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FISHERIES CLASSIFICATION OF MICHIGAN LAKES [1]

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ABSTRACT

The characteristics of lakes useful in assessing their fisheries potential are reviewed. Michigan lakes may be typed according to geology, alkalinity, climate and mid-summer temperature-oxygen profiles--in addition to other lake characteristics. Multiple correlation and regression analyses showed that fish productivity, as measured by sport fish catch in pounds per acre per year, was strongly related to (1) the relative abundance of bluegills (the panfish index)--an indicator of the trophic structure of the fish population, (2) climate--an index of biological turnover rate, (3) Secchi disk transparency--an index of plankton standing crop and, (4) the relative abundance of submerged vegetation--an index of macrophyte standing crop. Mean depth and area were of minor importance to fish productivity; alkalinity, amount of shoal area and temperature-oxygen type were unimportant factors. The distribution and relative abundance of bluegills, largemouth bass, black crappies, yellow perch, walleyes, smallmouth bass and trout were related to climate and to temperature-oxygen type.

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[1] A contribution from Dingell-Johnson Project F-29-R, Michigan

Introduction

Limnologists and fishery biologists have long recognized that Michigan's inland lakes are so diverse that no two of them have identical physical and biological properties. Yet it is apparent that some lakes share the more important characteristics. While it is difficult to form clear-cut groups from characteristics which vary over a continuous spectrum, such as area, depth, and alkalinity, a lake classification system would be of great value in understanding the nature of our lake resource and its biological potential. No one classification scheme will serve all needs. Rather, water scientists and managers need to develop a system for storing and retrieving data on the more important characteristics. Then each user can select those characteristics, and their value range, pertinent to his interest.

Here I review the characteristics of lakes which are useful in assessing fisheries potential. Knowledge from the fields of geology, limnology, and fisheries biology is integrated. Specifically, the history of the lake survey program in Michigan is reviewed; the magnitude and distribution of the inland lake resource are described; geologic, alkalinity, climatic, and oxygen-thermal types are considered; and finally, lake characteristics of greatest importance to both the production and the distribution of fish will be determined by critical analyses. The term "lake" includes reservoirs and ponds.

History of lake surveys

Systematic biological surveys of lakes were begun by the Michigan Fish Commission in 1883 (Cooper, 1974). Later surveys were performed by both research and management branches of the Fish Division, Michigan Department of Conservation (now Natural Resources). For the most part the limnological aspects of the early surveys were restricted to descriptions of lake size, maximum depth, and surface and bottom water temperatures. Since 1930, inventory methods have included mapping of area, depth and sediment, and measurements of temperature and dissolved oxygen profiles, Secchi disk transparency, and phenolphthalein and methyl orange alkalinity. Tests for pH and carbon dioxide were made prior to the 1950's. Samples of fish have been taken routinely to determine species present and their relative abundance. Samples of plankton, benthos, and macrophytes were taken in some years. Descriptions were usually made of water color, types and abundance of macrophytes, fish food organisms, possible sources of pollution, inlets and outlets, terrestrial vegetation, and land and water use. The inventory of Michigan lakes is far from being finished. So-called "complete" inventories, as described above, were made on about 1,000 lakes between 1930 and 1964, and partial inventories have been made on many others (Taube et al., 1964). Few lakes have been completely inventoried by fisheries personnel since 1960 due to a de-emphasis of this program; however, monitoring by the Water Quality Control Division of the Michigan Department of Natural Resources has increased. McMurray et al. (1933), Brown (1943), Hooper (1956), and Humphrys and Green (1962) have described inventory methods and published some of these data, but the bulk of the information remains in the files of the Fisheries Division.

Lake size and distribution

Brown (1943) and, more recently, Humphrys and Colby (1962), have tabulated the inland waters of Michigan. The latter authors reported 35,068 bodies totaling 840,867 surface acres, of which 29,546 were classified as natural lakes and ponds, natural lakes with dams, and lakes enlarged by marl dredging operations. However the majority of the waters listed are too shallow to support fish year-around. Most are very small; one-third of the natural and artificial waters tabulated were smaller than 1 acre, and over three-fourths were less than 10 acres. There are only 1,130 lakes and reservoirs larger than 100 acres; 20 of these are between 5,000 and 21,000 acres in size.

The distribution of lakes within the state is very irregular, with most of the lakes occurring in glacial outwash plains and moraines

Table 1.--Total number of lakes, and the methyl orange alkalinity of lakes which have been sampled, by geographical area and county

Area and County	Total lakes[1]	Number sampled	Alkalinity groups[2] 10	30	50	70	90	110	130	150	170	190	200+
Western Upper Peninsula													
Gogebic	1133	77	51	14	7	5	..	..	..	..	..	..	..
Ontonagon	592	17	9	4	1	2	1	..	..	..	..	..	..
Houghton	1248	30	22	5	2	1	..	..	..	..	..	..	..
Keweenaw	349	8	..	5	3	..	..	..	..	..	..	..	..
Baraga	1080	27	21	4	2	..	..	..	..	..	..	..	..
Iron	2130	77	29	12	12	11	3	5	2	1	2	..	..
Marquette	1783	94	40	18	11	4	4	13	2	2	..	..	..
Dickinson	353	15	2	1	3	1	..	2	1	3	2	..	..
Menominee	75	7	..	..	1	..	1	..	1	..	1	3	..
Eastern Upper Peninsula													
Alger	803	68	43	11	3	4	4	1	..	2	..	..	..
Delta	543	15	3	3	4	3	1	1	..	..	..	..	..
Schoolcraft	1035	48	15	11	7	6	3	4	1	1	..	..	..
Luce	692	44	26	3	3	4	3	3	1	..	1	..	..
Chippewa	520	14	7	1	1	1	2	1	1	..	..	..	..
Mackinac	439	10	1	1	1	1	4	2	..	..	..	..	..
Northern Lower Peninsula													
Emmet	239	7	..	..	..	..	..	2	..	4	1	..	..
Cheboygan	292	14	1	..	1	..	3	1	3	2	2	1	..
Presque Isle	174	9	..	1	1	..	..	3	2	..	..	1	1
Alpena	40	5	..	..	..	..	..	..	2	3	..	..	..
Montmorency	210	42	..	..	2	3	8	8	3	6	3	5	4
Otsego	333	28	2	2	3	2	4	5	6	4	..	2	..
Charlevoix	70	13	1	..	..	1	1	3	5	2	..	..	..

