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DAVID LEAR SHULL Ph. D. 1963

LIMNOLOGICAL CHARACTERISTICS OF TWO MICHIGAN MARL-FORMING WATERS

Thesis for the Degree of Ph. D.

MICHIGAN STATE UNIVERSITY

David Lear Shull

1963

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LIMNOLOGICAL CHARACTERISTICS OF TWO MICHIGAN MARL-FORMING WATERS

By

David Lear Shull

AN ABSTRACT OF A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Zoology

1963

ABSTRACT

LIMNOLOGICAL CHARACTERISTICS OF TWO MICHIGAN
MARL-FORMING WATERS

by David Lear Shull

A Michigan hypermarl temperate second-order lake and a hypermarl temperate third-order lake were studied with reference to the chemical-biological features, trophic levels, and methods for increasing productivity.

The lake basins lie in a glacial outwash plain. The matrix of the surrounding moraines has abundant limestone fragments and good drainage. The ground water contains comparatively large quantities of calcium-magnesium bicarbonate which fluctuate inversely with local rainfall.

Low trophic levels result from the high alkalinity, and particularly from the carbonate alkalinity which forms in direct relationship to summer temperatures and the physiological activities of plants. Effects of the alkalinity on production are threefold: (i) the aquatic vegetation, including Chara was rigidly suppressed in growth by heavy incrustations of carbonate, (ii) ninety per cent of the carbonate deposition occurred on the lake basin above the hypolimnion producing unusually steep slopes, reducing the productive zone of the macro-hydrophytes, and (iii) the high alkalinity of the water and the homogeneous marl soils adsorb and fix the soluble phosphorus of the water

(Barrett, 1952).

Hydrogen sulfide emanating from basin muds may have restricted plant growth since toxic quantities of sulfide accumulated in the waters of the hypolimnion.

Light penetration of marl forming water did not limit plant growth although high winds increased light extinction coefficients.

The ratio of calcium:magnesium in the water was about 2.4:1. The ratio of calcium:magnesium deposited as marl was about 10:1. The rate of decalcification ranged from 9.2 - 66.5 mg hr^{-1} $meter^{-2}$ and was inversely correlated with phytoplankton volumes. The maxima of calcium occurred with the development of aggressive carbon dioxide in the hypolimnion when marl was transformed to calcium bicarbonate.

The trophic level of the marl temperate third-order lake increased significantly with six applications of inorganic fertilizer. Plankton increased after each application, macrohydrophytes increased 4 - 6 fold, and bottom fauna 1 - 2 fold.

The addition of organic matter to marl resulted in increased production. Peat and sod substrates placed within the marl lake increased plant production 25 - 138 fold and bottom fauna production 3-1/3 - 12-1/2 fold, respectively. Burlap bags filled with peat or sewage sludge, planted with aquatic root stocks and placed in the lake basin, increased the plant production 400 fold on a ft^{-2} basis.

Barrett, P. H. 1957. Potassium concentrations in fertilized trout lakes. Limnology and Oceanography, Vol. II, No. 3.

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The author wishes to express appreciation to the Institute for Fisheries Research of the Michigan Department of Conservation who financed the program and to Dr. Frank Hooper of the Institute, who advised and assisted in many ways. The personnel of the Rifle River Experiment Station were very cooperative throughout the study.

Dr. Don W. Hayne, Institute of Statistics, N. C. State College, and Dr. William D. Baten have been most helpful with the statistical portions of this thesis.

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INTRODUCTION

Considerable attention has been given to marl lakes and upland marl deposits in Michigan by pioneers, industrialists, and chemists. Marl was a valuable raw material having many uses. On the shores of some marl lakes one finds the remains of old kilns where marl was burned to produce lime. Log houses mortared with quicklime still stand in Michigan. Marl has been used extensively for conditioning soils, as an additive in paints, and as an abrasive in tooth and scouring powders. During the 1800's and early 1900's a portland cement manufacturing industry flourished in Michigan near the marl lake deposits. Modern machinery and discovery of extensive limestone deposits prompted the cement industry to abandon marl lakes as sources of calcium carbonate. A recent demand for recreation facilities from a rapidly expanding population and tourist industry brought renewed interest in the marl lakes of the state.

Previous studies indicate that marl forming water is unique in its physical, chemical, and biological features. Raymond's study (1937) of a marl lake near Ann Arbor, Michigan, disclosed a paucity of phytoplankton organisms. Scant growths of aquatic vegetation in marl lakes were found by Welch (1935), Roelofs (1944), and Wohlschlag (1950). Poor fishing quality is usually associated with marl lakes.

The productivity of invertebrates and fish in an ecosystem is ultimately dependent on chlorophyll synthesizing aquatic vegetation. Plant life is sometimes utilized directly as food (Ball, 1948; Hubbs and Cooper, 1936). Other important Michigan fish depend directly on aquatic insects for food which in turn forage heavily on algae. Vegetated littoral areas support larger standing crops of bottom fauna than non-vegetated areas (Rawson, 1930; Baker, 1933; Juday, 1942; Ball, 1948; Wohlschlag, 1950, and others). Investigators may not agree on a precise relationship between plants and the eventual productivity of fish, but it is well known that lakes with a luxuriant flora support a correspondingly dense fauna.

Scant flora probably limit fish food organisms in marl lakes. Based on this thesis, the study was conducted:

(i) to obtain information about the chemical-biological features of a hypermarl temperate second-order lake and a hypermarl temperate third-order lake,

(ii) to determine the ecological factors contributing to the low biological productivity, and

(iii) to devise and test methods for altering the environment to increase productivity.

Description of Area

Two marl pit lakes of glacial origin located within the Ogemaw State Forest, Ogemaw County, Michigan, were selected for study.

Geology and Physiography

The bed rocks of the area are covered by glacial debris. There are only two known outcroppings south of the study area in the bed of the Rifle River. The underlying rocks in this part of Michigan are sedimentary formations of shale, limestone and dolomite. Extensive bed rock limestone formations are also found within fifty miles to the northeast and southeast of the area.

The Ogemaw region was covered by the Saginaw ice-lobe of the Labrador Ice Sheet. Glacier ice moved southwestward developing moraines across the central portion of the county which have a general northeast-southwest orientation. Two moraine systems lie from one-half to five miles apart in the northeast corner of the county and are separated by an outwash plain. The pit lakes selected for the study are in this outwash plain.

Glacial drift of the region varies in thickness from zero in the bed of the Rifle River to 700 ft in the West Branch Moraine. Examination of the glacial matrix at road cuts and gravel pits in the immediate study area reflects the character of the exposed bedrock on Michigan's northeast rim, i.e., many of the stones, rock fragments and rock "flour" are limestones and dolomites.

Ground Water

Six small streams and the two lakes studied comprise headwaters for the Rifle River draining south into Saginaw Bay. The streams have their origin in the West Branch till plain and moraine. The lakes are spring-fed. The spring water and ground water within the area are similar in chemical content and carry large quantities of calcium and magnesium bicarbonate. The drainage system approximates 16,000 acres. Fig. 1 and Table 1 show the physical and chemical features of the area which influence the limnology of North Lake and Pintail Pond.

Fig. 1. Surface geology, physiography, and soils of the study area

Streams

A - Andrews   C - Oyster   E - Lupton   G - Au Sable
B - Mayhue   D - Vaughn   F - Gamble

Lakes

N - North   P - Pintail   R - Rifle

Glacial Deposits

Moraine   Till Plain   Outwash Plain

Soils (Transparent overlays)

Rifle Peat   Kewaunee Loam   Roselawn Sand
Lupton Peat   Porcupine Gravelly Sandy Loam   Ogemaw Sandy Loam


GOODAR
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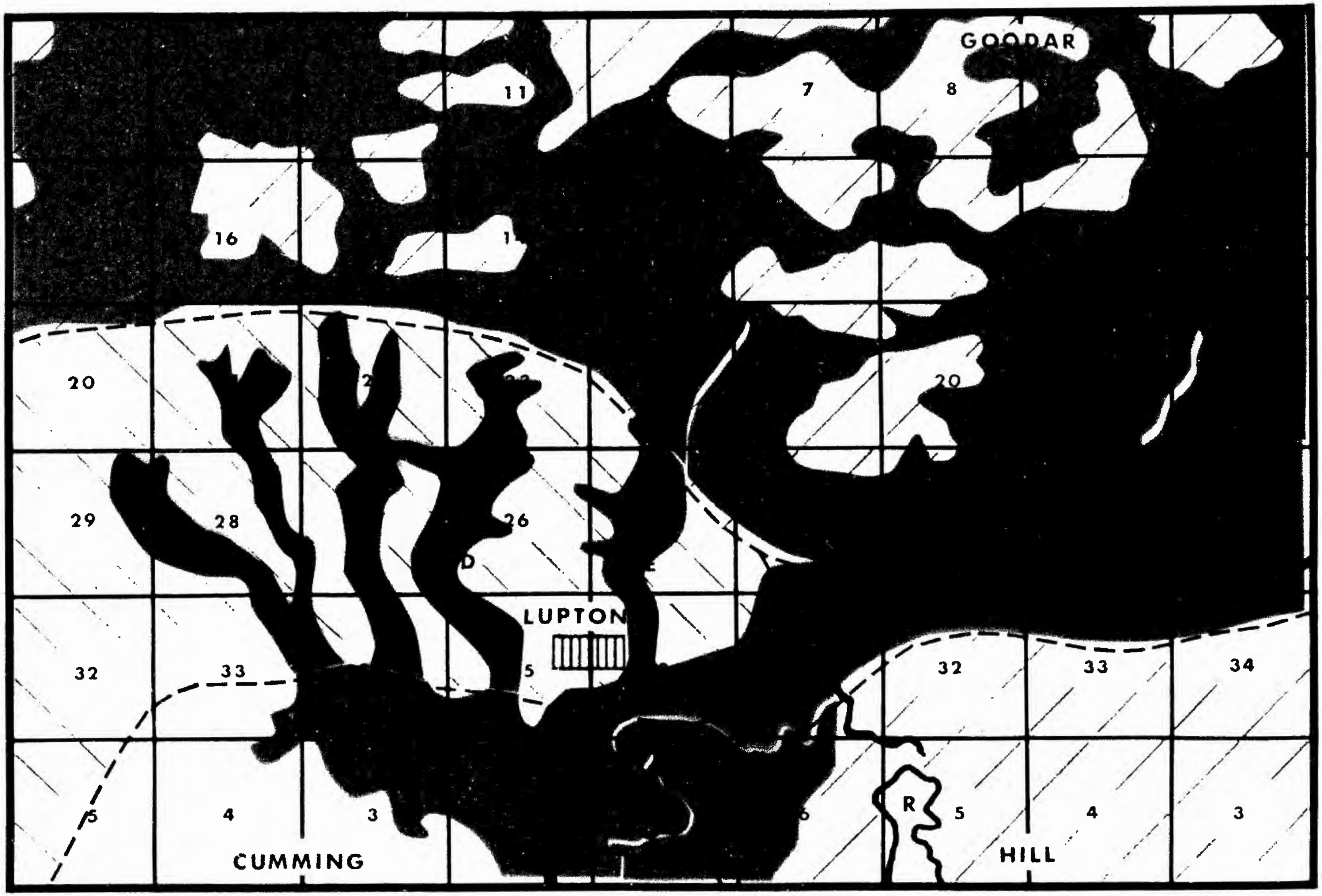
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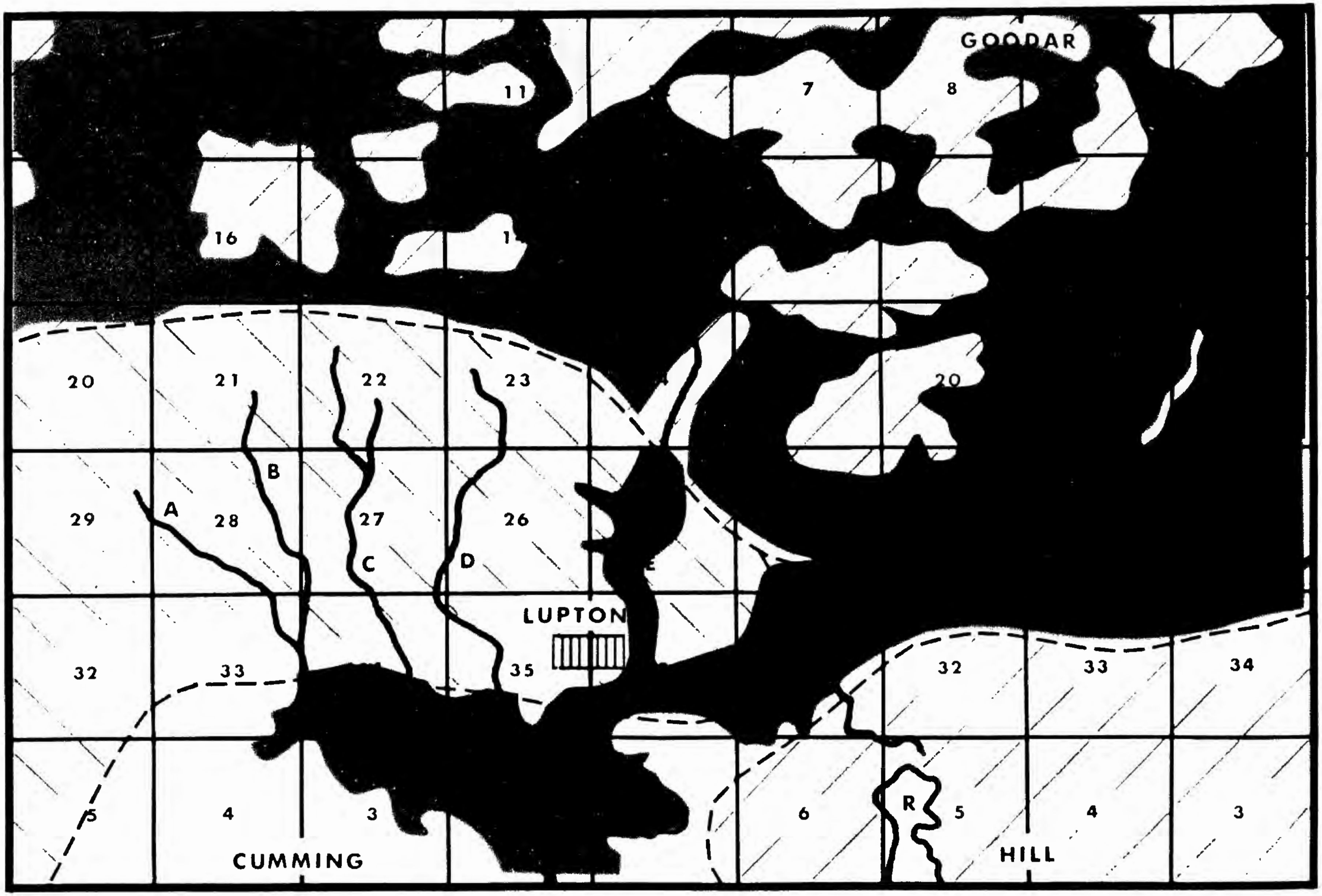

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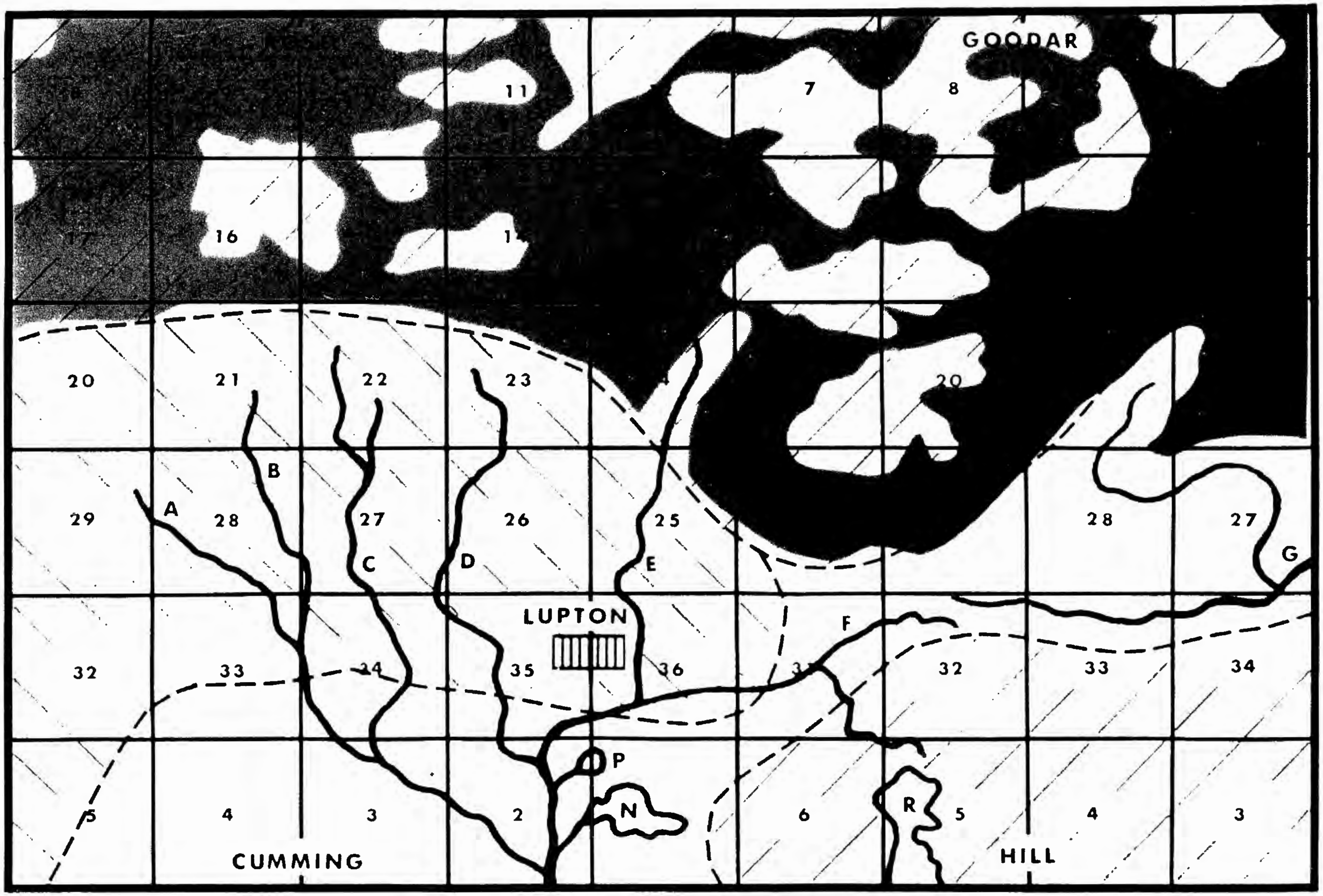
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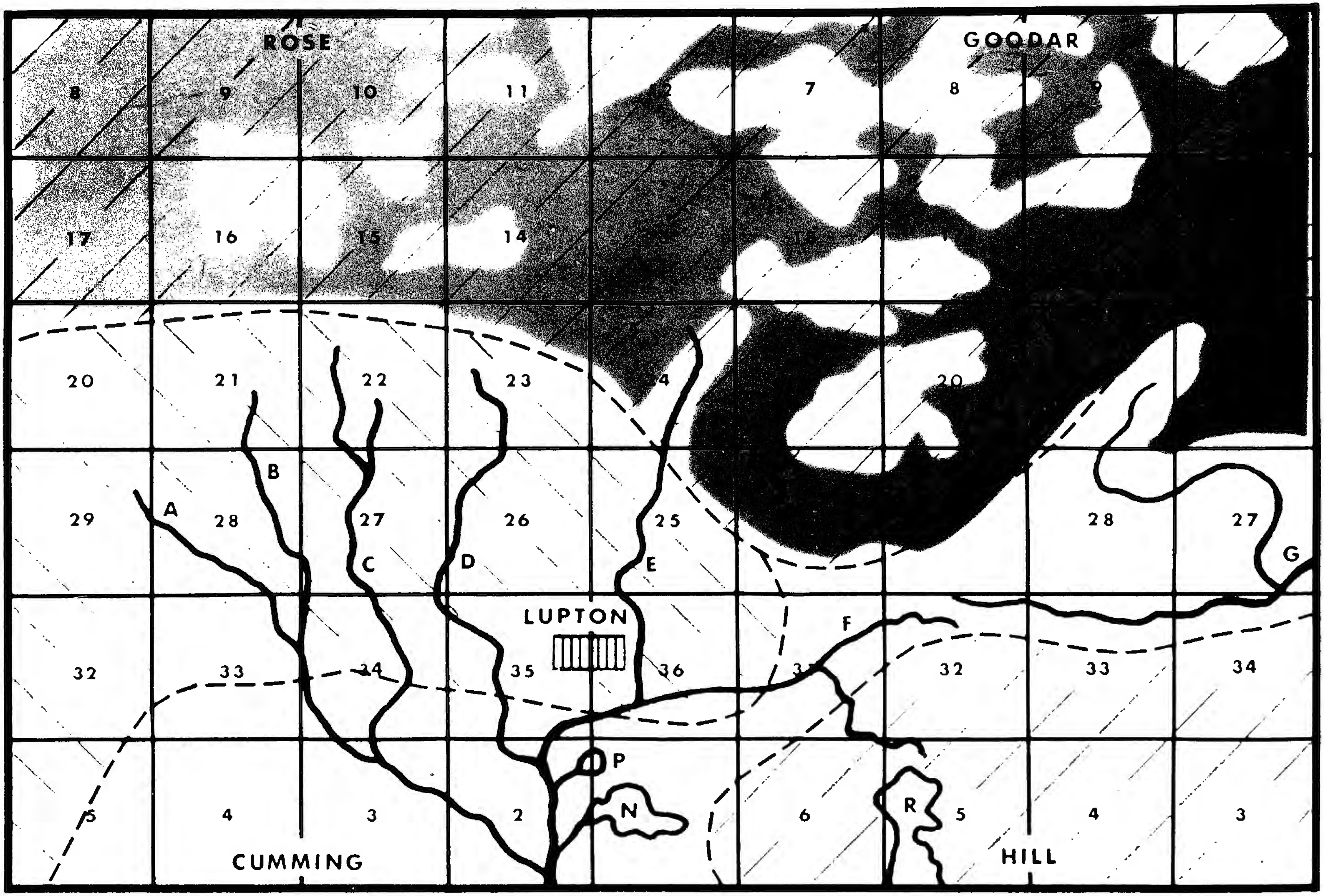
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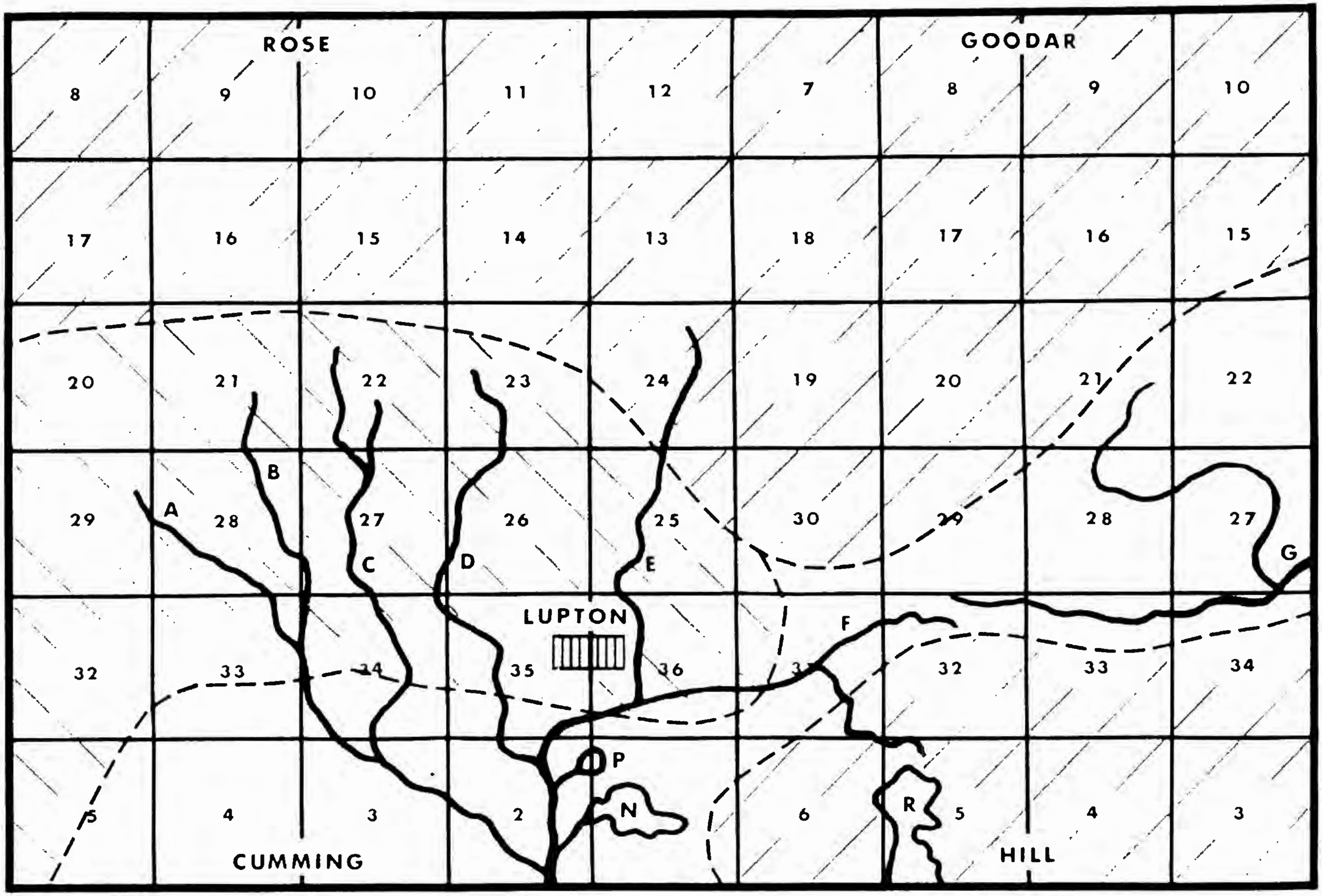
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TABLE 1.--Chemistry of Ground Water Issuing from the West Branch Moraine,[a] in Mg Liter^{-1}*

