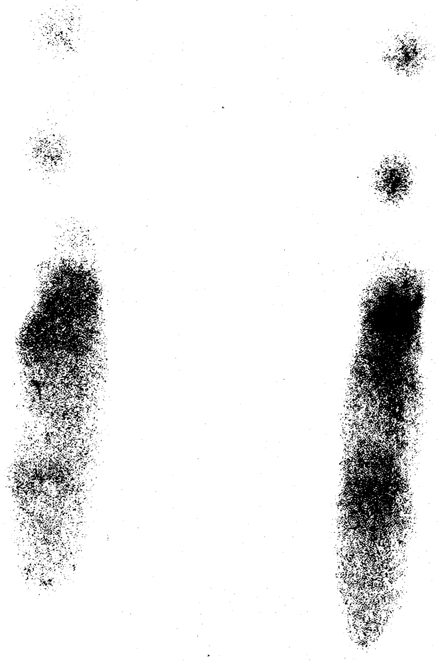

THE UNIVERSITY OF MICHIGAN
Biological Station

Limnological Features of Crooked and Pickerel Lakes, Emmet County, Michigan

Part I: Water Quality and Nutrient Budget

by

JOHN E. GANNON and DANIEL J. MAZUR

Part II: The Suitability of Soils for On-Site Wastewater Disposal

by

ARTHUR GOLD and JOHN E. GANNON

Technical Report No. 8

Douglas Lake

The University of Michigan Biological Station was established in 1909 at Douglas Lake near Pellston, Michigan, as a teaching and research facility. It occupies a 10,000-acre tract of semi-wilderness in northern lower Michigan, surrounded by a remarkable variety of upland and lowland deciduous and coniferous forests, meadows, marshes, bogs, dunes, lakes and streams. The three upper Great Lakes - Michigan, Huron and Superior - are nearby. As the largest and one of the most distinguished inland biological stations in the world, it serves as an intellectual meeting place for biologists and students from the United States and around the world.

The Biological Station is well-equipped for investigations of the diverse natural environments around it. In addition to the modern, winterized Lakeside Laboratory, which was funded by the National Science Foundation, the Station has 140 buildings, including laboratories, classrooms, and living quarters for up to 300 people. Special facilities include a library, study collections of plants and animals, a large fleet of boats, and a full array of modern laboratory and field equipment. The Station offers tranquility and harmony with nature - it is a place where plants and animals can be studied as they live.

Dr. David M. Gates, Director of the Station since 1971, and Mark W. Paddock, Assistant to the Director, have promoted new and exciting fields of research, including problem-oriented research to help cope with emerging environmental problems.

The Station is currently undertaking specific investigations in northern lower Michigan to provide information about the land, the water, and the people in the area. Results are made available to community leaders for use in long-term land-use planning. In addition, many research projects are underway, geared toward a better understanding of the structure and function of both aquatic and terrestrial ecosystems.

This publication is one of a series of reports that are issued periodically to disseminate information on research generated at the Biological Station. For further information concerning other publications in this series or information on the Biological Station in general, address inquiries to: The University of Michigan Biological Station, Pellston, Michigan 49769 (Phone 616-539-8406).

LIMNOLOGICAL FEATURES

of

CROOKED AND PICKEREL LAKES
EMMET COUNTY, MICHIGAN

PART I: WATER QUALITY AND NUTRIENT BUDGET[1]

by

John E. Gannon[2]

and

Daniel J. Mazur[3]

TECHNICAL REPORT NO. 8
BIOLOGICAL STATION
THE UNIVERSITY OF MICHIGAN
PELLSTON, MICHIGAN 49769

April 1979

---

[1] This report is based on research funded by the National Science Foundation (Grant No. AEN72-03483). Preparation of the report was supported by the Environmental Protection Agency as a sub-contract to a prime contract (EPA-No. 08-01-4612) to WAPORA, Inc.

[2] Present address: State University Research Center, Oswego, New York 13126

[3] Present address: Missouri Department of Natural Resources, Jefferson City, Missouri 65101

CONTENTS

Page

FIGURES

TABLES

INTRODUCTION

The University of Michigan Biological Station has been studying 40 inland lakes in Cheboygan and Emmet Counties, Michigan, since 1972. This research effort has been designed to provide ecological and sociological information pertinent to management of these lakes and their watersheds for the enhancement of long-term environmental quality. Preliminary results of these investigations are available in Gannon and Paddock (1974). Specific information on geology, hydrology and groundwater quality was presented in Richardson (1978). Sociological data on evaluations, behaviors, and expectations of residents of the study area were reported by Marans and Wellman (1977). Instances of utilization of information generated in this project for water quality and wastewater management purposes has been documented by Pelz (1977) and Pelz and Gannon (1978). Furthermore, information written especially for lake-oriented visitors and residents has been prepared in the Biological Station's Lakeland Report Series, Lake Profile Series, and other publications (Say et al., 1975; Foster, 1976; O'Neil, 1977).

Crooked and Pickerel Lakes have been investigated since the beginning of this problem-oriented research effort. The objective of this report is to provide a summary of salient limnological features of these two water bodies. Special emphasis will be given to the current water quality and trophic status of Crooked and Pickerel Lakes and to an estimate of nutrient (phosphorus and nitrogen) sources to these lakes. Complimentary information on suitability of lakeshore soils for on-site wastewater disposal is included as Part II of this report (Gold and Gannon, 1979).

DESCRIPTION OF STUDY AREA

Crooked and Pickerel Lakes are located near Little Traverse Bay of Lake Michigan in northwestern lower Michigan (Fig. 1). They lie in Emmet County (T35N, R4W) and are bounded by four townships (Bear Creek, Little Traverse, Littlefield, and Springvale). Typical of most lakes in this region, they were formed by melted ice blocks that were left by the retreating glacier over 10,000 years ago. These lakes are the beginning of the Inland Water Route, a series of interconnecting lakes and rivers that eventually empty into Lake Huron through the Cheboygan River.

Crooked and Pickerel Lakes have played an important role in the human history of northern lower Michigan. Although native people were primarily oriented towards the shorelines of Lakes Michigan and Huron, the Inland Water Route was used for passage from Lake Michigan to Lake Huron by canoe, thus avoiding the more hazardous journey around Waugoshance Point and through the Straits of Mackinac. The Inland Water Route

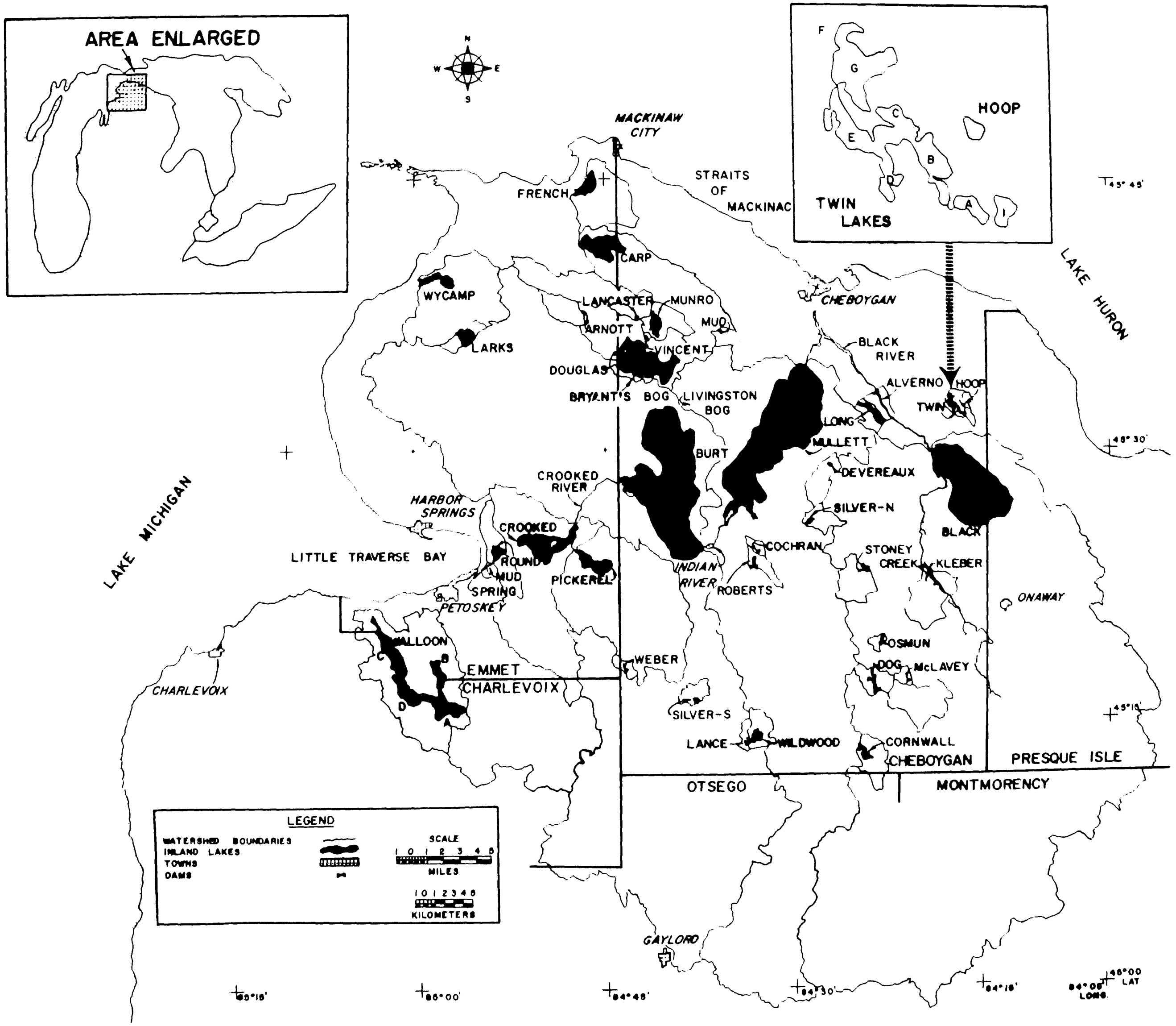

Fig. 1. Location of Crooked and Pickerel Lakes in northwestern lower Michigan in relation to other major inland lakes of the Cheboygan River watershed.

was also used extensively for transportation by European voyagers and settlers. During the logging era around the turn of the century, millions of board feet of white pine and other timber were floated down the Inland Water Route to sawmills; two of these mills were located on Crooked Lake at Oden and Conway.

At the same time, the railroad was built in this area and provided an overland transportation link to the south. Tourism flourished as vacationers came to Crooked and Pickerel Lakes by rail and stayed in resort hotels on the lakeshores. Commercial steamers carried vacationers from Crooked and Pickerel Lakes to Mullett Lake through the Inland Water Route. Crooked and Pickerel Lakes have continued to be popular for water-oriented recreation to the present day. To facilitate recreational boating activities, the Crooked River has been periodically dredged to a depth of 5 ft. since 1956. Water levels in Crooked and Pickerel Lakes were stabilized by construction of a lock and weir on the Crooked River at Alanson in 1964.

Crooked Lake was the only inland water body in northern lower Michigan with a railroad traversing a considerable distance of its shoreline. This allowed for earlier resort development on Crooked Lake than on other lakes of the region. In addition to resort hotels, cottages were built near the railway along the north shore, especially at Conway and Oden. The north shore of Crooked Lake was extensively dotted with seasonal dwellings in the early decades of this century while the south shore of the lake and all of Pickerel Lake's shores remained essentially undeveloped. Building of cottages and homes along all shorelines increased especially after World War II.

Since the north shore of Crooked Lake was first to be developed, it also was the first area to experience pollution problems. Contamination of nearshore water with human sewage was discovered along the north shore, especially near Oden, in the late 1960's and early 1970's. To alleviate this problem, a sanitary sewer was constructed to divert human sewage away from the north shore and into the Harbor Springs sewage lagoon and spray irrigation wastewater treatment system. Although the sewer was completed in Fall of 1975, most lakeshore residences were not hooked up to the sewer system until 1976. Lakeshore dwellings on the remainder of Crooked Lake's shoreline and all of Pickerel Lake continue to be serviced by conventional septic systems.

Human sewage was not the only source of pollution to Crooked Lake. A state fish hatchery has existed on the lake near Oden since 1920. The small stream emanating from the fish hatchery was the major source of ammonia-nitrogen and total phosphorus to Crooked Lake in 1975 (Gannon and Mazur, 1976). Further information on the fish hatchery and nutrient loading to Crooked Lake is presented in this report.

METHODS

Watershed Characteristics

Immediate watershed area is defined here as the area bounded by the highest elevation which continually surrounds a given lake without including other lakes. Total watershed area is the immediate watershed of a given lake plus the immediate watersheds of all other lakes that subsequently drain into the given lake. The watershed areas for Crooked and Pickerel Lakes were traced from U. S. Geological Survey quadrangle maps (1:62, 500 scale) onto a blank piece of paper and cut out with a pair of scissors. The area was determined by passing the piece of paper delineating the watershed area through a Hayashi Denko Automatic Area Meter, Model AAMS. Land-use types and their areal coverage were determined from LANDSAT satellite data (Rogers, 1977).

Limnological Characteristics

Morphometric features of Crooked and Pickerel Lakes were determined from hydrographic maps compiled by the Institute for Fisheries Research, Michigan Department of Natural Resources. The methods employed basically followed Welch (1948) and are discussed in Gannon and Paddock (1974).

Physiochemical data were obtained on a quarterly basis from Fall, 1972 through Winter, 1975 from a central deep station in both lakes (Figs. 2 and 3). Temperature profiles were recorded at one meter intervals, using a Whitney resistance thermometer. Light transparency was measured with a standard Secchi disc. Light penetration measurements were obtained with a submarine photometer fitted with Weston cells during Summer and Winter. Percent light transmission was calculated from the photometer readings. Apparent color of the water was estimated with a Hach colorimeter (pt-co units).

Water samples were obtained from three to five depth intervals, depending upon temperature profile characteristics, with a three-liter capacity Kemmerer bottle. Dissolved oxygen was determined titriometrically with the azide modification of the Winkler method (APHA, 1971). Alkalinity was measured titriometrically with an indicator solution of bromocresol-green and methyl-red (APHA, 1971). Specific conductance was determined on an Industrial Instruments Model RC-16B2 conductivity bridge and pH was measured potentiometrically on either a Beckman Model N or Model H-5 pH meter. All of the above variables were analyzed within 18 hours of collection.

Samples for remaining variables were filtered and frozen for later analysis. These samples were quick-thawed in a water bath to room temperature and chemical analyses were completed by the following methods. Calcium, magnesium, sodium, and potassium

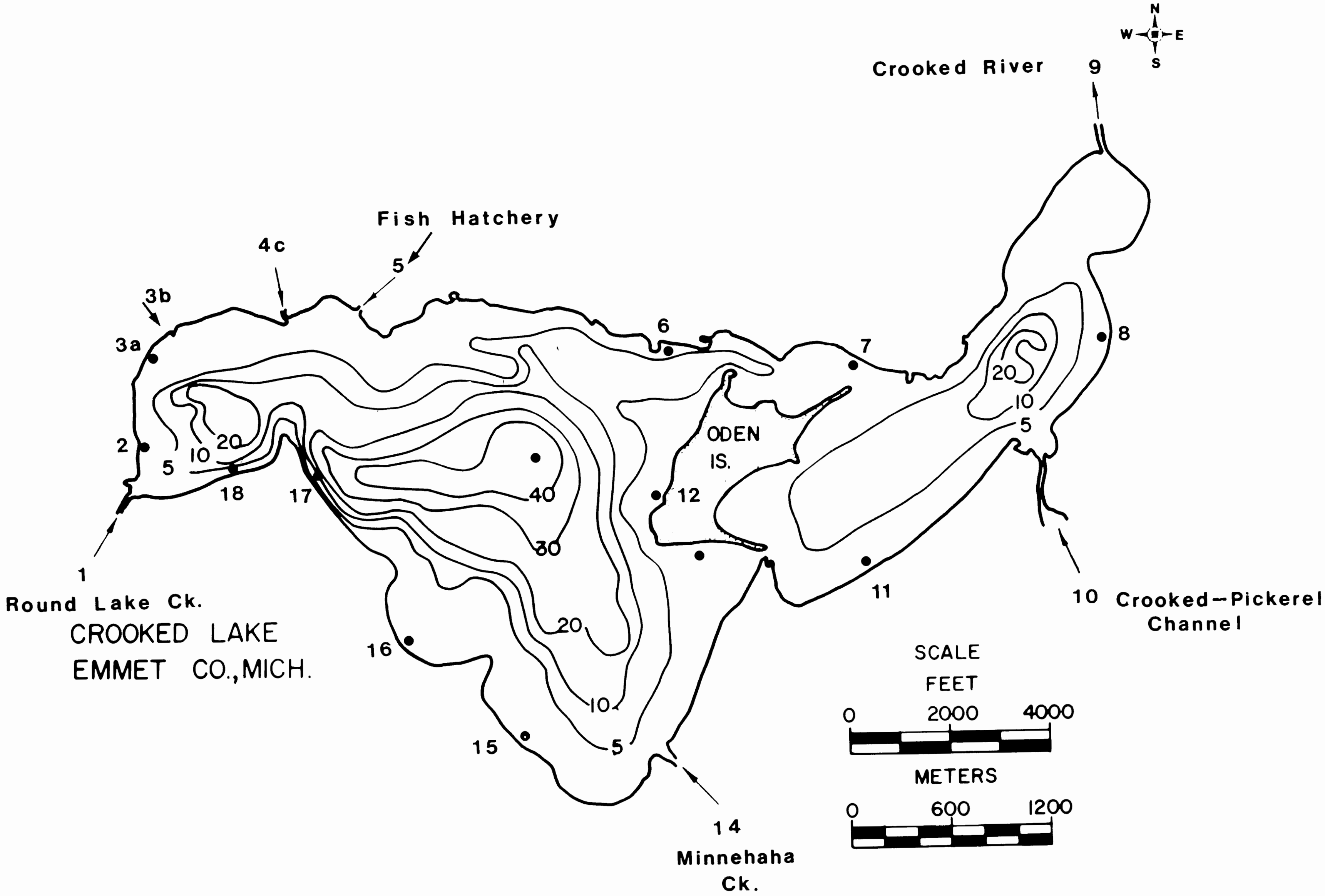

Fig. 2 Depth contour (morphometric) map of Crooked Lake, showing location of sampling stations. Depth contours are in feet.