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Table 1.--continued

Area and County	Total lakes[1]	Number sampled	Alkalinity groups[2]										
			10	30	50	70	90	110	130	150	170	190	200+
<u>Northern Lower Peninsula, cont.</u>													
Antrim	108	18	2	..	..	..	..	4	3	4	4	1	..
Leelanau	81	10	1	..	1	..	..	1	5	2	..	..	..
Benzie	142	9	2	..	..	..	1	2	..	4	..	..	..
Gd. Traverse	229	24	1	3	3	7	5	2	2	1	..	..	..
Kalkaska	306	57	8	2	7	6	11	13	5	5	..	..	..
Crawford	119	11	..	1	1	..	3	3	3	..	..	..	..
Oscoda	228	13	..	..	2	3	2	..	2	4	..	..	..
Alcona	186	24	1	..	1	1	3	5	7	4	2	..	..
Iosco	229	16	1	1	..	1	6	3	3	1	..	..	..
Ogemaw	185	32	1	1	1	3	6	8	4	2	2	3	1
Gladwin	47	13	..	..	1	..	..	2	1	6	2	1	..
Roscommon	112	2	..	..	..	..	..	1	1	..	..	..	..
Missaukee	152	1	..	..	..	..	1	..	..	..	..	..	..
Clare	348	22	1	4	2	1	3	6	4	1	..	..	..
Osceola	406	12	7	2	1	1	1	..	..	..	..	..	..
Wexford	202	8	2	2	..	3	..	..	..	1	..	..	..
Manistee	162	15	1	1	2	1	3	4	3	..	..	..	..
Mason	198	21	..	2	..	2	3	5	3	5	..	1	..
Lake	274	57	11	1	3	6	15	10	9	2	..	..	..
Oceana	249	11	2	1	..	3	..	2	1	2	..	..	..
Newaygo	460	48	2	4	2	3	11	11	13	2	..	..	..
Mecosta	328	26	..	3	..	..	1	12	6	2	2	..	..
Isabella	174	4	..	..	..	..	..	1	..	2	..	1	..
<u>Southern Lower Peninsula</u>													
Montcalm	471	27	..	..	3	1	2	2	6	2	6	3	2
Ionia	66	2	..	..	..	..	..	..	1	..	1	..	..
Kent	733	24	..	1	..	..	1	6	2	7	3	1	3
Muskegon	214	15	..	2	2	..	3	1	5	..	1	..	1

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Area and County	Total lakes[1]	Number sampled	Alkalinity groups[2]										
			10	30	50	70	90	110	130	150	170	190	200+
Southern Lower Peninsula, cont.													
Ottawa	147	5	..	..	..	..	..	2	2	1	..	..	..
Allegan	432	13	2	1	2	..	..	2	4	2	..	..	..
Van Buren	304	16	..	..	3	2	4	2	..	3	..	1	1
Berrien	165	5	1	2	..	..	..	..	..	1	1	..	..
Cass	443	20	2	..	2	1	..	1	2	6	4	1	1
St. Joseph	183	16	..	..	1	1	2	4	2	2	2	1	1
Kalamazoo	342	19	..	..	..	..	1	2	2	2	4	3	5
Barry	694	39	2	1	..	4	2	3	10	10	3	..	4
Calhoun	563	11	..	..	..	..	2	..	1	5	1	..	2
Branch	132	21	..	..	..	1	..	..	2	8	6	3	1
Hillsdale	320	19	..	..	..	2	..	1	8	4	2	2	..
Lenawee	208	7	..	..	..	..	..	4	1	..	..	..	2
Jackson	607	26	..	..	1	..	..	2	5	8	2	4	4
Washtenaw	331	43	1	..	..	2	2	10	4	6	8	5	5
Livingston	507	27	..	..	..	..	1	4	6	4	3	5	4
Oakland	1491	89	..	..	..	3	6	11	15	20	15	13	6
Lapeer	309	21	..	..	..	..	2	2	2	5	4	5	1
Genesee	148	10	..	..	..	1	2	1	3	..	..	1	2
Shiawassee	95	1	..	..	..	..	..	..	..	..	1	..	..
Ingham	101	1	..	..	..	..	..	1	..	..	..	..	..
Eaton	152	0	..	..	..	..	..	..	..	..	..	..	..
Clinton	161	3	..	..	..	..	..	1	..	1	..	1	..
Gratiot	244	1	..	..	..	..	..	..	..	..	..	..	1
Midland	5	4	..	1	..	..	..	..	1	1	1	..	..
Arenac	22	1	..	..	..	..	..	..	1	..	..	..	..
Bay	18	0	..	..	..	..	..	..	..	..	..	..	..
Saginaw	69	1	..	..	..	..	..	..	..	..	1	..	..
Tuscola	28	2	..	..	..	..	..	..	..	..	..	1	1

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Table 1. --concluded

Area and County	Total lakes [1]	Number sampled	Alkalinity groups [2]										
			10	30	50	70	90	110	130	150	170	190	200+
Southern Lower Peninsula, cont.													
Huron	6	0	..	..	..	..	..	..	..	..	..	..	..
Sanilac	23	0	..	..	..	..	..	..	..	..	..	..	..
St. Clair	189	0	..	..	..	..	..	..	..	..	..	..	..
Macomb	139	2	..	..	..	1	..	..	..	..	..	..	1
Wayne	160	5	..	..	..	..	..	..	..	..	2	..	3
Monroe	257	1	..	..	1	..	..	..	..	..	..	..	..
Totals	29,537	1620	324	132	110	110	147	211	190	178	95	69	57

[1] Includes natural lakes and ponds, natural lakes with dams and lakes enlarged by marl dredging as tabulated by Humprys and Colby (1962).

[2] Alkalinity groups: 10 = 0-19 ppm; 30 = 20-39 ppm; etc.