	$CaCO_3$	$MgCO_3$	Fe	Na	K	SiO_2	Cl	SO_4	Total Alk. (as $CaCO_3$)	pH
Lupton Springs	148.9	76.1	.04	1.8	-	-	3.0	13.2	222	-
Lupton Well	136.4	71.6	.3	8.9	-	-	4.0	15.2	211	-
Oyster (C)	131.8	72.2	.2	3.5	.5	8.1	0.0	16.0	198	7.9
Andrews (A)	130.6	75.4	.2	3.3	.5	8.9	0.0	17.3	218	8.1
Gamble (F)	133.1	70.9	.1	3.0	.4	8.1	0.0	16.5	200	8.0
Vaughn (D)	138.0	80.0	.05	3.5	.4	8.9	0.0	16.5	219	8.1

[a]Sampling point was near stream source.

*Analysis by courtesy of the Michigan Public Health Service.

Soils

As a rule, the productivity of a lake is related to the local soils. There are five soil types in the drainage system that affect the ground waters of the area.

Acid swamp and marsh soils (Rifle and Lupton types), with a water table 2-3 ft below the surface, have developed on the outwash plain and in the valleys of the streams crossing the till plain. .

Medium loam (Kewaunee type) is superimposed on the till plain and light loam soils (Porcupine, Ogemaw types) have developed on moraine deposits. Loam surface soils are acid and subsoils are highly alkaline. Drainage is free.

Acid sandy soils (Roselawn type) with rapid drainage have developed in pockets on the moraine.

Spring water entered the lakes from the moraine overlain by the Ogemaw Sandy Loam. Fig. 1 relates soil types to the physiography of the area.

METHODS

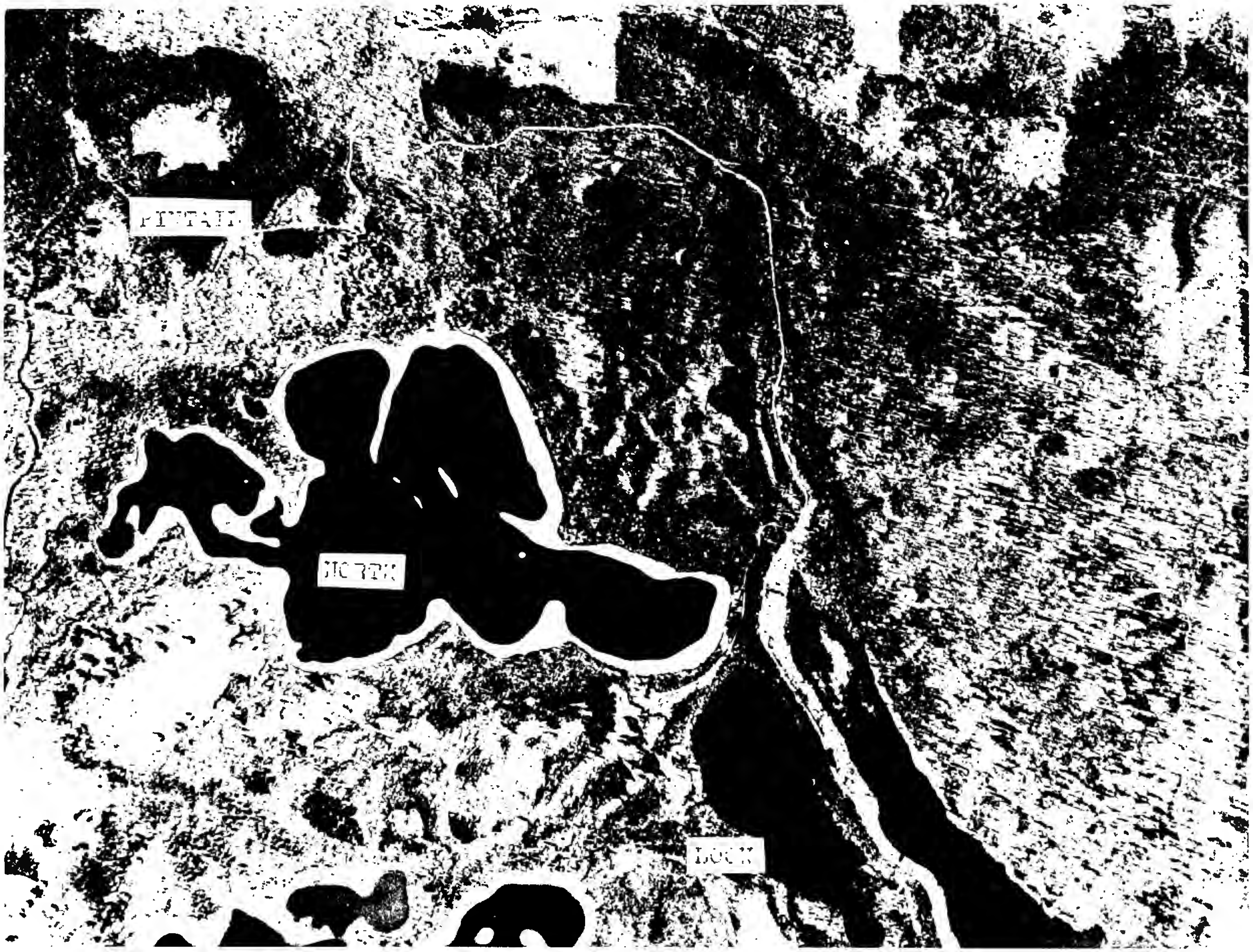
Description of Lakes

North Lake and Pintail Pond in Ogemaw County were selected for the following characteristics: (i) both lakes are of the hypermarl type having similar water and littoral zone soil characteristics, (ii) littoral zone soils of high, uniform marl content, (iii) limited public access, with motor boat control, (iv) access to springs feeding the lakes for ground water study, (v) Pintail is a small temperate, third-order marl lake, (vi) North is a temperate, second-order marl lake, and (vii) presence of marl and non-marl lakes in the same locality for comparative studies. Both lakes are spring fed; both have thick marl deposits and are filling with marl. Pintail Pond is a small body of pale blue-green water encompassing 2.26 acres in area with a maximum depth of 9 ft. North Lake is typically blue-green in color, 90.85 acres in area with a maximum depth of 54 ft. Fig. 2 shows the relative positions of the two lakes and the white marl littoral zone soils.

Chemical

The tendency of the sodium hydroxide titration method to overestimate the carbon dioxide content of water when only a few mg liter^{-1} are present has been noted by DeMartini (1938), Moore (1939), Ohle (1952), and Hutchinson (1957). Beyers and Odum (1959) titrated a hard spring water with a saturated CO_2 water and showed the pH-CO_2 relationship

Fig. 2. Aerial view of North Lake, Loon Lake and Pintail Pond.



was similar to the theoretical relationship. Moore's (1939) method of carbon dioxide calculation from the total alkalinity and pH was used in this study.

It has been shown (Moore, 1939; Hutchinson, 1957) that the phenolphalein test for alkalinity usually gives an overestimate of carbonate when small quantities are present. A nomograph based on pH and total alkalinity from Moore's (1939) equation was used in the calculation of carbonate alkalinity. Bicarbonate alkalinity was taken as the difference between the total alkalinity and carbonate alkalinity.

Total hardness, calcium, and magnesium determinations were made after the method of Betz and Noll (1950).

Total alkalinity and oxygen were determined by methods outlined in Standard Methods for the Examination of Water and Sewage (1946).

Measurements of phosphorous using a filter photometer and studies of organic and ammonia nitrogen by the Kjeldahl process were made by the methods of Ellis, Westfall and Ellis (1948).

Potassium analyses were made by a Beckman flame spectrophotometer after the method of West, Folse and Montgomery (1950).

The pH measurements were made in the field with a Hellige comparator and checked periodically by electrometric method to insure reliability.

Hydrogen sulphide was detected by the lead acetate method (modified from Rost, 1922). Commercially prepared filter papers impregnated with lead acetate are applied at the mouth of the flask. Sulphuretted hydrogen blackens the paper which is matched with color standards to give an approximation in mg liter^{-1}.

Physical

Light Penetration

Measurements of light penetration through water were made with a submersible photometer equipped with selenium cells, an opal diffusing glass, and color filters as follows: (i) Schott green filter with maximum sensitivity near 540 mμ and an effective range from about 480 mμ to 600 mμ; (ii) Schott red filter sensitive from 600 mμ to about 720 mμ; (iii) Schott blue with range of 360 mμ - 480 mμ with maximum near 430 mμ; (iv) an opal-flashed glass diffuser mounted above the filters. In optical and electrical detail, the instrument meets the specifications of the International Council for the Exploration of the Sea (Atkins _et al_., 1938).

Light measurements were made on cloudless days in an attempt to minimize variations that might otherwise affect the results of the study. Data are expressed in terms of per cent light transmission and coefficient of extinction (Ruttner, 1953).

Wind, Precipitation and Evaporation

An anemometer was used to measure miles of wind passing the instrument in a 24 hour period. Rainfall and evaporation were measured by standard U.S. Government meteorological instruments in hundreths of inches. Pan evaporation data were corrected after the method of Wüst (1936).

Temperature, Turbidity and Color

Temperatures were determined by reversing and electric-resistance thermometers. Turbidity was measured with a photoelectric colorimeter and turbidity standards (Theroux et al., 1943). Color was determined using the United States Geological Survey glass discs as outlined in Standard Methods (1946).

Biological

Plankton

Plankton samples were collected at the surface. A one-gallon water sample was reduced to 25 ml by centrifuge. Sedgewick-Rafter counts were made of larger organisms (after Welch, 1948) while smaller cells were counted after the method of Prescott (1951). Each cell of multi-celled organisms was counted separately. Since the cells in some filamentous types are not readily distinguishable, all filaments (green and blue-green) were measured and reported as microns of filaments liter^{-1} rather than by cell count. Differential counts of cells liter^{-1} were transformed to volumetric measurement. Volume plankter^{-1} measured in microns^3 liter^{-1} was obtained from counts, average measurements, and general shape, i.e., sphere, cylinder or cube (Welch, 1948).

Higher Aquatic Vegetation

Plant growth on the experimental plots was determined from random samples. A portable, numbered grid overlay was placed on the plot at the time of sampling, and a table of random numbers was used to determine the grid squares to be sampled. The samples collected from each plot and for each sampling date comprised about 21% of the entire plot. Harvest of the plants from the sample areas was accomplished with special rakes and self-contained underwater diving equipment. Standing crops were computed in terms of g ft^{-2}. Root systems were not harvested.

For all non-plot experiments it was feasible to harvest the entire crop of aquatic plants and obtain absolute measurements in g unit area^{-1}.

Bottom Fauna

The Ekman and Petersen dredges were used for separate sample series as conditions demanded. Samples were washed in the field in a 26 mesh per inch screen box and preserved. Two series of North Lake experimental plots and eleven stations in Pintail Pond were sampled. A portable grid overlay was placed over the plot and bottom fauna samples were collected by the method employed to collect plant samples.

Statistical Method

For biological populations increases in numbers are often proportional to the numbers already present, causing a change in the variance with increases in the mean level of the sample measurements. Logarithmic transformation has the effect of improving the closeness of the distribution to normality, i.e., skewness of the raw data tends to be eliminated after the transformation resulting in better statistical estimates (Bartlett, 1947). Logarithmic transformation has been applied to some of the data in this study.

LIMNOLOGICAL CHARACTERISTICS OF NORTH LAKE

Hydrography

Conditions controlling biological production may arise directly from size and form of the lake basin (Welch, 1935; Rawson, 1942). North Lake hydrographic data are indicated in Figs. 3, 4 and 5 and Table 2.

TABLE 2

Location...T.23N., R.3E., Sec's. 1,2. Ogemaw Co., Mich.
Area...90.85 acres
Maximum depth...54.0 ft.
Mean depth...19.04 ft.
Maximum effective length...3,700 ft.
Maximum effective width...2,200 ft.
Shore Development...1.7
Volume development...1.05
Slope of basin...10.51%
Slope of basin between 5 and 20 ft contours...16.45%
Volume...1,730.00 acre-ft.

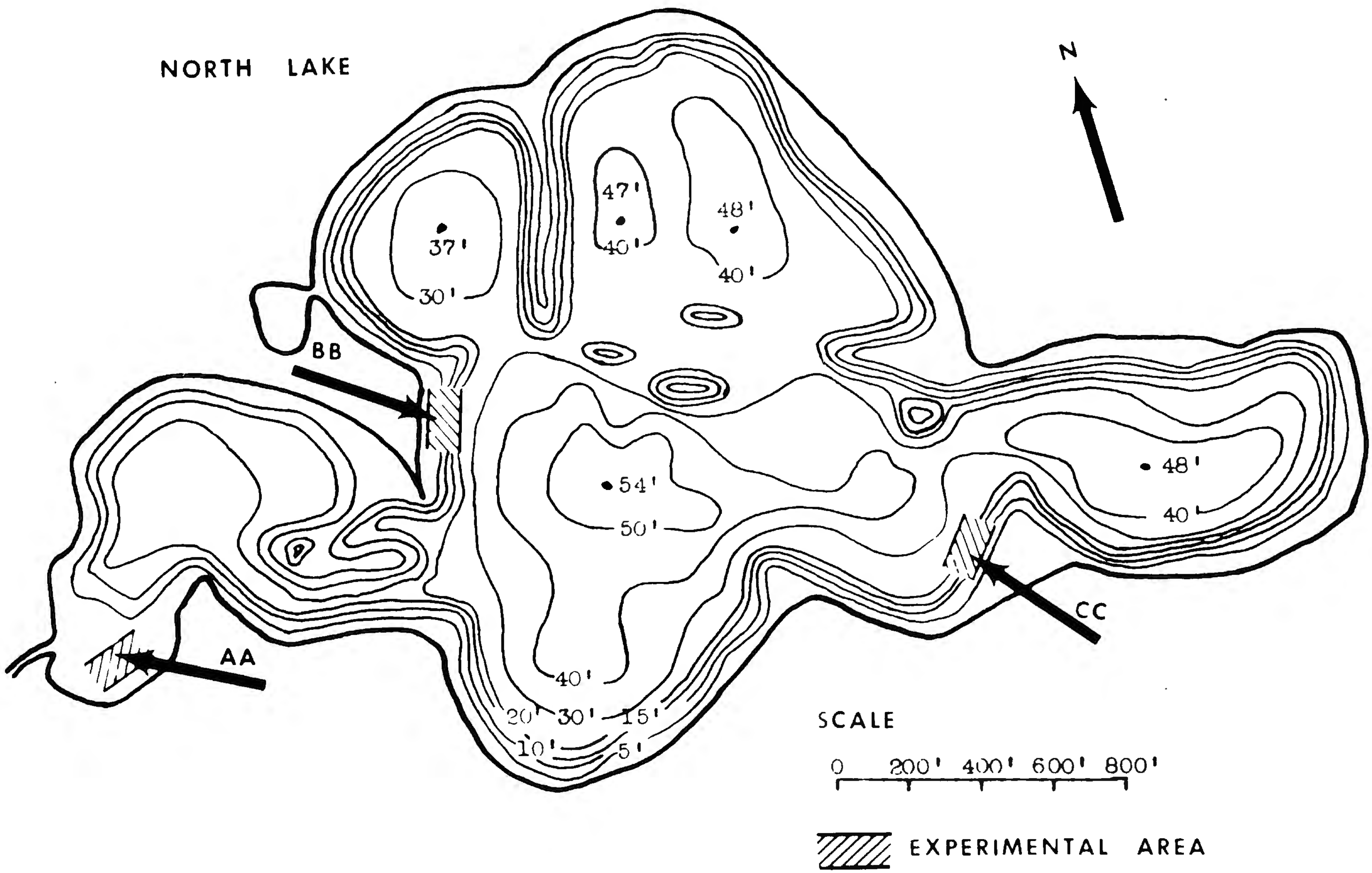
North Lake has no inflowing streams. Numerous seepage springs enter the lake near the northwest margin and deep within the main basin.

An outlet on the east end of the lake is active during the entire year. The discharge rate is about 1.8 ft^3 $second^{-1}$. Occasionally spring melt waters together with heavy rains fill the area drainage system causing the outlet to act temporarily as an inlet.

The lake has one small island, several small submerged islands, and bars all built by marl deposition (Fig. 2).

The mean slopes of the North Lake subsurface horizontal areas between the contours 5-10 ft, 10-15 ft, 15-20 ft, and 20-30 ft are abnormally steep for inland lakes.

Fig. 3. Hydrographic map of North Lake.


NORTH LAKE
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37'
30'
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40'
48'
40'
BB
54'
50'
48'
40'
40'
AA
CC
20'
30'
15'
10'
5'
SCALE
0
200'
400'
600'
800'
EXPERIMENTAL AREA

Fig. 4. Looking west over North Lake.

Fig. 5. Hooking bar built of marl.

Shore and Bottom Deposits

The outbuilt marl deposit forming the shore of North Lake varies in width from 100 - 680 ft and in depth from 1 - 50 ft. A peat overburden varies from 1 - 4 ft.