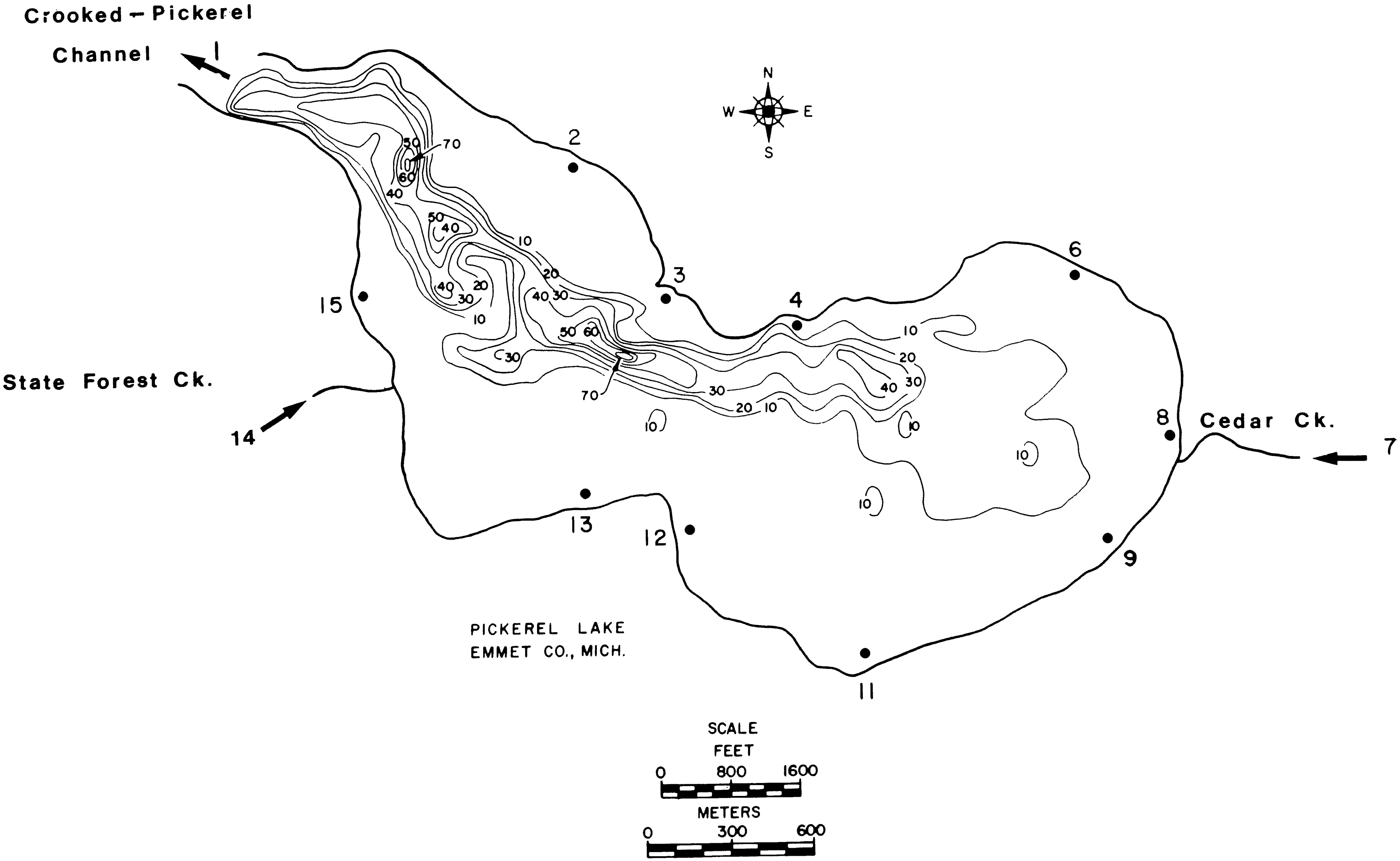

Fig. 3 Depth contour (morphometric) map of Pickerel Lake, showing location of sampling stations. Depth contours are in feet.

were determined on a Perkin-Elmer Model 305 atomic absorption spectrophotometer (EPA, 1974 a). Total phosphorus, soluble-reactive phosphorus, nitrate-nitrogen, ammonia-nitrogen, and silica were determined colorimetrically on a Beckman DB-GT spectrophotometer. Total phosphorus and soluble-reactive phosphorus were measured using a hybrid method of Gales et al. (1966) for digestion and Schmid and Ämbuhl (1965) for neutralization and color development. Nitrate-nitrogen and ammonia-nitrogen were determined by the methods of Müller and Widemann (1955) and Solórazano (1969), respectively. Silica was measured using the heteropole blue method (APHA,1971). Chloride was determined on the Beckman Model H-5 pH meter fitted with a salt bridge and chloride electrode (APHA,1971).

In the Fall of 1974, the Biological Station's chemistry laboratory was automated. A Technicon Autoanalyzer II was used to analyze September, 1974 and all 1975 samples colorimetrically (Technicon, 1972-73). Following the quick-thaw procedure, chemical measurements were performed by the following methods. Ammonia-nitrogen and nitrate-nitrogen* analyses were performed immediately. Simultaneously, sample aliquots for soluble and total phosphorus were poured into test tubes and placed in a gravity drying oven for several days until the sample evaported. Then the samples were digested with persulfate (Mentzel and Corwin, 1965), refrigerated overnight and

---

* Nitrate-nitrogen analysis also includes nitrite-nitrogen.

analyzed the next day. Silica (reported as Si) and chloride analyses were performed on thawed samples that sat at room temperature for one day. Phosphorus, ammonia-nitrogen and silica measurements were determined by automated methods (Technicon Industrial Methods 155-7W, 154-71W, and 186-72W), similar to the manual methods previously used. Nitrate-nitrogen was analyzed by a copper-cadmium reduction method (Technicon Industrial Method 158-7W). Chloride was measured with a mercuric thiocyanate and ferric ammonium sulfate automated method (EPA, 1974a).

Collection of plankton samples was made on each survey date from the central station in both lakes. A cylinder-cone plankton net with No. 20 (76 μm) nylon mesh, 0.25-m diameter, was towed from near bottom to the surface. Samples were examined qualitatively for species composition and relative abundance.

An Ekman grab (15 x 15 cm) was used to collect bottom samples at the central station in both lakes only in Summer, 1973. Samples were sieved with a No. 30 mesh screen and the invertebrates were identified and enumerated in the laboratory.

Nutrient Loading Determinations

Sources and quantities of phosphorus and nitrogen to Crooked and Pickerel Lakes were estimated from data collected from Summer, 1975 through Spring, 1976. Nutrient chemistry and other limnological data*, using previously described methods, were obtained at the central station and selected near-shore stations in both lakes (Figs. 2 and 3). Inshore stations were located at the mouths of inflowing streams, at the heads of outflows, and near concentrations of human development along the shoreline. Streams were monitored for discharge using Price and pygmy current meters and total phosphorus and inorganic nitrogen samples were obtained on a quarterly basis during the study period. An estimate of total nitrogen was obtained by doubling the inorganic nitrogen values since average inorganic and organic fractions were nearly equal in other nearby waters (EPA, 1975; Tierney et al., 1976).

Data were obtained on total phosphorus and inorganic nitrogen contributions from precipitation. Organic nitrogen was considered to be negligible. Precipitation records were from the nearby Pellston Airport. Chemical analyses were performed on precipitation samples collected at 10 sites in Cheboygan and Emmet counties. Total loading from precipitation of 2.5 kg/km^2/yr. total phosphorus and 10.6 kg/km^2/yr. total nitrogen was determined from these analyses.

---

* In addition to limnological data, inshore stations were sampled for coliform bacteria in Summer, 1975. Samples were collected in 100-ml glass containers supplied by a county sanitarian and promptly sent to the Bureau of Laboratories of the Michigan Department of Health for analyses. Although data on both total and fecal coliform bacteria were obtained, only fecal coliform results are reported here.

A recent study by Omernik (1976), who determined phosphorus and nitrogen export values from various land covers, appears to contain data most pertinent to the watersheds of Crooked and Pickerel Lakes. Watershed land cover data (Table 1) and nutrient export values from the north and northeastern forest and forage region of the United States (Table A-1) were employed. Omernik's (1976) "mostly agriculture" category was chosen instead of his "agriculture" category since our "agriculture/grassland" grouping contains both active and fallow farmland.

Nichols and Richardson (in Gannon and Paddock, 1974) made some preliminary calculations on nutrient loading from septic systems to lakes in Cheboygan and Emmet Counties, including Crooked and Pickerel Lakes. Assumptions on numbers of dwelling units, length of occupancy, and household use of phosphate-enriched detergents were too high. Furthermore, assumptions on nutrient movements from septic systems to the lakes were not based on local soils data. Their nutrient loadings from septic systems appear to be over-estimations. Consequently, considerable effort was focused on refining estimates of nutrient loading from septic systems in this investigation.

Loading of phosphorus and nitrogen to Crooked and Pickerel Lakes was calculated using information on household size, length of occupancy, household usage of septic systems, number of dwelling units on each soil type, and the percentage of nutrients that reach the lake from each soil type from lakeside septic systems. It was estimated from the 1970 U. S. census that the average household size in Emmet County was 3.25 persons per dwelling unit. The number of households within 300 ft. (92m) of the shoreline was obtained from the Emmet County Equalization Department and year-round and seasonal occupancy was estimated during Winter (Gold and Gannon, 1978). From a household survey conducted on nearby Walloon Lake (Project CLEAR, 1978), it was estimated that loading of phosphorus to septic systems from dishwater and laundry wastewater was 0.83 kg/household/yr. Dishwashing and laundry habits on Crooked and Pickerel Lakes were assumed to be the same as on Walloon Lake.

Estimations of 0.5 kg/person/yr phosphorus and 5.4 kg/person/yr nitrogen (Vollenweider, 1968) were used as the human waste contribution to the septic system. Including the phosphorus contribution from detergents, total loadings to the septic system of 2.46 kg/household/yr. phosphorus and 17.55 kg/household/yr nitrogen were estimated. The number and type of residences on specific soil types was used to calculate the amounts of phosphorus and nitrogen reaching the lakes. The type of residence was weighted (i.e., 1.0 for year-round occupancy, 0.5 for possible year-round occupancy and 0.25 for seasonal occupancy) and multiplied by the number of residences on each soil type. The soils were identified and transcribed from the Emmet County Soil Survey onto the home location map. From soil characteristics such as natural drainage, depth to seasonal high groundwater (Alfred et al., 1973), and phosphorus adsorption capacity (Schneider and Erickson, 1972), estimations were made on percentage of phosphorus and nitrogen that would reach the lakes through each soil type from septic systems. Then septic systems nutrient loading was calculated from the number and type of residence on each soil type, the total nutrient input per household per year, and percentage of nutrients reaching the lake (Tables A-2 through A-4).

RESULTS AND DISCUSSION

Water quality: Some basic considerations

Although inland lakes are individualistic and exhibit their own unique characteristics, scientists recognize a relatively simple system of grouping and classifying lakes into water quality types. Oligotrophic lakes are nutrient poor and are low in plant and animal productivity. Eutrophic lakes are high in nutrient content which stimulates high production of plants and animals. Lakes exhibiting intermediate characteristics are termed mesotrophic.

Lake residents normally equate good water quality with oligotrophic lakes. These water bodies exhibit clear waters, low turbidity from algae, low amounts of weed growths, and firm bottom sediments. Eutrophic lakes are normally considered poor in water quality with turbid waters high in algal content, high amounts of undesirable weeds, and mucky bottom sediments. Since eutrophic lakes are more productive, they often contain higher quantities of fish than oligotrophic lakes. Consequently, fishermen may consider water quality in eutrophic lakes as good. However, in extreme eutrophic conditions, desirable fish species such as walleye, yellow perch, northern pike, and bass are replaced by less desirable species such as carp, suckers, and bullheads. In most situations, water quality in a water body has been determined by its geological origins and natural features within its watershed. It is the challenge of the riparian community to understand the current water quality status of their lake and to minimize adverse changes in quality as they use and develop the lake and its watershed.

Ideally, current water quality data should be compared with historical records in order to establish any trends in water quality changes. Unfortunately, historical water quality information on Crooked and Pickerel Lakes is extremely scanty. Temperature, alkalinity, dissolved oxygen and pH measurements were occasionally collected by the Fish Division of the Michigan Department of Natural Resources during the past several decades. An examination of these records did not reveal any changes in water quality in Crooked or Pickerel Lakes beyond normal yearly variation. Consequently, current water quality status of these lakes must be determined by interpreting recent physicochemical and biological data and by applying some simple trophic state models that have been developed in recent years.

Watershed Characteristics

The watershed areas of Crooked and Pickerel Lakes are relatively large, encompassing parts of three counties (Fig. 4), and consist primarily of second growth deciduous and mixed (deciduous and coniferous) forests (Table 1). Agriculture and grassland comprises a larger fraction of land-use in Crooked Lake's watershed than in Pickerel Lake's drainage basin (Table 1). However, most agricultural activity occurs in upland areas away from the shore of both lakes. Marshy and swampy wetlands are an important feature and lie primarily near the north shore of Crooked Lake and along the south and east shores of Pickerel Lake.

Pickerel Lake's watershed is large in comparison to its lake surface area (Table 1). The lake is fed mostly by groundwater seepage since its inflowing streams are small. The outflow of Pickerel Lake is to Crooked Lake through the Crooked-Pickerel Channel, although reverse flow can sometimes occur depending on wind and current conditions.

Crooked Lake's immediate watershed (11,190 ha) is smaller than Pickerel Lake's drainage basin (13,660 ha). However, Spring, Mud, Round and Pickerel Lakes all flow into Crooked

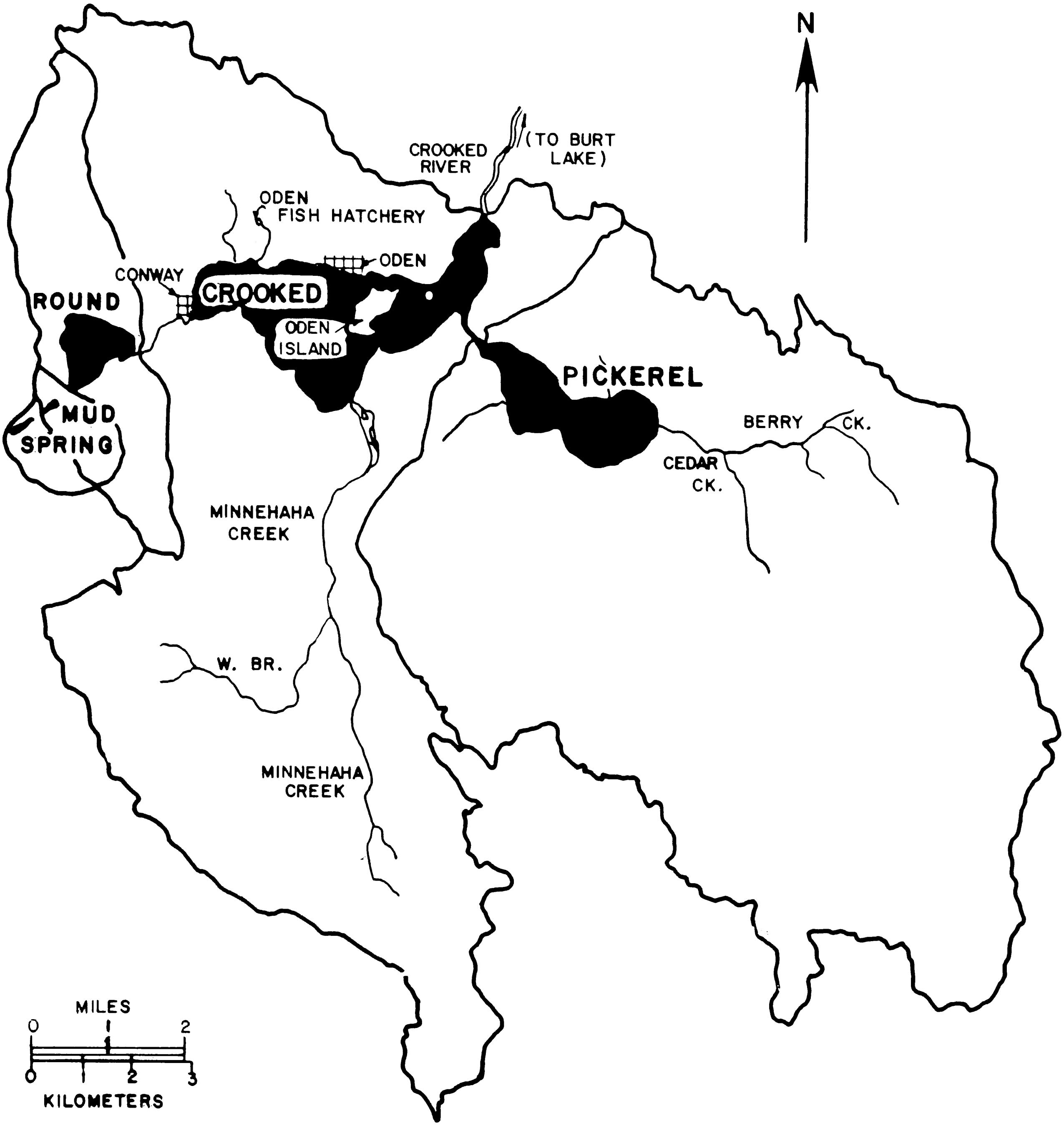

Fig. 4 The watershed bounderies of Crooked and Pickerel Lakes. Since Spring, Mud, Round and Pickerel Lakes all drain into Crooked Lake, the total watershed area of Crooked Lake includes the drainage basins of these neighboring lakes.

TABLE 1. LAND-USE TYPES IN THE CROOKED AND PICKEREL LAKE WATERSHEDS BASED ON LANDSAT DATA (ROGERS, 1977).

	CROOKED LAKE			PICKEREL LAKE		
Land-Use Type	Acres	km^2	%	Acres	km^2	%
Coniferous Forest *	1,025.3	4.1	3.5	2,985.0	11.9	8.9
Deciduous Forest	7,579.9	30.3	26.0	13,406.0	53.6	39.9
Mixed Forest	4,347.4	17.4	15.0	6,724.6	26.9	20.0
Sparce Forest **	8,045.1	32.2	27.7	6,698.0	26.8	19.9
TOTAL FOREST	20,997.7	84.0	72.2	29,813.6	119.2	88.7
Agriculture/Grassland ***	5,468.1	21.9	18.8	2,880.7	11.5	8.6
Urban/Bare Ground	236.4	1.0	0.9	73.2	0.3	0.2
Uncategorized	330.7	1.3	1.1	160.9	0.6	0.4
TOTAL LAND	27,032.9	108.2	93.0	32,928.4	131.6	97.9
Water	2,060.7	8.2	7.0	951.0	2.8	2.1
GRAND TOTAL †	29,093.6	116.4	100.0	33,879.4	134.4	100.0

---

* Includes both upland and swamp forests.

