent (Table III). The correlation coefficient of alkalinity

Fig. 4. Relationship of methyl orange alkalinity and the mean slope of the lake basin between the 5- and 20-foot contours for 27 lakes of Oakland County, Michigan.

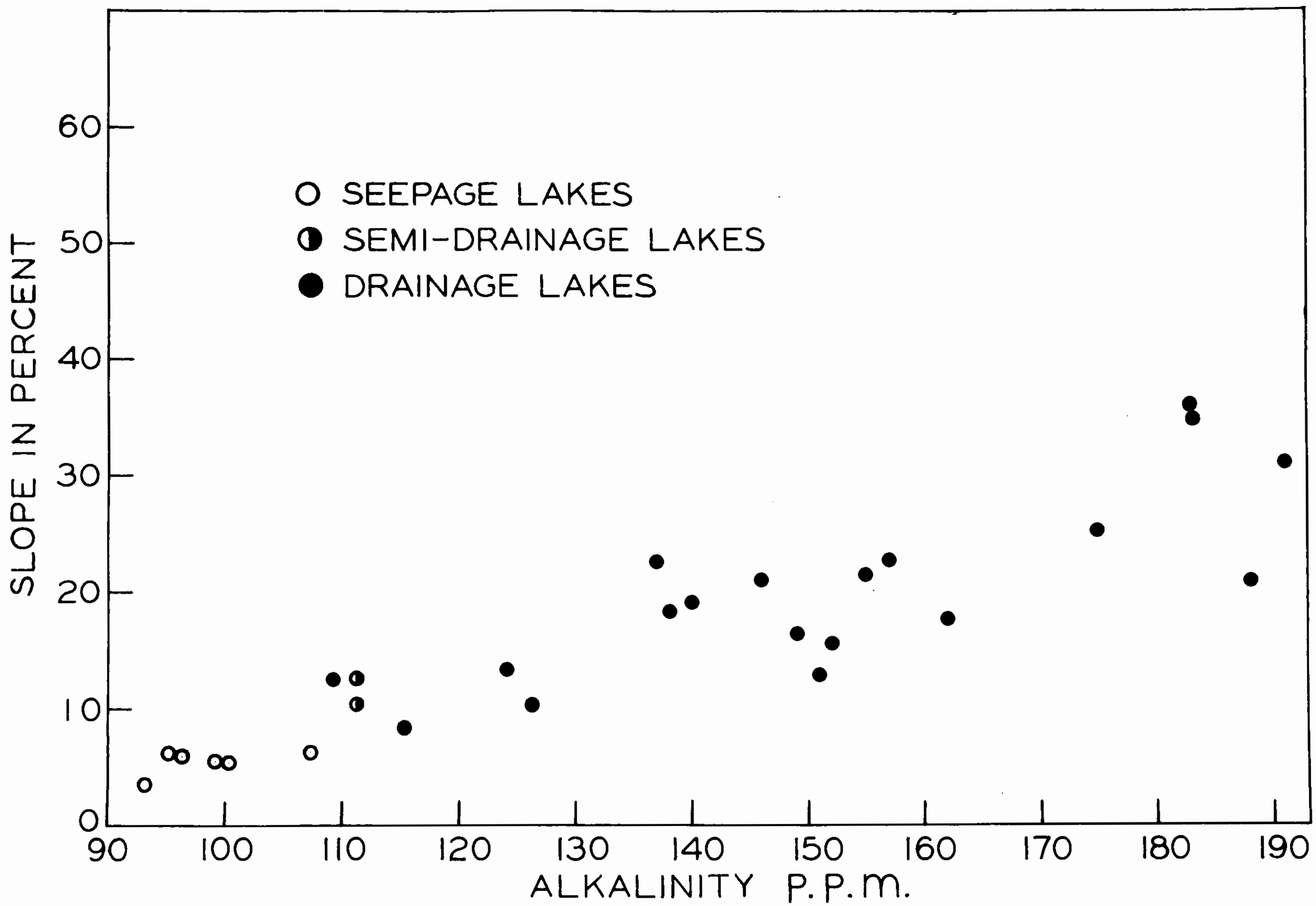

SEEPAGE LAKES
SEMI-DRAINAGE LAKES
DRAINAGE LAKES
SLOPE IN PERCENT
0
10
20
30
40
50
60
90
100
110
120
130
140
150
160
170
180
190
ALKALINITY P.P.M.