The classification of benthic regions follows that outlined by Welch (1935). In North Lake the littoral zone extends from the shore line to a depth of about 20 ft; the sublittoral, 20 - 30 ft; the profundal, 30 ft to maximum depth.

The littoral zone underlies 44.7% of the surface area. Most of the substrate in this zone is a deep bed of finely divided, amorphous, marl particles. The term "marl" as used here applies to a comparatively pure calcium carbonate with very small proportions of clay, magnesium, gypsum, and organic matter. Marl concretions are found in the shallows around the lake. Analysis of soil samples from this zone averaged 37.7% calcium.

Dredgings and core samples, taken near the lower limits of the sublittoral and within the profundal, revealed that these regions were generally covered by a thin layer of marl resting on deep beds of pulpy peat. The calcium carbonate content of bottom soils increased from lake to shore.

North Lake Physical Characteristics

Temperature

Temperature readings were made of North Lake waters for a three year period. Only minor differences between years were noted, and thus the measurement for one year will be presented here. Table 3 shows the

TABLE 3.--Thermal Conditions in North Lake. Temperatures are expressed in degrees centigrade; thickness and limits are in feet.

	Temperature		Epilimnion	Thermocline			Hypolimnion	
					Temperature			
Date	Surf	Bottom	Lower Limit	Thick-ness	Upper limit	Lower limit	Upper limit	Thick-ness
3/1/53	3.9	3.4	--	non stratified			--	--
5/9/53	16.0	6.9	5.0	7.5	13.9	8.9	12.5	41.5
6/30/53	23.0	7.4	8.0	15.0	22.8	9.1	23.0	31.0
7/13/53	25.6	7.2	10.0	15.0	22.7	9.0	25.0	29.0
8/3/53	23.6	7.0	12.5	13.5	23.1	8.4	26.0	28.0
8/11/53	22.8	6.9	14.0	12.0	22.4	8.6	26.0	28.0
8/31/53	25.3	7.3	12.0	16.0	23.1	9.6	28.0	26.0
9/15/53	17.9	7.4	19.0	9.0	17.5	9.1	28.0	26.0
10/31/53	10.9	7.4	30.0	6.0	10.4	8.4	36.0	18.0
11/11/53	7.5	7.5	--	non stratified			--	--
1/23/54	0.0	3.9	--	non stratified			--	--
2/28/54	1.0	4.0	--	non stratified			--	--

thermal conditions.

The temperatures at the upper thermocline limit were directly proportional (K = 1.3) to the prior seven-day average air temperature. The lower thermocline limit had temperatures nearly identical with the ground water temperatures in the study area.

The effect of heavy summer rainfall was to cool the epilimnion and depress its lower limit while warming the thermocline.

Conductivity

Measurements of North Lake water conductivity were made to obtain an indication of the quantity of electrolytes present. Surface waters varied from 255 to 292 x 10^{-6} mho at 25° C. Waters near the bottom in the main basin varied from 280 to 383 x 10^{-6} mho at 25° C. The data do not show the constancy of conductivity through depth and season that have been reported in other temperate, second order, marl lake studies (Raymond, 1937).

Light Penetration and Turbidity

The penetration of solar energy into the upper strata of natural waters exerts a profound influence on all biological organisms within the hydrosphere. In his study of solar penetration and photosynthetic productivity, Strickland (1958) has reviewed the light absorptive qualities of plant pigments found in marine phytoplankters. He concludes that "for all practical purposes, the only parameter that needs measured in photosynthetic studies is the total radiant energy between 3800-7200 A." Strickland's study indicates that chromatic adaptability of a mixed population of plants in an ecosystem makes the total amount of radiant energy more important than its wave lengths. Talling (1955) found little plant growth below a depth at which the intensity of radiation (400-700 mu) was less than 5 per cent of the subsurface intensity. Lenoble (1956) showed that absorption, due to dissolved salts in the ocean, was not photosynthetically significant, giving reason to doubt that the anions and cations present in fresh water marl-forming lakes are absorptive enough to limit plant growth. For the North Lake study, it was desirable to evaluate the effects of the dissolved or suspended materials in marl-forming waters on the sunlight penetrating the trophogenic zone and to determine if light was a limiting factor in plant growth in North Lake. The test was a comparison of the transmission characteristics of North Lake water and two non-marl lakes (Rifle, Loon), each supporting luxuriant growths of vegetation.

The light transmission characteristics of natural waters have been reviewed by Clarke (1939), Utterback (1941), Ruttner (1953), Edmondson (1956), Hutchinson (1957), and Strickland (1958). Light, in general, is known to diminish in intensity in its passage through water in such a way that the percentage penetration may be plotted as a straight line on semi-logarithmic paper (Clarke, 1939). Chandler (1942), Hutchinson (1957), Strickland (1958), and others have shown that certain conditions, such as differences in the amount of suspended material at various depths, may cause irregular variations in a plot of the transparency of different layers of water. In this study the percentage of surface light reaching a given depth was plotted on semi-logarithmic paper. The slope of the plotted line on such a graph is an index of the relative transparency of the water with the steeply sloping lines representing less transparent water. Irregularities in the graphs may be attributed to suspended material at various depths.

Light Penetration into Marl and Non-marl Lakes

The percentage transmission of surface incident light of different wave lengths through North Lake water has been graphed as Fig. 6. Rifle Lake light transmission characteristics are presented in Fig. 7. Under mean wind conditions, the light transmission characteristics of the two lakes seem to follow the same basic pattern. Principal differences are quantitative, not qualitative (Table 4). For corresponding depths in the two lakes, North Lake receives more light of all the wave lengths measured, with few exceptions. More light in the green and red portion of the spectrum penetrates the 0-2 ft stratum of water in Rifle Lake.

The penetration of total light into Rifle and Loon Lakes (non-marl forming) and North Lake (marl-forming), is shown in Fig. 8 and Table 5. North Lake receives a considerably greater percentage of surface incident light at all levels tested.

Light extinction coefficients for the three lakes on several sampling dates are listed in Table 6. Loon Lake had the greatest extinction coefficient (54.2). Its light extinction coefficient within weed beds for the same date was 49.0. North Lake exhibits the greatest range of extinction coefficients (40.0 - 48.3). Rifle Lake extinction coefficients lie within the North Lake range.

Fluctuations in Light Penetration with Wind

The variation and greater range of extinction coefficients in North Lake may be explained in part as the result of wind conditions (Table 6). On occasions, sudden increases in turbidities were observed with stronger than usual winds. Strong continuous winds produce waves that pound the marl terrace loosening the marl particles which are then

Fig. 6. Percentage transmission of surface incident light of different wave lengths through North Lake. (Sept. 13, 1953; Secchi disc 7'1").

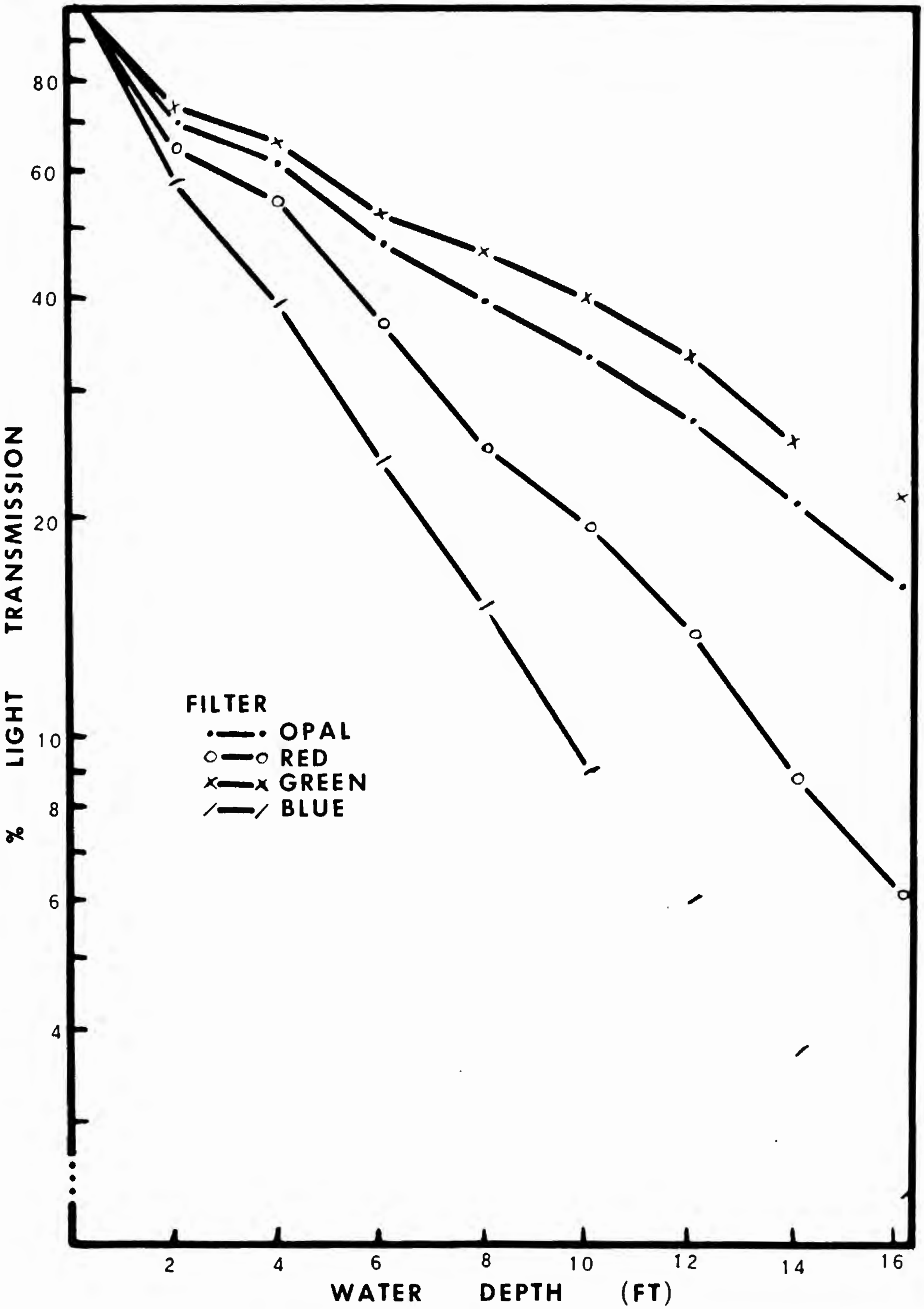

% LIGHT TRANSMISSION
80
60
40
20
10
8
6
4
WATER DEPTH (FT)
2
4
6
8
10
12
14
16
FILTER
OPAL
RED
GREEN
BLUE

Fig. 7. Percentage transmission of surface incident light of different wave lengths through Rifle Lake. (Sept. 12, 1953; Secchi disc 8'2").

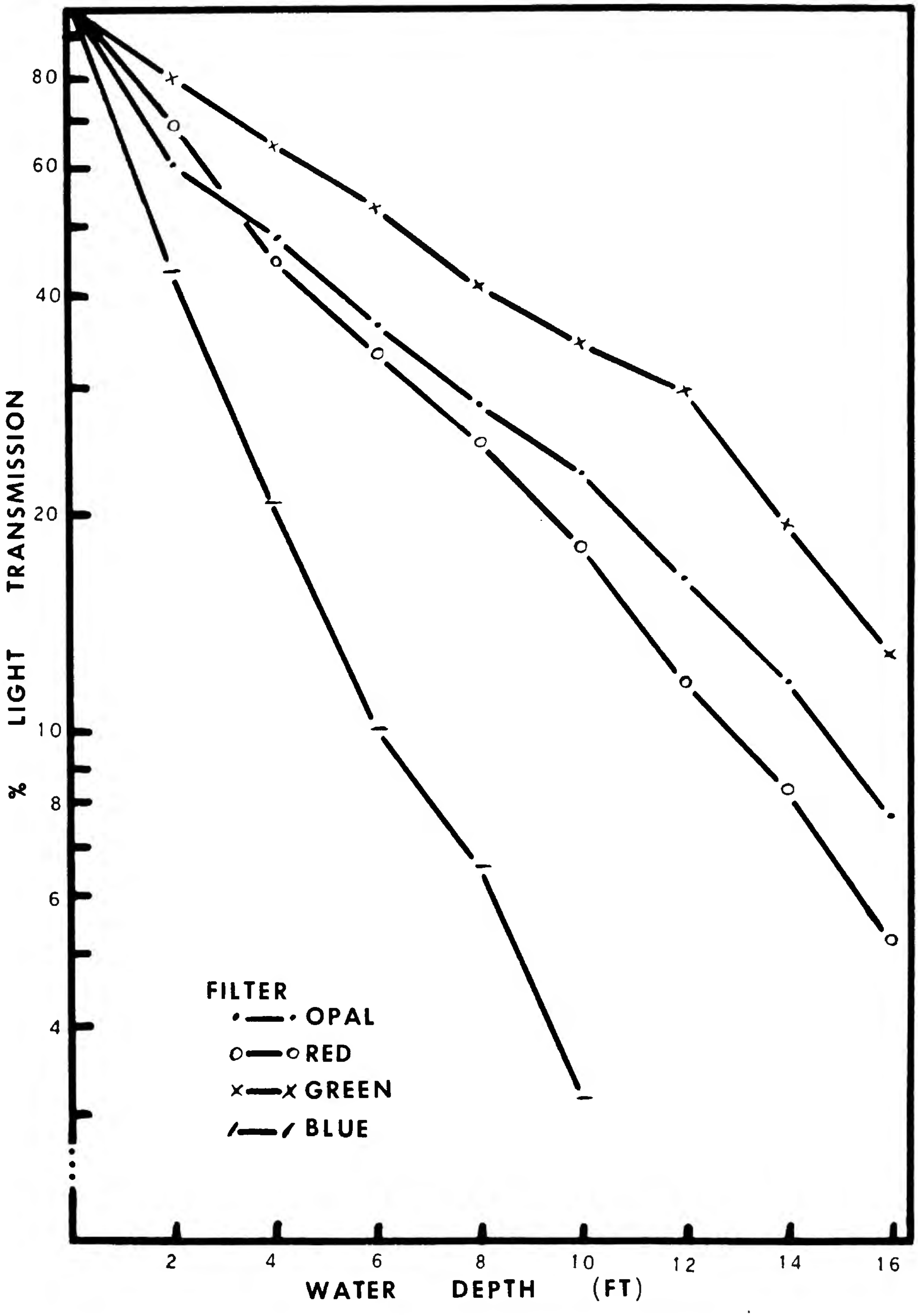

80
60
40
20
10
8
6
4
% LIGHT TRANSMISSION
2
4
6
8
10
12
14
16
WATER DEPTH (FT)
FILTER
OPAL
RED
GREEN
BLUE

TABLE 4.--Percentage transmission of light of different wave lengths through North and Rifle Lakes

Depth (ft)	North Lake (Sept. 13, 1953)				Rifle Lake (Sept. 12, 1953)			
	O[a]	G	R	B	O	G	R	B
2	69.8	72.0	62.9	57.1	59.6	78.2	67.9	42.8
4	60.3	64.2	53.1	38.3	47.8	63.1	44.0	20.6
6	46.3	50.8	36.1	23.4	36.0	51.8	32.9	9.0
8	38.5	44.8	24.6	14.9	28.0	40.4	24.8	6.3
10	32.3	39.0	19.1	8.7	22.7	33.9	17.8	3.1*
12	26.3	32.3	13.4	5.8*	16.0	29.0	11.9	1.5*
14	20.1	24.9	8.5	3.6*	11.4	18.8	8.2	.8*
16	15.5	20.5*	5.9*	2.3*	8.2	12.3	5.1*	.4*
	(Secchi disc 7'1")				(Secchi disc 8'2")			

[a]O = opal, G = green, R = red, B = blue filters.

*Probable values based on extension of transmission curve. Percentage of light transmitted in one meter of water is termed the <u>transmission coefficient</u> (Ruttner, 1953).

Fig. 8. Comparison of light penetration in North, Rifle and Loon Lakes. Measurements obtained for North, Sept. 9, Loon and Rifle, Aug. 25, 1953 using the opal diffusing filter.

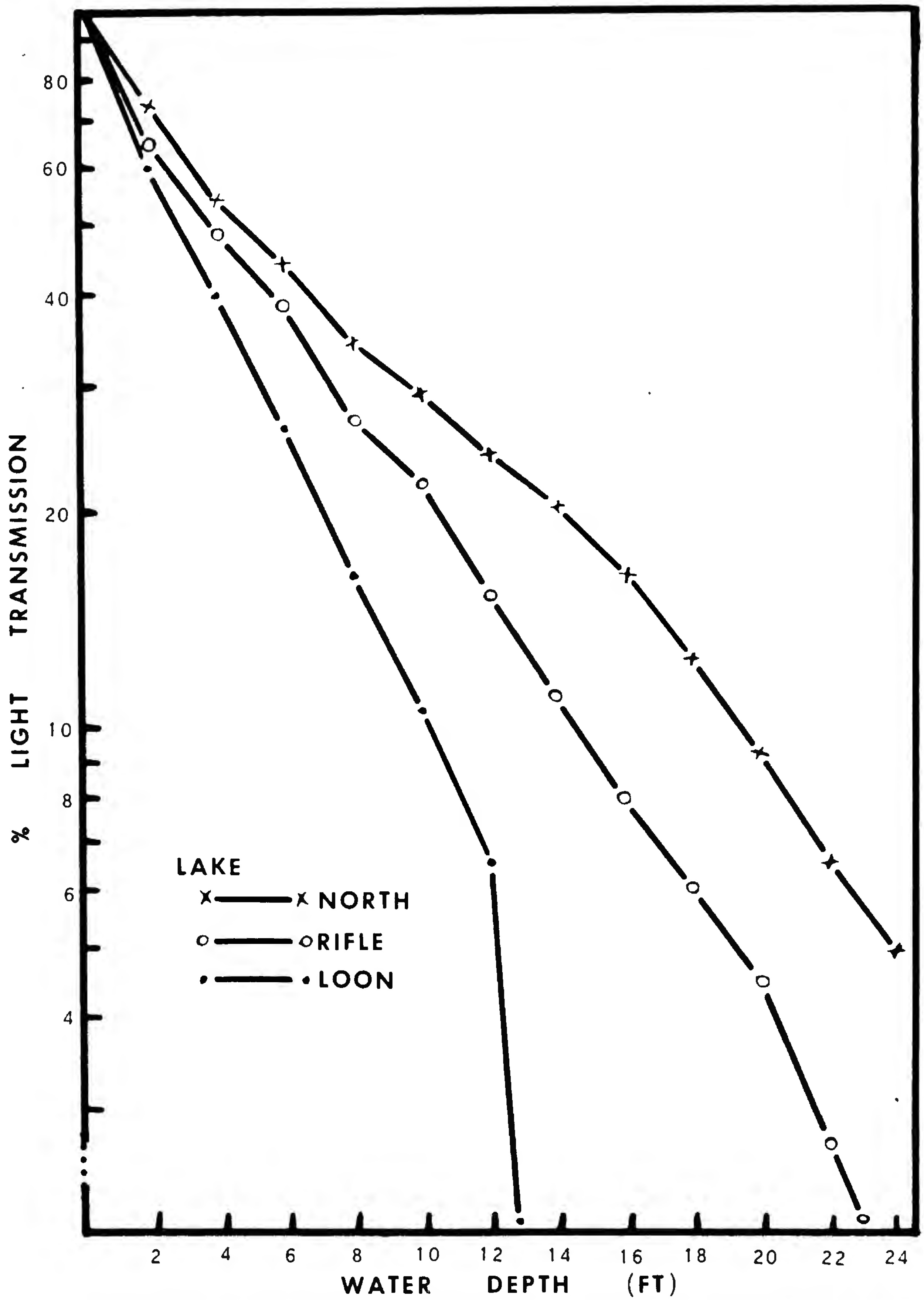

80
60
40
20
10
8
6
4
% LIGHT TRANSMISSION
LAKE
NORTH
RIFLE
LOON
2
4
6
8
10
12
14
16
18
20
22
24
WATER DEPTH (FT)

TABLE 5.--Percentage transmission of light (Opal diffusing filter) through Loon, Rifle and North Lakes

Depth (ft)	Loon (Aug. 25)	Rifle (Aug. 25)	North (Sept. 9)
2	59.8	63.5	71.9
4	39.3	47.5	53.0
6	25.9	38.4	43.8
8	16.1	26.5	33.3
10	10.6	21.8	28.9
12	6.3	15.0	23.6
14	-	-	20.1
16	0.0	8.0	16.0
18	-	-	12.2
20	-	4.4	9.0
22	-	2.6	5.8
24	-	1.4	4.5
26	-	.9	3.7
28	-	.6	2.7
30	-	.4	2.0

TABLE 6.--Wind[a] and light extinction coefficients (k) in three lakes

Date (1953)	North		Rifle		Loon	
	wind	k	wind	k	wind	k
July 12			49	43.0		
Aug. 9			39	45.2		
Aug. 13			99	44.2		
Aug. 23	60	46.2				
Aug. 24	68	46.0				
Aug. 25			33	47.2	33	54.2
Aug. 31	78	48.2				
Sept. 3	92	48.3				
Sept. 9	48	40.7				
Sept. 12			35	48.1		
Sept. 13	37	40.0				

[a]Miles of wind as measured by an anemometer for the three day period before light measurements were taken.

(k) per cent of light held back in one meter of water.

swept outward into the lake by the returning undercurrents. On a specific occasion (Sept. 20, 1954) when winds were twice those normally observed, the limit of visibility (determined by Secchi disc) was reduced to three feet near the wave swept shore and gradually increased to eight feet near the center of the lake. Fig. 9 is a diagram in which light extinction coefficients are plotted against the summation of three days' wind prior to taking light measurements. The three-day wind summation was used because observations had shown that this length of time is required for the flocculant marl particles to settle and lake water to clear. The winds, for the period of study, ranged from 60 - 150% of a three-year mean.