** Includes shrubby uplands and wetlands.

*** Includes grassy uplands and marshy wetlands.

† Totals from LANDSAT data differ slightly from those determined with an area meter (see Table 2).

Lake. Consequently, Crooked Lake's total watershed is much larger (25,170 ha), encompassing its immediate watershed and the drainage areas of these neighboring lakes (Fig. 4). Although groundwater seepage is undoubtedly a significant source of Crooked Lake water, inflows from Minnehaha Creek and other streams are important contributors. The Crooked River is the only surface outlet for Crooked Lake.

Information is not available on the numbers of people living in the watersheds of Crooked and Pickerel Lakes. The region is predominantly rural and sparcely populated. Over 1,800 year-round residents were reported in adjacent Littlefield and Springvale townships* in 1970. The number of people living on or near the lakeshores is of particular interest for water quality considerations. About 400 dwelling units are located within 90 m of the Crooked Lake shoreline. Most of these dwellings are located on the north shore and are currently serviced by the wastewater sewer line. Only 112 dwelling units are located on Crooked Lake's south shore and on Oden Island. Pickerel Lake is more sparcely populated, with 134 dwelling units reported on or near its shoreline (Gold and Gannon, 1979).

---

* These townships comprise the largest land area in the watersheds of the two lakes.

Limnological Characteristics

Morphometry

Crooked Lake is about twice as large in surface area as Pickerel Lake. Crooked Lake is aptly named since its shoreline is so irregular. Its shoreline development factor is two times higher than Pickerel Lake and its shoreline is three times longer than Pickerel Lake (Table 2). Consequently, the potential for over-development is considerably greater on Crooked Lake than on Pickerel Lake. Both lakes are moderately deep with maximum depths over 18 m. The average depth of Pickerel Lake (3.9 m) is slightly greater than Crooked Lake (3.0 m). Both lakes contain large expanses of shallow areas suitable for development of weed beds that provide favorable habitat for fishes (Fig. 2, Fig. 3, Table 2).

The current water quality is generally good in both Crooked and Pickerel Lakes and the quantity of water flowing in and out of them is at least partially responsible. Water residence time is the amount of time water remains in the lake's basin before being completely replaced by inflowing water. Calculations of water residence times for these lakes is somewhat complicated by the hydrology of the Crooked-Pickerel Channel, since currents alternately flow in and out of the channel. However, the net flow is from Pickerel to Crooked Lake. Furthermore, because of the geographical locations of the channel and Oden Island, it appears that water from the channel is dis-

TABLE 2. MORPHOMETRIC FEATURES OF CROOKED AND PICKEREL LAKES, EMMET COUNTY, MICHIGAN. DEFINITIONS ARE ACCORDING TO HUTCHINSON (1957).

Variable *	CROOKED LAKE		PICKEREL LAKE	
	Metric	English	Metric	English
Z_m	18.6 m	61.0 ft.	21.3 m	69.8 ft.
$\bar{Z}$	3.0 m	9.8 ft.	3.9 m	12.8 ft.
1	5.58 km	3.5 mi	4.09 km	2.5 mi.
b_x	3.09 km	1.9 mi	1.69 km	1.0 mi
$\bar{b}$	1.69 km	1.1 mi	1.09 km	0.7 mi
L	29.63 km	18.4 mi	10.57 km	6.6 mi
A_o	959.59 ha	2,371 acres	427.06 ha	1,055 acres
A_d	111.9×10^2ha	27,649 acres	136.6×10^2ha	33,750 acres
V	$29{,}534.7 \times 10^3 m^3$	$1{,}040 \times 10^6 ft^3$	$17{,}176.8 \times 10^3 m^3$	$605 \times 10^6 ft^3$
D_1	2.7		1.4	
D_v	0.5		0.5	
A_d/A_o	11.7		32.0	

---

* Abbreviations: Z_m, maximum depth; $\bar{Z}$, mean depth ; 1, maximum length; b_x, maximum width; $\bar{b}$, mean width; L, shoreline length; A_o, lake surface area; A_d, watershed area; V, volume; D_1, shoreline development factor ; D_v, volume development factor ; A_d/A_o, ratio of watershed area to lake surface area.

charged primarily through Crooked River and does not significantly mix with Crooked Lake water west of the island. Water from the Crooked-Pickerel Channel comprises about 39% of the flow of the Crooked River, while the remaining 61% represents the outflowing waters of Crooked Lake. The water residence times for Crooked and Pickerel Lakes have been estimated as 4.2 and 4.7 months, respectively. Although these lakes contain a relatively large volume of water, they both have comparatively short water residence times and can flush out pollution inputs rather quickly. In contrast, nearby Walloon Lake has a water residence time of 3.2 years and, therefore, is more sensitive to pollution than Crooked and Pickerel Lakes.

Physicochemistry: Off-shore conditions

Crooked and Pickerel Lakes are basically similar in most physicochemical characteristics. Both lakes thermally stratify during Summer. A uniformly warm layer, the epilimnion, generally extends from the surface to about 8 m. A zone of rapid temperature change, called the thermocline, occurs from 8 m to 13 m. The deepest portion of the lake from 13 m to the bottom is uniformly cold and is known as the hypolimnion. Wind generated currents are primarily confined to the epilmnion during Summer. Two complete circulation periods occur in Spring and Fall when the lake is mixed from top to bottom. Slight inverse stratification occurs during Winter under ice cover when temperatures are slightly warmer near bottom than they are near the surface. The onset and duration of ice cover varies from year to year, depending on meteorological conditions. Generally, ice cover remains from mid-December to early April. Ice disappears from Crooked Lake in Spring earlier than most other lakes of the region, presumably because of groundwater seepage especially along the north shore.

Crooked and Pickerel Lakes contain clear, unstained waters that allow for excellent light penetration. Transparency, as measured by the Secchi disc, was only slightly greater in Pickerel Lake than in Crooked Lake (Table 3). Both lakes contain hard water with high concentrations of alkalinity, specific conductance, and ionic constituents, especially calcium and magnesium. The waters are alkaline with pH generally above 8.0 throughout the photic zone. The inorganic nutrients, phosphorus and nitrogen, average slightly higher in Crooked Lake than in Pickerel Lake. In contrast, silica concentrations are slightly higher in Pickerel Lake (Tables 3 and 4).

Phosphorus is considered to be the limiting nutrient for plant growth in both Crooked and Pickerel Lakes because soluble and total phosphorus concentrations are extremely low relative to nitrogen. The low amount of phosphorus in the water is at least partially controlled by chemical interactions between the water and bottom sediments. Both lakes contain abundant

TABLE 3. COLOR, LIGHT, AND DISSOLVED OXYGEN (D.O.) CHARACTERISTICS OF CROOKED AND PICKEREL LAKES, EMMET COUNTY, MICHIGAN. DATA FROM CENTRAL DEEP STATIONS.

Lake	Color (pt-co)	Secchi Disc Yearly Range (m)	1% T* Summer (m)	Near Bottom D.O. Summer (mg/l)	Near Bottom D.O. Winter (mg/l)
Crooked Lake	10	2.0-5.0	8.8	0	7.3
Pickerel Lake	20	2.5-6.0	8.5	0.1	6.8

---

* Depth of light penetration to 1% of surface illumination

TABLE 4. CHEMICAL AND CHLOROPHYLL *a* FEATURES OF CROOKED AND PICKEREL LAKES AT DEEP CENTRAL STATIONS DURING SUMMER AND WINTER.*

Variable	CROOKED LAKE Summer	CROOKED LAKE Winter	PICKEREL LAKE Summer	PICKEREL LAKE Winter
T.A. (mg/l)	141.0	158.6	136.4	163.8
Sp. Cond. (μmhos/cm)	289.5	314.9	285.0	326.1
pH	8.4	8.1	8.4	8.0
S-PO_4 (μg/l)	4.0	7.0	5.9	4.0
T-PO_4 (μg/l)	11.9	11.3	9.8	18.3
NO_3-N (μg/l)	44.2	356.5	62.1	320.0
NH_3-N (μg/l)	20.1	40.3	18.0	44.3
SiO_2 (μg/l)	2,578.8	3,475.8	2,665.3	3,686.8
CI (mg/l)	12.5**	2.5	10.9**	3.7
Ca (mg/l)	38.7	42.2	38.4	48.9
Mg (mg/l)	13.9	12.7	13.4	13.1
K (mg/l)	0.8	0.8	0.7	0.9
Na (mg/l)	2.1	2.2	2.2	2.5
Chl. *a* (μg/l)	3.3**	2.0	2.8**	0.7

---

* Data are means for the euphotic zone (> 1% light transmittance) in Summer, 1973 and 1974 and Winter, 1974 and 1975 except where otherwise indicated. T.A. is total alkalinity as $CaCO_3$ and Sp. Cond. is specific conductance corrected to 25C

** 1974 data only.

calcium and inorganic carbon, a situation conducive for marl deposition. Marl is precipitated calcium carbonate ($CaCO_3$) or lime, and forms the characteristic grayish-white, clay-like bottom sediments and coatings on rock and other firm substrates. Phosphorus ions in the water column adsorb on marl particles, settle into the bottom sediments and become unavailable to stimulate algae and weed growths.

As long as dissolved oxygen content remains high, co-precipitation of phosphorus with marl is an important mechanism in maintaining high water quality in Crooked and Pickerel Lakes. However, under anaerobic conditions, phosphorus is released from the sediments and becomes available for plant growth. Currently, anaerobic conditions are confined to the near bottom waters of the deepest portions of Crooked and Pickerel Lakes during the Summer stratification period. During the Summers of 1973 and 1974, the bottom 4 m of Crooked Lake and the bottom 2 m of Pickerel Lake contained less than 1% saturation of dissolved oxygen. Consequently, dissolved oxygen depletion in the hypolimnion is slightly greater in Crooked Lake than in Pickerel Lake.

Chemistry and bacteria: Near-shore conditions

Nutrient chemistry and coliform bacteria tests were conducted on near-shore areas and at mouths of inflowing streams of Crooked and Pickerel Lakes in order to locate any "hot spots" of human wastewater contamination.

The highest concentrations of total phosphorus occurred in the stream emanating from the Oden Fish Hatchery on Crooked Lake during all seasons. Phosphorus below the fish hatchery was 15 times higher than at the Crooked Lake central station during summer (Fig. 5). High concentrations in comparison with the central station were also observed near the village of Oden and off Oden Island's west side. Phosphorus values below a small, private fish pond (Station No. 4c) did not differ significantly from central station values.

The streams below both the State and private fish culture facilities were consistently high in inorganic nitrogen during all seasons. Values at these respective locations were 19 and 25 times higher than at the central station in summer (Fig. 6). Other comparatively high inorganic nitrogen concentrations were noted near the villages of Conway and Ponshewaing and at the mouth of Minnehaha Creek (Fig. 6).

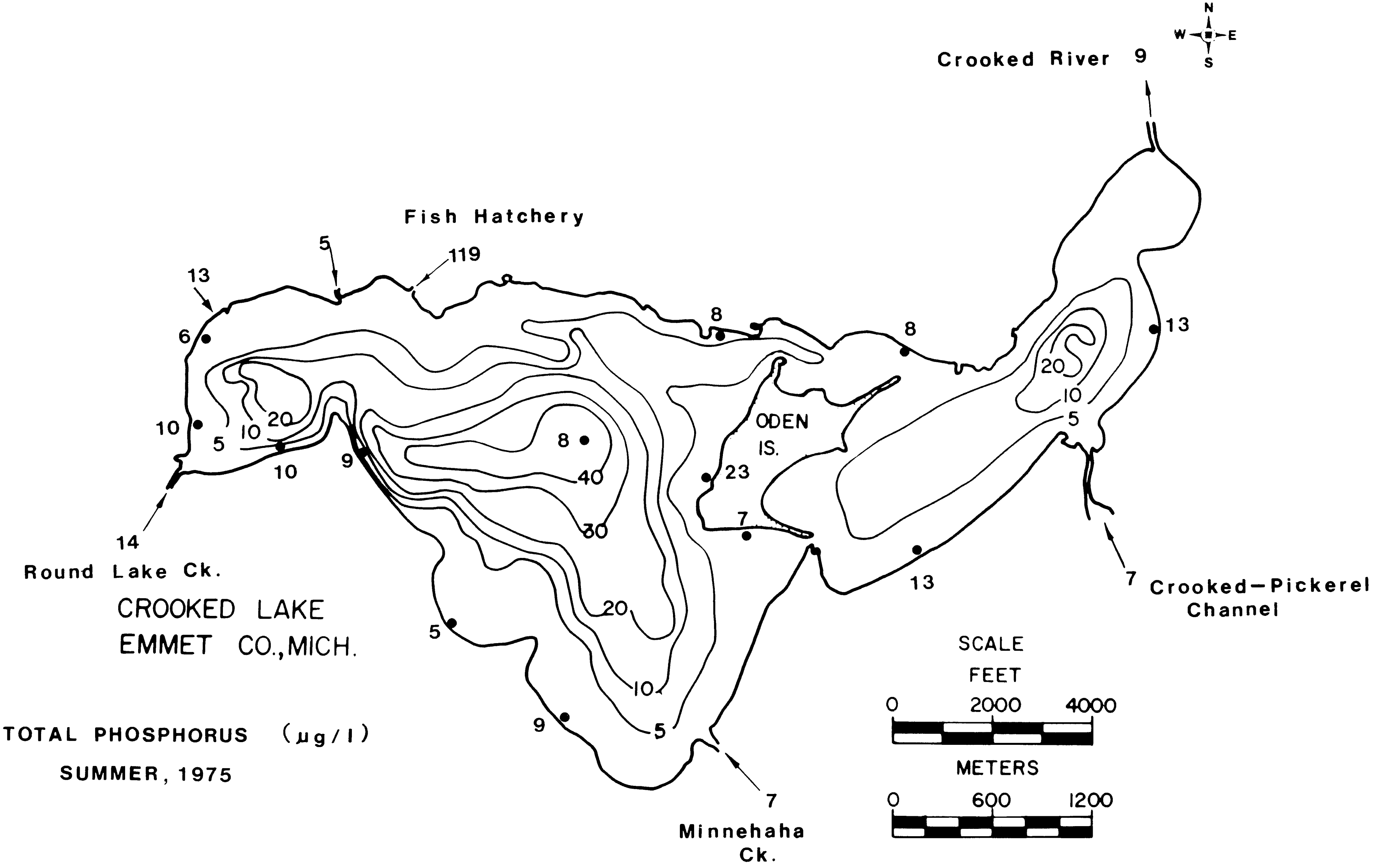

Fig. 5 Comparison of total phosphorus concentrations (µg/l) between the central station and selected near-shore locations in Crooked lake during summer, 1975.

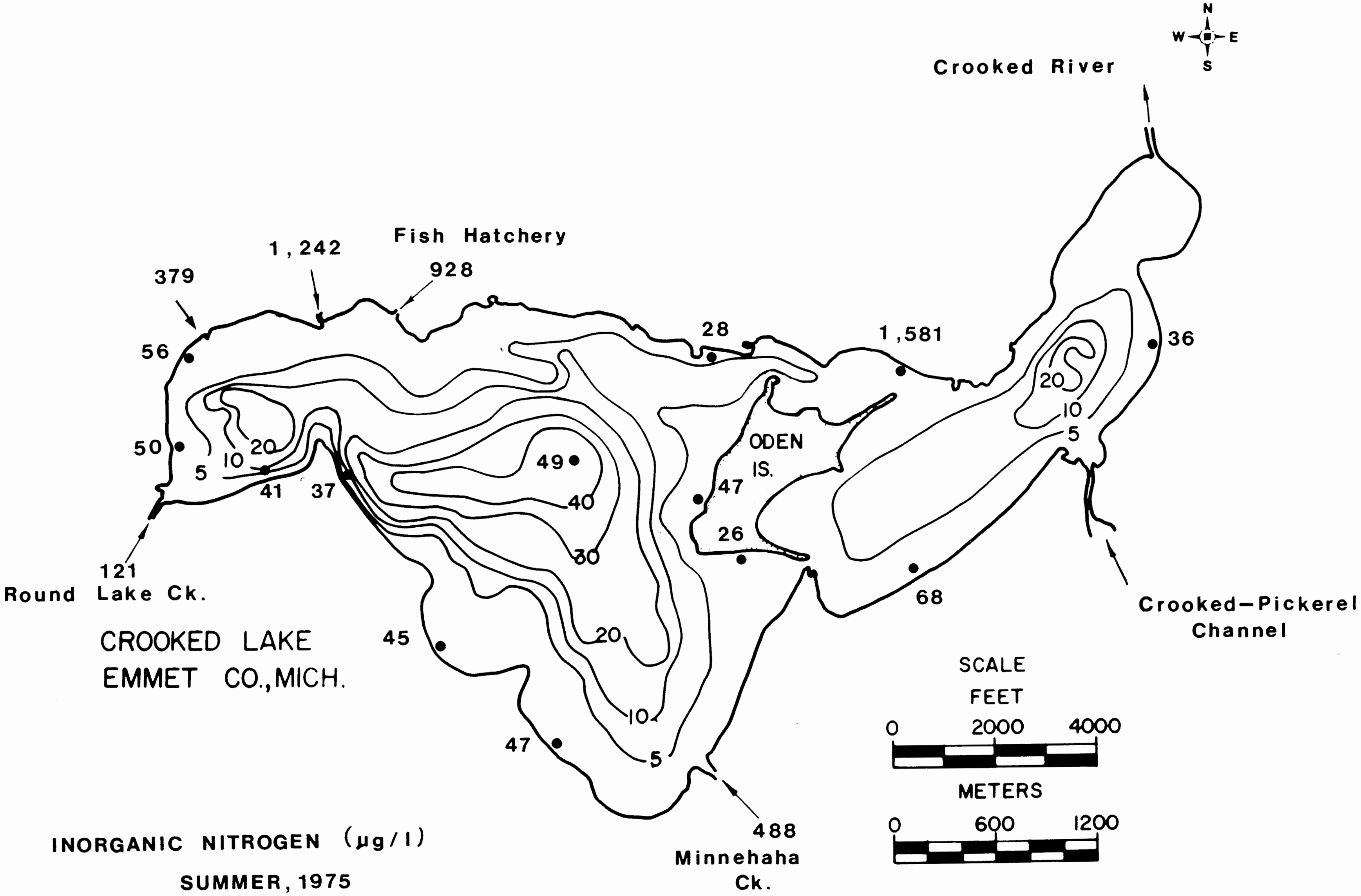

Fig. 6 Comparison of inorganic nitrogen (NO_2-N, NO_3-N and NH_3-N) concentrations (µg/l) between the central station and selected near-shore locations in Crooked Lake during summer, 1975.