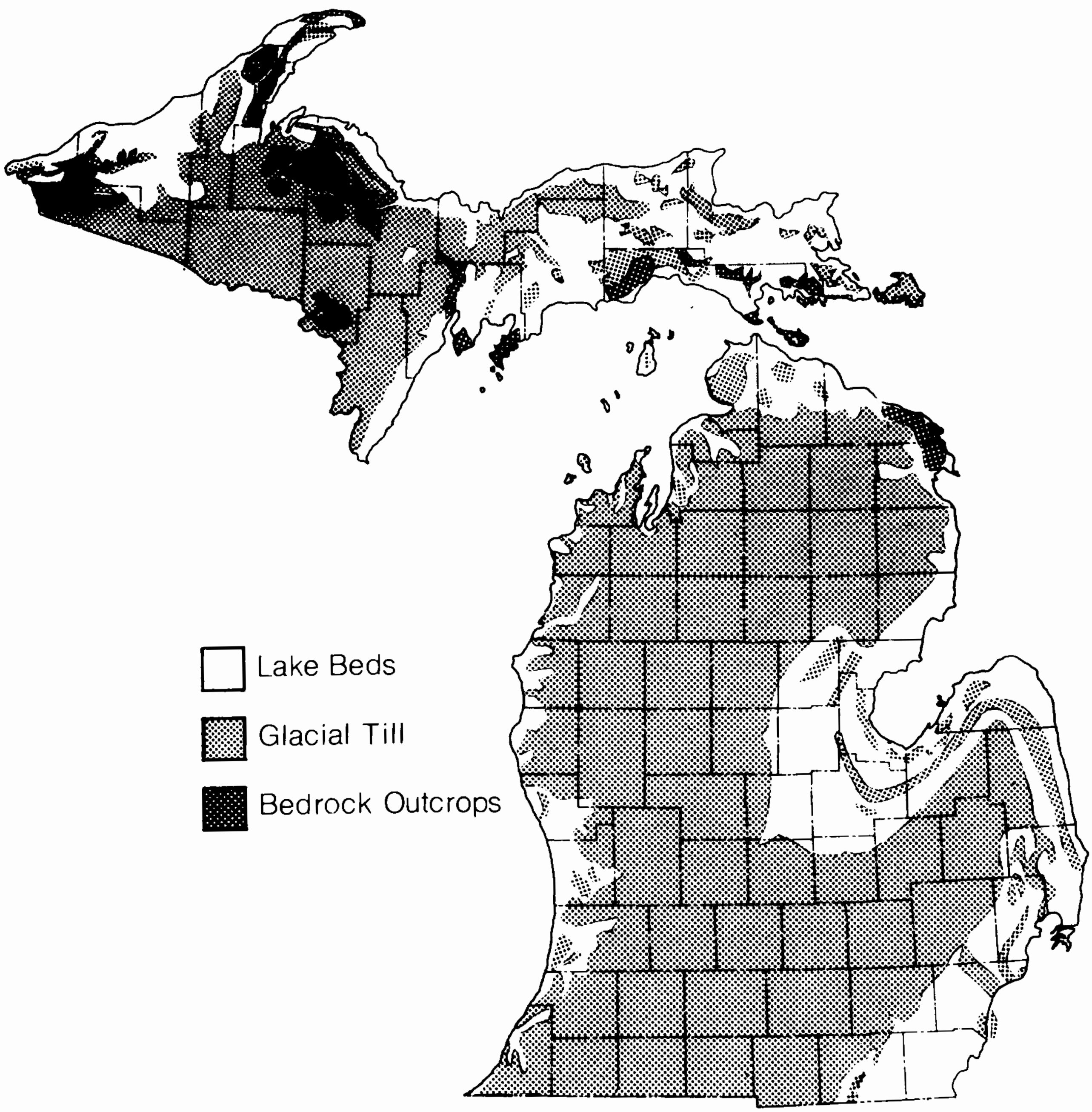

Figure 1.--Distribution of glacial till, bedrock outcrops and lake beds in Michigan. (From Martin, 1955, 1957)

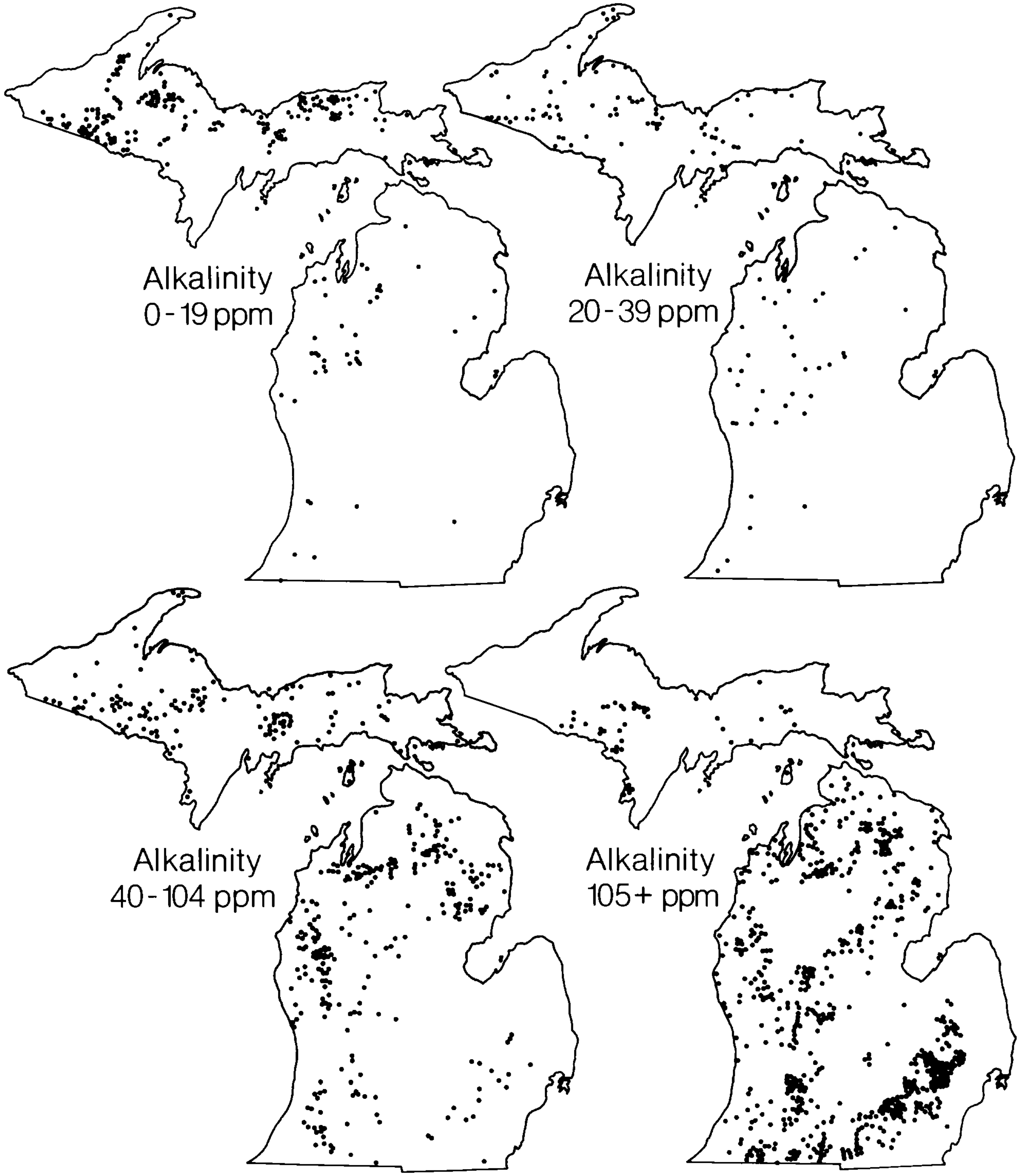

Figure 2.--Distribution of lakes by alkalinity type.

(Table 1 and Figs. 1 and 2). Lowland areas around Lake Erie, southern Lake Huron and Saginaw Bay, and the interior of the Lower Peninsula have very few lakes with fisheries potential, whereas Iron, Marquette, Oakland, and Gogebic counties have large numbers of useful lakes. Cheboygan County, with several very large lakes, has the greatest inland lake resources--over 51,000 acres or 10% of the county's surface.

Geologic types

The surface topography and soils of Michigan were strongly influenced by materials transported and deposited by continental glaciers (Fig. 1). Most lakes were formed in thick deposits of glacial till and therefore tend to be unaffected by the underlying bedrock. Some lakes were formed in areas where the bedrock is exposed and, therefore, some correlation between lake chemistry and bedrock chemistry may exist. Still other lakes lie on areas once submerged beneath ancient great lakes. Among lakes of each group there are limnological similarities useful in predicting their fisheries potential.

The lakes formed in glacial till are widely distributed in Michigan (Figs. 1 and 2). They range from very small to very large and from very shallow to quite deep. Alkalinity varies regionally, but the deep lakes with high inputs of carbonate-rich groundwater tend to be harder than the shallow, bog-type lakes.