Paired observations of wind and light penetration into North Lake Fig. 9A show a highly significant correlation coefficient (+ .93). High winds result in large light extinction coefficients.

The Rifle Lake data show no association between wind and light extinction coefficient (Fig. 9B). Lack of correlation is attributed to the presence of dense aquatic vegetation within Rifle Lake. This contention is based on a study of light measurements made inside and outside of Loon Lake vegetation beds. The measurements showed that the Loon Lake vegetation reduced the extinction coefficient by 5.2 - 9.6%. Plants noticeably stabilized the substrate and slowed down detritus laden currents, causing some of the material to settle to the bottom.

Variations in wind affect the North Lake light transmission characteristics quantitatively and qualitatively. Figs. 10A and B illustrate these differences in light transmission characteristics. A smaller percentage of incident light of all wave lengths penetrated North Lake waters when winds for a preceding three-day period were

Fig. 9. Light extinction coefficients and wind. Wind units are in anemometer miles for three days prior to sampling date.

A. North Lake light extinction coefficient-wind correlation diagram

B. Rifle Lake light extinction coefficient-wind correlation diagram

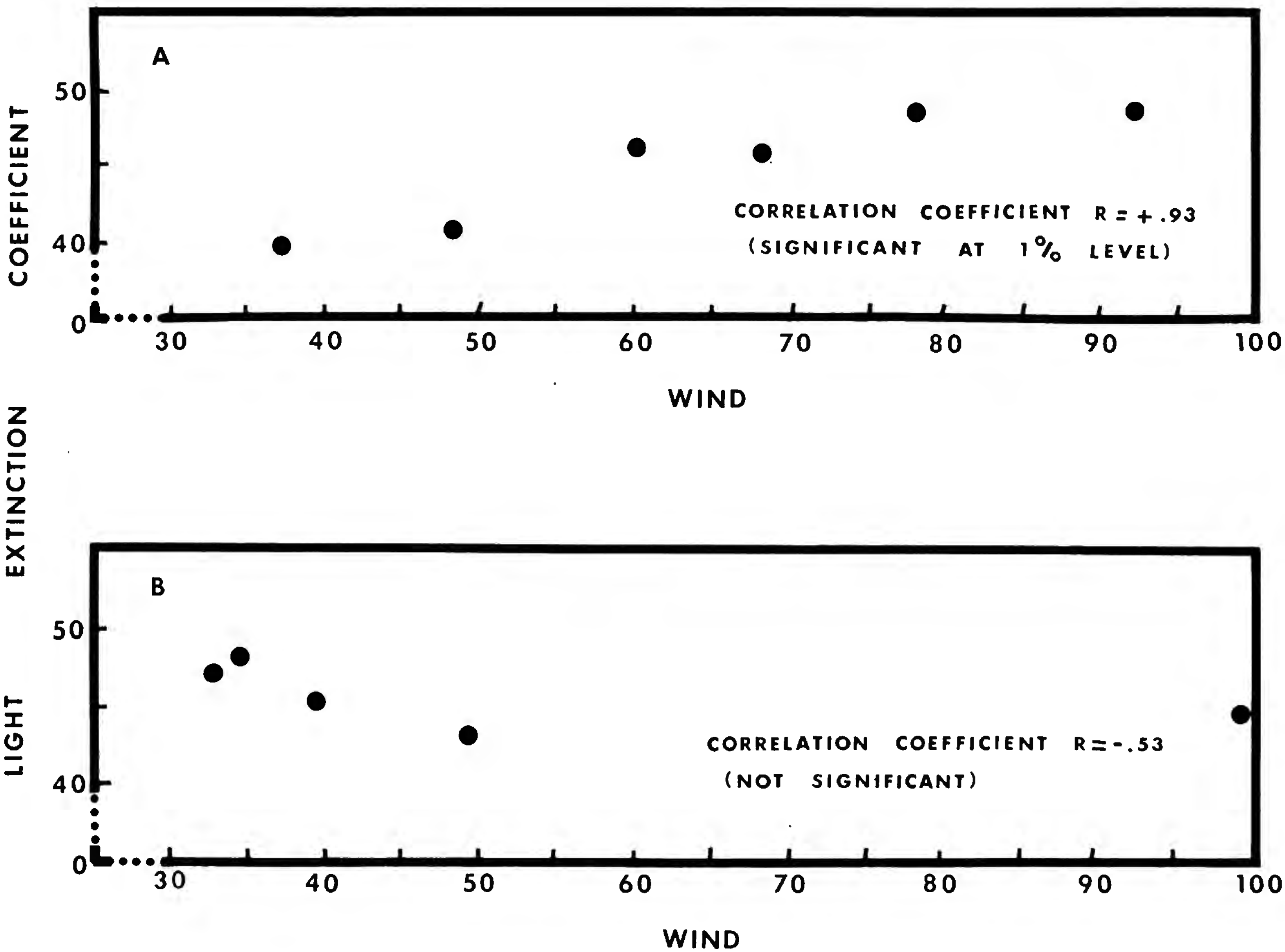
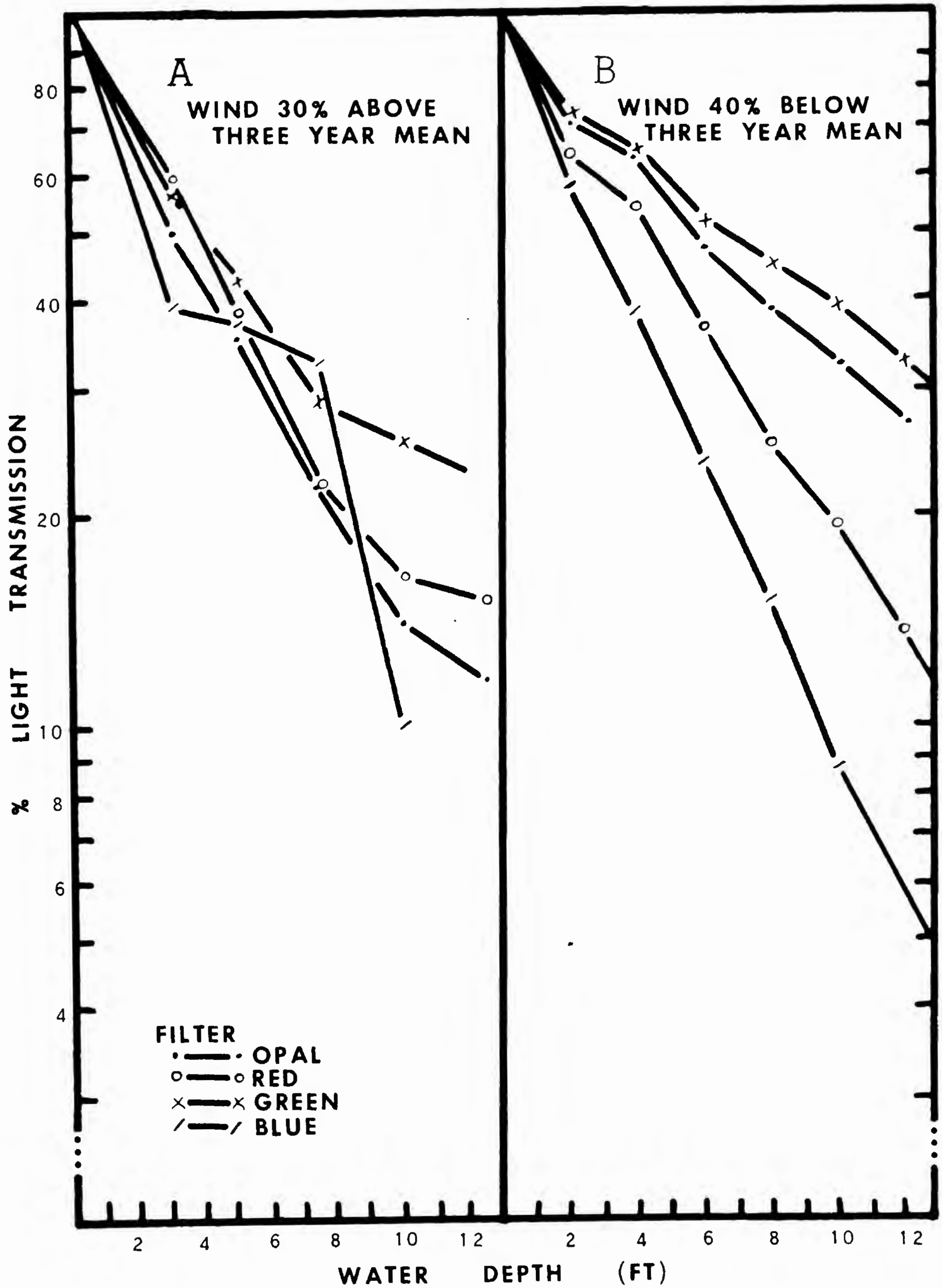

LIGHT EXTINCTION COEFFICIENT
A
50
40
0
30
40
50
60
70
80
90
100
WIND
CORRELATION COEFFICIENT R = + .93
(SIGNIFICANT AT 1% LEVEL)
B
50
40
0
30
40
50
60
70
80
90
100
WIND
CORRELATION COEFFICIENT R = -.53
(NOT SIGNIFICANT)

Fig. 10. Change in transmission of light through North Lake water with wind.

A. Transmission of light of different wave lengths through North Lake when winds are abnormally high. (Secchi disc 6', Aug. 31, 1953).

B. Transmission of light of different wave lengths through North Lake when winds are abnormally low. (Secchi disc 7'1", Sept. 13, 1953).


A
WIND 30% ABOVE THREE YEAR MEAN
B
WIND 40% BELOW THREE YEAR MEAN
% LIGHT TRANSMISSION
80
60
40
20
10
8
6
4
FILTER
OPAL
RED
GREEN
BLUE
2
4
6
8
10
12
WATER DEPTH (FT)

abnormally high, i.e., the total light penetration was one-half as great at the thirteen foot level. As the light penetration decreased during windy periods, changes in the spectral quality were noted, i.e., light values in the blue and red regions of the spectrum in the upper water strata were greater. The surface loss of the impinging light for the two series of light measurements when winds were above and below average was 12.5% and 10.4% respectively.

Ruttner (1953), in summarizing the work of others, shows the compensation point to vary from 0.4 - 1.5% of surface light intensity. Clark (1954) reports that plants grow at depths at which the light intensity is greater than .3% of the surface value, and Talling (1955) states that about 5% of the subsurface light intensity is needed. More light of all wave lengths penetrates North Lake water at corresponding depths than other lakes producing luxuriant growths of hydrophytes. Winds reduce the penetration of sunlight into North Lake, but seldom enough to limit photosynthetic activity.

North Lake Chemical Characteristics

This study reports: (i) the seasonal and vertical chemical differences in a Michigan temperate, second-order lake actively precipitating marl, (ii) an estimate of the productivity of a marl lake, and (iii) the relationship of the marl precipitate to the basin morphology. The association of steep basin slopes and marl deposits in other lakes has been noted by Hale (1903), Wohlschlag (1950), and Ruttner (1953).

Tests on North Lake water were made of the pH, alkalinity, calcium hardness, magnesium hardness, hydrogen sulphide, oxygen and carbon dioxide. Water samples were collected from March 3, 1953 to

February 28, 1954. Sampling was biweekly during summer stagnation and monthly when the lake was not stratified. During summer stagnation, tests were made on water from the surface, upper and lower thermocline, and the 45 ft depths. During periods of homothermy and winter stagnation, water was analyzed from the surface, 25, and 45 ft depths.

The chemical data of North Lake water are presented in the figures of the text as averages for the epilimnion, thermocline, and hypolimnion. When the lake was not thermally stratified, averages are presented for an upper stratum of 0 - 12 ft, a middle stratum of 12 - 37 ft, and a lower stratum of 37 - 50 ft. Graphs of these averages show the main chemical differences in the water strata. Specific chemical data are shown in Appendix I.

Temperature measurements characteristic of the North Lake water throughout the year are shown in Table 3.

Chemical data helpful in characterizing North Lake are presented in Table 7. The March analyses show conditions in North Lake when waters are homothermal at the beginning of vernal circulation, and the August analyses are indicative of conditions from May to November when the lake is thermally stratified. Mid-November samples show chemical conditions in North Lake when the water became homothermal again in the fall and circulation began. The conditions during winter stagnation are shown by a January water analysis.

Alkalinity

Alkalinity is a measure of the compounds in water causing the pH to shift toward the alkaline side of neutrality. The formation of the marl deposits and consequently the productivity of North Lake are

TABLE 7.--Selected Chemical Analysis of North Lake Water Showing Chemical Change Throughout One Year

Depth	C°	pH	O_2	CO_2	CO_3	HCO_3	Ca	Mg	Non-Carb. Hardness
			- - - Spring Circulation (3/1/53) - - -						
0	3.9	8.0	11.0	2.7	1.6	141.6	99.4	62.1	18.3
15	4.0	8.0	9.7	2.8	1.7	150.3	100.5	62.1	10.6
25	3.9	8.0	8.7	2.9	1.8	158.3	102.9	62.1	5.1
45	3.8	7.8	7.5	5.5	1.2	173.8	111.7	69.6	6.3
			- - - Mid Summer Stagnation (8/31/53) - - -						
0	25.3	8.4	8.9	0.0	4.5	160.7	83.8	83.3	1.8
13*	23.0	8.4	8.9	0.0	4.6	164.2	87.4	85.0	3.6
28*	9.7	7.7	3.2	7.2	0.0	187.2	103.9	88.7	5.1
45	7.3	7.3	0.0	20.2	0.0	208.1	116.5	90.5	-
			- - - Fall Circulation (11/11/53) - - -						
0	7.5	8.0	9.5	3.2	2.0	180.0	112.0	75.0	5.0
25	7.5	8.0	9.6	3.3	2.0	180.7	108.2	75.2	.7
45	7.5	7.9	9.2	4.4	0.0	183.8	110.2	75.0	1.4
			- - - Mid Winter Stagnation (1/28/54) - - -						
0	0.0	8.2	13.1	0.0	3.3	182.2	121.7	79.9	16.1
25	3.0	8.1	11.4	2.0	2.6	180.5	119.1	77.1	13.1
45	3.9	7.8	6.4	5.9	0.0	191.8	121.5	79.3	8.9

*Limits of thermocline

determined by the kind and quantity of alkalinity in the water. North Lake is therefore classified an alkalitrophic lake.

The annual average alkalinity of North Lake upper waters was 165.3 mg liter^{-1} and for water near the bottom, 187.5 mg liter^{-1}. This is high for Michigan Lakes. A mean of 132 mg liter^{-1} has been reported (Hooper, 1956) for 241 lakes surveyed by the Michigan Institute of Fisheries Research.

The alkalinity of North Lake water is the result of carbonates and bicarbonates. Hydroxide was not found. Table 8 and Fig. 11 show the vertical and seasonal variations in the carbonates and bicarbonates for the period March through February.

Bicarbonate

The bicarbonate of North Lake waters increased with depth. Even during homothermy the tendency to stratify vertically persisted (Table 7, Nov.). Bicarbonate was low throughout the lake from March through June. The minimum occurred in the surface waters in March.

Within the epilimnion, bicarbonates remained low through September and then increased toward the end of summer stagnation. A maximum was reached during winter stagnation.

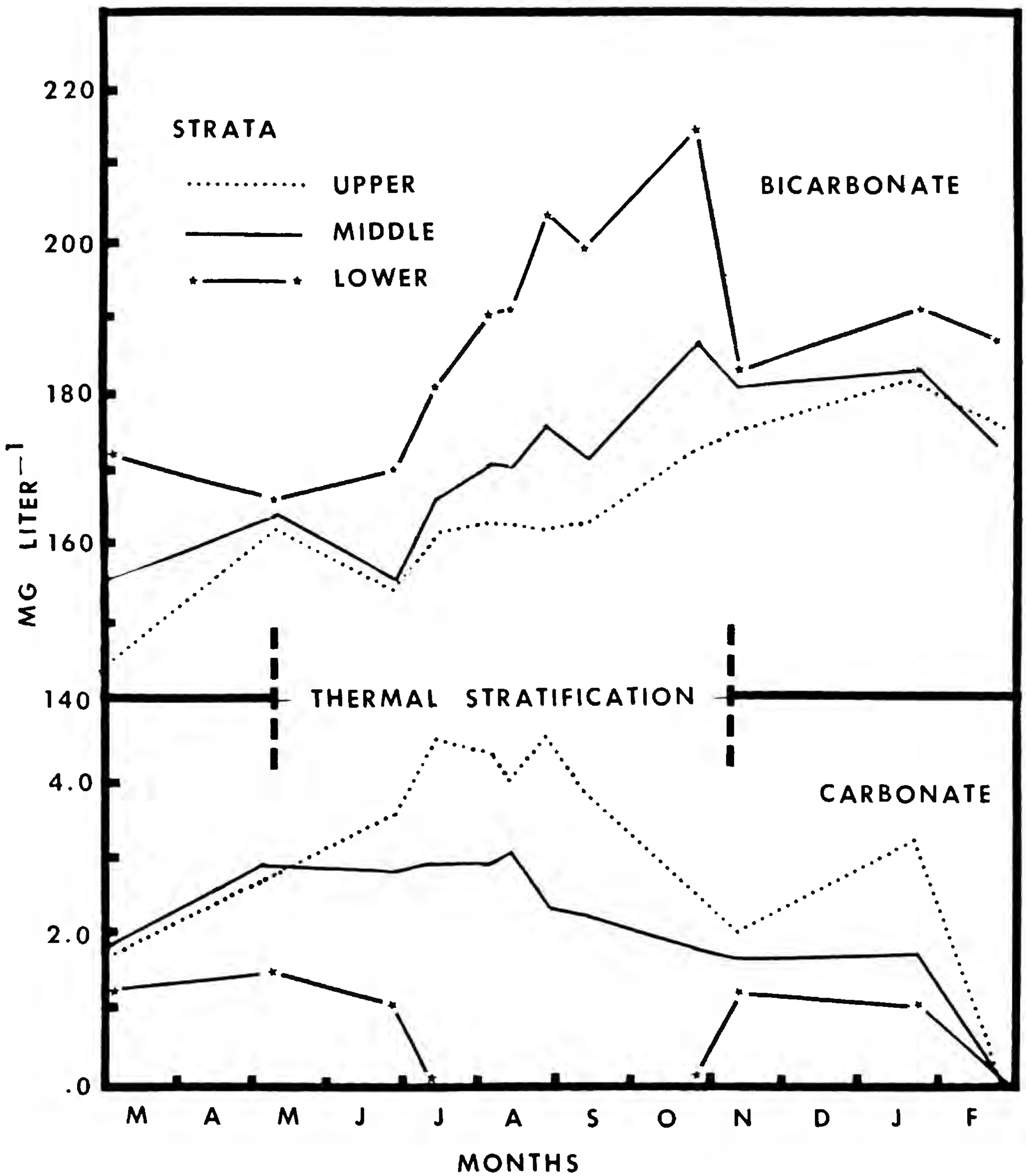
Bicarbonates of the thermocline and hypolimnion increased after June, reaching a maximum at fall turn-over. Some of this increase may be attributed to the transformation of carbonates settling from above, but since the quantities of carbonate present in the upper waters are not commensurate with the increases in the bicarbonate observed for deeper waters, other explanations are needed. Large increases in calcium and aggressive carbon dioxide in these strata for the corresponding period indicate that most of the increased bicarbonate

TABLE 8.--Bicarbonate and Carbonate Alkalinity in North Lake Water

Date	Depth (ft)	CO_3	HCO_3	Date	Depth (ft)	CO_3	HCO_3	Date	Depth (ft)	CO_3	HCO_3
3/1/53	S	1.6	141.0	8/3	S	4.6	162.4	10/31	S	3.0	169.1
	15	1.7	150.3		13	3.7	164.8		25	2.4	168.1
	25	1.8	158.3		25	2.0	176.3		30	1.8	177.0
	45	.6	187.0		45	0.0	193.8		36	.8	186.2
									45	0.0	218.9
5/9	S	2.9	162.1	8/11	S	4.5	159.9	11/11	S	2.0	180.0
	6	2.9	164.3		14	3.3	165.9		25	2.0	180.7
	13	2.9	164.4		25	2.8	174.5		45	0.0	183.8
	25	3.0	165.0		45	0.0	194.4				
	45	0.0	167.9								
6/30	S	3.5	156.6	8/31	S	4.5	160.7	1/28/54	S	3.3	182.2
	8	3.3	147.7		13	4.6	164.2		25	2.6	180.5
	23	2.0	163.0		28	0.0	187.5		45	0.0	191.8
	45	0.0	174.7		45	0.0	208.1				
7/13	S	4.5	161.7	9/15	S	3.7	161.2	2/28	S	0.0	158.2
	10	4.4	160.5		20	3.8	164.8		25	0.0	172.4
	25	0.0	172.5		28	0.0	188.3		45	0.0	187.5
	45	0.0	183.6		45	0.0	209.3				

CO_3 and HCO_3 expressed as mg $liter^{-1}$

Fig. 11. Bicarbonate and carbonate alkalinity of North Lake water. Average values for three strata are shown: (i) the epilimnion, thermocline and hypolimnion during thermal stratification and (ii) an upper stratum of 0 - 12 ft; a middle stratum of 12 - 37 ft; a lower stratum of 37 - 50 ft when the lake was not stratified.



STRATA
UPPER
MIDDLE
LOWER
BICARBONATE
CARBONATE
THERMAL STRATIFICATION
MG LITER⁻¹
220
200
180
160
140
4.0
2.0
.0
M A M J J A S O N D J F
MONTHS

resulted as benthic deposits of $CaCO_3$ were transformed to soluble alkalinity. As further evidence of this, dredgings from the deepest basin during this period were mainly pulpy peat and contained little marl.