Coliform bacteria data were obtained only in Summer, 1975. Only the station near Conway was contaminated with fecal coliform bacteria (1600 colonies/ml).* Low bacterial counts were observed elsewhere along the shores of Crooked Lake (Fig. 7).

In contrast to Crooked Lake, concentrations of phosphorus and nitrogen in the near-shore areas of Pickerel Lake were almost identical with central station values during all seasons although only Summer data are presented here (Figs. 8 and 9). A relatively high concentration of inorganic nitrogen was recorded only once at Station No. 15 (Fig. 9). Fecal coliform bacteria counts in Summer, 1975 were low throughout Pickerel Lake and did not indicate any sources of human contamination (Fig. 10).

Biology

Detailed phytoplankton data are not available for Crooked and Pickerel Lakes. Qualitative observations indicate that both lakes are in a healthy water quality condition. Although filamentous blue-green algae are present in both lakes, they rarely form a predominate component of the algal community.

---

* The Michigan Department of Health considers waters with fecal coliform bacteria counts greater than 200/ml to be polluted and unfit for bodily contact, such as swimming.

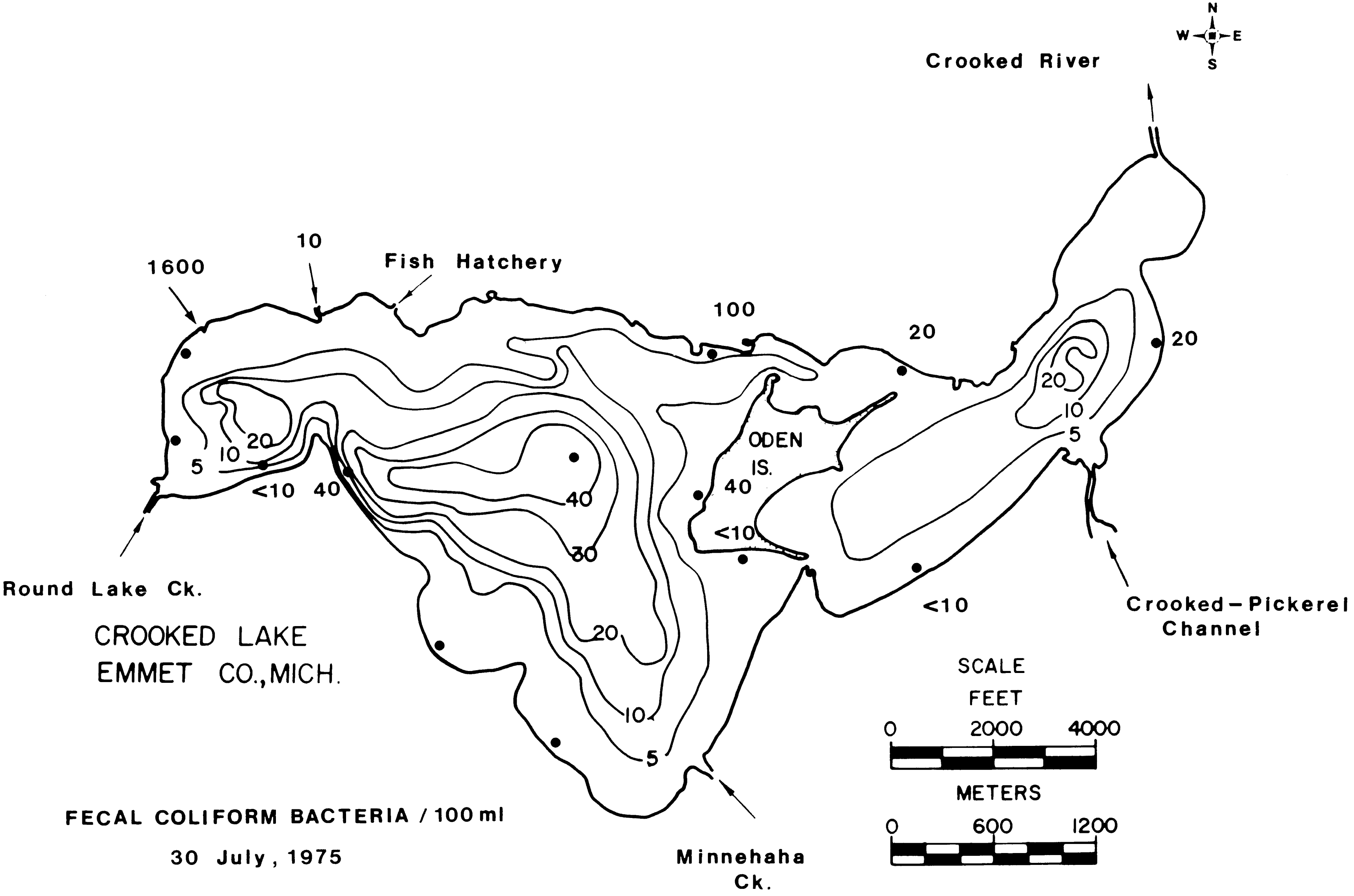

Fig. 7 Fecal coliform bacteria (number of colonies/100 ml) at selected near-shore locations in Crooked Lake during July, 1975).

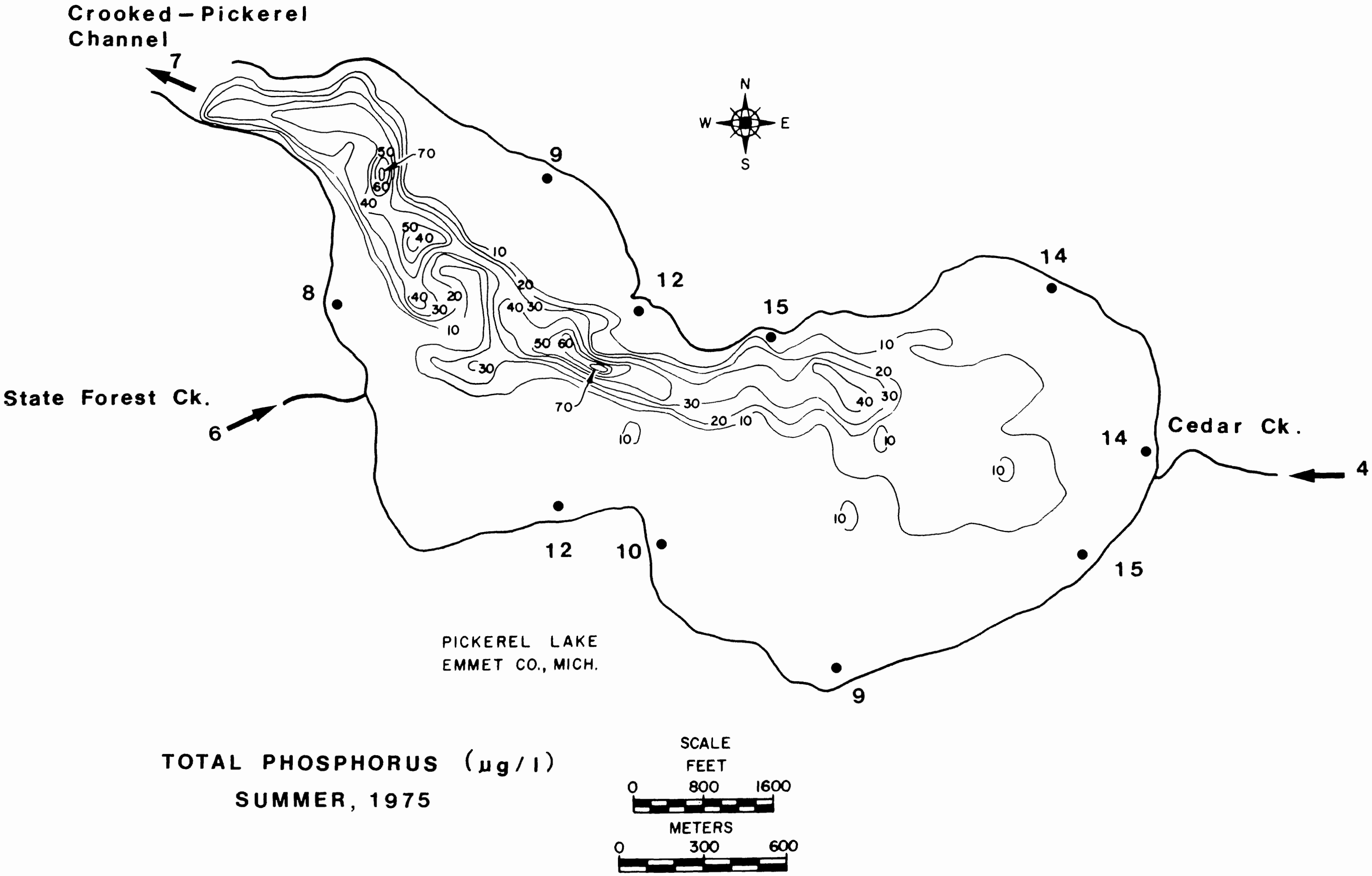

Fig. 8 Comparison of total phosphorus concentrations (µg/l) between the central station and selected near-shore locations in Pickerel Lake during Summer, 1975.

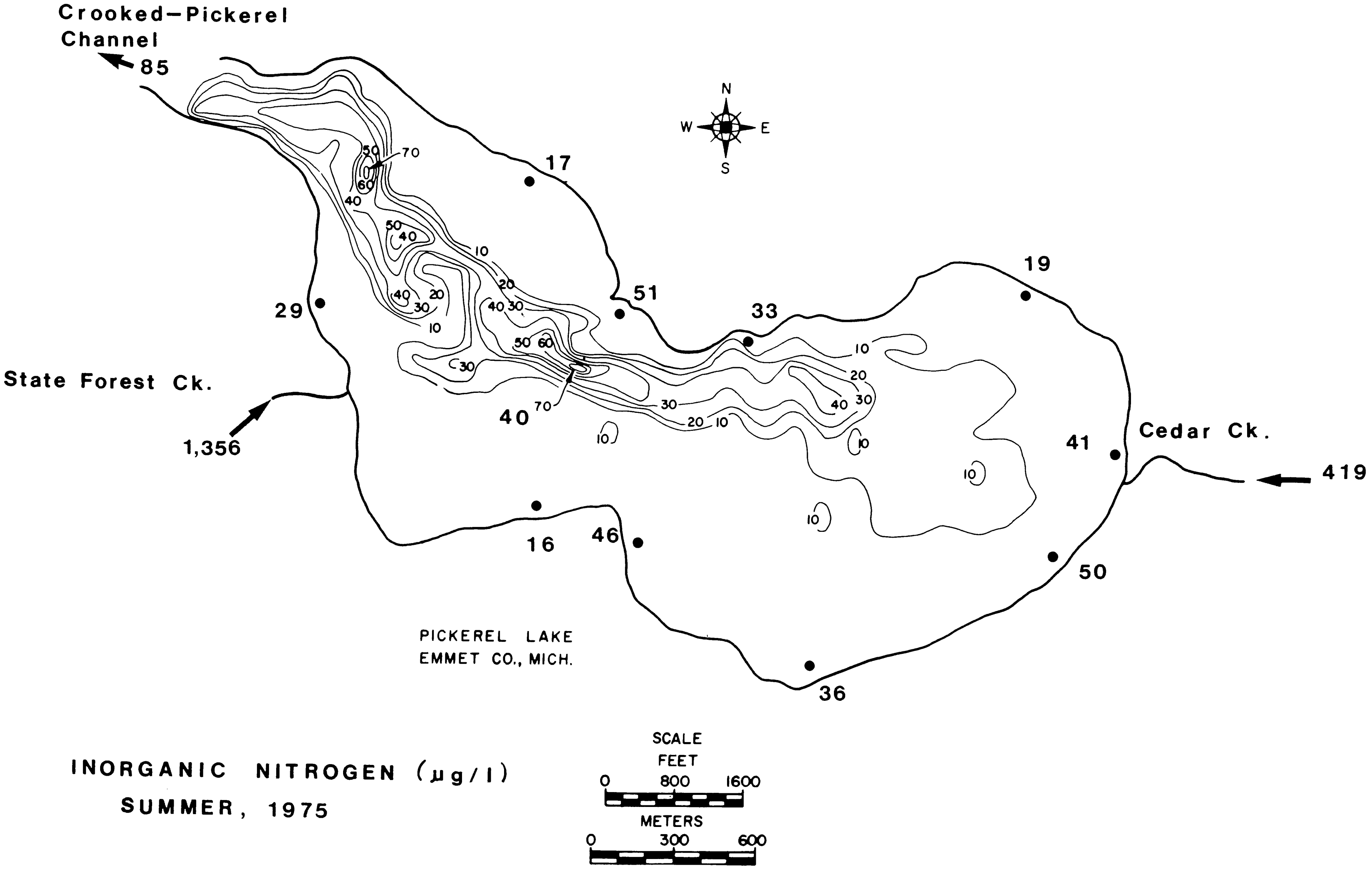

Fig. 9 Comparison of inorganic nitrogen concentrations (µg/l) between the central station and selected near-shore locations in Pickerel Lake during Summer, 1975.

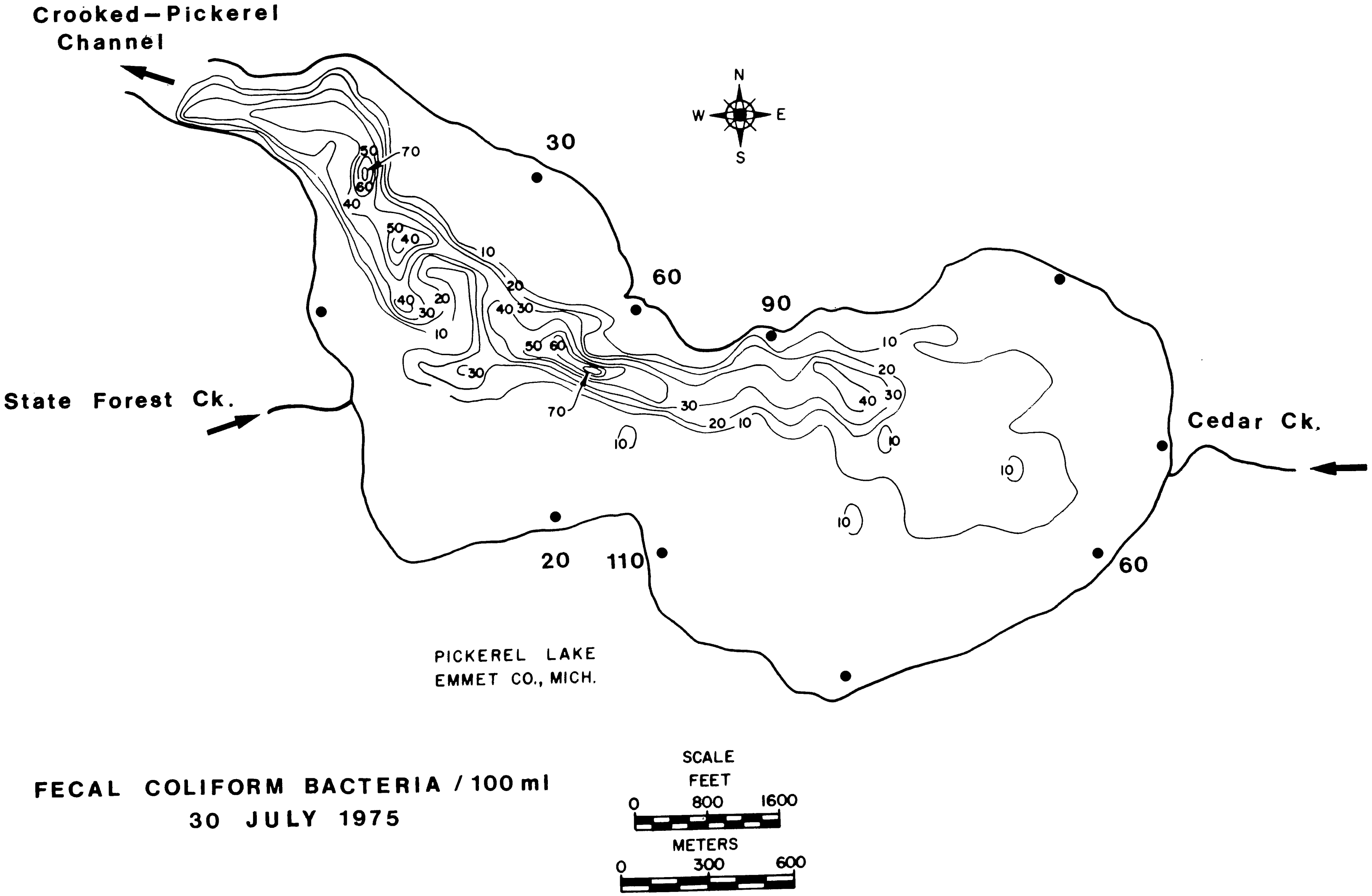

Fig. 10 Fecal coliform bacteria (number of colonies/100 ml) at selected near-shore locations in Pickerel Lake during July, 1975.

Substantial algal blooms have not been observed in Pickerel Lake. In contrast, algal blooms, usually consisting of diatoms and *Dinobryon*, have been noticeable in Crooked Lake.

Chlorophyll *a*, a measure of the quantity of algae, was slightly higher in Crooked Lake than in Pickerel Lake (Table 4). Although chlorophyll *a* averaged near 3.0 µg/l in the photic zone during Summer for both lakes, the maximum recorded value was higher for Crooked Lake (8.9 µg/l in Fall, 1974) than for Pickerel Lake (4.2 µg/l in Spring, 1974). Phytoplankton composition and chlorophyll *a* indicate that the waters of both Crooked and Pickerel Lakes are oligo-mesotrophic, with Crooked Lake slightly closer to the eutrophic side of the trophic continuum.