Only five areas with bedrock outcrops contain many lakes of importance to fisheries. These are: a large area in the northwestern part of Marquette County and the eastern part of Baraga County, the tip of the Keweenaw Peninsula, portions of Isle Royale, the periphery of Drummond Island, and the eastern edge of Alpena and Presque Isle counties. Additional areas with a few bedrock lakes are the Porcupine Mountains, the western end of Gogebic County, the vicinity of Iron Mountain, the two peninsulas of Delta County, and scattered places in Mackinac County. Typically, bedrock lakes are relatively shallow, and many are subject to depletion of dissolved oxygen. They range from small to quite large. Those in the western half of the Upper Peninsula tend to be very soft with the exception of the hardwater (marly) lakes near Iron Mountain. The bedrock lakes in the eastern half of the Upper Peninsula lie on limestone and, therefore, tend to be hardwater unless acids produced by decomposition and by bogs and swamps have an overriding influence. If the general pattern holds, the lakes on Drummond Island, which have not been surveyed yet, will be hard water.

Lakes which lie on ancient lake beds may be divided into those pinched-off from (a) bays or (b) river mouths by sand bars and sand dunes, (c) those scoured on the Cheboygan lowland, and (d) others (Scott, 1921; Dorr and Eschman, 1970).

The (a) subgroup includes the preeminent lakes of the Grand Traverse Bay region such as Crystal, Glen, Elk, Torch, and (probably) Charlevoix, which were derived from bays of Lake Michigan. Walloon Lake appears to belong in this subgroup; however Scott observed that the highest bench mark (the Algonquin) lies slightly below the apparent outlet. All these lakes are large, very deep, and rich in marl and dissolved oxygen.

The (b) subgroup includes the dendritic-shaped lakes along the Lake Michigan coast between Frankfort and Saugatuck which were derived from drowned river mouths. A possible example on the Lake Huron coast is Van Etten Lake in Iosco County. These lakes are medium to large, of intermediate depth, and resemble reservoirs in that they have high flushing rates and high concentrations of minerals.

The (c) subgroup includes the very large lakes at the tip of the Lower Peninsula, such as Paradise, Burt, Black, and Douglas. Their basins were scoured under water, then isolated as the region rebounded upward when the glaciers retreated (Dorr and Eschman, 1970). They are relatively shallow for their size. Mullett Lake is the deepest, with a maximum depth of 148 feet. All have hard water, reflecting the influence of the limestone bedrock.

The (d) subgroup includes small to large lakes formed on the beds of ancient great lakes. Their shallow basins were apparently created by the actions of wind and/or glacier. Some occur around the edges of the present Great Lakes (Bass Lake, Mason County; Devils Lake, Alpena County; Indian Lake, Schoolcraft County; Brevoort Lake, Mackinac County; and Howe, Pine, Rush, and Conway lakes, Marquette County); others occur inland, especially on the eastern half of the Upper Peninsula (Carp, Frenchman, and Wegwass lakes, Chippewa County; Betsy Lake, Luce County; Gogebic Lake, Gogebic and Ontonagon counties; and some small lakes in the Allegan State Forest). A number of small lakes in the drainage basin of the Two Hearted River (Luce County) also lie on the sandy lake plain, according to the map of Martin (1957); however their shape and relatively great depth (up to 74 feet) suggest that they are pits in glacial till. The waters of the (d) subgroup tend to be soft unless influenced by limestone bedrock.

While most of the natural lake basins in Michigan were formed by the action of glaciers, wind, or lake currents, some were formed by diastrophism, groundwater, or rivers (Scott, 1921). The singular possible example of a lake formed directly by movement of the earth's crust is Canyon Lake, in the Huron Mountains of Marquette County. The long (one-quarter mile), narrow (100 feet wide), deep (78 feet) shape, plus the steep rock cliffs forming the sides, led Scott to suggest that Canyon Lake lies on a fault.

The action of groundwater on cracks in limestone bedrock leads to the formation of sink holes, and in some instances, to sink hole lakes. The most curious example is Rainy Lake, Presque Isle County, whose water level is maintained by a plug of sediment. In 1894, 1925, and 1950, the plug failed and the lake drained dry. Other lakes in Presque Isle County reported to be sinks are Sunken, Swan, an unnamed lake in T. 33 N., R. 8 E., Sec. 36, and, possibly, parts of Long Lake. Tanner (1960) suggested that South Twin, North Twin, West Lost, Hemlock, and Section Four lakes in Otsego County were sinks, raising the possibility that many other cone-shaped lakes lying on relatively thick glacial till between Alpena and Petoskey may be sinks also. In the limestone area of southeastern Michigan, the basin of Ottawa Lake, Monroe County, has been attributed to this cause. This "lake" dries up most summers.

Oxbow lakes were meander loops of rivers which became isolated by sandbars when the river changed course. Several examples occur along the Grand River in Ottawa County: Jubb, East Manville, and Bass River bayous. The example cited by Scott (1921) for the Huron River, Washtenaw County, is now flooded by Ford Lake (reservoir). The oxbow lakes are shallow and prone to periodic fish kills.

Alkalinity types

Alkalinity, or bound carbon dioxide, has been used to type lakes according to habitat and biota in Wisconsin, Minnesota, and Michigan (Prescott, 1962; Moyle, 1956; Hooper, 1956). Based on the review by Hooper (1956) the most appropriate groupings for Michigan lakes are 0-19 ppm (very soft), 20-39 ppm (soft), 40-104 ppm (medium), and greater than 105 ppm (hard). On this basis 20% of the 1,620 lakes sampled to date are very soft, 8% are soft, 25% are medium, and 47% are hard (Table 1).

Hardwater lakes predominate in lower Michigan and softwater lakes predominate in upper Michigan, especially in the Lake Superior watershed (Table 1 and Fig. 2). The major exceptions to this pattern are the southeastern Upper Peninsula lakes noted earlier which are influenced by limestone, the hardwater glacial till lakes in Dickinson, Iron, and southern Marquette counties, and the softwater glacial till lakes in the Osceola-Wexford county area.

The relationship between alkalinity and drainage type noted by Hooper (1956) for southern Michigan lakes was found statewide. Seepage lakes tend to be softer than semi-drainage (intermittent outlet) or drainage (permanent outlet) lakes. For a test group of 178 lakes scattered throughout the state the correlation coefficient was 0.52. Productivity, as reflected by Secchi disk transparency, was also correlated with drainage ($r = 0.39$, $N = 151$) but the relative abundance of submerged vegetation was not related to drainage. Alkalinity was weakly correlated with both measures of productivity for the state as a whole ($r = 0.20$, $N = 152$; $r = 0.20$, $N = 130$); however among Upper Peninsula lakes, some of which were brown-water, the relationship was not significant.

Lake alkalinities were examined in relation to the soil maps of Veatch (1943) and Whiteside et al. (1956) and the surface geology maps of Martin (1955, 1957). Some correlation was found, as noted in the section on geologic types; however the predictive value of these maps was poor because of (1) the drainage-alkalinity relationship, (2) acids produced by decomposition, bogs and swamps, (3) overlap of soil types within a drainage basin, and (4) inadequate information on subsoils or local conditions.

Climatic types

The thermal characteristics of a lake, and indirectly its biota and productivity, depend primarily on the climate of the region and stratification within the lake. Climate varies significantly within Michigan due to latitude and the influence of the Great Lakes. A number of indices of climate are available; however because most aquatic organisms require warm temperatures for growth, average cumulative growing-degree-days above a base of 55 F (March 1-October 31) seems most appropriate (Fig. 3). With this index, lakes in the warmest part of the state (Cass County) differ by a factor of 2.4 from lakes in the coldest part of the state (Baraga County). Groupings of 900-1300, 1300-1800, and 1800-2200 degree-days were found to be useful in the subsequent analysis of fish distribution, but climate is best treated as a continuous variable, as was done in the following analysis of fish productivity.