The fall circulation caused decreases in the bicarbonate of the deeper waters as they were mixed and brought upward. Decreases occurred at all depths in the lake from mid-winter stagnation to spring homothermy. Bicarbonate of the upper, middle, and lower water fluctuated between 141 mg liter^{-1} in March to 182 mg liter^{-1} in January; 158 mg liter^{-1} in June to 190 mg liter^{-1} in October; 168 mg liter^{-1} in May to 219 mg liter^{-1} in October, respectively. The greatest fluctuations took place in the lower levels.

Carbonate

Variations in carbonate of the water with respect to depth and season provide a basis for conclusions regarding marl formation in North Lake. In general, the vertical distribution of carbonate is inversely related to depth.

Fluctuations in the carbonate of the epilimnion are directly related to changes in water temperatures. Highest concentrations of carbonate were associated with temperatures considered by Meyers *et al*. (1952) to be optima for plants. In general, carbonates increased from March to August, became highest in June and August, then decreased until the fall circulation period.

The carbonate in the upper waters of the thermocline varied greatly and were inversely related to those in the lower portion of the thermocline. Ruttner (1953) and others theorize that some carbonate settles into deeper waters. The relationship reported here would be expected if most of the carbonate in the lake originated in the warm upper waters and settled into deeper waters from above. In general, the carbonate of deeper water decreased from the early part of stratification to the latter part of the period.

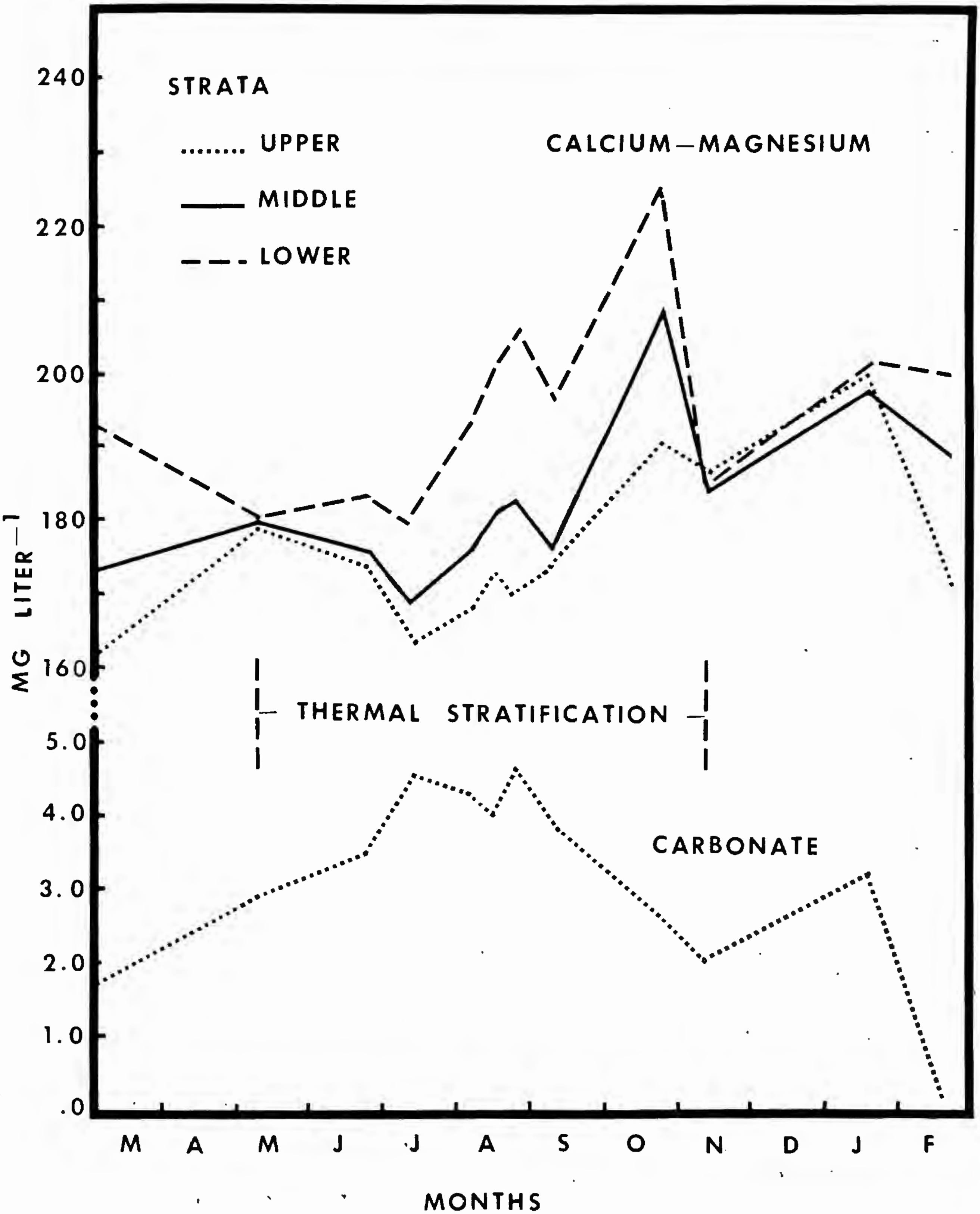
The upper portion of the hypolimnion contained carbonates throughout most of the year; lower hypolimnion waters were void of carbonate except during the spring circulation period.

The annual minimum for the lake (0.0 mg liter^{-1}) occurred late in the winter stagnation period; the maximum (4.6 mg liter^{-1}) occurred in August.

Hardness

The ions responsible for hardness in natural water are calcium, magnesium, iron, and aluminum. Iron and aluminum were not expected in the alkaline waters of North Lake and an analysis of the marl deposits indicates little enters the lake. Most of the hardness is calcium-magnesium bicarbonate and carbonate. In the epilimnion, increases in the carbonate are correlated statistically ($r = -.903$, May 5-Oct. 31) with losses of calcium and magnesium. The calcium and magnesium in the thermocline and hypolimnion also vary with changes of the carbonate in the epilimnion (Fig. 12). When water temperatures cool below optimum for photosynthesis and the lake is not thermally stratified, the relationship between quantities of carbonate and calcium-magnesium in the upper waters is direct, i.e., increases or decreases in the one are associated with increases or decreases in the other. Epilimnial carbonate and calcium-magnesium hardness of intermediate and deeper waters show a similar but less specific relationship.

Fig. 12. Relationship between carbonate in the upper water and calcium-magnesium throughout North Lake. Average values for three strata are shown: (i) the epilimnion, thermocline and hypolimnion during thermal stratification and (ii) an upper stratum of 0 - 12 ft; a middle stratum of 12 - 37 ft; a lower stratum of 37 - 50 ft when the lake was not stratified.


STRATA
UPPER
MIDDLE
LOWER
CALCIUM—MAGNESIUM
240
220
200
180
160
5.0
4.0
3.0
2.0
1.0
.0
MG LITER⁻¹
THERMAL STRATIFICATION
CARBONATE
M A M J J A S O N D J F
MONTHS

About 15 mg liter^{-1} monocarbonate hardness (SO_4) in the water of North Lake declined during summer stagnation, at fall turn-over and late in the period of winter stagnation.

Calcium

Seasonal and vertical variations in the hardness of North Lake water essentially reflect the fluctuations in calcium. About 60% of the total hardness is due to calcium hardness.

Calcium maxima in the thermocline and hypolimnion (50-53 mg liter^{-1}) were reached just before fall turn-over. The calcium maximum of the upper water (49 mg liter^{-1}) was reached during winter under the ice.

Calcium minima of 35-37 mg liter^{-1} were reached mid-point of summer stagnation in the epilimnion and thermocline. Hypolimnial calcium minimum of 45 mg liter^{-1} was reached early in the summer stagnation period.

North Lake surface waters contain more calcium than would be expected in an equilibrium with CO_2 of the atmosphere. Calcium supersaturation in North Lake waters was least (4.50 mg liter^{-1}) in March and greatest (17.3 mg liter^{-1}) in the early stages of summer stagnation. The average supersaturation in North Lake waters for the year was 12.2 mg liter^{-1}. Ohle (1952) also noted calcium supersaturation (about 10 mg liter^{-1}) in the hard water of lakes of northern Germany and concluded that the excess was colloidal calcium carbonate.

Seasonal fluctuations of calcium at all depths were considerable. The fluctuations in calcium of the water of the epilimnion were correlated ($r = -.846$, May 9-Oct. 31) with the carbonate present. The carbonate varied directly with the water temperature. The increase in the calcium in the thermocline and hypolimnial waters late in the summer stagnation period is correlated with a corresponding increase of aggressive carbon dioxide, indicating that calcium carbonate (marl) substrate was transformed into soluble calcium bicarbonate. Decreases in North Lake calcium associated with fall circulation are the result of calcium carbonate and calcium sulfate precipitation.

Calcium losses within North Lake based on flow rates, evaporation, and chemical differences between inlet and outlet waters ranged from 4.1 mg hr^{-1} $meter^{-2}$ when ice covered, to 19.2 mg hr^{-1} $meter^{-2}$ during summer. Enrichment of the calcium content of North Lake water as a result of evaporation averaged 9.5 mg hr^{-1} surface $meter^{-2}$ for ice free periods and doubled on hot windy days in July and August.

The seasonal effect of precipitation, transformation, and evaporation on the total calcium in North Lake is shown in Table 9. The three major periods of calcium loss were: (i) mid-point in the period of summer stagnation in association with high temperatures and increased photosynthetic activity of plants, (ii) fall circulation when the CO_2 of deeper waters was lost as they circulated upward, and (iii) toward the end of the winter stagnation period.

Magnesium

About 40% of the total hardness of North Lake water is magnesium hardness. Magnesium maxima occurred about mid-point of summer stagnation; the minima, early in the same period. Magnesium of the North Lake waters showed little seasonal variation. Both calcium and magnesium increased with depth; magnesium-calcium ratio decreased with depth.

TABLE 9.--Seasonal Fluctuations in the Calcium of the Water of North Lake Computed on an Areal Basis (1953-54)

Date	Calcium (mg cm^{-2})	Date	Calcium (mg cm^{-2})
3/1	66.18	8/31	61.86
5/9	66.84	9/15	63.69
6/30	69.12	10/31	76.53
7/13	63.82	11/11	66.89
8/3	64.58	1/31	73.50
8/11	68.97	2/28	69.44

Dissolved Gases

Carbon Dioxide-Oxygen

The carbon dioxide-oxygen-temperature relationships in the water of North Lake are indicated in Table 7. Surface waters are usually oxygen saturated and carbon dioxide deficient. From mid-June to mid-August, the oxygen curve in North Lake was positive heterograde. In the hypolimnion the relationship between carbon dioxide and oxygen was inverse, showing the gradients to be of biogenic origin.

Carbon Dioxide and pH

Table 7 shows the distribution of free CO_2 in North Lake by depth and season. The epilimnion was devoid of CO_2 from late June to mid-September; a maximum of 26 mg $liter^{-1}$ occurred in the hypolimnion in mid-September.

Vertical and seasonal variations in the pH of North Lake may be attributed to variations in carbon dioxide. The accumulation of carbon dioxide in the hypolimnion of North Lake from the decomposition of organic matter brought a lowering of the pH to 7.2 near the mud-water interface during August. Lowering of the pH below 7.2 was prevented by the geochemical solution of the North Lake marl substrate which further buffered the waters. Maximum pH readings of 8.4 were made at the surface during the period July-August.

Carbon Dioxide Deficiency, Marl Precipitation, and Basin Physiography

Ruttner (1953) uses a graphical method for estimating the attached CO_2 (CO_2 of equilibrium) for specific bicarbonate concentrations which he then substracts from the free CO_2 to obtain aggressive CO_2. Unless the quantities of CO_2 are sufficient to be aggressive, a deficiency exists, marl is formed and alkalitrophic characteristics develop. The carbon dioxide deficiencies and subsequent marl deposition in North Lake occurred: (i) in the upper waters through the year, (ii) in the thermocline for most of the stratification period and in the middle strata for a time after fall turn-over, and (iii) in the hypolimnion as it formed in the spring of the year and the lower waters in early winter.

In the presence of a carbon dioxide deficiency one would expect calcium carbonate to precipitate from the waters in relationship to the quantities present (Table 10). Thus the data indicate the deposition from upper waters of North Lake was 1.2 times greater than that from middle waters. Deposition from these two strata was 10.5 times greater than from lower waters.

The unusual physiography of the North Lake basin (Fig. 3) is attributed to the vertical differences in carbon dioxide deficiency which cause vertical differences in carbonate deposition. Most marl is

TABLE 10.--Vertical and Seasonal Distribution of CO_3 and Aggressive CO_2 Calculated on an Areal Basis in North Lake (1953-1954)

Date	Epilimnion[a] Limits (ft)	Epilimnion[a] mg cm^{-2} CO_3	Epilimnion[a] mg cm^{-2} CO_2	Thermocline[b] Limits (ft)	Thermocline[b] mg cm^{-2} CO_3	Thermocline[b] mg cm^{-2} CO_2	Hypolimnion[c] Limits (ft)	Hypolimnion[c] mg cm^{-2} CO_3	Hypolimnion[c] mg cm^{-2} CO_2
3/1	0-12	.586	-	12-37	1.143	.305	37-50	1.198	.903
5/9	0-5	.441	-	5-13	.652	-	13-50	2.052	-
6/30	0-8	.854	-	8-23	1.279	-	23-50	.984	1.246
7/13	0-10	1.373	-	10-25	1.325	-	25-50	.000	6.969
8/11	0-14	1.665	-	14-26	1.098	-	26-50	.876	5.585
9/15	0-20	2.196	-	20-28	.512	.003	28-50	.134	9.354
10/31	0-30	2.194	-	30-36	.256	.883	36-50	.258	5.087
11/11	0-12	.732	-	12-37	1.447	-	37-50	.079	.417
1/31	0-12	1.135	-	12-37	1.905	-	37-50	.118	-
2/28	0-12	.000	-	12-37	.000	2.759	37-50	.000	4.653

When lake not thermally stratified:

[a]Stratum of 0-12 ft
[b]Stratum of 12-37 ft
[c]Stratum of 37-50 ft

Lake stratified May 9-November 11, 1953.

deposited in the shallow water above the lower limit of the epilimnion. This limit lies between 10-20 ft for most of the stagnation period, moving to 30 ft toward the end of the period. Less deposition occurs in the thermocline having a lower limit of 13-28 ft, but near the end of stagnation, it moves to the 36 ft level. The terrace of marl (Fig. 3) in North Lake thus develops outward from the shore, filling the lake and creating abnormally steep slopes in the basin to the 30 ft level (Table 11).

Table 11 shows one exception, i.e., the per cent mean slope for the area between the shore line and the 5 ft contour. This gradual slope (shore - 5 ft) is maintained by the erosive action of waves and ice. The marl material eroded here by waves and shore currents is carried and then deposited to form the "hooks", bars, and submerged islands found within the lake (Figs. 2, 4 and 5). Marl materials from this zone also contributed significantly to shore building. Wind driven ice during spring thaws gouges the substrate and pushes considerable quantities of marl up the gradual slope onto the shore (Fig. 13). The lake becomes smaller as this marl is permanently stabilized by plants.

Fig. 13. Shaping of the terrace and shore building by wind driven ice.

View 1. Wind driven lake ice (upper right) gouging the marl substrate from the shallows and piling up on shore.

View 2. Wind driven ice melting away leaving an encroaching marl ridge deposit. Marl ridges are stabilized by the cinquefoil Potentilla fruticosa.

TABLE 11.--Mean Slope of North Lake Substrate between Depth Contours

Depth Contour (ft)	% Mean Slope
Shore--5	8.78
5--10	22.66
10--15	18.66
15--20	15.50
20--30	12.26
30--40	8.81
40--50	7.70

Mean slopes calculated after the method of Welch, 1948.

Hydrogen Sulfide

About .13% of the North Lake marl substrate is sulfate. The main source of sulfate in North Lake is the drainage basin since the quantity of sulfur contained in protoplasm is ordinarily too small to cause significant enrichment of the waters through the processes of decomposition alone. According to Ruttner (1953), the bacteria (*Microspora*, *Desulfovibrio*) reduce sulfate to sulfide in the presence of organic matter.

Hydrogen sulfide was produced in the marl muds of North Lake in sufficient quantity to be of significant ecological importance. Although hydrogen sulfide was detectable by odor in the marl muds taken from all depths, it was first detected chemically in the water near the substrate in the hypolimnion when the dissolved oxygen disappeared late in August. By late October, the hydrogen sulfide concentrations in the thermocline and hypolimnion varied from trace-2.5 mg liter^{-1} and test animals lowered into the toxic water were killed. Doudoroff *et al*. (1950) concluded that hydrogen sulfide can be toxic to some freshwater fish in concentrations well below 1 mg liter^{-1}. The emanation of hydrogen sulfide from the marl substrate was undoubtedly injurious to macrohydrophytes since Meyers et al. (1952) report 1 mg $liter^{-1}$ for 1 hour is injurious to most species of green plants.

Losses of calcium and non-carbonate hardness (SO_4) from the water of North Lake substantiate the belief that calcium sulfate formed and precipitated. With the elimination of the thermal barrier, circulating oxygen-saturated surface waters were mixed with waters containing the hydrogen sulfide. Ruttner (1953) and Zobell (1946) indicate that the oxidation of hydrogen sulfide proceeds in two steps as follows:

(i) $2H_2S + O_2 \longrightarrow 2H_2O + S_2$ + 122 calories

(ii) $2S + 3O_2 + 2H_2O \longrightarrow 2H_2SO_4$ + 282 calories

The sulfuric acid (ii) would be transitory in presence of the calcium bicarbonate of North Lake water, and calcium sulfate would be expected to form as follows:

(iii) $H_2SO_4 + Ca(HCO_3)_2 \longrightarrow CaSO_4 + 2H_2O + 2CO_2$

Oxygen Depletion

The oxygen depletion in the hypolimnion of a biochemically stratified lake may be indicative of the lake productivity (Rawson, 1942; Ruttner, 1953; Hutchinson, 1957). The extent of oxidation in the hypolimnion is largely dependent upon the amount of oxidizable substances present and these originate in the trophogenic zone. Lakes producing an abundance of organic matter have larger amounts of oxidizable substances and greater oxygen deficiencies in the hypolimnion. Consequently, an estimation of the production within the trophogenic zone can be determined from the decomposition within the tropholytic zone, providing the organic production and decomposition within the two zones are about equal.

North Lake organic production is considered about equal to decomposition. Peat accumulates very slowly only in the deeper basins and small quantities of allogenic detritus enter the lake basin via the inlet during heavy spring rains. The relatively pure calcium carbonate substrate indicates that little autogenic detritus accumulates.

Phytoplankton growing within the photosynthetic zone assimilates carbon dioxide in volume about equal to the volume of oxygen discharged (Sargent and Hindman, 1943). For every 22.4 cm^3 of oxygen discharged into the water by photosynthesis, about 12 mg of carbon are fixed. The fixed carbon includes the small quantity simultaneously lost by respiration (Harvey, 1955). Similarly then, one would expect the release of 12 mg of carbon as carbon dioxide to require the extraction of 8.7 mg (32/44x12) of oxygen from the water.

The oxygen of the North Lake hypolimnion was depleted .065 mg $cm^{-2}day^{-1}$, a rate only slightly more than half that reported for Lake Mendota by Hutchinson (1957). Following Mortimer's (1941) classification, the daily oxygen losses place North Lake at the lower limit of the eutrophic category. North Lake oxygen depletion rates are given in Table 12.

If the assumption is made that these decreases in oxygen result from oxidation of organic matter produced in North Lake, the productivity of the trophogenic zone is about .517 kg carbon surface $hectare^{-1}day^{-1}$. Based on the period of thermal stratification, the production of North Lake in terms of fixed carbon was estimated to be 90.92 kg $hectare^{-1}$. Using Fleming's (1940) conversion from carbon to dry organic matter: (i) the North Lake productivity was 1.17 kg dry organic matter $hectare^{-1}$

TABLE 12.--O_2 Depletion, Depletion Rates, Deficits and Deficit Development Rates in the North Lake Hypolimnion

Between Dates (1953)	O_2 depleted ($mg\ cm^{-2}$)	Rate O_2 depleted ($mg\ cm^{-2} day^{-1}$)	O_2 deficit ($mg\ cm^{-2}$)	O_2 deficit development rate ($mg\ cm^{-2} day^{-1}$)
5/9	.000	.000	.000	.000
5/9 to 7/13	9.158	.141	5.092	--
7/13 to 8/3	.777	.037	5.548	.022
8/3 to 8/11	.438	.055	5.986	.055
8/11 to 9/15	.954	.027	6.298	.008
9/15 to 10/31	.140	.003	--	--
Average				
7/13 to 9/15	--	--	5.731	.028
5/9 to 10/31	11.467	.065	--	--

day^{-1} and (ii) the North Lake production was 206.39 kg dry organic matter hectare^{-1}.

Hypolimnetic oxygen deficits

Rawson (1942) used actual deficits and found them related to productivity. Hutchinson (1957) states, "The relative deficit, expressed per unit of the hypolimnion surface, between vernal circulation and the height of summer stratification, or better still the relative areal deficit acquired during this period per unit time, appears to give, in holomictic lakes between 20 and 75 m deep, a fair indication of the biological productivity of a lake." He further points to "a very striking proportionality between the hypolimnetic areal deficit and the mean organic seston per unit area" for the several lakes studied.