Species composition of zooplankton was basically similar in Crooked and Pickerel Lakes. There was a general absence of species indicative of extreme oligotrophic or eutrophic waters in both lakes and, therefore, zooplankton composition was most characteristic of mesotrophic conditions. The greater relative abundance of the cladoceran, *Chydorus sphaericus,* in Crooked Lake indicates that the waters of Crooked Lake are slightly more eutrophic than Pickerel Lake (Bricker and Gannon, unpublished data). Crooked Lake contained the oligo-mesotrophic indicator rotifers, *Notholca foliacea, N. michiganensis,* and *Synchaeta asymmetrica,* as well as the eutrophic indicators, *Polyarthra euryptera* and *Trichocerca multicrinis*. Similarly, the oligo-mesotrophic indicative rotifers, *Conochiloides natans*, and *N. michiganensis*, as well as the eutrophic species, *P. euryptera* and *T. multicrinis*, occurred in Pickerel Lake (Stemberger, unpublished data).

Similarly, the composition of the benthic organisms in Crooked and Pickerel Lakes were indicative of water bodies mesotrophic in character. Both lakes contained oligotrophic indicators such as the burrowing mayfly nymph, *Hexagenia*, and fingernail clams, *Sphaerium*. Likewise, eutrophic indicators such as the oligochaete worm, *Limnodrilus hoffmeisteri*, and several genera of chrionomid midge larvae were observed in both lakes. The Shannon-Weiner species diversity index was slightly higher in Pickerel Lake (0.57) than in Crooked Lake (0.43), and is indicative of slightly more oligotrophic conditions in Pickerel Lake than in Crooked Lake (Weid, unpublished data).

An examination of Michigan Department of Natural Resources records reveals that both Crooked and Pickerel Lakes contain fish populations indicative of healthy water quality conditions. Desirable species, such as northern pike, walleye, black bass, yellow perch, and bluegill are prevalent in both lakes. Growth rates of these fishes are near state-wide averages in both Crooked and Pickerel Lakes.

Trophic State

It is readily apparent from the preceding limnological inventory that Crooked and Pickerel Lakes are in good water quality condition. Physiochemical data and biological indices of water quality suggest that both lakes border between oligotrophy and mesotrophy (i.e., oligo-mesotrophic) on the trophic continuum of lake types, with Crooked Lake somewhat more mesotrophic than Pickerel Lake. In other words, Crooked Lake is only slightly poorer in water quality than Pickerel Lake. Better definition of the trophic status of these lakes can be obtained by applying some simple criteria and indices of trophic condition.

Summer average chlorophyll *a*, total phosphorus, and Secchi disc transparency have frequently been used to establish the trophic state of lakes. Although the actual values differentiating trophic levels are somewhat subjective, criteria established by EPA (1974b) have been widely used in recent years. Using EPA (1974b) criteria, Crooked and Pickerel Lakes are both oligotrophic based on chlorophyll *a*. Crooked Lake is mesotrophic based on total phosphorus and Secchi disc transparency, and Pickerel Lake is oligo-mesotrophic using these variables (Fig. 11). Chlorophyll *a* and total phosphorus are probably better than transparency in assessing the trophic condition in these lakes. Transparency is affected by suspension of marl floc as well as by algal turbidity in both lakes. Therefore, Secchi disc readings are not sufficiently accurate for predicting trophic conditions in such lakes. Nevertheless, all three variables indicate that Crooked Lake is slightly closer to the eutrophic end of the trophic continuum than Pickerel Lake.

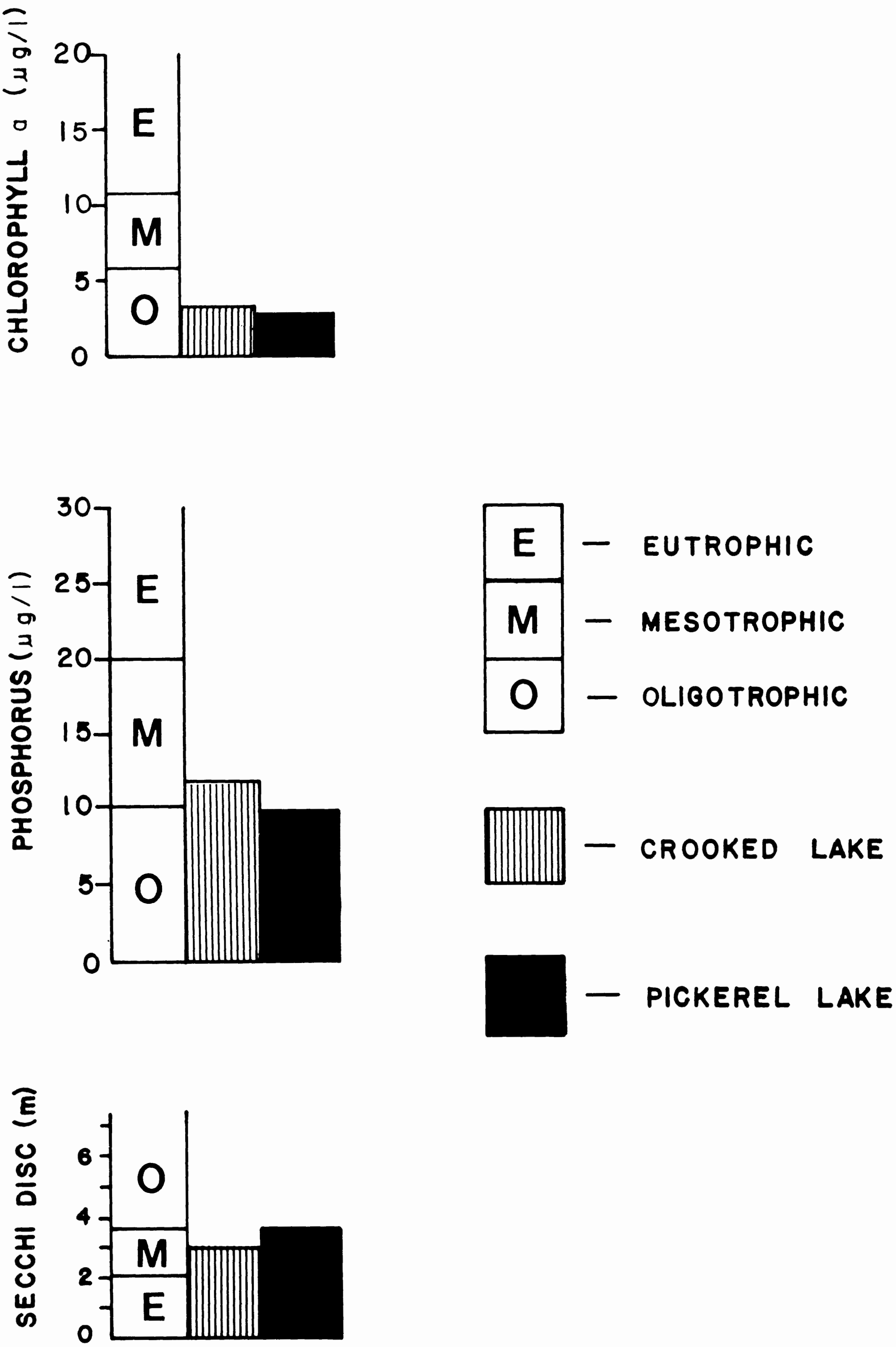

Fig. 11 Trophic classification of Crooked and Pickerel Lakes based on three limnological variables and using criteria established by EPA (1974b).

Recognizing the relationships of chlorophyll *a*, total phosphorus and Secchi disc transparency to trophic condition, Carlson (1977) developed a trophic state index (TSI) based on these variables. Lakes are rated on a scale of 1-100 with higher numbers representing more eutrophic waters. Carlson's index can be computed for the three variables independently or a weighted combination of all three can be employed. Because Secchi disc readings can be misleading in marl lakes and because other nutrients besides phosphorus can sometimes become limiting to algal growth in Summer, I have chosen to use Carlson's index based on chlorophyll *a* for Crooked and Pickerel Lakes. Both lakes are classified as oligotrophic using this method, although Crooked Lake is closer to mesotrophy than Pickerel Lake. In comparison with other lakes in Cheboygan and Emmet Counties, Pickerel and Crooked Lakes rank second and fifth highest, respectively, in water quality of 39 lakes investigated (Fig. 12).

The above criteria concerns only the near-surface, offshore waters of lakes. Uttermark and Wall (1975) developed a subjective lake condition index (LCI) that uses easily detectable measures of eutrophication, many of which are observable from the shoreline, including presence or absence of algal blooms and excessive weed growths. Lakes are rated on a scale of 0-23, higher values indicating poorer (more eutrophic) water quality. Although the LCI is not strictly related to trophic states, a

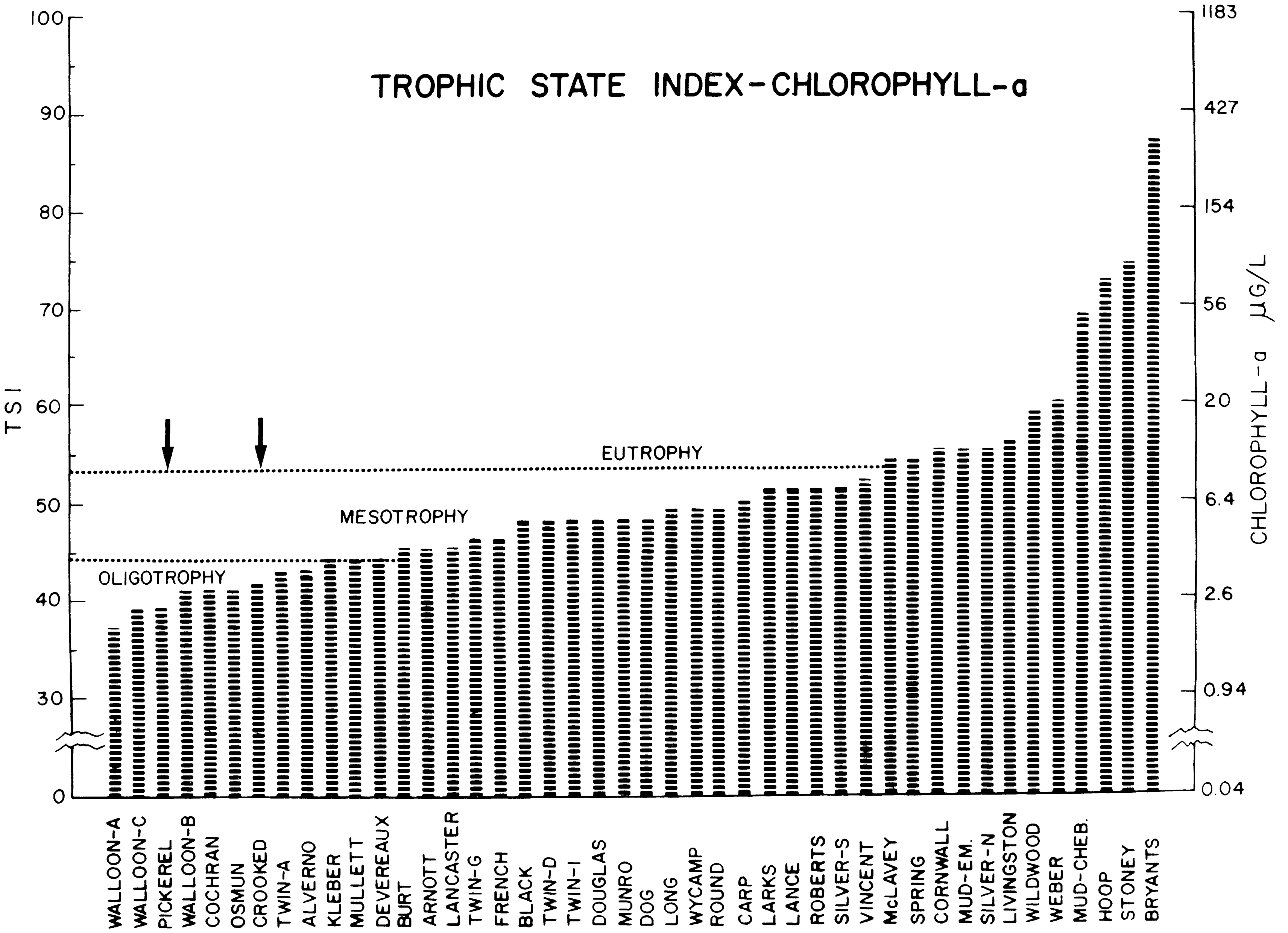

Fig. 12 Classification of lakes in Cheboygan and Emmet Counties, Michigan, using Carlson's (1977) trophic state index (TSI) for chlorophyll *a*. The positions of Crooked and Pickerel Lakes are identified by arrows. The divisions between oligotrophy and eutrophy are estimations that appear to be most suitable for the study area.

reasonable comparison between LCI and trophic classification was obtained in Wisconsin lakes (Uttermork and Wall, 1975). Crooked and Pickerel Lakes were determined to have LCI values of 7 and 5, respectively. Consequently, both lakes are classified as mesotrophic by this method with Crooked Lake again being closer to the eutrophic side of the trophic spectrum than Pickerel Lake (Fig. 13).

Nutrient loading

It is important to emphasize that nutrient loading determinations are relatively new to science and, therefore, they still are largely estimations. The values presented here are considered to be the best estimations with the available data for Crooked and Pickerel Lakes and information from the literature on nutrient loading. The greatest uncertainties are in the nutrient contributions from land cover. The amount of nutrients actually reaching the lakes from forest, agricultural, and urban areas is difficult to predict without better knowledge of run-off and groundwater flow patterns. Use of soils data has improved our ability to estimate nutrient contributions from septic systems. However, important variables such as, direction of groundwater flow, slope of land, age and condition of the septic system, and its distance from the lakeshore, were not known and, consequently, were not used in the nutrient loading analysis. However, several of these variables are

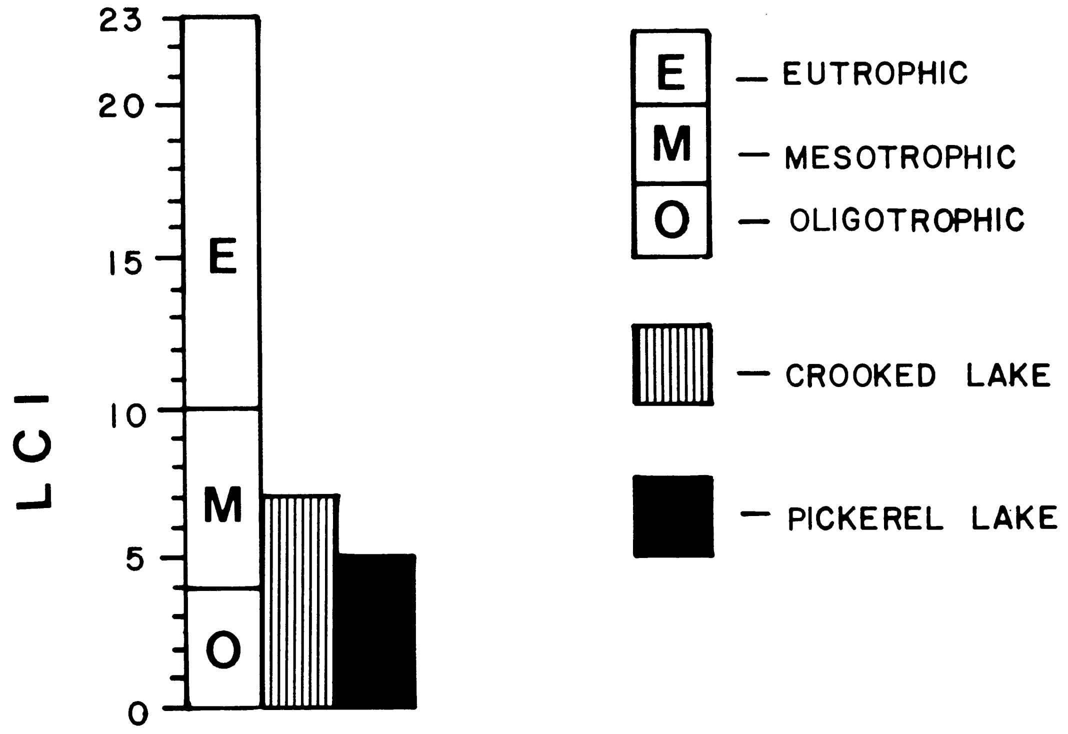

Fig. 13 Trophic classification of Crooked and Pickerel Lakes based on the lake condition index (LCI) of Uttormark and Wall (1975).

considered on the soil suitability maps (Gold and Gannon, 1979). Estimates of nutrient loading from lakeside lawn fertilization were not available for the study area, but this nutrient source is at least partially included in the coefficient for nutrient export from urban land cover.

Phosphorus loading was considerably higher to Crooked Lake than to Pickerel Lake in 1975-76 (Table 5). The discharge of nutrient-laden water from the Oden Fish Hatchery constituted the major man-induced source of phosphorus to Crooked Lake, representing 14.1% of total phosphorus loading. Considering all inflowing creeks, the stream from the fish hatchery contributed 69% of the phosphorus during the year and as high as 80% during Summer. Septic systems were another major human source of phosphorus, representing 9.4% of total phosphorus loading. In contrast, septic systems only contributed 4.0% of total phosphorus loading to Pickerel Lake. Nutrient loading was highest from forested lands in both lakes since the greatest portion of land in both watersheds is wooded.