Table III

Morphometric features, alkalinity and classification of

Oakland County lakes

Lake	Drainage classification	Methyl orange alkalinity, p.p.m.	Slope between 5- and 20-foot contours in per cent	Ratio of volume of epilimnion to total volume	Area in acres	Mean depth, in feet
Townsend	Drainage	191	30.9	0.19	26	22.3
Greens	Drainage	188	20.8	0.33	109	21.6
Parke	Drainage	183	35.8	0.32	44	14.4
Cemetery	Drainage	183	35.6	0.19	24	24.9
Cedar Island	Drainage	175	25.2	0.30	144	27.0
Woodhull	Drainage	162	17.5	0.37	135	14.8
Upper Proud	Drainage	157	22.5	0.37	55	12.6
Lower Pettibone	Drainage	155	21.3	0.39	89	19.8
Commerce	Drainage	152	15.4	0.46	262	24.7
Loon	Drainage	151	12.6	0.36	78	19.5
Sugden	Drainage	149	16.1	0.42	66	16.9
Mill	Drainage	146	20.9	0.25	30	18.0
Mohawk	Drainage	140	19.0	0.34	23	11.7
Oxbow	Drainage	138	18.1	0.40	270	25.3
Schoolhouse	Drainage	137	22.6	0.24	37	16.3
Union	Drainage	126	10.1	0.44	465	28.5
Crescent	Drainage	124	13.1	0.51	90	13.1
Middle Straits	Drainage	115	8.1	0.64	171	11.8
Elizabeth	Semi-drainage	111	10.2	0.71	363	31.0
Cooley	Semi-drainage	111	12.6	0.57	86	9.8
Upper Straits	Drainage	109	12.5	0.43	323	12.5
Pine	Seepage*	107	6.4	0.61	395	21.4
Williams	Seepage	100	5.3	0.68	155	14.3
Scott	Seepage	99	5.7	0.58	77	11.5
Bogie	Seepage	96	6.0	0.67	76	8.8
Orchard	Seepage*	95	6.2	0.68	788	23.1
Walled	Seepage*	93	3.5	0.76	670	12.4

*Outlet functions during years of high water levels.

with slope is 0.74. There is a high negative correlation between alkalinity and the ratio of epilimnion volume to total volume (-0.78). The correlation of alkalinity and mean depth is considerably less, 0.34. There is also a small negative correlation between alkalinity and surface area, -0.31. The correlation coefficient of alkalinity and maximum depth (0.14) and area with slope (-0.18) are probably not significant.

It is believed that the alkalinity of the water indirectly influences the shape of the basin by its relationship to the precipitation and sedimentation of marl (calcium carbonate). When marl is deposited in lakes, shallow marl benches are formed and a sharp drop-off to deep water is created. The abrupt slopes associated with marl deposits have been noted by other authors (Hale, 1903; Eggleton, 1931; Wohlschlag, 1950; Ruttner, 1953). The above data suggest that marl accumulation begins to influence the morphometry of southern Michigan lakes of the size and depth studied when the methyl orange alkalinity exceeds 105 p.p.m. As alkalinity increases, the extent of the marl deposits in the littoral zone increases. Marl benches are built around the lake at various points, and, in extreme cases, a steep marl drop-off is formed around the entire lake.

Although the mode of formation of marl benches has never been adequately described, the depth of marl deposits, as shown in the maps of Hale (1903) and Blatchley and Ashley (1901), suggests that such abrupt slopes are formed by the encroachment of shallow-water marl deposits upon the center of the lake.