North Lake hypolimnetic areal relative oxygen deficits for the summer stagnation period averaged 5.7 mg cm^{-2}, a value much less than that given for Lake Mendota, Green Lake or Fureso by Hutchinson (1957). The rates of deficit development for North Lake may be seen in Table 12. The most rapid rate of oxygen deficit development occurred early in August.

North Lake Organic Seston

Theoretically, large hypolimnetic oxygen deficits are expected in lakes having a high productivity. A plot of the data for several lakes shows that the hypolimnetic oxygen deficit is directly proportional to the organic seston ($k = 4.82$). Thus it is feasible to estimate the quantity of organic seston in North Lake from the calculated hypolimnetic areal oxygen deficit. Table 13 shows the relationships and an estimate of organic seston in North Lake.

TABLE 13.--A Comparison of Organic Seston and Areal Relative Hypolimnetic Oxygen Deficit in Five Lakes*

Lake	Areal O_2 Deficit [mg cm^{-2} (Y)]	Organic Seston [mg cm^{-2} (X)]	Lake Type
Green	13.8	2.77	Eutrophic
Mendota	10.9	2.40	Eutrophic
Fureso	8.0	1.55	Eutrophic
North	5.5	1.14**	Eutrophic (Alkalitrophic)
Black Oak	4.3	0.93	Oligotrophic

*Data for Green Lake, Lake Mendota, Fureso and Black Oak Lake modified after Hutchinson (1957).

**Estimate of North Lake organic seston.

North Lake Biota

Vegetation of the Marl Flats

The marl flats around the lake are thinly covered with peat. The predominating trees of the flats are *Thuja occidentalis* and *Betula sp*. The dominant shrubby plants near shore are *Myrica Gale var. subglabra* (Myricaceae) and *Alnus incana* (Betulaceae). Probably the most conspicuous shrub around the lake and one often growing above marl deposits is the Cinquefoil *Potentilla fruticosa* with its characteristic yellow flowers and compound leaves of five leaflets.

Macrohydrophytes

North Lake does not support an abundant growth of aquatic vegetation. Seven plant families and eleven species were found on the marl terrace and lake bottom. All plants were coated heavily with calcium carbonate with the deposits being of three types: (i) an intimate incrustation firmly attached to plant parts produced in situ, (ii) a looser, more porous layer resulting from physiological action of the periphyton, and (iii) flocculant marl particles transported by water currents and deposited on plant parts where they become lodged.

Plant growth in North Lake was compared with plant growth in Loon Lake. Loon Lake supports an abundant flora on its rich organic substrate.

Potamogeton pectinatus, although the most common plant in North Lake, was very sparsely distributed over the marl "bench", the submerged islands and peninsulas, in water from 1 - 6 ft in depth. Their identity as plants, in some cases, was scarcely distinguishable because of the thick calcium carbonate incrustations. Potamogeton gramineus was rare in North Lake and dwarfed in contrast to those growing in nearby Loon Lake. The Loon Lake plants were twice as heavy bearing mature spikes 16 days earlier than North Lake plants. Potamogeton illinoensis was found in the bay of North Lake on marl substrates containing more organic matter. Najas flexilis, found abundantly in the bay but sparsely throughout the remainder of the lake, was coarse in appearance, closely tufted, growing about 5 inches in height, and producing few fruits. By contrast, Loon Lake plants grew taller and bore abundant fruits which matured nearly a month sooner than those of North Lake.

Chara did not thrive in the hard, marl-forming waters of North Lake. Chara vulgaris grew sparsely around most of the shore, only occurring abundantly around submerged branches in shallow water. Most of the plants were about one inch in height and grew in water 6 inches in depth. Chara grew much better on the organic matter added to the North Lake substratum. Calcium carbonate incrustations on all plants were heavy. Loon Lake plants of the same species grew to 5 inches in height and were not as heavily incrusted with calcium carbonate.

Myriophyllum exalbescans, found in the bay near the outlet, fruited 2 weeks later and were smaller than Loon Lake plants.

Vallisneria americana grew in small clumps near the outlet of North Lake where the marl was mixed with organic matter. Fruits developed by September 20.

Small plants of Sagittaria latifolia were found growing within the outlet in rich organic substrate.

Several patches of Nuphar advena were located within the shallow bay near the outlet. This plant did not occur at any other place in the lake.

Scirpus validus and Scirpus acutus grew on the beaches and in the water to a depth of 6 inches. These plants are reported to thrive on marl substrates, yet the distribution in North Lake was limited.

The North Lake Plankton

An extensive study of the North Lake plankton was not undertaken. Table 14 lists the organisms found in the samples collected.

Flora of the Marl Concretions

Marl concretions of calcium carbonate from pea to baseball size litter the marl terrace and shoals of North Lake. Cross sectional inspection of the concretions revealed a structure of concentric layers. The outer greenish layer contained several species of algae which were microscopically examined after small portions of the inhabited layer were placed in a .2 normal sulfuric acid bath to remove adherent calcium carbonate. The algae inhabiting the concretions with a notation of prominence are listed in Table 15. Eyster (1958) suggests that concretion formation in Bass Lake may be attributed to the extreme phosphate deficiency.

TABLE 14.--North Lake Plankton

- Protozoa
  - Sarcodina
    - *Difflugia sp.*
    - *Amoeba sp.*
  - Mastigophora
    - *Trachelomonas sp.*
    - *Dinobryon sertularia*
    - *Dinobryon calciformis*
    - *Ceratium hirundinella*
    - *Glenodinium armatum*
- Rotatoria
    - *Polyarthra trigla*
    - *Monostyla lunaris*
    - *Keratella cochlearis*
- Arthropoda
  - Crustacea
    - *Bosmina obtusirostris*
    - *Cyclops sp.* (nauplius)
- Cyanophyta
  - Myxophyceae
    - *Schizothrix sp.*
    - *Oscillatoria sp.*
    - *Anabaena sp.*
    - *Chroococcus limneticus*
    - *Chroococcus dispersus*
- Chlorophyta
  - Chlorophyceae
    - *Spirogyra micropunctata*
    - *Spirogyra sp.*
    - *Mougeotia sp.*
    - *Zygnema sp.*
    - *Oedogonium sp.*
    - *Cosmarium sp.*
    - *Scenedesmus bijuga*
    - *Arthrodesmus sp.*
- Bacillariophyceae
    - *Cymbella turgida*
    - *Cyclotella sp.*
    - *Fragillaria crotonensis*
    - *Synedra sp.*
    - *Pinnularia sp.*
    - *Navicula sp.*

TABLE 15.--Algae Inhabiting the North Lake Marl Concretions

Organism	Abundance
Myxophyceae	
Oscillatoriaceae	
Schizothrix fasciculata	abundant
Lyngbya Martensiana	abundant
Lyngbya versicolor	occasional
Lyngbya aerugineo-caerulea	occasional
Phormidium sp.	abundant
Rivulariaceae	
Calothrix fusca	occasional
Calothrix Braunii	occasional
Chroococcaceae	
Chroococcus sp.	occasional
Aphanothece microspora	occasional
Diatomaceae	
Cymbellaceae	occasional
Naviculaceae	occasional

The Littoral Benthic Community

Examination of the North Lake substrate indicated a rich and varied community of aufwuchs in addition to the sparse population of higher aquatic plants. At times, especially late October, filamentous aquatic fungi, bacteria, and algae become so abundant that a "mat" formed over large areas of the marl substrate. Diatoms, ciliate protozoa (*Vorticella*), nematodes, and rotifers were abundant within the "mat".

Certain littoral areas (Fig. 3) were selected for plant growth experiments and studied in detail. Table 16 lists the benthic organisms found on these plots prior to substrate alteration.

Fish and Fishing

The fish population of North Lake is composed of 8 families, 20 species, and hybrids of the 2 sunfishes (Table 17).

TABLE 16.--North Lake Benthic Organisms

Flora

- Cyanophyta
  - Mxyophyceae
    - Hormogonales
      - *Oscillatoria*
- Chlorophyta
  - Chlorophyceae
    - Zygnematales
      - *Mougeotia*
      - *Spirogyra*

Fauna

- Mollusca
  - Gastropoda
    - Prosobranchiata
      - *Goniobasis*
- Arthropoda
  - Insecta
    - Coleoptera
      - *Halipus*
    - Tricoptera
      - *Limnephilus*
      - *Oecetis*
    - Diptera
      - *Calopsectra*
    - Ephemeroptera
      - *Hexagenia*
      - *Caenis*
    - Odonata
      - *Erythemis*
      - *Didymops*
      - *Gomphus*
      - *Macromia*
  - Crustacea
    - Amphipoda
      - *Hyalella*

TABLE 17.--Fishes of North Lake

Centrarchidae
- *Micropterus dolomieu*
- *Micropterus salmoides*
- *Lepomis megalotis**
- *Lepomis gibbosus**
- *Lepomis machrochirus*
- *Ambloplites rupestris*
- *Pomoxis nigro-maculatus*

Esocidae
- *Esox lucius*

Salmonidae
- *Salmo trutta*
- *Salvelinus fontinalis*

Cyprinidae
- *Cyprinus carpio*
- *Semotilus atromaculatus*
- *Notropis cornutus*
- *Hyborhynchus notatus*

Percidae
- *Perca flavescens*
- *Poecilichthys exilis*

Coregonidae
- *Leucichthys sp.*

Catostomidae
- *Catostomus commersonnii*

Ictaluridae
- *Ictalurus melas*
- *Ictalurus nebulosus*

*hybrids between these sunfishes

The poor fishing quality of North Lake is evident in the comparison of fishing quality indices for North, Loon, and Dollar Lakes (Table 18). Both Loon and Dollar Lakes are non-marl lakes having the same species of fish but an abundance of higher aquatic plants.

TABLE 18.--Comparison of the North, Loon, and Dollar Lakes Fishing Quality Indices

Lake	Quality Index	1946	1948	1949	1950	1951	1952	1954	Average
North Lake	% Unsuccessful angling days	72.7	69.3	78.9	86.6	80.3	79.0	84.8	70.8
	Number of fish per hour	0.38	0.58	0.19	0.09	0.22	0.18	0.12	.251
	Pounds of fish per hour	0.163	0.271	0.123	0.086	0.116	0.099	0.091	0.136
Loon Lake	% Unsuccessful angling days	60.0	32.1	35.0	20.4	23.9	38.1	37.2	35.2
	Number of fish per hour	0.57	0.93	1.61	2.99	3.18	1.98	1.49	1.83
	Pounds of fish per hour	0.490	0.374	0.507	0.676	0.652	0.434	--	0.522
Dollar Lake	% Unsuccessful angling days	22.6	30.3	19.6	22.9	12.9	24.0	26.9	25.6
	Number of fish per hour	1.31	0.76	2.15	2.22	2.41	1.77	1.71	1.76
	Pounds of fish per hour	0.297	0.152	0.447	0.401	0.473	0.344	--	0.352

Note: 1 angling day = one fisherman fishing 1/2 hour or more. Data compiled from the files of the Michigan Institute for Fisheries Research. 1946 and 1954 statistics based on partial year's data.

LIMNOLOGICAL CHARACTERISTICS
OF PINTAIL POND

Hydrography

The important hydrographic data are summarized in Table 19 and Fig. 14.

TABLE 19.--Pintail Pond Hydrography

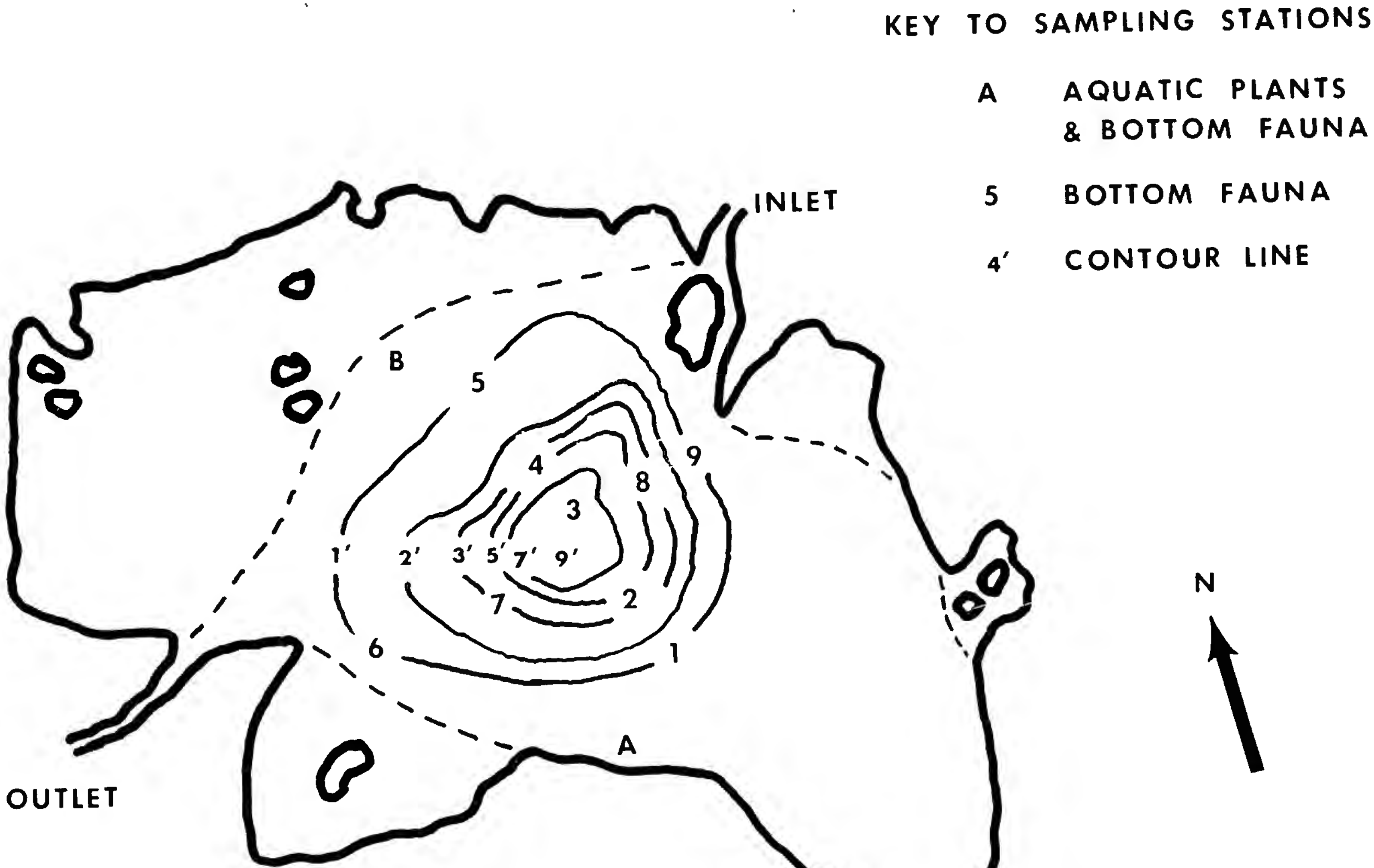
Location...T. 23N., R 3E., Sec's. 1,2. Ogemaw Co., Mich.
Area...2.26 acres
Maximum depth...9 ft
Mean depth...1.3 ft
Maximum effective length...475 ft
Maximum effective width...325 ft
Shore Development...1.3
Volume Development... .42
Slope of Basin... .24
Volume...126,364.53 ft^3

Inlet waters flow from a spring located approximately 90 ft from the north edge of the pond. Some seepage water enters the pond after rainfall, but in general, the spring can be considered the principal source of inflowing waters. An outlet on the southwest side of the pond is active throughout the year.

Shore and Bottom Deposits

Underlying the pond is a thick, gray marl deposit. Marl at the north end is 16 ft deep under about 2 ft of peat and water. The slope of the lake basin is gradual and uniform. The substrate is

Fig. 14. Hydrographic map of Pintail Pond. Dotted line represents the position to which the waters recede after the spring rains.



PINTAIL POND

finely divided, amorphous, marl particles. Neutralization value of the substrate material was 94.4% as compared to calcium carbonate. No concretions are present.

Physical Characteristics of Pintail Pond

Temperature

Spring waters flowing into Pintail Pond varied little in temperature from the average of 9.9° C. The daily average pond and outlet water temperatures closely followed the daily average air temperatures.

Conductivity

Conductivity of the spring water varied from 212-368, with an average of 318 x 10^{-6}mho at 25° C. Conductivity decreased with rainfall.

Conductivity of pond water varied between 241-368, with an average of 299 x 10^{-6}mho at 25° C. Highest conductivity of the waters of the pond occurred immediately after the fertilizer was added. Ionization of the fertilizer and transformation of some of the calcium carbonate substrate to soluble calcium bicarbonate after fertilization account for the increases. Supporting data and discussion of these conclusions follow in the text.

The conductivity measurements of the outlet ranged from 234-322 and averaged 273 x 10^{-6}mho at 25° C.

Table 20 shows the conductivity of Pintail water.

Turbidity

The average turbidity of the spring was 7 units. The range was 1-23 units. Highest values were associated with long periods of heavy rainfall.

TABLE 20.--Conductivity of Pintail Water
(10^{-6} x 25° C, 1953)

Date	Spring	Pond	Stream
7/1	212	241	278
7/13	364	332*	322
7/15	364	368**	363
7/27		300*	
7/29		351**	
8/12		267*	
8/13		294**	
8/24		298*	
8/26		368**	
8/31	368	278	250

*one day before fertilizer added.

**one day after fertilizer added.

The turbidity of pond and outlet water averaged 16 units prior to addition of the chemical fertilizer. The range before fertilization was 3-28 units. The data show that turbidities increased as phytoplankton populations increased. Average Secchi disc measurements were 78 in. before fertilizer was added to Pintail Pond in 1952. Secchi disc readings were 6 in. when turbidity reached its maximum after the last of the six applications of fertilizer in 1953.

Chemical Characteristics of Pintail Pond

Sampling Stations and Results of Analyses

Water samples for chemical analyses were taken four times a month at Pintail Spring, Pintail Pond, and Pintail Outlet (Fig. 14) which made it possible to measure chemical changes in the water as it flowed through the system. These changes in the chemistry of the water are of special importance quite apart from a specific interest in a temperate hyper-marl lake of the third-order (Pintail Pond). Chemical determinations of inlet waters of most deep marl lakes are complicated because the seepage occurs within the basin. It is hypothesized that the changes in the chemistry of the water passing from Pintail Spring, Pond, and Outlet are analogous in many ways to changes that occur in spring waters entering the basin of a deep lake which are then circulated biannually.

Cold Pintail Spring water of pH 7.2 flowed from the glacial outwash devoid of carbonate, low in oxygen, high in carbon dioxide (26 mg liter^{-1}) and calcium-magnesium hardness (215 mg liter^{-1}). The ratio of calcium:magnesium in the water was 2.4:1. Noncarbonate hardness (SO_4) was about 4 mg liter^{-1}. Concentrations of phosphorous, nitrogen, and potassium in the water of the spring were low. About 19% of the calcium and 6% of the magnesium entering the system were deposited as marl.

Phosphorus and nitrogen in the water of the pond were 2.5 and 1.5 fold greater respectively than in the water of the spring. Potassium concentrations were about the same in the water of the spring and pond.

The concentration of phosphorus and nitrogen in the water of the pond is attributed to the biogenic activities of the plants and bacteria. The synthesis of protoplasm is a process which concentrates phosphorus and nitrogen. In addition, phosphorus is not taken up by the plants solely in proportion to demands, but may be stored in concentrations many times the normal content (Ruttner, 1953). The nitrogen fixation capability of bacteria and some algae (Hutchinson, 1944) also results in concentrations of nitrogen. Through the activity of bacteria, fungi, green algae, and animals, organic matter is broken down and the concentrated nutrients released to the pond water.

Table 21 shows the averages of the chemical characteristics for Pintail Spring, Pond, and Outlet water. Detailed data are shown in Appendix II.

Causes of the Chemical Fluctuations in the Water of Pintail Spring and Pond

Rainfall

Large fluctuations in hardness, alkalinity, calcium and magnesium in the water of the spring were caused by precipitation. As precipitation increased, the bicarbonate alkalinity, hardness, calcium and magnesium decreased. The statistical correlations were significant at the 1% level, except for magnesium which was significant at the 5% level. Since direct dilution of the spring water was not a factor, the greater quantities of ground water probably contained less soluble salts because (i) the more rapid flow reduced the time for solution of the minerals from the glacial debris, and (ii) the ground water became progressively less acid as the carbon dioxide of the soil was absorbed and diminished.

The quantitative relationships between rainfall and: (i) bicarbonate alkalinity, (ii) calcium-magnesium hardness, and (iii) calcium hardness in the spring water are shown by the predicting line formulae in Table 22.

TABLE 21.--The Chemical Characteristics of Pintail Spring, Pond, and Outlet Water, (Three year averages for the period March-November)

	Spring	Pond	Outlet
Temperature °C	9.9	23.1	23.5
pH	7.2	8.1	8.1
O_2 mg liter^{-1}	3.4	6.7	6.6
CO_2 mg liter^{-1}	26.0	2.5	2.0
CO_3 mg liter^{-1}	0.0	2.2	2.5
HCO_3 mg liter^{-1}	211.2	202.0	174.1
Ca mg liter^{-1}	55.1	47.7	44.9
Mg mg liter^{-1}	22.3	21.2	20.9
Total Hardness mg liter^{-1}	215.3	193.1	185.0
Carbonate Hardness mg liter^{-1}	211.2	204.2	176.6
Phosphorous			
Total ug liter^{-1}*	7.50	17.80	20.33
Soluble ug liter^{-1}*	1.56	.75	.25
Nitrogen			
Total ug liter^{-1}*	.74	1.62	1.19
Organic ug liter^{-1}*	.61	1.14	1.00
NH_4 ug liter^{-1}*	.13	.54	.15
Potassium mg liter^{-1}*	.48	.50	.49

*Averages for July-August. Chemical analyses of water samples collected previous to pond fertilization and mid-way between fertilization periods thereafter.