Crooked Lake also received higher quantities of nitrogen than Pickerel Lake (Table 6). Major sources of nitrogen to both lakes were from forests and agricultural lands. Fish Hatchery and Minnehaha Creeks were also important sources of nitrogen to Crooked Lake. Because of the higher proportion of nitrogen loading from land cover, the contribution of nitrogen

TABLE 5. SOURCES AND QUANTITIES OF TOTAL PHOSPHORUS (P) FOR CROOKED AND PICKEREL LAKES, 1975-1976

CROOKED LAKE			PICKEREL LAKE		
Sources	Kg/yr.	%	Sources	Kg/yr.	%
Creeks			Creeks		
Round	26.6	1.2	Cedar	47.4	3.1
Conway	7.6	0.4	State Forest	10.8	0.7
Crooked	5.0	0.2			
Fish Hatchery	303.8	14.1			
Minnehaha	97.8	4.6			
Precipitation	321.7	14.9	Precipitation	143.2	9.2
Septic Systems	201.7	9.4	Septic Systems	61.9	4.0
Land Cover			Land Cover		
Forest	748.2	34.7	Forest	1,063.0	68.4
Agriculture	368.4	17.1	Agriculture	195.6	12.6
Urban	72.9	3.4	Urban	31.7	2.0
TOTAL	2,153.7	100.0	TOTAL	1,553.6	100.0

TABLE 6. SOURCES AND QUANTITIES OF TOTAL NITROGEN (N) FOR CROOKED AND PICKEREL LAKES, 1975-1976

CROOKED LAKE			PICKEREL LAKE		
Sources	Kg./yr.	%	Sources	Kg/yr.	%
Creeks			Creeks		
Round	1,301.6	1.7	Cedar	4,076.0	6.3
Conway	445.4	0.6	State Forest	550.6	0.8
Crooked	2,320.2	3.1			
Fish Hatchery	5,056.3	6.7			
Minnehaha	8,533.0	11.2			
Precipitation	7,973.3	10.5	Precipitation	3,548.4	5.5
Septic Systems	2,357.2	3.1	Septic Systems	494.2	0.8
Land Cover			Land Cover		
Forest	34,539.0	45.5	Forest	49,069.2	76.1
Agriculture	11,865.0	15.6	Agriculture	6,300.0	9.8
Urban	1,538.7	2.0	Urban	468.3	0.7
TOTAL	75,929.7	100.0	TOTAL	64,506.7	100.0

to both lakes from septic systems was relatively minor. However, nitrogen loading from septic systems was five times higher to Crooked Lake than Pickerel Lake.

Since phosphorus is the limiting nutrient for plant growth in Crooked and Pickerel Lakes, phosphorus loading is the most critical factor to the present and future water quality of these lakes. The importance of lake morphometry, i.e. mean depth and water residence time, to the susceptibility of lakes to phosphorus loading has been developed into a simple model by Vollenweider (1975). When data for Crooked and Pickerel Lakes are placed on the Vollenweider phosphorus loading plot, the trophic state and potential rate of eutrophication can be assessed (Fig. 14). Crooked and Pickerel Lakes are both classified as oligo-mesotrophic by this method, with Crooked Lake slightly closer to the eutrophic end of the trophic continuum. This is in agreement with other methods of trophic state determinations that were discussed previously. Both lakes are below the "permissible" loading level as determined by Vollenweider, i.e., water quality of both lakes should not appreciably change given the phosphorus loading levels of 1975-1976. However, Crooked Lake is nearly exceeding the "permissible" level and, therefore, may decline in water quality at a slightly faster rate than Pickerel Lake (Fig. 14).

Two events have occurred since 1975-1976 that apparently have reduced phosphorus loading to Crooked Lake from human

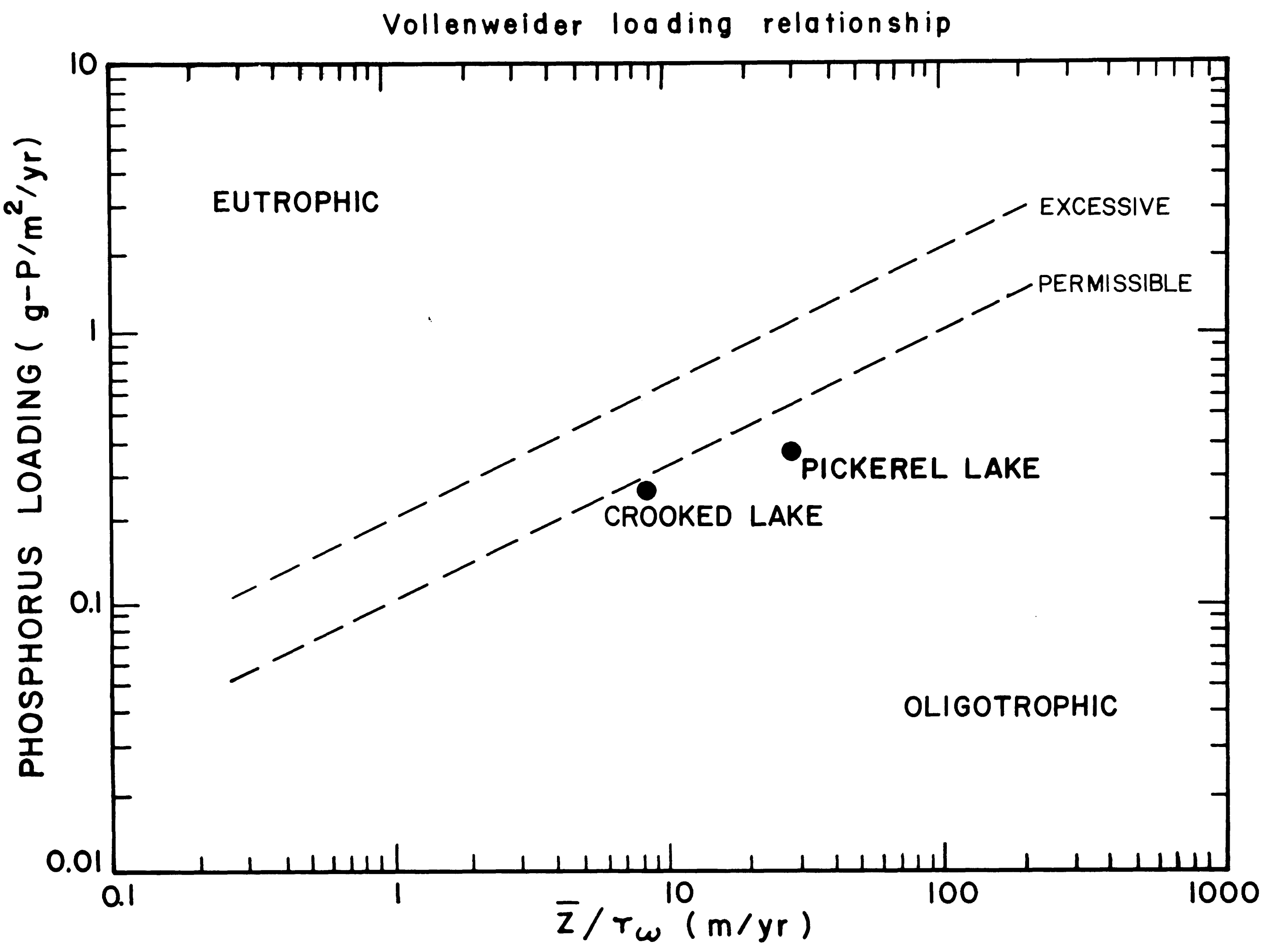

Fig. 14 Positions of Crooked and Pickerel Lakes on the Vollenweider (1975) theoretical phosphorus loading plot based on 1975-76 data.

sources. Dwellings on Crooked Lake's north shore have been serviced by a sewer and central sewage treatment system since Fall, 1976. Consequently, nutrients from wastewater that formerly entered the lake from septic systems have been diverted out of the watershed. In addition, the Oden Fish Hatchery, recognizing its pollution problems, changed its fish culture operation to reduce nutrient loading to Crooked Lakes. The lowermost raceways were converted to settling ponds to act as nutrient traps and a decision was made to shift the hatchery from fish production to brood stock maintenance.

Unfortunately, comprehensive nutrient budget data for 1977 are not available for Crooked Lake and, therefore, the impact of these changes on water quality improvement cannot be properly assessed. However, limited data on phosphorus loading from the fish hatchery was obtained in Summer, 1977. If phosphorus contributions from precipitation, other creeks, and land cover are assumed to be the same in 1975 and 1977, then an indication of the amount of phosphorus reduction from elimination of north shore septic systems and changes in fish hatchery operations can be obtained. The amount of phosphorus discharged from the fisn hatchery was nearly three times lower in 1977 than in 1975. Similarly, it was estimated that phosphorus from septic systems was reduced by a factor of three (Table 7).

Another event in 1977 should have had a slight effect in reducing phosphorus in Crooked and Pickerel Lakes. A ban on

TABLE 7. COMPARISON OF SOURCES AND QUANTITIES OF TOTAL PHOSPHORUS (P) ENTERING CROOKED LAKE DURING SUMMER, 1975 AND SUMMER, 1977*.

Sources	1975		1977	
	Kg.	%	Kg.	%
Fish Hatchery Creek	87.6	14.9	33.3	6.7
Septic Systems	50.4	8.6	16.2	3.2
Other **				
Precipitation	131.8	22.4	131.8	26.4
Land Cover	297.4	50.6	297.4	59.5
Other Creeks	20.8	3.5	20.8	4.2
TOTAL	588.0	100.0	499.5	100.0

---

* Summer is a three-month period (June, July and August).

** These data were obtained only in 1975, and phosphorus contributions from these sources were assumed to be the same in 1975 and 1977.

phosphates in detergents went into effect throughout the State of Michigan on October 1, 1977. We estimate that the phosphate ban should reduce phosphorus loading to septic systems by about 34%.

CONCLUSIONS

The present water quality of Crooked and Pickerel Lake is good. Both lakes are classified as oligo-mesotrophic with water quality slightly better (more oligotrophic) in Pickerel Lake than in Crooked Lake.

Phosphorus is the limiting nutrient to plant growth in both lakes. Consequently, the rate of change in water quality can largely be influenced by controlling phosphorus loading rates. We have little or no control over nutrient inputs from natural sources (i.e., precipitation on the lake surface, runoff and groundwater inflow from the watershed, aquatic birds, leaves, pollen, etc.). However, nutrient inputs from cultural sources (i.e., runoff from residential and agricultural land, lakeshore lawn fertilization and sewage) can be reduced. Total phosphorus loading was within theoretical "permissible" limits for both lakes in 1975-76. Indications are that a reduction in phosphorus loading from north shore dwellings and the Oden Fish Hatchery has occurred on Crooked Lake since 1975-76. The ban on phosphates in detergents, that took effect in Fall, 1977, will also reduce phosphorus loading to both lakes.

Further reductions in phosphorus loading should be encouraged to protect and maintain water quality in these lakes. Reduction in lakeshore lawn fertilization and construction of lakeshore greenbelts are recommended. Septic systems located on soils suitable for on-site wastewater treatment should be properly maintained. For dwellings located on soils unsuitable for on-site sewage treatment, the ecological and economic consequences of any wastewater management alternatives should be carefully considered.

ACKNOWLEDGEMENTS

The entire research staff at the University of Michigan Biological Station contributed to the field and laboratory work on Crooked and Pickerel Lakes in numerous ways. Their assistance is gratefully acknowledged. We especially thank Art Gold for input on the nutrient loading determinations. Gerald Krausse performed the chemical analyses. We also thank Marilyn Munger for document preparation.

REFERENCES CITED

Alfred, S. D., A. G. Hyde, and R. L. Larson. 1973. *Soil survey of Emmet County, Michigan.* U. S. Dept. Agriculture, Soil Conservation Serv., Washington, D. C., 99 p.

American Public Health Association. 1971. *Standard methods for the examination of water and wastewaters.* 13th ed., APHA, N. Y., 874 p.

Carlson, R. E. 1977. A trophic state index for lakes. *Limnol. Oceanogr.* 22:361-369.

Environmental Protection Agency. 1974a. *Methods for chemical analysis of water and wastes.* EPA Nat. Envir. Res. Center, Cincinnati, OH, 312 p.

______. 1974b. *The relationships of phosphorus and nitrogen to the trophic state of northeast and north-central lakes and reservoirs.* Nat. Eutrophication Surv., Working Paper No. 23, 28 p. & App.

______. 1975. *Report on Lake Charlevoix, Charlevoix County, Michigan.* Nat. Eutrophication Surv., Working Paper No. 188, 14 p. & App.

Foster, W. L. 1976. *Profile of the land: Natural features of the Inland Water Route region of northern lower Michigan.* Univ. Michigan Biol. Sta., Info. Report. No. 2, 29 p.

Gales, M., Jr., E. Julian, and R. Kroner, 1966. Method for quantitative determination of total phosphorus in water. *J. Amer. Waterworks Assoc.* 58:1363.

Gannon, J. E. and M. W. Paddock. 1974. *Investigations into ecological and sociological determinants of land use decisions - A study of inland lake watersheds in northern Michigan.* Univ. Michigan Biol. Sta., Tech. Report No. 1, 314 p.

______ and D. J. Mazur. 1976. Sources of nutrients (phosphorus and nitrogen) for Crooked Lake, Emmet County, Michigan. Univ. Michigan Biol. Sta., Unpubl. Report, 14 p.

Gold, A. and J. E. Gannon. 1979. The suitability of soils for on-site wastewater disposal, Pickerel and Crooked Lakes, Emmet County, Michigan. Univ. Michigan Biol. Sta., Tech. Report No. 8, Part II, 18 p.

Hutchinson, G. E. 1957. *A treatise in limnology. Vol. I. Geography, Physics, and Chemistry.* Wiley, New York, 1015 p.

Marans, R. W. and J. D. Wellman. 1977. *The quality of non-metropolitan living: Evaluations, behaviors, and expectations of northern Michigan residents.* Univ. Michigan, Inst. Social Res., 428 p.

Mentzel, D. W. and N. Corwin. 1965. The measurement of total phosphorus on seawater based on the liberation of organically bound fraction by persulfate oxidation. *Limnol. Oceanogr.* 10:280-288.

Müller, R. and O. Widemann. 1955. Nitratbestimmung in Seewasser. *Jahrbuch V. Wasser* 22:247-271.

Omernik, J. M. 1976. *The influence of land use on stream nutrient levels.* Environmental Protection Agency, Report No. EPA-600/3-76-014, 106 p.

O'Neil, W. 1977. *This land and man: An historical look at the use of land and natural resources in the Inland Water Route region of northern Michigan.* Univ. Michigan Biol. Sta., Info. Report No. 3, 21 p.

Pelz, D. C. 1977. *Utilization of environmental knowledge on northern Michigan.* Univ. Michigan, Inst. Social Res., 174 p.

______ and J. E. Gannon. 1978. Utilization of environmental knowledge for watershed management in northern Michigan. *Envir. Manag.* 3:in press.

Project CLEAR. 1978. *Environmental features of Walloon Lake and its' watersheds (Emmet and Charlevoix Counties, Michigan), with special reference to nutrient management.* Univ. Michigan Biol. Sta., Tech. Report No. 6, 81 p.

Richardson, C. J. 1978. *Investigations into ecological and sociological determinants of land-use decisions. Part II: Influence of land-use patterns, geology, and precipitation chemistry on nutrients in groundwater and lake water quality.* Univ. Michigan Biol. Sta., Tech. Report No. 4, 190 p.

Rogers, R. H. 1977. *Application of LANDSAT to the surveillance of lake eutrophication in the Great Lakes basin.* Bendix Aerospace Div., Ann Arbor, MI.

Say, E. W., M. W. Paddock, J. E. Gannon, and W. L. Foster. 1975. *Inland lake protection in northern Michigan.* Univ. Michigan Biol. Sta., Educ. Ser., Publ. No. 1, 40 p.

Schmid, M. and H. Ambühl. 1965. Die bestimmung geringster Mengen von Gesamtphosphor in Wasser von Binnenseen. *Schweiz. Z. Hydrol.* 27:184-192.

Schneider, I. F. and A. E. Erickson. 1972. *Soil limitations for disposal of municipal wastewaters.* Michigan State Univ., Agri. Exp. Sta., Res. Report No. 195, 54 p.

Solorzano, L. 1969. Determination of ammonia in natural waters by the phenolhypochlorite method. *Limnol. Oceanogr.* 14:799-801.

Technicon. 1972-73. Industrial Methods. Technicon Instruments Corp., Tarrytown, NY.

Tierney, D. P., R. Powers, T. Williams, and S. C. Hsu. 1976. *Actinomycete distribution in northern Green Bay and the Great Lakes: Taste and odor relationships in eutrophication of nearshore waters and embayments.* Environmental Protection Agency, Report No. EPA-905/9-74-007, 167 p.

Uttormark, P. D. and J. P. Wall. 1975. *Lake classification - A trophic characterization of Wisconsin lakes.* Environmental Protection Agency, Report No. EPA-660/3-75-033, 165 p.

Vollenweider, R. A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. Organization Econ. Co-op. Devel., Paris, 159 p. & 34 figs.

Vollenweider, R. A. 1975. Input-output models with special reference to the phosphorus loading concept in limnology. *Schweiz. Z. Hydrol.* 37:53-84.

Welch, P. S. 1948. *Limnological methods.* Blakiston, Philadelphia, PA, 381 p.

APPENDIX A

DATA USED IN ESTIMATING NUTRIENT LOADING TO CROOKED AND PICKEREL LAKES FROM SEPTIC SYSTEMS

TABLE A-1. TOTAL PHOSPHORUS AND TOTAL NITROGEN EXPORT (kg/km^2/yr.) FROM LAND COVER. VALUES ARE MEANS FOR THE NORTH AND NORTHEASTERN UNITED STATES (OMERNIK, 1976), AND WERE USED IN THE CROOKED AND PICKEREL LAKES NUTRIENT LOADING CALCULATIONS.

Land Cover	Phosphorus	Nitrogen
Forest	8.6	397
Agriculture (mostly)	16.3	525
Urban	31.7	669

TABLE A-2. ESTIMATED PHOSPHORUS (P) AND NITROGEN (N) INPUTS FROM SEPTIC SYSTEMS TO CROOKED LAKE'S NORTH SHORE IN 1975. THIS PORTION OF THE LAKE HAS BEEN SERVICED BY A SEWER SINCE 1976.

	Percent Reaching Lake		Number of Dwellings			Amt. Reaching Lake	
Soil Type	P(%)	N(%)	Y-R	PY-R	S	P(kg/yr)	N(kg/yr)
Au Gres loamy sand (AuB)	35	65	50	1	84	61.6	815.6
Deford fine loamy sand (Df)	75	50	2	0	0	3.7	17.5
Carbondale muck (Ca)	75	50	0	0	2	0.9	4.4
Kalkaska loamy sand (KaB)	25	65	19	0	16	14.1	262.4
Made land (Ma)	35	50	34	0	20	33.6	342.2
Roscommon mucky sand (Rc)	75	50	1	0	4	3.7	17.6
Rubicon sand (RuB)	25	65	2	0	4	1.9	34.2
Tawas muck (Ta)	75	50	8	0	3	16.1	76.8
Wet alluvial land (Wt)	75	50	0	0	2	0.9	4.4
TOTAL			116	1	135	136.5	1,575.1

---

* Y-R is year-round occupancy; PY-R is possible year-round occupancy; S is seasonal occupancy.