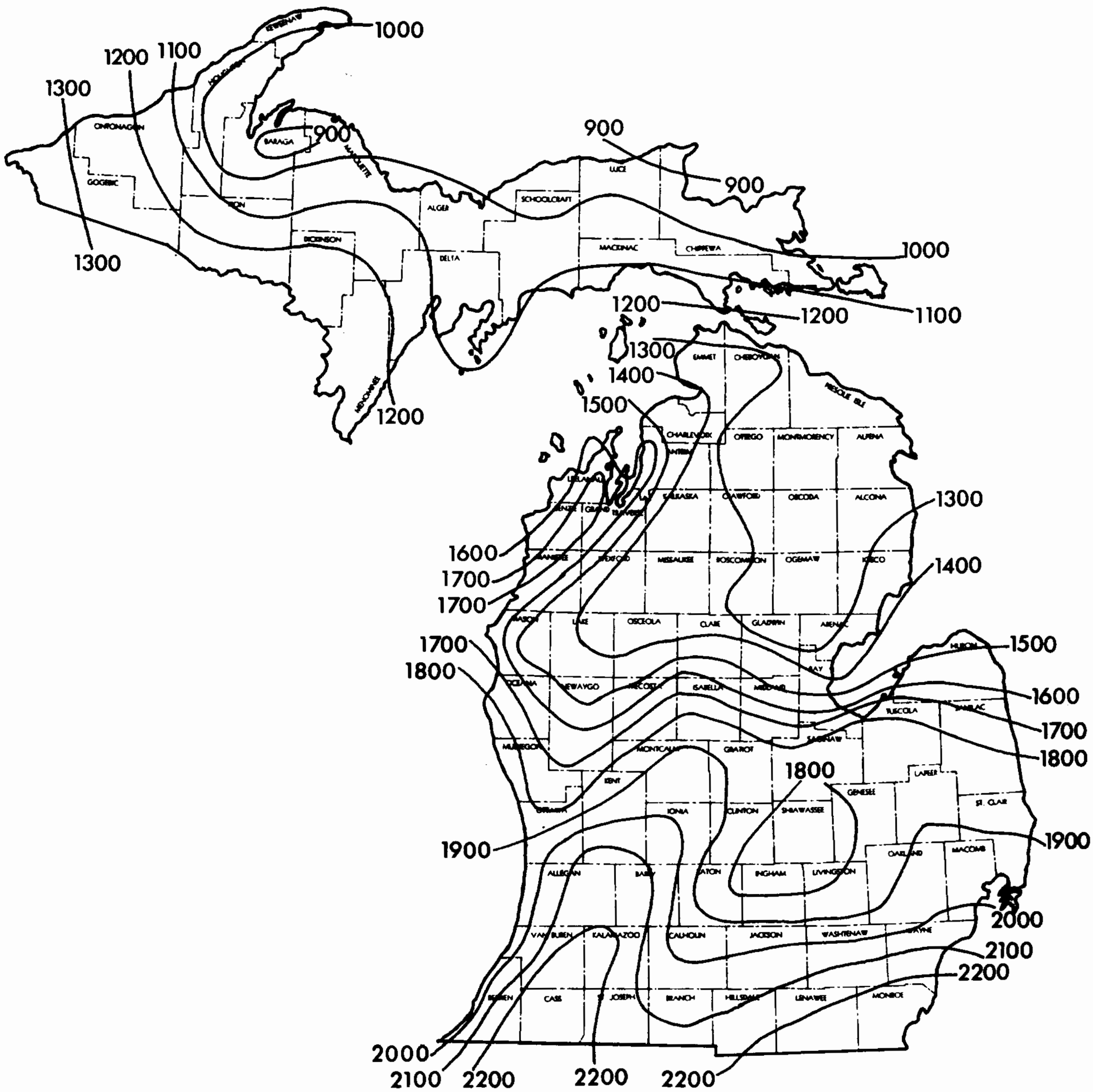

Figure 3.--Average cumulative growing-degree-days above a base of 55° F, March 1-October 31. (From Van den Brink et al., 1971)

Oxygen-thermal types

In many Michigan lakes temperature and oxygen reach critical levels for fish and other organisms during mid-winter or mid-summer. Five oxygen-thermal types may be recognized based on oxygen and temperature profiles in late July to mid-August, and a sixth type was created for lakes in which severe fish kills occur during the winter or summer due to depletion of dissolved oxygen (DO):

(1) Stratified lakes with at least 2 ppm DO at all depths,

(2) Stratified lakes in which DO falls to 2 ppm in the hypolimnion,

(3) Stratified lakes in which DO falls to 2 ppm between the 5-foot level of the thermocline and the top of the hypolimnion,

(4) Stratified lakes in which DO falls to 2 ppm between the bottom of the epilimnion and the 5-foot level of the thermocline,

(5) Unstratified lakes,

(6) Lakes subject to frequent, severe, fish kills (DO falls to near zero throughout the lake).

The selection of 2 ppm DO as a reference point was somewhat arbitrary but appears to be useful. While few fish can survive indefinitely at this concentration, they are able to make feeding forays into these areas of low oxygen. Another advantage is that the problem of interpreting profiles, which become asymptotic as DO approaches zero, is avoided.

Most lakes in Michigan can be readily placed into one of the first five types, but a few vary from year to year due to the effects of weather on the amount of mixing at spring overturn, on time and depth of stratification, and on productivity. Some lakes are rapidly changing to type 4 because of cultural eutrophication. The general progression of oxygen-thermal types is from deep, unproductive lakes with a large volume of cold, well-oxygenated water to shallow, productive lakes with no cold water. The major exceptions are polluted lakes, brown-water lakes with high biological oxygen demand, and clearwater lakes in which much photosynthesis takes place in the thermocline. The following table shows the ranges of mean depth in feet (Z) and ratio of volume of epilimnion to total volume (VE/VT) encountered in a sample of about 300 diverse lakes:

Oxygen-thermal type	Z	VE/VT
1	15.6-111.0	0.37-0.63
2	12.2- 35.2	0.32-0.68
3	8.6- 36.9	0.36-0.85
4	3.7- 23.2	0.36-0.99
5	2.8- 23.5	1.00

Analysis of fish productivity

Methods

Multiple regression and correlation methods were used to evaluate the importance of certain lake characteristics to fish productivity. The independent variables tested were: area in acres, percent shoal (0-15 feet deep), mean depth in feet, methyl orange alkalinity in ppm, alkalinity divided by mean depth, Secchi disk transparency in feet, relative abundance of submerged vegetation (ranked 1-5 = sparse-abundant), climate index, oxygen-thermal types and a panfish index. The panfish index was defined as the fraction of the total sport catch (by weight) made up of bluegills (Lepomis macrochirus), pumpkinseeds (Lepomis gibbosus) and black crappie (Pomoxis nigromaculatus). The bluegill was by far the predominant of these three species in all lakes analyzed except two. Because these species, and the bluegill in particular, are lower on the food chain than other sport fishes such as bass (Micropterus salmoides and M. dolomieui) and northern pike (Esox lucius), the panfish index reflects the trophic structure of the fish community within a lake. Fish communities with high panfish indices have trophic pyramids with relatively large basal components and relatively small apices; fish communities with low panfish indices have trophic pyramids with relatively small basal components and relatively large apices.