TABLE 22.--Correlation Between Rainfall and Chemistry of Pintail Spring Water

Date	Rainfall	Alkalinity	Hardness	Calcium	Magnesium
7/8/52	.51	226.0	--	--	--
7/11	.00	--	216.4	146.4	70.0
7/13	.00	217.0	223.0	150.7	72.3
7/23	.88	214.0	211.6	139.7	71.9
8/3	1.64	158.0	174.0	102.8	71.3
8/13	.04	220.5	216.6	141.6	75.0
8/17	.01	217.5	221.0	140.7	80.3
8/28	.00	217.0	227.3	150.9	76.4
9/14	.15	223.3	226.5	150.5	76.2
5/10/53	.01	212.9	222.0	159.6	62.4
7/1	2.29	138.6	155.0	89.0	62.0
7/6	1.99	140.6	154.6	88.8	65.8
7/13	.00	217.1	222.2	147.1	78.3
7/15	.00	221.4	222.4	147.1	75.3
7/27	.00	230.1	228.2	139.4	88.8
7/29	.01	224.0	227.2	140.4	86.8
8/13	.58	228.3	225.2	142.2	83.0
8/24	.00	--	228.8	140.8	88.0
8/26	.07	--	227.4	141.9	85.5
Correlation Coefficient		-.923**	-.961**	-.944**	-0.580
Variance ratio		80.6	192.1	130.3	2.02
Predicting line		Y = 225.1 + (-36.5)X	Y = 225.9 + (-31.1)X	Y = 147.7 + (-25.9)X	Y = 74.3 + (-1.58)X

**Highly significant (1% level)

Calcium-Magnesium-Phytoplankton Relationship

The effect of rainfall on certain chemical constituents of the Pintail Spring water explains some but not all of the chemical fluctuations that occurred in the pond. A test of correlation between phytoplankton volume and: (i) hardness, (ii) calcium, (iii) magnesium, (iv) bicarbonate alkalinity, showed that fluctuations in the chemistry of the pond water were directly related to variations in the volume of the phytoplankton. Increases in phytoplankton volume caused decreases in the chemical constituents. Chemical pauperization of the water of Pintail Pond is therefore attributed to the physiological activity of the phytoplankters and subsequent precipitation of calcium carbonate. Although it has been noted that changes in the carbonate in lake water are coincident with changes in phytoplankton (Ruttner, 1953), quantitative relationships have not been reported. The data and the quantitative relationships between phytoplankton volume and chemical pauperization of Pintail Pond water are shown in Table 23.

Pintail Pond Biota

Vegetation of the Marl Flats

The marl deposit around the pond is overlaid by a mat of *Eleocharis*. Cedar, larch, and spruce are the predominating plants on the mat. *Sarraccenia purpurea* is abundant.

Plankton

Few detailed studies have been made of the plankton of hypermarl lakes. Perhaps the most notable is that of Raymond (1937) of Bass Lake in southern Michigan. Pintail Pond is a much smaller body of

TABLE 23.--Correlation Between Phytoplankton Volume and Pintail Pond Total Hardness, Calcium, Magnesium and Bicarbonate Alkalinity

Date	Plankton Volume	Alkalinity	Hardness	Calcium	Magnesium
7/9/52	.091	215.2	205.6	132.6	73.0
7/13	.260	209.7	210.8	137.1	73.7
8/27	3.099	147.0	166.4	98.5	67.9
7/13/53	1.046	203.2	206.4	134.4	72.0
7/15	.215	212.9	214.2	141.7	72.5
7/27	1.176	193.1	204.2	126.9	77.3
Correlation Coefficient		-.988**	-.944**	-.948**	-.580
Variance ratio		96.00	32.69	35.60	2.02
Predicting line		Y = 218.7 + (-22.4)X	Y = 215.5 + (-14.6)X	Y = 141.3 + (-12.9)X	Y = 74.3 + (-1.58)X

**Significant to 1% level.

Dates on which rain fell were excluded from this study.

water. The growing season is shorter and the alkalinity is about 25 mg liter^{-1} higher. Two other differences need to be noted in making a comparison of the plankton of the two lakes. Pintail Pond received plant nutrients artificially and low magnifications of the microscope were used in the study to improve the accuracy of the counts. Consequently, species identification was not always feasible. Table 24 lists the plankters of Pintail Pond with a notation of those organisms found in Bass Lake by Raymond (1937).

The plankton volume before treatment with fertilizer was .09 mm^3 liter^{-1}. Bacteria, Microcystis, Dictyosphaerium, and diatoms (Navicula, Synedra, Pinnularia, Fragillaria and Cymbella) were the most abundant organisms.

Flora of Pintail Pond

The macrophydrophytes of Pintail Pond were restricted to a few species. Scirpus validus grew in the soft marl shoals to a depth of one foot. Chara, Najas flexilis, and Potamogeton pectinatus occurred sparsely to depths of six inches. All the plants were small and heavily incrusted with calcium carbonate.

Mougeotia, Anabaena, and Spirogyra grew among the particles of substrate although none was abundant prior to fertilization.

Fauna of Pintail Pond

The light gray marl substrate, devoid of aquatic vegetation, did not support a large or diversified population of invertebrates. Table 25 lists the organisms taken from Pintail Pond.

Samples collected from the barren marl substrate indicated that the most numerous organisms were Diptera of the subfamily Tendipedinae

TABLE 24.--Pintail Pond Plankton

Cyanophyta

*Oscillatoria sp.
*Chrooccoccus limneticus
Chroococcus dispersus
Chroococcus Prescottii
*Anabaena sp.
Aphanathece sp.
Gomphosphaeria lacustris
*Coelosphaerium sp.
**Merismopedia elegans
Merismopedia glauca
*Microcystis flos-aquae
Schizothrix sp.
Spirulina laxa
Rhabdoderma sp.

Chlorophyta

*Dictyosphaerium pulchellum
*Pediastrum Boryanum
*Spirogyra micropunctata
*Spirogyra sp.
Mougeotia sp.
Mougeotia calcarea recurva
Zygnema sp.
Oedogonium sp.
Chlamydomonas globosa
Cosmarium bioculatum
Cosmarium subcrenatum
Cosmarium sp.
Arthrodesmus sp.
Staurastrum sp.
Scenedesmus bijuga
Tetraedron minimum

Chrysophyta

*Dinobryon divergens
Dinobryon sertularia
Dinobryon calciformis

Bacillariophyceae

Anomoeneis exilis
*Cymbella sp.
Cymbella turgida
*Cyclotella sp.
Gomphonema Augur
*Fragilaria crotonensis
*Synedra sp.
*Pinnularia sp.
*Navicula sp.

Pyrrhophyta

*Ceratium hirundinella
*Peridinium sp.
Glenodinium armatum

Euglenophyta

Trachelomonas sp.
Phacus sp.

Protozoa

*Difflugia sp.
Amoeba radiosa

TABLE 24. Continued

Rotatoria

*Keratella cochlearis	*Monostyla lunaris
*Polyarthra trigla	

Cladocera

*Bosmina obtusirostris
Sida crystallina

Copepoda

*Cyclops sp.
(nauplium)

*Found in Bass Lake by Raymond (1937).

**Genus found in Bass Lake by Raymond (1937).

TABLE 25.--Pintail Pond Invertebrate Fauna

Insecta

Ephemeroptera
- Ephemeridae
  - Hexagenia
- Baetidae
  - Caenis

Coleoptera
- Haliplidae
  - Halipus

Odonata
- Libellulidae
  - Dorocordulia
- Coenagrionidae
  - Hetaerina
- Aeschnidae
  - Aeschna
  - Coryphaeschna
- Gomphidae
  - Gomphus

Diptera
- Tendipedinae
  - Tendipes
  - Calopsectra
  - Cryptochironomus
  - Glyptotendipes
  - Microtendipes
  - Pseudochironomus
- Pelopiinae
  - Procladius
  - Pentaneura
  - Tanypus
- Heleidae
  - Bezzia
- Culicidae
  - Chaoborus

Hemiptera
- Hydrometridae
  - Hydrometra

Crustacea

Cladocera
- Daphnidae
  - Daphnia

Amphipoda
- Talitridae
  - Hyalella

Decapoda
- Cambarinae

Hydracarina

Annelida

Hirudinea

Oligochaeta

Mollusca

Goniobasis

Physa

(*Tendipes*, *Calopsectra*, *Crytochironomus*). These increased in number with increasing water depth. *Hexagenia limbata* was the only mayfly collected from these barren marl areas and its numbers decreased as water depth increased. Although widely distributed in Michigan, *Hexagenia limbata* is particularly abundant in lakes with soft marl deposits (Hunt, 1953).

The deepest depression in the basin of Pintail Pond was barren of plants even though it contained a much higher ratio of organic matter to marl than the other areas sampled. The rapid rate of filling, light, and the unstable substrate are the factors believed to limit the plant growth here. The depression area supported the largest population of the midge *Tendipes* and the only population of *Chaoborus*. No Ephemeroptera were found in benthic samples taken from the depression.

The fauna in Pintail Pond was more varied and abundant in shallow areas characterized by white marl covered with a sparse but uniform growth of plants. In this respect, the Pintail Pond bottom fauna was similar to that found in many other types of lakes (Rawson, 1930; Juday, 1942; Ball, 1948; Wohlschlag, 1950), i.e., vegetation covered substrates support a richer fauna. Mayflies and midges were the most numerous bottom fauna at vegetated stations in Pintail Pond. The association was *Caenis*, *Calopsectra* (90%) - *Chara*, *Najas* (100%).

The average standing crop of bottom fauna in Pintail Pond in July was about 93 organisms ft^{-2}. Wohlschlag (1950) sampled light gray marl substrates in July in Wabee Lake and found a comparable standing crop of bottom fauna. Ball and Tanner (1951) report 186 organisms ft^{-2} in July for North Twin Lake which is a small, shallow, soft water lake having a sand and peat substrate. Records of natural lakes (Ball, 1948) show that Pintail Pond bottom fauna populations are about 62 per cent that of lakes considered to have average productivity.

ALTERATION OF ENVIRONMENT

Addition of Chemical Fertilizer to Pintail Pond

An analysis of the waters and substrate of North Lake and Pintail Pond showed that biological production might be limited by the low level of available plant nutrients. To test this hypothesis, six applications of a complete fertilizer (10% N, 6% P, 4% K) were made to Pintail Pond, and the responses of plankton, vascular aquatic plants, and bottom fauna were measured. The fertilizer was spread at a rate of 14.9 kg N, 8.9 kg P, and 5.9 kg K as available N, P_2O_5 and K. The pond was treated twice during the first year of the study (July 11 and August 15, 1952) and four times the second year (July 14, 28, August 12, 25, 1953). No fertilizer was applied during the third year of the study (1954).

First Year Plankton Study

Within a week following the first fertilizer application (July 11, 1952), the pond water was no longer the light green color, characteristic of marl lakes; it had changed to the darker yellowish-brown seston color of eutrophic lakes.

Within two weeks following the first fertilization date, a plankton bloom had changed the appearance of Pintail Pond. Filamentous algae were observed growing attached to the substrate and began to accumulate around the emergent aquatic plants near the shore. Between July 24 and August 13 the Mougeotia, which developed on the marl substrate soon after the first fertilizer treatment, became detached and floated to the surface where it entered the plankton sample.

The second application of fertilizer (August 15) was followed by further increases in plankton volume. By August 23, most of the pond was covered by small floating masses of algae.

Thus plankton blooms occurred after each of the two applications of fertilizer to the marl pond (Table 26). Microcystis, Dictyosphaerium, Dinobryon, Mougeotia, and several different species of diatoms comprised most of the plankton volume.

Second Year Plankton Study (1953)

Prior to fertilization in the second year, plankton volumes in July averaged 5.7 times greater than the corresponding volumes of the first year. Thus considerable carry-over effect from the previous year's fertilizer is indicated.

Pintail Pond received four applications of fertilizer during the second year of the study and the plankton volume increased after each one (Table 26). The average plankton volume remained higher throughout the second year and showed less fluctuation than the previous year.

Dinobryon made up most of the plankton volume early in July. Dictyosphaerium increased after each fertilizer application and with Mougeotia soon became the predominant phytoplankton form. Increases in diatoms, Ceratium, Keratella, and nauplium followed the blooms of Dictyosphareum and Mougeotia. Microcystis contributed comparatively less to the total plankton volume the second year.

Third Year Plankton Study (1954)

Chemical fertilizer was not added to the pond during the third year. The early July plankton volumes for the third year averaged 77.5% of the preceding year, but were 4.4 times as great as corresponding volumes prior to the first fertilizer treatment.

TABLE 26.--Pintail Pond Plankton Volume for Three Years (mm^3 $liter^{-1}$)

1952		1953		1954	
Date	Volume	Date	Volume	Date	Volume
7/9	.174	7/6	.834	7/8	.656
7/14	.260	7/13	1.169	7/15	.896
7/24	.256	7/15	.215	7/31	.735
8/3	.479	7/17	1.326	8/3	1.297
8/13	2.065	7/19	1.315	8/7	1.266
8/17	3.232	7/21	1.372	8/13	2.402
8/27	3.099	7/27	1.310	8/17	2.141
9/14	.656	8/4	1.953	8/25	2.070
		8/12	1.492	9/25	1.685
		8/15	1.210		
		8/24	1.611		
		8/28	2.507		
		9/13	1.232		

Dinobryon contributed most of the plankton volume the third year. Diatoms, Keratella, Ceratium, Dictyosphaerium and Microcystis contributed to total plankton volumes in the order listed. The peak plankton volume the third year occurred about the middle of August.

Table 26 shows the changes in plankton volume for the three years. The study showed that each of the six fertilizer applications was followed by an increase in the phytoplankton volume and changes in the composition of the plankton populations. Fertilizer tended to increase the comparative volume of Chlorophyta in the population. Using Rawson's (1956) algal indicators of lake types as a guide, the six applications of fertilizer changed the flora from the oligotrophic type to high mesotrophic. Measurements of each of the three years (1952, 1953, 1954) indicate that the carry-over effect of the fertilizer from the previous year raised the plankton volume about 3 fold the year following (Table 26). Increases in the periphyton of Pintail Pond were noted after fertilization, but these were not regularly measured.

Response of the Macrohydrophytes to the Fertilizer

Two stations (A and B) were established in Pintail Pond to evaluate artificial fertilization on higher aquatic plants in a marl lake. These stations were selected because they had a sparse, uniform plant coverage. Station A was predominantly Chara; station B, Najas. The substrates were gray-white marl.

Both stations were marked off in a grid and thirty-eight samples were drawn randomly (12 in 1952; 14 in 1953; 12 in 1954) from each station by mid-July of each year. The data show that significant increases in the standing crops of the aquatic plants resulted from fertilization and were directly related to the quantity of fertilizer added.

Data from Stations A and B (Table 27) indicate that both Chara and Najas responded well to two applications of fertilizer added in 1952. Four additional applications of fertilizer (1953) produced increases in Chara but no significant increase in Najas. If the changes

TABLE 27.--Weight(g) of Macrohydrophytes in Pintail Pond Before and After Fertilization

Sample No.	Station A 1952	Station A 1953	Station A 1954	Station B 1952	Station B 1953	Station B 1954
1	3.6	6.6	17.4	2.1	6.4	6.0
2	2.5	7.2	16.7	3.1	13.0	10.5
3	4.5	10.0	20.1	2.0	9.2	11.1
4	2.7	6.3	23.3	3.6	5.0	15.6
5	4.4	8.1	19.1	1.9	3.2	12.1
6	3.0	4.5	17.9	.9	11.5	7.2
7	2.4	7.1	18.0	.1	8.9	6.8
8	3.8	8.7	15.8	1.3	10.8	9.9
9	5.4	7.6	19.4	.4	12.4	16.3
10	4.2	6.9	18.9	5.2	10.3	11.5
11	4.1	8.0	18.1	1.2	9.3	8.5
12	1.5	8.1	21.8	1.9	7.7	12.0
13		7.3			7.1	
14		4.7			9.5	
Total	42.1	101.1	226.5	23.7	124.3	127.5
$\overline{X}$	3.5	7.2	18.9	1.9	8.9	10.6

Analysis of Variance for Stations A and B

(a) Between years F --- 5,320**

(b) About regression F --- 4,314**

**Significant at 1% level

in samples represent actual population changes, factors in the environment other than those supplied in the fertilizer limited Najas but not Chara.

Figs. 15 and 16 show the changes in the vegetation with six applications of fertilizer.

Bottom Fauna Response

The bottom fauna of Pintail Pond were collected by mid-July from two different types of stations. (1) Stations A and B characterized by Chara and Najas. Thirty-eight samples were drawn randomly (12 in 1952; 14 in 1953; 12 in 1954) from each station. The depth of the water at these stations was about 1 ft. (2) Stations 1 through 9 were barren of aquatic plants. Twelve samples were collected from each station during the first and third years of the study. The depth of the water at these stations varied from 1-9 ft.

Vegetated Substrates (Stations A and B)

Tables 28 and 29 show the results of sampling the bottom fauna at vegetated stations A and B. Mayflies (Caenis) and midges (Calopsectra) made up about 90% of the total number collected each of the three years. Using the first year's standing crop of bottom fauna at Station A as a base, increases of 185% had occurred after six applications of fertilizer. At Station B, increases of 233% took place. Since the bulk of the counts were of the above two organisms, the increases in number were approximately equal to increases in volume. A statistical comparison of average bottom fauna sample size for stations A and B is shown in Fig. 17.

Fig. 15. Pintail Pond, Station A

View 1. Vegetation before fertilization (July 15, 1952).

View 2. Vegetation after six applications of fertilizer (July 19, 1954).

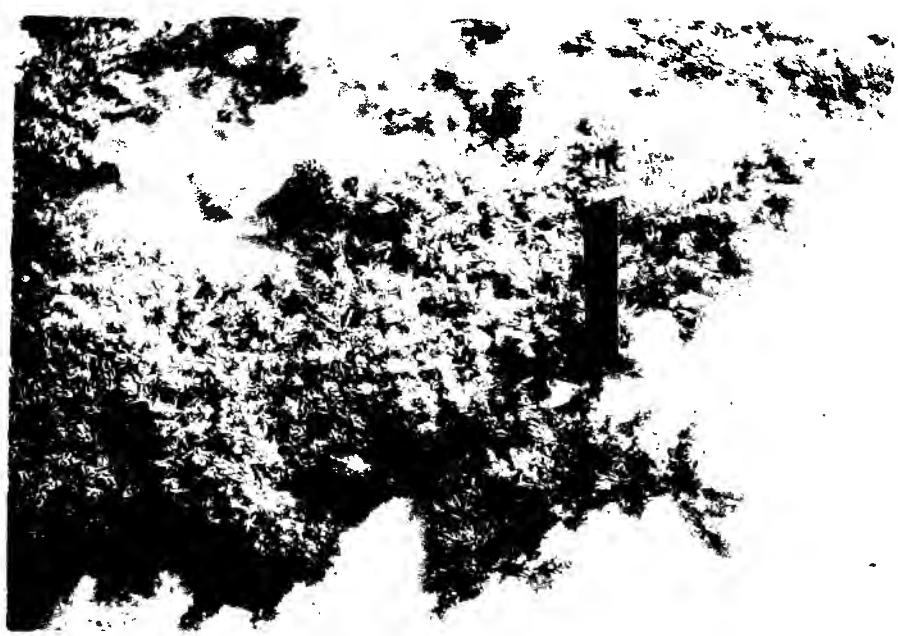


Fig. 16. Pintail Pond aquatic vegetation for three years at Station A and B. Plotted points are means, two standard errors from means, and ranges for each sample group. The data are the sample weights (g) transformed to logs (Bartlett, 1947).