TABLE A-3. ESTIMATED PHOSPHORUS (P) AND NITROGEN (N) INPUTS FROM SEPTIC SYSTEMS TO THE SOUTH SHORE OF CROOKED LAKE, INCLUDING ODEN ISLAND, IN 1975. THIS PORTION OF THE LAKE CONTINUES TO BE SERVICED BY SEPTIC SYSTEMS.

Soil Type	Percent Reaching Lake		Number of Dwellings			Amt. Reaching Lake	
	P(%)	N(%)	Y-R	PY-R	S	P(kg/yr)	N(kg/yr)
Au Gres loamy sand (AuB)	35	65	13	0	9	13.1	174.0
Au Gres sand (ArB)	35	65	0	0	3	0.7	8.6
Blue Lake loamy sand (B1B)	65	65	1	0	1	2.0	14.3
Blue Lake loamy sand (B1F)	65	65	0	0	4	1.6	11.4
Brevort mucky loamy sand (Br)	55	50	10	0	11	17.3	111.9
Bruce fine sandy loam (By)	35	50	2	0	0	1.7	17.6
Emmet sandy loam (EmB)	25	65	4	0	0	2.5	45.6
Iosco loamy fine sand (I1B)	55	65	0	1	1	0.3	2.9
Johnswood cobbly loam (JoC)	25	85	9	2	9	7.5	182.7
Kalkaska sand (KaB)	25	65	0	1	7	1.4	25.7
Kalkaska sand (KaC)	25	65	3	0	1	2.0	37.1

Continued

TABLE A-3 Cont.

Soil Type	Percent Reaching Lake P(%)	Percent Reaching Lake N(%)	Number of Dwellings Y-R	Number of Dwellings PY-%	Number of Dwellings S	Amt. Reaching Lake P(kg/yr)	Amt. Reaching Lake N(kg/yr)
Made land (Ma)	35	50	2	0	0	1.7	17.5
Roscommon mucky sand (Rc)	75	50	2	0	1	4.2	19.7
Sandy lake beaches (Sb)	35	65	5	1	0	4.7	62.7
Thomas loam (ToA)	35	50	3	1	9	4.5	50.4
TOTAL			54	5	56	65.2	782.1

TABLE A-4. ESTIMATED PHOSPHORUS (P) AND NITROGEN (N) INPUTS FROM SEPTIC SYSTEMS TO PICKEREL LAKE IN 1975.

Soil Type	Percent Reaching Lake P(%)	N(%)	Number of Dwellings Y-R	PY-R	S	Amt. Reaching Lake P(kg/yr)	N(kg/yr)
Au Gres loamy sand (ArB)	35	65	0	0	7	1.5	20.0
Carbondale muck (Ca)	75	50	0	0	4	1.8	8.8
East Lake loamy sand (EaB)	25	65	1	0	4	1.2	22.8
Kalkaska loamy sand (KaB)	25	65	7	0	20	7.4	135.9
Roscommon mucky sand (Rc)	75	50	5	0	20	18.4	87.8
Saugatuck sand (ScB)	35	50	3	0	18	6.5	65.8
Tawas muck (Ta)	75	50	1	0	12	7.4	35.1
Thomas mucky loam (Tm)	35	50	0	0	4	0.9	8.8
Thomas loam (ToA)	35	65	0	0	16	3.4	45.6
Warners mucky loam (Wm)	75	50	4	2	9	13.4	63.6
TOTAL			21	2	114	61.9	494.2

LIMNOLOGICAL FEATURES
OF
CROOKED AND PICKEREL LAKES, EMMET COUNTY, MICHIGAN

PART II. THE SUITABILITY OF SOILS FOR ON-SITE WASTEWATER DISPOSAL[1]

by

Arthur Gold

and

John E. Gannon[2]

Technical Report No. 8
Biological Station
The University of Michigan
Pellston, Michigan 49769

April, 1979

---

[1] This report is based on research funded by the National Science Foundation (Grant No. AEN72-03483). Preparation of the report was supported by the Environmental Protection Agency as a sub-contract to a prime contract (EPA-No. 08-01-4612) to WAPORA, Inc.

[2] Present address: State University Research Center, Oswego, NY 13126.

CONTENTS

FIGURES

BACKGROUND

Septic systems rely on the soil to purify domestic wastewater. However, soil types vary considerably in their capacity to effectively treat wastewater. Septic systems operating in ill-suited soils can be a threat to public health and can have adverse effects on water quality of nearby lakes and streams. Soil suitability for wastewater disposal is primarily determined by slope, permeability, depth to seasonal high groundwater level, and phosphorus adsorption capacity. Depth to bedrock can also be a factor where overlying soils are extremely shallow. One of these variables, or more likely the integrating influence of a combination of them, may restrict the use of on-site waste disposal by septic systems.

Septic systems, if properly designed and carefully installed, may function adequately on sites with slopes up to 12% (Warshall, 1976). Slopes up to 15% grade present moderate limitations for wastewater disposal if engineering modifications of the drain field such as serial distribution are employed. Systems on severe slopes may experience problems with prematurely failing drain fields or ponding effluent. Installation of septic systems on steep slopes will require additional expense and attention to eliminate the potential for accelerated erosion and sedimentation.

Permeability is the rate at which water moves through the soil, and is a major consideration in on-site inspection for septic system permits. Permeability usually changes with each soil horizon and various on-site disposal systems use different horizons for wastewater treatment. Drain field trenches are generally placed two feet below the surface, which diminishes the importance of soil permeability above that level. Mounds and raised drain fields developed in Wisconsin rely on the permeability of the surface soil layers (Converse et al., 1976).

Depth to seasonal high groundwater is a primary consideration in on-site analysis for septic tank permits. The highest levels of purification are achieved when the wastewater passes through unsaturated soils. Effluent moves through spaces between soil particles, increasing the contact of the effluent with the soil and increasing the time before the liquid reaches groundwater (Baker and Bouma, 1975). This enhances the potential of the soil for phosphorus adsorption and for the physical screening of bacteria (McCoy and Ziebell, 1975). Under saturated conditions, wastewater flows through the largest soil spaces, minimizing contact between the effluent and soil particles.

Phosphorus adsorption capacity differs with soil types and is a major factor in the ability of a soil to purify wastes. Limnological data indicates that phosphorus is the limiting nutrient for aquatic productivity in Crooked and Pickerel Lakes (See Part I of this report). Septic systems are one source of phosphorus loading to the lakes.

A series of overlay maps have been prepared to provide guidelines for future wastewater management planning on the shorelines of Crooked and Pickerel Lakes, Emmet County, Michigan. The maps integrate information on soil suitability and illustrate the capacity of the land near these lakes to purify septic system effluent. An overlay map depicting depth to bedrock was not constructed since bedrock is not found close to the surface in the study area. When presently existing septic systems need replacing, new septic systems or other on-site wastewater management alternatives should be designed to compensate for any site specific soil limitations. Of course, the use of the overlay maps should not preclude on-site inspection for suitability of wastewater disposal.

METHODS

Overlay maps for slope, permeability, depth to seasonal high groundwater, and phosphorus adsorption capacity were prepared, based on development capability criteria established by the U. S. Soil Conservation Service (1966) and Schneider and Erickson (1972). The classification and distribution of soil types in the watersheds of Crooked and Pickerel Lakes were obtained from Alfred et al. (1973).

Location of dwelling units in the study area was acquired from Williams and Works (1976)*. On 20 February 1978 we visually surveyed the dwellings within 300 feet of the lakeshore to estimate the number of permanent and seasonal residences. Over three feet of snow existed on the ground at the time of the survey. Criteria used to determine year-round occupancy

---

* At least eight additional dwellings were built since 1976 and were included on the map.

included recently plowed drives, fresh tire tracks, trash containers, and chimney smoke. Indications of occasional occupancy were recorded as possible seasonal use in winter.

The phosphorus adsorption capacities depicted on the overlay map are as follows (Schneider and Erickson, 1972):

Rate Class	Pounds per acre in upper three feet of soil
High	>1,600
Medium	1,300 ~~to~~ 1,600
Low	<1,300

Phosphorus adsorption data were unavailable for four soil types in the study area. The following estimates were provided by Forrest (personal communication*):

Soil Series	Phosphorus Adsorption Capacity
Dighton Series, fine subsoil variant	High
Saugatuck Series	High
Johnswood Series	High
Blue Lake Series	Low

The following characteristics of slope, depth to seasonal high groundwater, and permeability are depicted for each respective soil property (Alfred, et al. 1973):

Slope (Percent)	Depth to Seasonal High Groundwater (feet)	Permeability (inches per hour)
0-6	>4	6.3 - 20.0
6-12	2-4	2.0 - 6.3
12-18	<4	0.63 - 2.0
>18		<0.63

---

* Forest, Michael, Soil Scientist, U.S. Soil Conservation Service, Gaylord, MI 49735.

permeability values represent the lowest rate that occurs in the upper five to six feet of soil.

Each variable is depicted on a separate transparency that lies on two base maps, one showing location of total dwelling units and the other indicating year-round residences. Increasing degrees of shading are employed to indicate greater restriction imposed by each variable on development and on-site wastewater disposal. When all four transparencies are viewed together, greater restrictions for wastewater disposal are indicated by the darkest areas.*

A limited number of booklets (23" X 17") containing the transparent overlays and base maps were prepared and deposited at Emmet County governmental offices and at the University of Michigan Biological Station. Prints of the overlays on the base map of year-round residences appear in Appendix A.

RESULTS AND DISCUSSION

Dwelling Units

Based on our visual survey and data from Williams and Works (1976), we estimate that 112 dwelling units are located within 300 feet of the shore on the south side of Crooked Lake and on Oden Island and 134 on Pickerel Lake. Approximately 55% of these dwellings on Crooked Lake indicated year-round occupancy. In contrast, 21% of the residences on Pickerel Lake appeared

---

* Those soils exhibiting high groundwater and rapid permeability may be more limited in their capacity to treat wastewater than these overlays actually depict.

to be year-round. Frequency of year-round dwellings was especially low (10%) along the north shore and at Botsford Landing.

Slope

Emmet County's Health Code does not specifically restrict on-site disposal systems based on slope characteristics (Michigan District Health Department No. 3, 1968). However, county sanitarians consider slope in their inspection of suitability of a site for septic treatment.

Gently sloping terrain characterizes most of the shoreline of Crooked and Pickerel Lakes and does not limit the functioning of septic systems in most of the study area. The only exception is the eastern side of Graham Point on Crooked Lake where slopes greater than 12% are located.

Permeability

Permeability of less than 1.0 inch per hour is considered too slow to allow for adequate treatment (Goldstein and Moberg, 1973). The Emmet County Sanitary Code requires a permeability rate greater than 2.0 inches per hour by the percolation test (Michigan District Health Department No. 3, 1968). No restriction is imposed on soils with extremely rapid permeability (i.e., greater than 10 inches per hour). However, coarse soils with very rapid permeability can introduce contaminants to groundwater.

Approximately one-half of the dwelling units on the south shore of Crooked Lake are situated on Au Gres sands and Thomas loamy sands (Alfred et al., 1973) which have permeability too slow for adequate septic treatment. Nineteen residences southeast of Graham Point are located on Johnswood cobbly loam.

The moderately slow permeability of this soil type should be recognized when considering on-site disposal alternatives.

Sixty homes bordering Pickerel Lake are underlain by soils with permeability below all acceptable standards for septic treatment (Goldstein and Moberg, 1973). Approximately one-half of these homes, located on Ellsworth Point, are situated on Saugatuck sands which have extremely slow permeability in the upper horizons. Kalkaska sands on the southeast shore of Pickerel Lake exhibit permeability adequate for septic treatment.

Depth to Seasonal High Groundwater

Sites with high groundwater levels (permanent or seasonal) are not suitable for septic system use. The groundwater level during the wettest season should be at least four feet below the bottom of the trenches in a subsurface tile absorption field and four feet below the pit floor in a field using seepage pits (Goldstein and Moberg, 1973). Emmet County requires that finish grade be at least six feet above the known high groundwater level (District Health Department No. 3, 1968). The county allows some filling to obtain this distance.*

Mounds may be used for safe and effective disposal of septic tank effluent where depth to seasonal high groundwater level is greater than two feet from the surface (Converse et al., 1976). Areas with seasonal high groundwater levels less

---

* The soils of Emmet County have been interpreted to a depth of five feet (Alfred, et al., 1973). However, the depth to seasonal high groundwater was not recorded if the water table was more than four feet from the surface. Knowledge of soil types and depth of groundwater to at least six feet below the surface would be useful for on-site wastewater management decisions.

than two feet from the surface are severely limited for on-site disposal (Goldstein and Moberg, 1973).

Seasonal high groundwater levels occur within two feet of the surface in most of the lakeside soils of Crooked and Pickerel Lakes. Consequently, adequacy of septic treatment is severely limited during periods of high groundwater for the majority of riparian dwelling units. Notable exceptions are the Emmet sandy loams on Oden Island and the Kalkaska sands underlying some of the dwelling units on Pickerel Lake's Ellsworth Point and Botsford Landing.

Phosphorus Adsorption Capacity

The phosphorus adsorption capacity of most soils around Crooked Lake is adequate for septic treatment. However, Blue Lake loamy sand and Roscommon muck, underlying a few residences on the south shore, and Emmet sands, under most dwellings on Oden Island, have low phosphorus adsorption capacities.

Approximately 30% of the dwellings on Pickerel Lake are on Warners mucky loam, Tawas muck, or Roscommon mucky sands which exhibit low phosphorus adsorption capacities. However, adjacent inland soils near the south shore consist of Kalkaska sands with higher phosphorus adsorption capacities.

CONCLUSIONS

Most of the dwelling units on the south shore of Crooked Lake are located on soils with characteristics severely limiting their capacity to treat wastewater from conventional septic systems. High seasonal groundwater levels are the major constraint along most of the shoreline. In addition, soils with low permeability rates underly approximately one-half of the existing dwellings. Residences on Oden Island are situated on soils with some limitations but on-site waste treatment such as mounds or other innovations could be instituted. More than 50% of the dwellings on the south shore of Crooked Lake and on Oden Island are year-round. This factor should be considered when reviewing wastewater management alternatives.

Much of the development surrounding Pickerel Lake is on soils not capable of effectively treating septic system wastes. Seasonal high groundwater levels are again the major constraint, although low permeability and phosphorus adsorption problems also exist. Therefore, alternative on-site methods of wastewater disposal should be considered. For example, a large tract of Kalkaska sands located south of developments at Botsford Landing and Ellsworth Point are highly suitable for on-site wastewater treatment. This method may not be feasible on the north side since only small, scattered parcels of suitable soils are available there. Holding tanks for pump-out disposal offer a possible on-site alternative. Only 21% of the dwellings around Pickerel Lake are year-round residences. This factor may influence the choice of wastewater management methods.

The Crooked-Pickerel Channel area is one of the largest and most important wetlands in the watershed of Crooked and Pickerel Lakes. Soils in this area consist largely of Tawas and Carbondale muck which exhibit serious limitations to development and on-site wastewater disposal. The wetland functions as an important breeding and nursery ground for game fish and other aquatic organisms, provides habitat for game birds and animals, and protects the quality of surface and groundwater resources. Retainment of the soils and vegetation of the Crooked-Pickerel Channel area in their natural condition is ecologically sound and worthy of consideration.

ACKNOWLEDGEMENTS

We thank M. Secrest and B. Burley for assistance in preparing the soil maps, D. Mazur for help on the visual survey of year-round dwelling units, and M. Munger for typing the manuscript.

REFERENCES CITED

Alfred, S. D., A. G. Hyde, and R. L. Larson. 1973. Soil Survey of Emmet County, Michigan. U.S. Dept. of Agriculture, in cooperation with Michigan Agricultural Experiment Station, 99 p.

Baker, F. G. and J. Bouma. 1975. Measurment of soil hydraulic conductivity and site selection for liquid waste disposal. *In*: Individual on-site wastewater systems, Proc. Nat. Conf., National Sanitation Foundation, Ann Arbor, MI.

Converse, J.C., R. J. Otis, J. Bouma, W. Walker, J. Anderson, and D. Stewart. 1976. Design and construction procedures for mounds in slowly permeable soils with or without seasonally high water tables. Univ. Wisconsin, Unpubl. mimeo., 35 p.

Goldstein, S. N. and W. J. Moberg, Jr. 1973. Wastewater treatment systems for small communities. Commission on Rural Water, Washington, D.C., 340 p.

McCoy, E. and W. A. Ziebell. 1975. Effects of effluents on groundwater. *In*: Individual on-site wastewater systems, Proc. Nat. Conf., National Sanitation Foundation, Ann Arbor, MI.

Michigan District Health Department No. 3. 1968. Emmet County Sanitary Code, Emmet County, Michigan, 4 p.

Schneider, I. F. and A. E. Erickson. 1972. Soil limitations for disposal of municipal wastewaters. Michigan State University Agricultural Experiment Station, East Lansing, in cooperation with Michigan Water Resources Commission, Farm Science Research Report No. 195, 54 p.

U.S. Soil Conservation Service. 1966. Land-capability classification. Dept. of Agriculture, Handbook No. 210, 21 p.

Warshall, P. 1976. *Septic tank practices.* Mesa Press, Bolinas, CA 76 p.

Williams and Works. 1976. Little Traverse Bay Area Facility Plan, Springvale-Bear Creek area segment for wastewater collection and treatment. Emmet County, Michigan, Williams and Works, Inc., Grand Rapids, Michigan.

APPENDIX A

Maps of the Crooked and Pickerel Lakes area, depicting variables that influence adequacy of soils for on-site wastewater disposal.