The annual catch of fish by anglers in pounds per acre was used as a measure of a lake's fish productivity. The data selected for analysis represent reasonable averages for steady-state fisheries of natural fish populations. Although the fish populations of some lakes were supplemented by stocking with small fish (mainly trout), they had a negligible effect on the analysis. Trout-only lakes which are managed exclusively by stocking were excluded.

Two types of catch estimates were available. First, catch estimates by Clark (1941), Christensen (1953), Patriarche (1960) and Christensen (unpublished data) based on sampling at 31 experimental lakes during the period 1930-1965 (most of the data used in the analysis were collected in the 1950's) and, secondly, catch estimates derived by Gale C. Jamsen (personal communication) from questionnaires mailed to 2% of the licensed sport fishermen in 1973 (41 lakes used in the analysis) and 1% of the anglers in 1970 (2 lakes used in the analysis). Included in the 43 so-called lakes surveyed by mail are six lake pairs, each comprised of two discrete but nearby lakes. A weighted average of the independent variables was used to represent each lake pair in the analysis. The mail survey of 1974 and our files also provided most of the information needed for two other lakes plus some useful data for 12 additional lakes. Eight lakes were included in both the experimental and mail survey groups. Catch estimates expressed in terms of numbers of fish (some experimental lakes and all mail survey lakes) were converted to estimates in pounds per acre based on specific or general knowledge of the average size of fish caught.

Data from the experimental and mail survey lakes were analyzed separately because fishing pressure and harvest rates may have increased significantly between the 1950's (and earlier) and the early 1970's, and because the estimates may have different reliabilities. While not very precise, these catch data reflect the relative differences among lakes within each group. The lakes with estimated catches of sport fishes are listed in Table 2. The variables used in the multiple regressions and correlations are given in Table 3. The fit to the linear regression model was improved by the following transformations: $\log_{10}$ catch, $\log_{10}$ area, $\log_{10}$ vegetation rank, $\log_{10}$ alkalinity $\div$ mean depth, and the reciprocal of $\log_{10}$ Secchi disk transparency.

Results

Only six lake characteristics were related to catch: panfish index, climate, Secchi transparency, vegetation rank, mean depth, and area (Table 4). These are listed in approximate order of importance--the exact ranking depending upon which variables were included and excluded, and on the type of catch estimate. Among the experimental lakes group these six variables accounted for 86% of the variation in catch; the first four variables alone explaining 85% of the variability. Among the mail survey lakes all six variables accounted for 88%, and the first four variables 78%, of the variation in catch.

Mean depth and area were more important factors among the mail survey lakes, which on the average were deeper and larger, than the experimental lakes. The apparent importance of area to fish productivity may have been due in part to its influence on fishing pressure ($r = -0.87$, $N = 56$), anglers preferring to fish in the safety of smaller bodies of water. The correlation between catch and fishing pressure was strong for both the experimental lakes ($r = 0.87$, $N = 31$) and the mail survey lakes ($r = 0.96$, $N = 56$) suggesting that, by and large, the lakes were being fished in proportion to their productivity and that fish catch was, in fact, an index of productivity. Surprisingly, the analysis showed that alkalinity, amount of shoal and oxygen-thermal type were unimportant to fish production. The logarithm of alkalinity divided by mean depth, analogous to the morphoedaphic index (Ryder et al., 1974), explained only 8% ($N = 31$) and 33% ($N = 42$) of the variability in catch from the experimental lakes and the mail survey lakes, respectively. Essentially all of the correlation was due to mean depth.

Multiple regression analyses provided four equations for predicting the pounds of fish caught (Table 5). As indicated by the high

Table 2.--Name, location and estimated catch of sport fishes (pounds per acre) for 31 experimental lakes and 45 mail survey lakes

Experimental lakes			Mail survey lakes		
Name	County	Catch	Name	County	Catch
Fletcher	Alpena	10	Hubbard	Alcona	7
Fine	Barry	37	AuTrain	Alger	14
Paw Paw	Berrien	23	Long	Alpena	12
Craig	Branch	91	Elk-Skegemog	Antrim	3
Duck	Calhoun	30	Torch	Antrim	1
Birch	Cass	15	Gun	Barry	31
Christiann	Cass	23	Thornapple	Barry	141
Lobdell	Genesee	36	Crystal	Benzie	2
Fife	Gd. Traverse	20	Paw Paw	Berrien	122
Bear	Hillsdale	22	Coldwater	Branch	56
Big Portage	Jackson	8	Marble	Branch	103
Bear	Manistee	12	Diamond	Cass	109
Hamlin	Mason	7	Black	Cheboygan	9
Pontiac	Oakland	40	Burt	Cheboygan	3
Devils Wash Basin	Ogemaw	6	Mullett	Cheboygan	4
Devoe	Ogemaw	3	Fenton	Genesee	65
Grebe	Ogemaw	6	Lobdell	Genesee	42
Grousehaven	Ogemaw	1	Gogebic	Gogebic	9
Jewett	Ogemaw	27	Littlefield	Isabella	51
Lodge	Ogemaw	14	Gull	Kalamazoo	33
Scaup	Ogemaw	4	Campau & Camp	Kent	76
South Pond	Ogemaw	15			
Otsego	Otsego	5	Nepessing	Lapeer	85
Stearns Bayou	Ottawa	105	Glen	Leelanau	2
Houghton	Roscommon	10	Leelanau	Leelanau	7
Corey	St. Joseph	33	Devils & Round	Lenawee	44
Minnewaukon	St. Joseph	60	Whitmore	Livingston	91

(continued, next page)

Table 2. --concluded

Experimental lakes			Mail survey lakes		
Name	County	Catch	Name	County	Catch
Saddle	Van Buren	36	Manistique	Luce	9
Sugarloaf	Washtenaw	29	Hamlin	Mason	16
Whitmore	Washtenaw	25	Chippewa	Mecosta	37
Winnewana	Washtenaw	140	Sanford	Midland	53
			Wolf	Muskegon	115
			Croton & Hardy	Newaygo	17
			Cass	Oakland	33
			Kent	Oakland	111
			Maceday	Oakland	54
			Orchard	Oakland	42
			Orion	Oakland	41
			Pontiac	Oakland	102
			Wolverine	Oakland	42
			Otsego	Otsego	12
			Grand	Presque Isle	10
			Higgins	Roscommon	8
			Houghton	Roscommon	23
			Indian	Schoolcraft	4
			Mitchell & Cadillac	Wexford	34

Table 3.--Summary of data used in multiple regression analysis of fish productivity for the 31 experimental and 45 mail survey lakes