Alkalinity classification of southern Michigan lakes

The range of alkalinities of 241 Michigan lakes south of Highway M-46, surveyed by the Institute for Fisheries Research between 1930 and 1954, is from 6 p.p.m. to 241 p.p.m. The mean alkalinity is 132 p.p.m. Only

6 per cent of these lakes have alkalinities of 200 p.p.m. or more, and only 13 per cent have alkalinities under 100 p.p.m. Seepage and semidrainage lakes range between 6 p.p.m. and 203 p.p.m. and average of 80 p.p.m. Drainage lakes range between 50 p.p.m. and 241 p.p.m. and average 150 p.p.m. Although most lakes with alkalinities over 190 p.p.m. are marl lakes, few have the abruptly sloping littoral zone discussed above. Nearly all lakes within this range are shallow, unstratified lakes. The three seepage lakes of unusually high alkalinity (160-205 p.p.m.) (Fig. 5) are small, shallow alkaline bog lakes in Washtenaw County. The surface water of these lakes contains free carbon dioxide supplied by the decay of the encroaching vegetation. Their high alkalinity is due to the action of carbon dioxide upon marl deposits within the lake. In shallow unstratified lakes there is probably a larger budget of carbon dioxide available throughout the year than in the deep stratified lakes in which much of the carbon becomes bound in the deposits of organic matter in deep water.

The alkalinity data for the Michigan lakes south of Highway M-46 for which records are available (Table IV), indicate certain geographical trends in water hardness. Although these data are inadequate for certain counties, lakes of southwestern Michigan counties (Allegan, Berrien, Van Buren and Cass) have an average alkalinity below the average for lakes in south central and southeastern Michigan. Kalamazoo and Branch counties appear to be more alkaline than other southern Michigan counties that have been adequately sampled. Cass and Allegan counties have seepage lakes of unusually low alkalinity (6-32 p.p.m.).

Birge and Juday (1911) classified Wisconsin lakes on the basis of bound carbon dioxide content. Lakes having less than 5 c.c. of bound carbon dioxide per liter (22 p.p.m. methyl orange alkalinity) were classified as soft; lakes having between 5 and 22 c.c. of bound carbon dioxide

Fig. 5. Frequency of occurrence of various values of methyl orange alkalinity of surface water of 220 Michigan lakes south of Highway M-46.