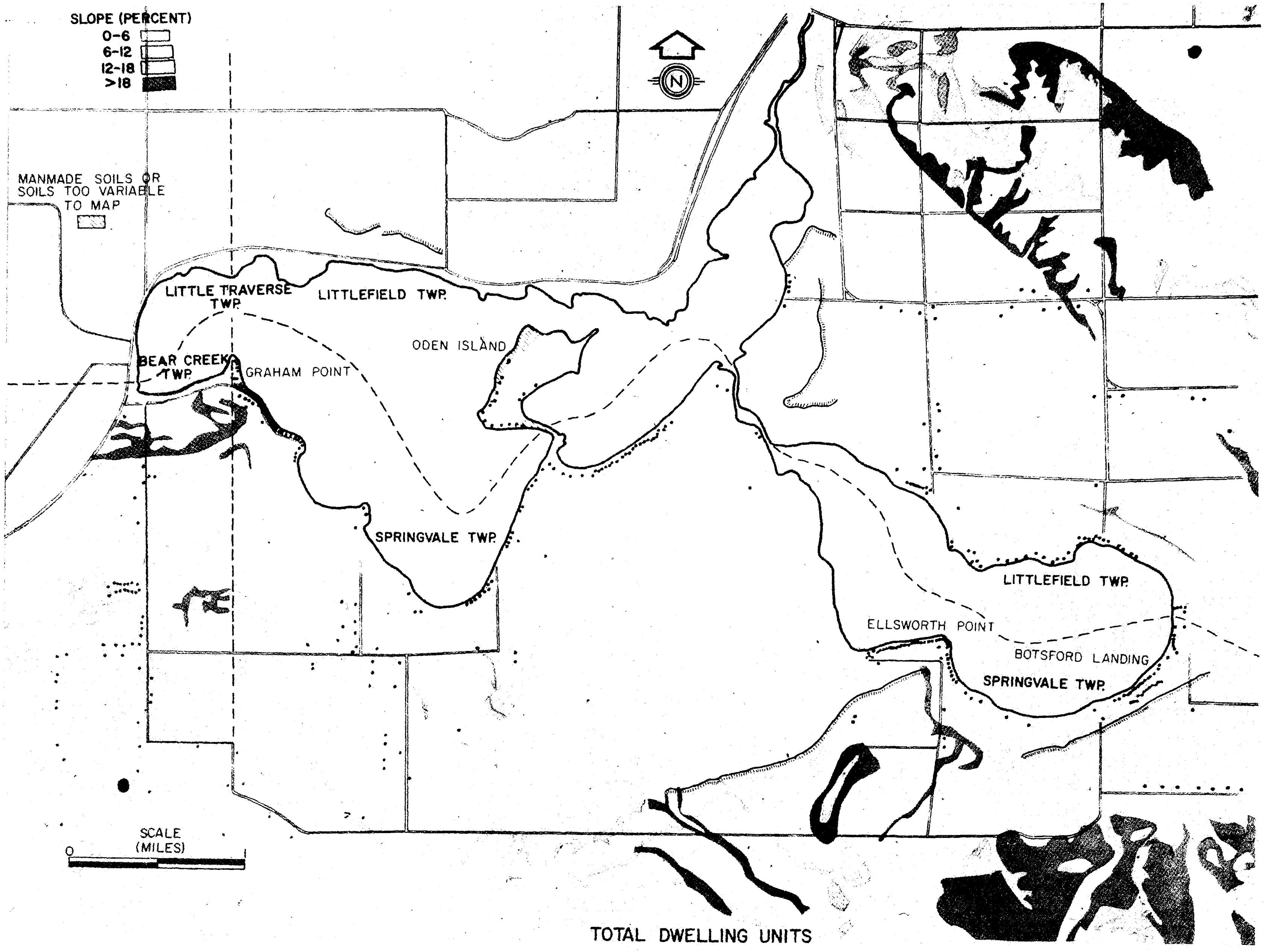

Fig. A-1 Slope. Darker shading indicates more severe limitations to on-site wastewater disposal on Figures A-1 through A-5

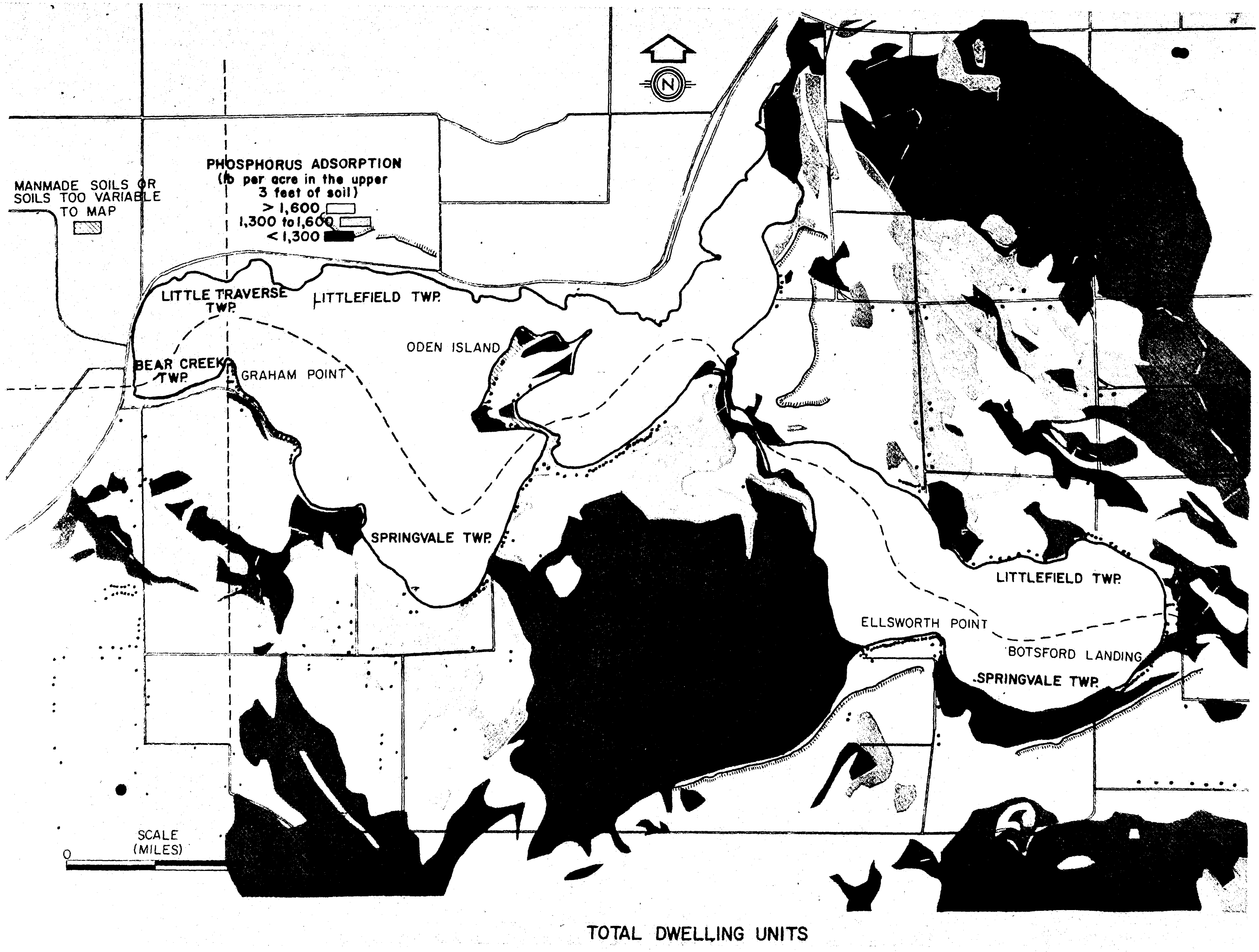

Fig. A-2 Phosphorus adsorption capacity

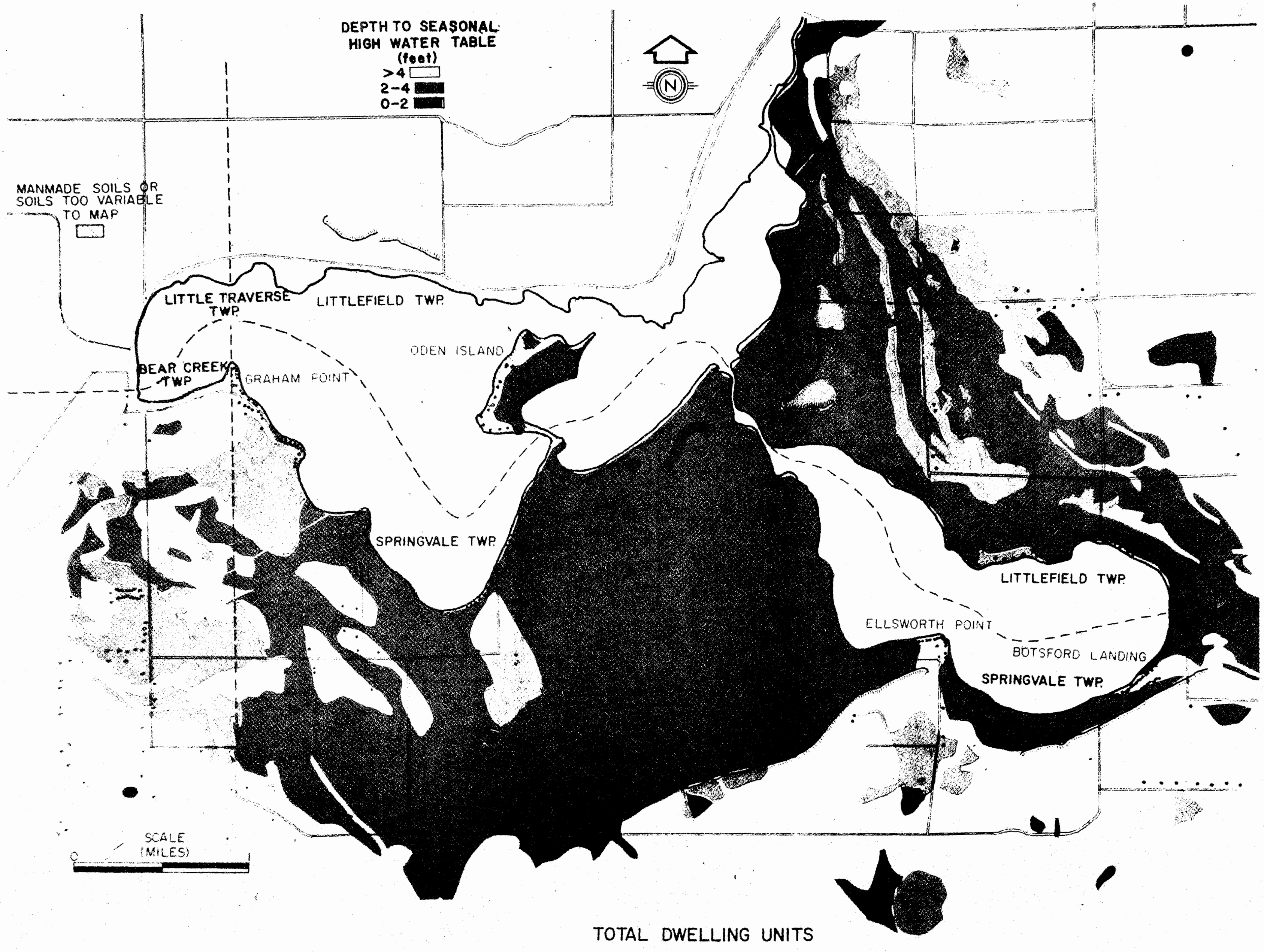

Fig. A-3 Depth to seasonal high groundwater

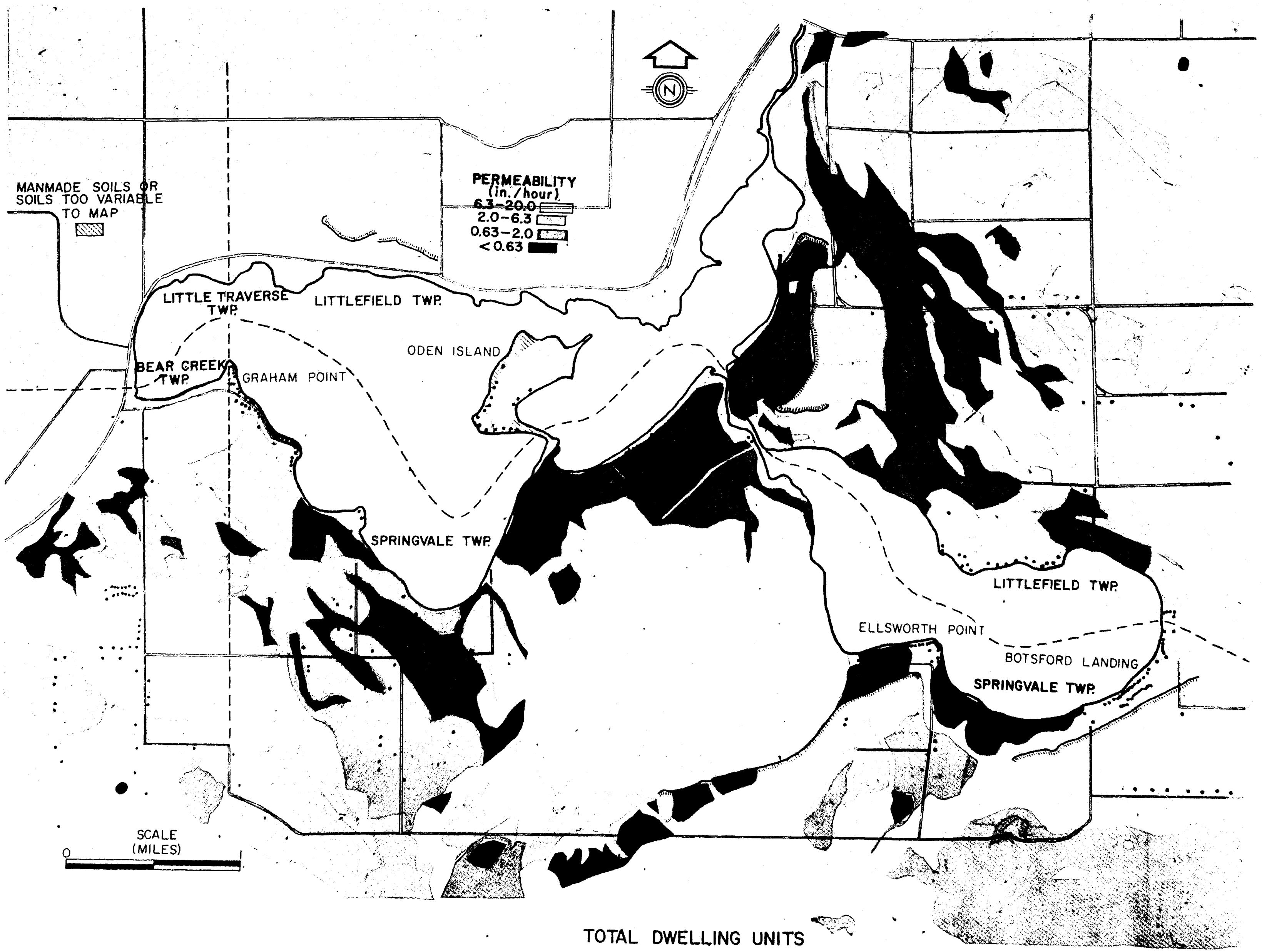

Fig. A-4 Permeability

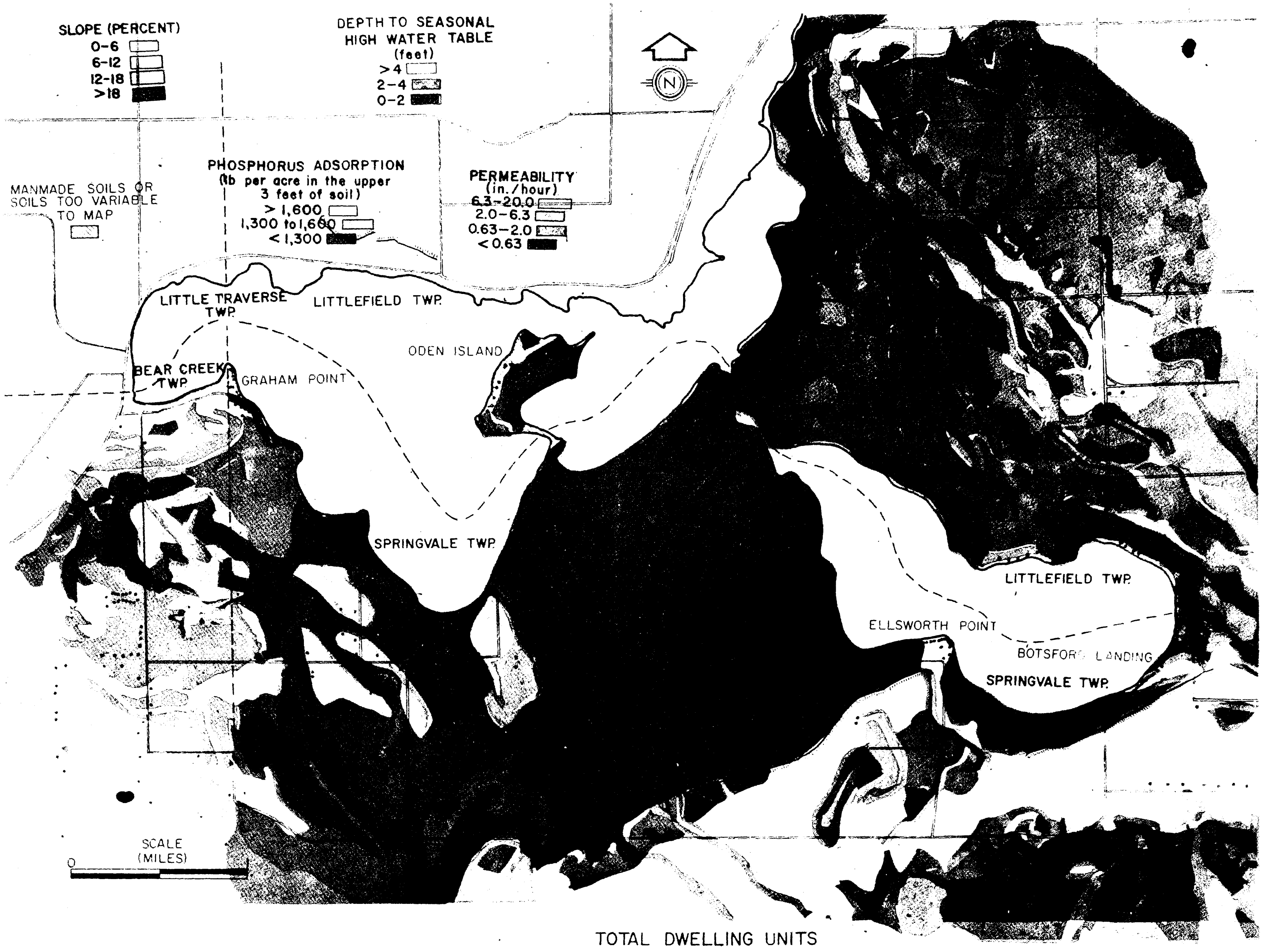

Fig. A-5 A composite map of the four variables that affect suitability of soils for on-site wastewater disposal