Lake characteristics	Experimental lakes		Mail survey lakes	
	Mean	Range	Mean	Range
Area	1450	1-20,044	4844	183-20,044
Percent shoal	70	10-100	54	10-95
Mean depth (Z)	12.5	2.2-43.0	22.9	5.0-111.0
Alkalinity (A)	121	33-168	123	25-214
A ÷ Z	14.2	3.1-70.5	8.4	1.1-25.0
Secchi	9.0	2-17	10.1	2-23
Vegetation rank	3.8	1-5	3.2	1-5
Climate index	1742	1300-2200	1664	1050-2200
Oxygen-thermal index	3.8	1-5	3.3	1-5
Panfish index	0.54	0.00-0.89	0.28	0.01-0.70
Catch	28.8	1-140	41.9	1-141

Table 4.--Simple correlation coefficients (r) for the six lake characteristics related to fish productivity, and partial correlation coefficients (p) and coefficients of determination (R^2) from multiple correlations with four or six of the lake factors (NS = not significant at the 0.05 level)

Lake characteristics	Experimental lakes			Mail survey lakes [1]		
	r	p		r	p	
		four-factor	six-factor		four-factor	six-factor
Panfish index	+0.77	+0.72	+0.72	+0.78	+0.48	NS
Climate index	+0.74	NS	+0.40	+0.70	+0.43	+0.51
1 ÷ $\log_{10}$ Secchi	NS	+0.58	+0.49	+0.38	+0.48	NS
Log_{10} vegetation	+0.65	+0.55	NS	+0.52	+0.49	NS
Mean depth	NS	....	NS	-0.58	....	-0.65
Log_{10} area	NS	....	NS	-0.84	....	-0.48
R^2		0.85	0.86		0.78	0.88

[1] Forty-four lakes were used in the multiple correlation with four factors and 42 lakes were used in the multiple correlation with six factors.

Table 5.--Multiple regression coefficients for the best equations relating catch of fish ($\log_{10}$ pounds per acre) to four or six lake characteristics

Lake characteristic	Experimental lakes equation number		Mail survey lakes equation number	
	1	2	3	4
Constant	-0.3322	-0.2487	-0.7881	+1.698
Panfish index	+0.9928	+0.9880	+1.0433	+0.3510
Climate index	+0.00022	+0.00035	+0.00055	+0.00056
$1 \div \log_{10}$ Secchi	+0.2829	+0.2351	+0.5902	+0.1133
Log_{10} vegetation	+0.6151	+0.3585	+0.6621	-0.1527
Mean depth	...	-0.0100	...	-0.0114
Log_{10} area	...	+0.00025	...	-0.3547

coefficients of determination the predicted catches were in good agreement with the estimated catches. Among the experimental lakes some of the greatest deviations (high predictions) were for those lakes censused prior to the end of World War II, a time when fishing pressure was lower statewide. Among the mail survey lakes the reasons for the discrepancies were not as apparent but it is suspected that the estimates for some southern Michigan lakes are too high. As a whole the mail survey estimates were higher than the experimental lake estimates, possibly due, in part, to a statewide increase in fishing pressure and harvest rate since the 1950's.

The equations developed here need to be refined with additional data before they can be used confidently to predict the catch of fish from all lakes in the state. The area term of equation 4 has been given too much weight because small lakes could not be included in the mail survey. Equation 3 does not give reasonable predictions when Secchi disk readings are less than 4 feet, possibly because the logarithm of Secchi disk transparency is not linearly related to the logarithm of fish catch at extreme values. Obvious examples are lakes which are so grossly polluted that their fish populations have diminished. Substances which interfere with the use of Secchi disk as a measure of plankton productivity, such as brown-water stains and bottom materials suspended by wave action, may disrupt all the equations to some degree, although recent work by Alfred M. Beeton and John P. Crumrine (personal communication) suggests that the effects of stains may be small. All the experimental and mail survey lakes were clear to light-brown in color. The importance of the climate term in equations 1 and 2 may be underestimated because no experimental lakes were in the coldest areas of the state. Overall, equation 1 appears to be the best for predicting the fish productivity of Michigan lakes.

Analysis of fish distribution

Methods

The multiple correlation analysis pointed up the importance of the bluegill in determining total fish productivity. The next problem was to determine if the distribution and relative abundance of the bluegill, and of other important species as well, were related to lake typology. Additional data were sought from the files for lakes representing the broadest possible range of climatic and oxygen-thermal types. These two lake characteristics were chosen because fish species are known to differ in their temperature and oxygen requirements (Environmental Protection Agency, 1973), and because the panfish index was strongly correlated with the climate index for both the experimental lakes (r = 0.69) and the mail survey lakes (r = 0.71). The relative abundance of each principal sport species was ranked (none reported, sparse, common, abundant, stocked fingerlings will survive) for each of 207 lakes based on creel census and/or netting records. An additional 24 lakes which, so far as is known, had no native fish prior to intensive fisheries management were used in the analysis of trout distribution. A rigorous statistical analysis was not attempted because of the subjective nature of the abundance rankings; rather, relative abundance was graphed against climate type and oxygen-thermal type, and distribution patterns were determined by inspection.

Results

The distribution patterns were fairly well defined (Table 6). Coldwater species of fish--the trouts--which are routinely stocked in lakes which have few piscivorous fish, thrive best in oxygen-thermal types 1, 2 and 3. These types of lakes contain at least a 5-foot strata of cool, oxygenated water in the thermocline. Lake trout (*Salvelinus namaycush*) are known to thrive best in type 1; brook trout (*Salvelinus fontinalis*), brown trout (*Salmo trutta*) and rainbow trout (*Salmo gairdnerii*) are not as exacting and will thrive in types 4 and 5 as well, if they are located in relatively cold climates of 1300 growing degrees or less. Rainbow trout are able to survive the critical summer period in any lake within the warmest part of the state if the lake is deep or has inflows of cool water.

Table 6.--Percentage of lake types, with respect to oxygen-thermal indices, containing abundant or common populations of bluegills, largemouth bass, black crappie, yellow perch, walleye and smallmouth bass. For trout the percentages refer to lakes managed for these species and to lakes in which planted trout are known to survive. The numbers of lakes used for computing the percentages are given also.

Species, and oxygen-thermal index	Climate index (hundreds)			Species, and oxygen-thermal index	Climate index (hundreds)		
	9-13	13-18	18-22		9-13	13-18	18-22
Bluegill				Yellow perch			
5	35	85	100	5	100	100	62
4	38	100	100	4	100	87	77
3	25	88	100	3	75	81	100
2	41	60	100	2	82	100	75
1	10	12	100	1	90	100	100
Largemouth bass				Walleye			
5	35	75	100	5	61	25	0
4	56	100	100	4	19	13	4
3	33	88	100	3	25	6	0
2	35	60	100	2	18	0	0
1	10	50	100	1	20	0	0
Black crappie				Smallmouth bass			
5	22	58	62	5	39	33	0
4	19	73	54	4	25	20	8
3	4	25	47	3	42	31	18
2	0	0	38	2	35	60	25
1	0	12	0	1	70	100	0
Trout				Number of lakes analyzed [1]			
5	32	0	0	5	23(2)	12	8
4	28	0	8	4	16(2)	15	26
3	75	35	50	3	24(12)	16(1)	17(1)
2	80	100	88	2	17(3)	5	8
1	92	100	100	1	10(3)	8	2

[1] Additional lakes used for the trout analysis are in parentheses.