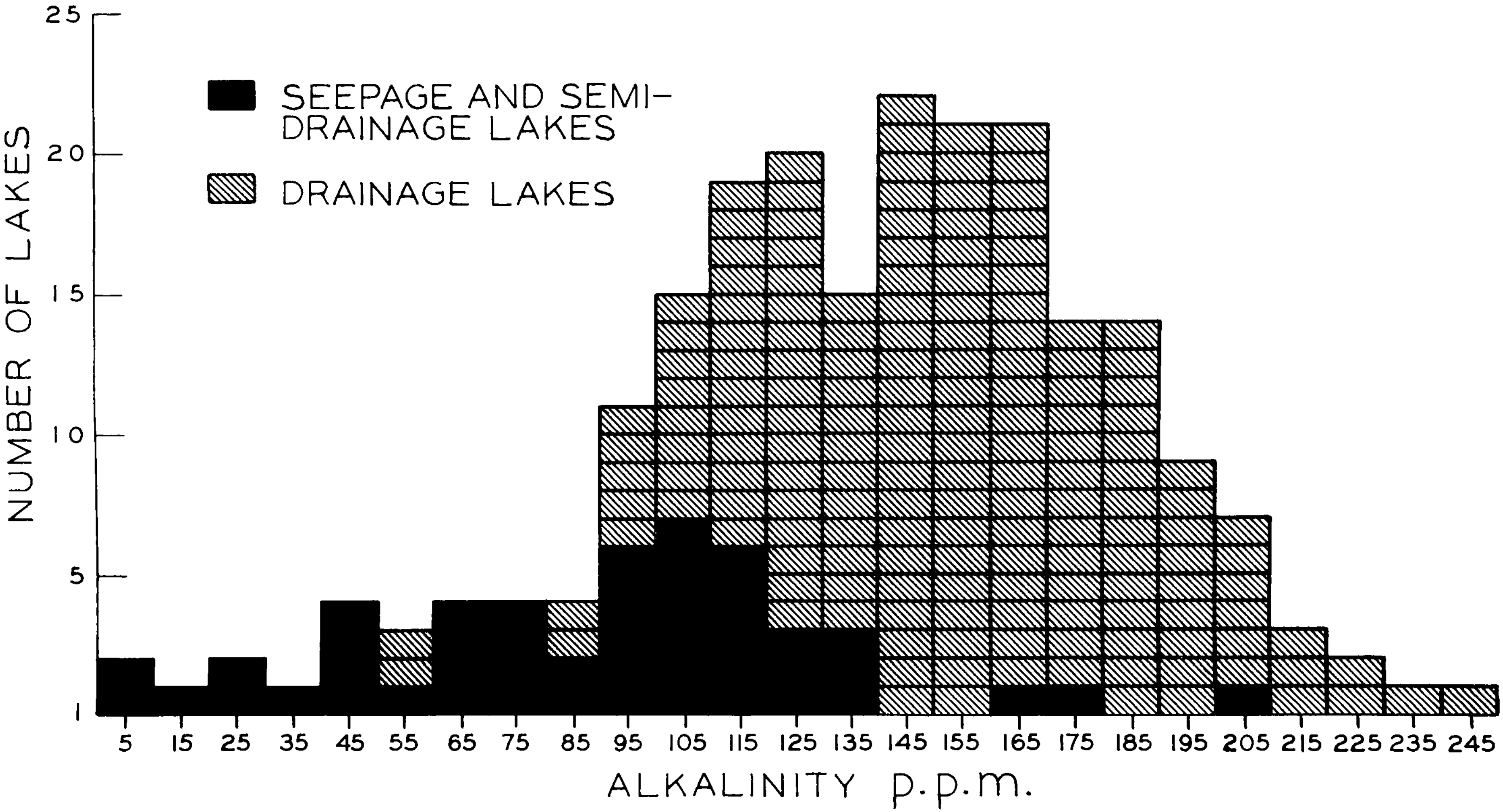

SEEPAGE AND SEMI-DRAINAGE LAKES
DRAINAGE LAKES
NUMBER OF LAKES
25
20
15
10
5
1
5 15 25 35 45 55 65 75 85 95 105 115 125 135 145 155 165 175 185 195 205 215 225 235 245
ALKALINITY p.p.m.

Table IV. -Methyl orange alkalinity of lakes in counties south of Highway M-46

County	Drainage lakes			Seepage and semi-drainage lakes			All lakes
	Number	Alkalinity in p.p.m.		Number	Alkalinity in p.p.m.		Mean alkalinity in p.p.m.
		Mean	Range		Mean	Range	
Allegan	6	121	55-149	3	32	14-60	92
Barry	16	149	105-225	2	70	70-71	140
Berrien	1	153	...	1	38	...	95
Branch	13	157	113-184	...	...	...	157
Calhoun	3	190	183-200	2	83	65-102	138
Cass	8	162	122-199	5	32	6-53	112
Clinton	2	152	130-175	1	115	...	140
Hillsdale	16	147	124-185	2	96	62-130	139
Jackson	19	164	100-230	3	104	48-135	149
Kalamazoo	14	173	105-241	...	...	...	173
Kent	10	142	105-181	1	25	...	131
Lapeer	1	190	...	1	130	...	160
Lenawee	4	111	97-124	...	...	...	111
Livingston	7	167	107-207	2	96	91-102	151
Montcalm	9	124	88-197	4	85	41-124	112
Oakland	30	148	100-191	11	96	78-111	134
St. Joseph	7	135	90-207	1	73	...	127
Van Buren	3	96	50-144	...	...	...	96
Washtenaw	17	158	111-198	9	134	106-203	151
All others (7 counties)	5	156	125-179	2	79	60-99	134
Totals	191			50			
Mean		150			8[illegible]		132

per liter (22-89 p.p.m. methyl orange alkalinity) were classified as medium lakes, and lakes having over 22 c.c. of bound carbon dioxide were classed as hard. Using this classification, 90 per cent of the southern Michigan lakes would be classified as hard, 8 per cent as medium and 2 per cent as soft. Moyle (1949) felt that this system was inadequate for Minnesota lakes and proposed a system which classed lakes with an alkalinity under 20 p.p.m. as very soft, between 21 and 40 p.p.m. as soft, and between 41 and 90 p.p.m. as medium hard. Lakes over 90 p.p.m. were classed as hard. Moyle also added two additional categories of alkaline lakes having a high sulfate content. He pointed out that 40 p.p.m. meythl orange alkalinity is a natural point of division between soft and medium hard-water categories in Minnesota from the stand-point of both aquatic flora and fish production. In both systems of classification the lower limit of hard-water lakes appears to have been arbitrarily set at about 90 p.p.m. This point of separation is too low to be a natural division for southern Michigan lakes. Lakes with a summer methyl orange alkalinity ranging from 91 to 100 p.p.m. (e.g. Fine and Whitmore) appear to be quite similar in biological and physical properties to lakes whose alkalinity ranges from 40 to 90 p.p.m. (e.g. Minnewaukon). Both categories of lakes have littoral soils composed chiefly of sand and peat, although small amounts of marl may be present. For southern Michigan, a point of division more easily recognized in character of both the habitat and the biota is at an alkalinity of 105 p.p.m. Above this concentration marl tends to accumulate in the basin and begins to influence the slope of the littoral zone. In this way the habitat is modified considerably. Although mixtures of marl and organic materials are found in southern Michigan lakes having alkalinities below 105 p.p.m., there are rarely extensive marl deposits in such lakes.

ALKALINITY CLASSIFICATION AND LAKE MANAGEMENT

These studies suggest that certain habitat features may be associated with various ranges of alkalinity. Stratified lakes falling in the "hard" category, as defined above, tend to have narrow, marl shoals and little cover in the form of rooted plants. In these lakes an encroaching shoreline due to marl deposition has created a characteristic morphometry. Lakes in glacial basins that were originally deep have lost much of their shallow water areas, and at the present time these lakes have steep sides and a comparatively large volume of water below the thermocline (morphometric oligotrophic). Such lakes frequently retain adequate oxygen for fish life in the deeper regions, thus are suitable for cold-water fish (ciscoe, trout). The oxygen curves of such lakes often show a minimum or a maximum in the thermocline (heterograde oxygen curves). Shallower basins of this type are now suitable for only warm-water species.

Two types of lake improvement might prove practical on these lakes. (1) Increasing cover by brush shelters or by the establishment of areas with rooted aquatic vegetation. Both of these measures will provide cover for young fish and will also tend to concentrate the fish where they might be harvested by anglers. Although brush shelters provide cover, it is doubtful whether or not they will furnish additional fish food. Rooted vegetation should, on the other hand, provide an increase in the amount of food, since most plants harbor an abundance of fish food organisms. (2) Enlarging the shallow water areas of the lake by impoundment. Flooding of adjacent lands of organic soil and covered with vegetation will increase the amount of available free carbon dioxide. This, in turn, should reduce the deposition of marl. Flooding will also add areas of lake bottom of the proper depth and soil type for rooted plants and bottom living animals.

Southern Michigan lakes between 41 and 105 p.p.m. in alkalinity (medium hard) tend to have gradual sloping shoals an abundance of rooted plants and water of somewhat greater transparency than the hard water lakes. In these lakes cover is usually adequate if not overabundant. The management problem most frequently encountered is stunting of pan fish. In these lakes efforts should be made to balance the population by encouraging predators and perhaps by eliminating rooted plants.

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