Warmwater species--bluegill, largemouth bass (*Micropterus salmoides*) and black crappie--were most abundant in lakes located in the warmest climate with the largest volume of warmwater (types 4 and 5). Even deep, well-oxygenated lakes in southern Michigan, with a relatively small layer of warmwater habitat, support sizable populations of these species. The black crappie is most abundant in the very eutrophic lakes and reservoirs.

Coolwater species--yellow perch (*Perca flavescens*), walleye (*Stizostedion vitreum*) and smallmouth bass (*Micropterus dolomieui*)--are widely distributed but thrive best in the cooler waters. Walleyes and smallmouth bass are not found in many lakes which have habitat conducive to good survival because of rather exacting spawning requirements. The walleye is most abundant in the large, unstratified (type 5) lakes of northern Michigan; the smallmouth bass thrives best in the deep, well-oxygenated lakes (types 1 and 2) of northern Michigan. The ubiquitous perch is least abundant in the warmest lakes.

Discussion

In considering the fisheries potential of inland waters the primary questions of what kinds and how many fish a lake will support were satisfactorily answered by lake characteristics long recognized as being relevant. The main value of these analyses is a recognition of which characteristics are most important and how they may be used systematically (see front cover). The strength of the multiple correlations, explaining 78 to 88% of the variation in fish catch, is remarkable considering the complexity of aquatic ecosystems and the difficulties of obtaining representative measurements of such dynamic variables as fish productivity and Secchi disk transparency. Multiple correlation analyses of fish production in lakes outside of Michigan, by Ryder et al (1974), Jenkins (1970), Carlander (1955) and Hayes and Anthony (1964), have explained no more than 62 to 73% of the variation, and usually much less.

The multiple correlation analysis showed that fish productivity could be explained largely with indices of the trophic structure of the fish community (panfish index) and primary productivity. The percentage abundance of the bluegill, which is relatively low on the food chain, is a simple but adequate index to the structure of the fish community. The percentage abundance of fishes at the middle of the trophic structure, such as yellow perch and trout, and of those near the top, such as walleye, bass and northern pike, is of minor importance in explaining differences in total catch among the lakes studied.

An index to primary productivity was provided by Secchi disk (representing phytoplankton standing crop), submerged vegetation rank (representing macrophyte standing crop) and the climate index (representing turnover rate). Recent work by Michalski and Conroy (1972), and others, has confirmed the utility of the Secchi disk reading as a measure of primary production. The logarithm of Secchi disk transparency appears to be linearly related both to the logarithm of chlorophyll a (data of Michalski and Conroy, 1972) and to the logarithm of fish catch (this report) except, perhaps, for extreme values. It should be emphasized that both Secchi disk transparency and vegetation rank were important as measures of productivity. They are only weakly correlated in Michigan lakes ($r = 0.31$, $N = 118$).

Indices of primary production should be strongly correlated with nutrient (primarily phosphorus) loading rates (Vollenweider, 1970). For regions of homogeneous soils, such as the Canadian Shield, Schindler (1971a) has suggested that nutrient concentration will be directly proportional to drainage area and inversely related to lake volume. Only indirect indices of nutrient loading and productivity--mean depth, drainage type and alkalinity--were examined for Michigan lakes. The correlations (r) between Secchi disk transparency and these factors were relatively weak--0.48 ($N = 138$), 0.39 ($N = 151$) and 0.20 ($N = 152$), respectively.

It is doubtful that low alkalinity (carbon) itself limits algal production (Schindler, 1971b; Thorpe, 1942). At the other extreme, many highly alkaline lakes--the predominant type in southern Michigan

--are unproductive due to the adsorption of nutrients by calcium carbonate precipitates (Wetzel, 1972). While significant amounts of marl are precipitated at alkalinities as low as 105 ppm (Hooper, 1956), Barrett (1952) estimated that the lower limit of alkalitrophy is between 120 and 160 ppm methyl orange alkalinity. This would mean that as many as 36% of the Michigan lakes surveyed to date are potentially alkalitrophic. On the other hand, many lakes in this range are highly productive due to high inputs of nutrients or for unknown reasons. Thus alkalinity is not a reliable indicator of productivity. Secchi disk transparency and estimates of macrophyte abundance (even subjective ones) are more direct and more reliable indices of productivity.

Evidence that fish productivity is related to depth and total dissolved solids (or its correlates: alkalinity and conductivity) was reviewed recently by Ryder et al. (1974). For Michigan lakes alkalinity divided by mean depth was a weak prediction of fish catch (R^2 = 9-33%) and, also, of fish standing crops (R^2 = 20%) (Schneider, 1973). It should be noted that only two of the lakes with catch data had alkalinities of less than 40 ppm, which in Minnesota was the boundary between soft and hardwater lake communities (Moyle, 1956). On the other hand, the Michigan data appear to be well within the recommended range of the morphoedaphic index. While the morphoedaphic index has explained as much as 73% of the variability in some sets of data (Ryder et al., 1974), in other sets of data the fit has been poor (Jenkins and Morais, 1971).

The importance of climate to lake productivity has been widely acknowledged but has received too little analytical attention. Ryder et al. (1974) attempted to remove climatic effects by working within "relatively" homogeneous climatic zones such as the north temperate. Such a zone is too broad. By including the climate index in regressions with the morphoedaphic index the coefficients of determination increased from 8% to 57% for the experimental lakes (N = 31), and from 33% to 69% for the mail survey lakes (N = 42).

Whether average cumulative growing-degree-days above a base of 55° F is the most appropriate index for climate cannot be critically evaluated until fish productivity data from a greater range of climates are examined. Other indices have been used with some success. Jenkins and Morais (1971) reported that number of frost-free days, log area, and log age were significantly correlated with the catch from U.S. reservoirs, but only 17% of the variation was explained. Brylinsky and Mann (1973) noted that variables related to solar input, such as latitude and mean annual air temperature, had higher correlations with phytoplankton production than did morphological factors or nutrient concentrations. Beckman (1943) noted a general relationship between mean air temperature and the onset of growth by Michigan fishes. These studies, plus the analysis of fish distribution made here, indicate that climate influences the fish productivity of lakes by affecting (1) annual rates of primary production, (2) fish growing seasons and (3) the species composition of the fish community.

The distribution and relative abundance of fishes within Michigan are related to climate and to oxygen-thermal types--simple expressions of preferred habitat zones defined by temperature and oxygen. Predictability could be improved further if the relative volume of warm (epilimnion) versus cold (thermocline plus hypolimnion) habitat within a lake were taken into account by means of multivariate analysis. This ratio varies greatly, among type 4 lakes in particular, due to factors which affect depth of stratification and productivity--such as area (fetch) and pollution.

The major features of the lake ecosystem as pertains to the fisheries potential of Michigan lakes can be summarized as follows (see front cover). Fish catch, through fishing pressure, is determined by primary productivity (as indexed by Secchi disk transparency, macrophyte abundance and climate) and the trophic structure of the fish community (as indexed by bluegill relative abundance). The species composition of the fish community is dependent upon the relative amounts of cold-, cool- and warm-water habitat (as determined by climate, oxygen-thermal types and ratio of epilimnion volume to total volume) which, in turn, depend upon depth, area, and the balance between oxygen production and oxygen demand.

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