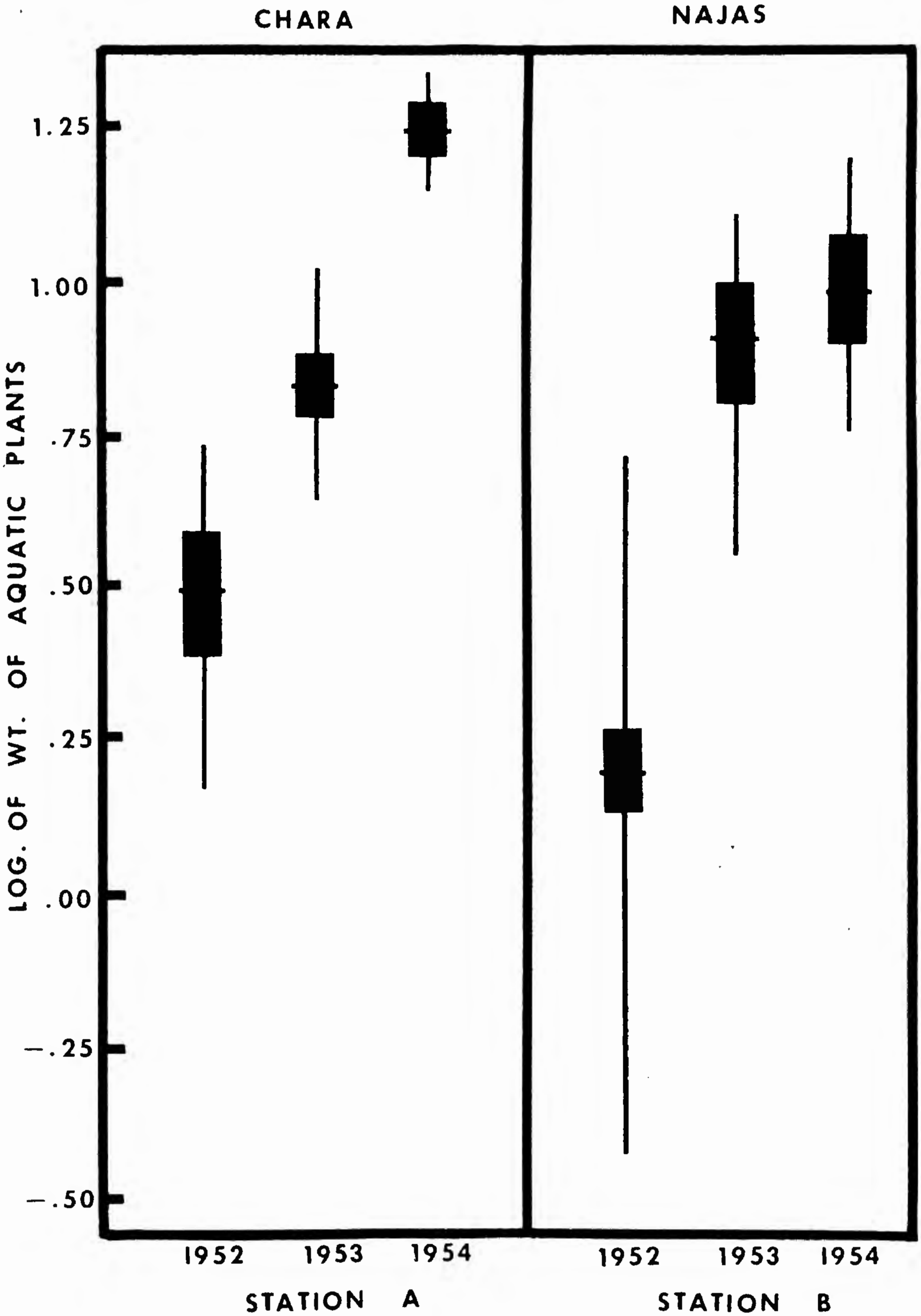

CHARA
NAJAS
LOG. OF WT. OF AQUATIC PLANTS
1.25
1.00
.75
.50
.25
.00
−.25
−.50
1952
1953
1954
STATION A
1952
1953
1954
STATION B

TABLE 28.--Numbers of Bottom Fauna Ft^{-2} Collected from Vegetated Stations A and B in Pintail Pond During the Fertilization Experiments

	1952		1953		1954	
	A	B	A	B	A	B
Ephemeroptera						
Ephemeridae	3.8	2.7	.7	1.9	.3	.6
Baetidae	10.2	4.6	8.0	12.3	37.2	28.5
Diptera						
Tendipedinae	63.2	41.8	122.7	95.4	97.2	80.5
Pelopiinae	.1	.3	.9	1.5	1.3	1.9
Heleidae			1.1	.2	1.5	.3
Coleoptera						
Haliplidae			.1			
Odonata						
Libellulidae			1.0			
Coenagrionidae			.1	.6	2.7	1.9
Aeschnidae				.5	.9	.7
Gomphidae				.5		.4
Hemiptera						
Hydrometridae					.1	
Hydracarina	3.2	2.7	6.8	2.7	3.0	2.2
Cladocera				113.3	1.6	1.9
Amphipoda			1.1	1.4	1.3	1.0
Annelida	.4	.4	1.1	1.2	2.1	1.2
Decapoda			.4			

TABLE 29.--Numbers of Bottom Fauna in Samples from Vegetated Stations in Pintail Pond Before and After Fertilization

Sample No.	Station A 1952	Station A 1953	Station A 1954	Station B 1952	Station B 1953	Station B 1954
1	51	72	90	14	42	41
2	25	54	95	50	128	52
3	56	78	72	29	48	91
4	36	85	54	61	39	114
5	68	119	75	22	27	53
6	29	64	97	17	93	44
7	34	97	101	13	70	36
8	44	56	74	35	84	57
9	73	103	112	17	92	127
10	56	80	93	55	67	83
11	43	87	67	20	61	56
12	35	92	88	24	55	78
13		73			68	
14		89			64	
Total	550	1,149	1,018	357	938	832
$\overline{X}$	45.8	82.1	84.8	29.8	67.0	69.2
No. of Species	9	16	18	10	17	18

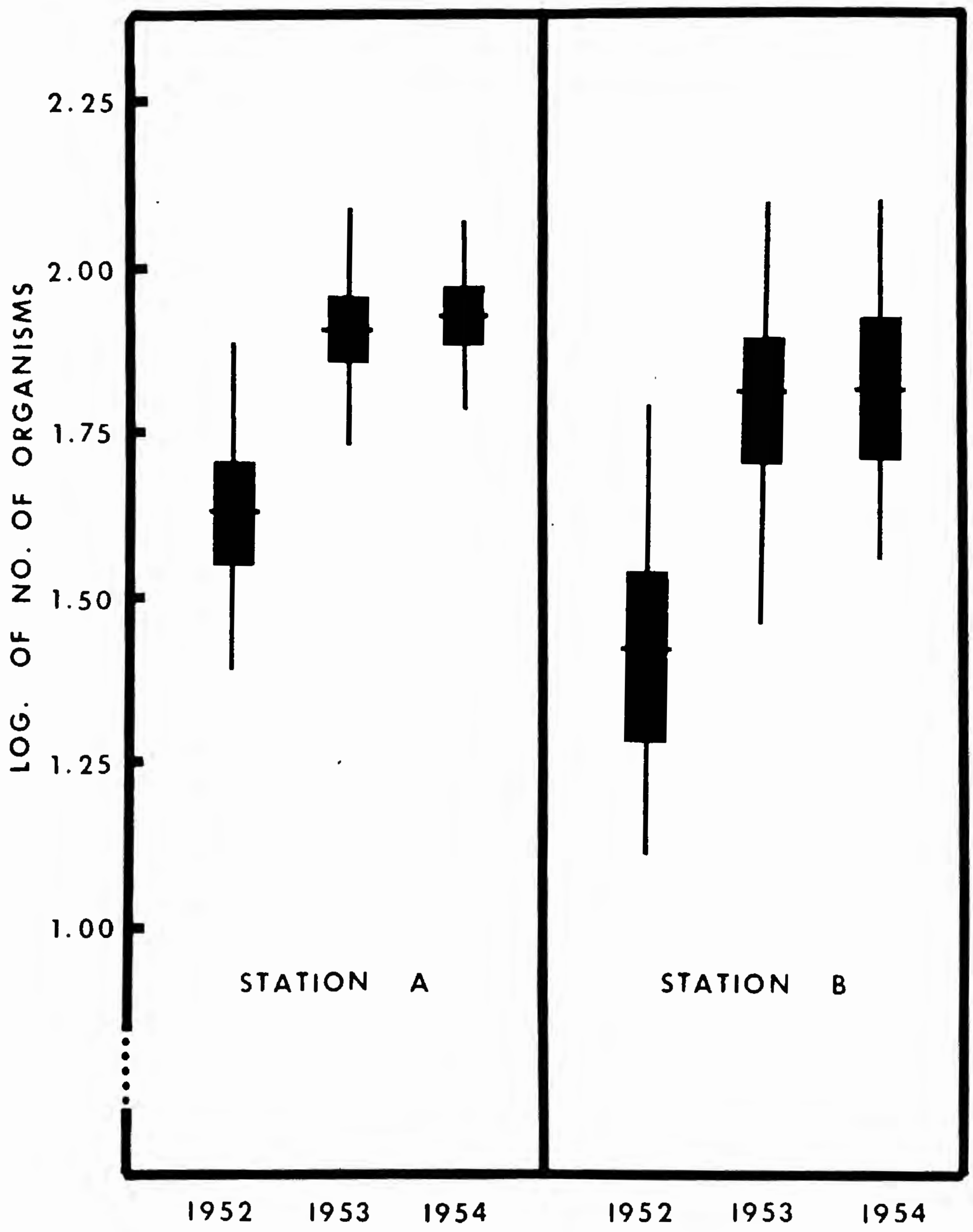
Analysis of Variance for numbers of midges at Stations A and B

(a) Between years F --- 63.7**

(b) About regression F --- 147.8**

**Significant at 1% level

Fig. 17. Pintail Pond bottom fauna sample size for three years from Stations A and B. Plotted points are the means, two standard errors from the means and the ranges for each sample group.


2.25
2.00
1.75
1.50
1.25
1.00
LOG. OF NO. OF ORGANISMS
STATION A
STATION B
1952
1953
1954
1952
1953
1954

Midges were the most numerous organisms at both stations, and populations were of sufficient size for an analysis of variance. The test showed significant differences in midge populations: (i) between Stations A and B and (ii) between the years that the observations were made. Differences in numbers of organisms inhabiting the stations are attributed to the predominance of *Najas* at Station B and *Chara* at Station A. Differences between years are attributed to the fertilizer applications.

Several organisms not found in samples collected the first year appeared in later samplings. *Halipus*, *Coryphaeschna*, *Aeschna*, *Hetaerina*, *Gomphus*, *Daphnia*, and *Hyalella*, found only in the last sample series, indicate that applications of fertilizer produced a more suitable habitat for these organisms.

Substrates Without Vegetation

Bottom fauna samples were collected from each station (1-9) before and after the applications of fertilizer. Stations 1, 5, 6 and 9 were of 1 ft depth while Stations 2, 4, 7 and 8 were at a depth of 4 ft. The substrates of all stations were characterized by a homogeneous, light gray marl, except station 3, located in 9 ft of water, which contained a considerable amount of organic matter. The location of each sampling station is shown in Fig. 14.

Samples taken at the one foot depth contained midges (Tendipedinae, Pelopiinae and Heleidae), and mayflies (Ephemeridae and Baetidae). *Tendipes* and *Hexagenia* were most numerous. Samples from the four foot depth contained the same organisms but there were fewer mayflies and more midges. Samples from 9 feet of water contained the largest numbers of midges and the only *Chaoborus* found in the pond. No mayflies were taken from the deeper station. Ten genera were found at the nine stations before fertilizer was added to the pond.

Samples collected after six applications of fertilizer indicate that numbers of bottom fauna had increased while distribution remained about the same. Two genera of midges, Hydracarina, *Hyalella*, and Oligochaeta were found after fertilization that were not found in the samples taken before fertilization. Ephemeroptera (nearly all *Hexagenia*) were twice as abundant after fertilization. Diptera and other forms were about 1.8 times as abundant after fertilizer application. *Hexagenia* was much the largest organism in these samples and consequently volume increases are correlative to increases in the number of *Hexagenia* in the samples. Tables 30 and 31 show the numbers of bottom fauna collected from non-vegetated stations in Pintail Pond before and after six applications of fertilizer.

TABLE 30.--Numbers of Bottom Fauna Ft^{-2} Collected from Non-Vegetated Stations in Pintail Pond Before and After Six Applications of Fertilizer

	1 ft		4 ft		9 ft	
	1952	1954	1952	1954	1952	1954
Ephemeroptera						
Ephemeridae	2.8	6.1	1.3	1.4		
Baetidae	.3	.5	.3	1.9		
Diptera						
Tendipedinae	6.7	10.9	18.7	38.9	19.8	34.5
Pelopiinae	.3	1.0	.3	1.0	.3	1.2
Heleidae	.4	.4	.4	.4		
Culicidae				.07	8.0	13.0
Hydracarina				.4		
Amphipoda				.1		
Annelida				.2		.3

TABLE 31.--Numbers of Bottom Fauna in Samples Collected from Non-Vegetated Stations in Pintail Pond Before and After Six Applications of Chemical Fertilizer

Sample No.	1952 Before Fertilization, Depth of Station (ft) 1	4	9	1954 After Fertilization, Depth of Station (ft) 1	4	9
	(S-1)	(S-2)	(S-3)	(S-1)	(S-2)	(S-3)
1	6	12	21	7	13	46
2	9	3	2	10	36	9
3	8	18	12	5	38	31
4	6	7	19	16	29	28
5	4	23	26	12	25	40
6	3	11	15	13	17	12
	(S-5)	(S-4)		(S-5)	(S-4)	
1	2	11		3	23	
2	5	27		5	56	
3	5	20		6	0	
4	2	12		10	49	
5	10	23		4	42	
6	3	5		6	36	
	(S-6)	(S-7)		(S-6)	(S-7)	
1	4	14		12	29	
2	7	7		6	11	
3	5	25		7	11	
4	2	19		16	29	
5	4	9		30	24	
6	6	10		18	15	
	(S-9)	(S-8)		(S-9)	(S-8)	
1	6	8		21	39	
2	4	6		8	13	
3	7	2		7	15	
4	12	5		3	6	
5	8	4		9	7	
6	3	3		8	9	
Av. no. $sample^{-1}$	6.0	11.3	15.4	10.8	24.6	27.8
Total species	9	7	3	11	14	5

S-5 Station designator

Chemical Changes

Phosphorus in the Spring Water

The phosphorus of the spring water deviated little from an average of about 7 ug liter^{-1} even though rainfall varied considerably (Fig. 18). Changes in the phosphorus of the spring water, therefore, do not cause fluctuations of phosphorus in the water of the pond.

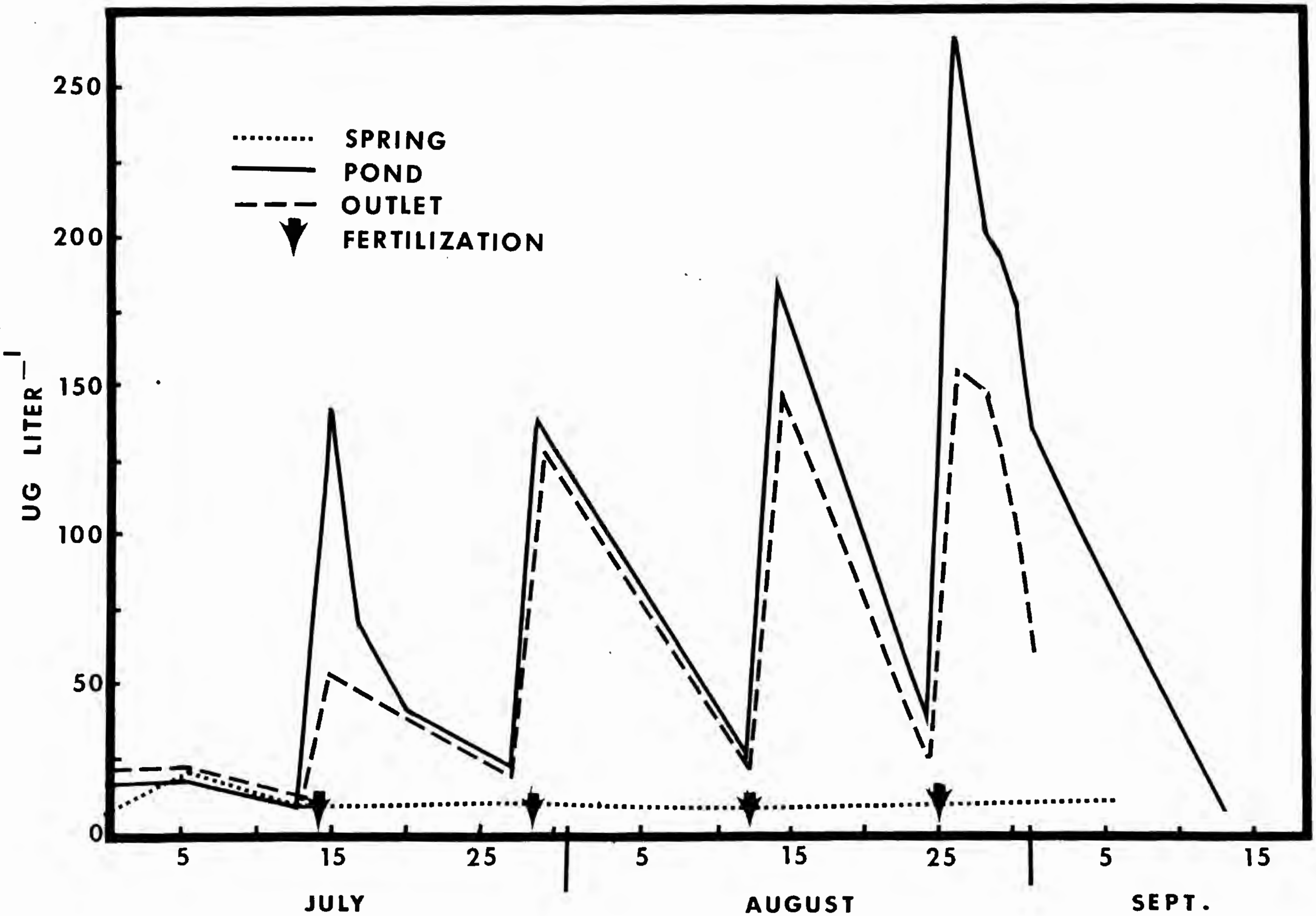
Phosphorus in the Pond Water

The pre-fertilization phosphorus of the pond water was about 15 ug liter^{-1} which is less than that normally found in lakes. Juday and Birge (1931) reported 23 ug liter^{-1} for Wisconsin lakes; Moyle (1949) reports about 47 ug liter^{-1} for Minnesota lakes.

Theoretically about 1 mg liter^{-1} phosphorus (P) was added to the pond with each application of the fertilizer. Within 24 hours, 80% of this had disappeared and the phosphorus in the water of the pond was 125-270 ug liter^{-1} with the larger concentrations occurring when fertilizer was added toward the end of the experiment. The rate of adsorption-absorption of the phosphorus decreased 2-3 days after the application of the fertilizer and the decline to about pre-fertilization levels occurred within 2 weeks.

Each application of chemical fertilizer the second year produced progressively higher maxima which were then followed by higher minima phosphorus concentrations in the water of the pond (Fig. 18). The data thus indicate progressively less adsorption by the marl substrate as phosphorus was added. This hypothesis is further substantiated by the observation that soluble phosphorus concentrations in the pond water of the first year were much lower than those of the second year

Fig. 18. Concentration of total phosphorus in the Pintail Spring, Pond and Stream water (1953). The increase and then the decline of the phosphorus concentrations in the water of the Pond for the first and last fertilizer treatments are based on daily phosphorus determinations. Maxima and minima resulting from the other treatments are shown.


SPRING
POND
OUTLET
FERTILIZATION
UG LITER⁻¹
0
50
100
150
200
250
5
15
25
5
15
25
5
15
JULY
AUGUST
SEPT.

(Tables 59 and 60 Appendix II).

Organic phosphorus increased after each fertilizer treatment and soluble phosphorus remained in high concentrations in the water of the pond for 5-6 days after the fertilizer was added (Table 60).

The data show therefore that most of the phosphorus added to a hypermarl pond disappears from the water within one day. However, not all the phosphorus is immediately precipitated, and 3-20 times normal concentrations are available within the water for several days which is long enough to be absorbed by plants. Tables 59 and 60, Appendix II, show the phosphorus data for Pintail Spring, Pond and Outlet.

Potassium

Potassium determinations for Pintail Spring, Pond and Stream waters were made during the first year of the study. Potassium in the spring water ranged between .2-.7 mg liter^{-1} and averaged .3 mg liter^{-1}. The pre-fertilization potassium tests of Pintail pond waters indicate that concentrations are about .5 mg liter^{-1} which is lower than those usually found in eutrophic lakes (Barrett, 1957). Potassium in the water of Pintail outlet was almost the same as that of the pond. The application of the chemical fertilizer raised the potassium concentration in the pond from a pre-fertilization value of about .7 mg liter^{-1} to 2.7 mg liter^{-1}. Theoretically, about 1.7 mg liter^{-1} was added to the pond with each fertilizer treatment. Thus one would have predicted the potassium concentration in the water of the pond to be about 2.4 mg liter^{-1} after fertilization. Absorption-adsorption of potassium apparently was slow. Potassium concentrations in the water remained higher than normal for 3 weeks after the application of the fertilizer.

Table 55 of Appendix II shows the data.

Calcium-Magnesium Hardness

The pond and stream water hardness trends the first year were basically dissimilar from those of the spring water (Fig. 19). Spring water fluctuated between 174-227 mg liter^{-1}; pond water, between 152-211 mg liter^{-1}; stream water, 151-209 mg liter^{-1}. A study of differences shows conclusively that all fluctuations in pond and stream water chemistry do not originate at the water source. It has been shown that fluctuations in water chemistry of this pond may be attributed to phytoplankton populations in the pond and local rainfall.

Hardness data for the spring and pond the second year of the study (1953) are shown in Fig. 20. Spring water hardness fluctuated from 222-229 mg liter^{-1}. The pond hardness fluctuated between 181-214 mg liter^{-1}, decreasing generally through the summer but noticeably increasing immediately after each fertilizer application. The increases in the hardness of the water of Pintail Pond following each fertilizer application resulted from: (i) the addition of calcium to the pond in the superphosphate fertilizer and (ii) re-solution of calcium and magnesium from the pond substrate when the fertilizer was added. Re-solution was undoubtedly the greatest factor since computations show that the amount of calcium and magnesium in the superphosphate could not have raised the calcium concentration of the pond more than 2.5 mg liter^{-1}. Since the increases in pond hardness following each fertilizer application varied from 1.8-25 mg liter^{-1}, it is evident that re-solution of the marl substrate must have taken place. Fig. 20 shows the relationship between pond hardness prior to the addition of the

Fig. 19. Calcium-magnesium hardness in Pintail Spring, Pond and Stream Water (1952). Increases in hardness after each fertilization (See also Fig. 20) resulted from the re-solution of the calcium carbonate substrate. (See text, p. 110, 115). Low hardness in the spring water between July 24 - Aug. 15 is the result of heavy rainfall (See text p. 78). Low hardness in pond and stream water between July 17 - Aug. 10 and Aug. 20 - Sept. 10 is attributed to the metabolic activities of the phytoplankton (See text p. 81).

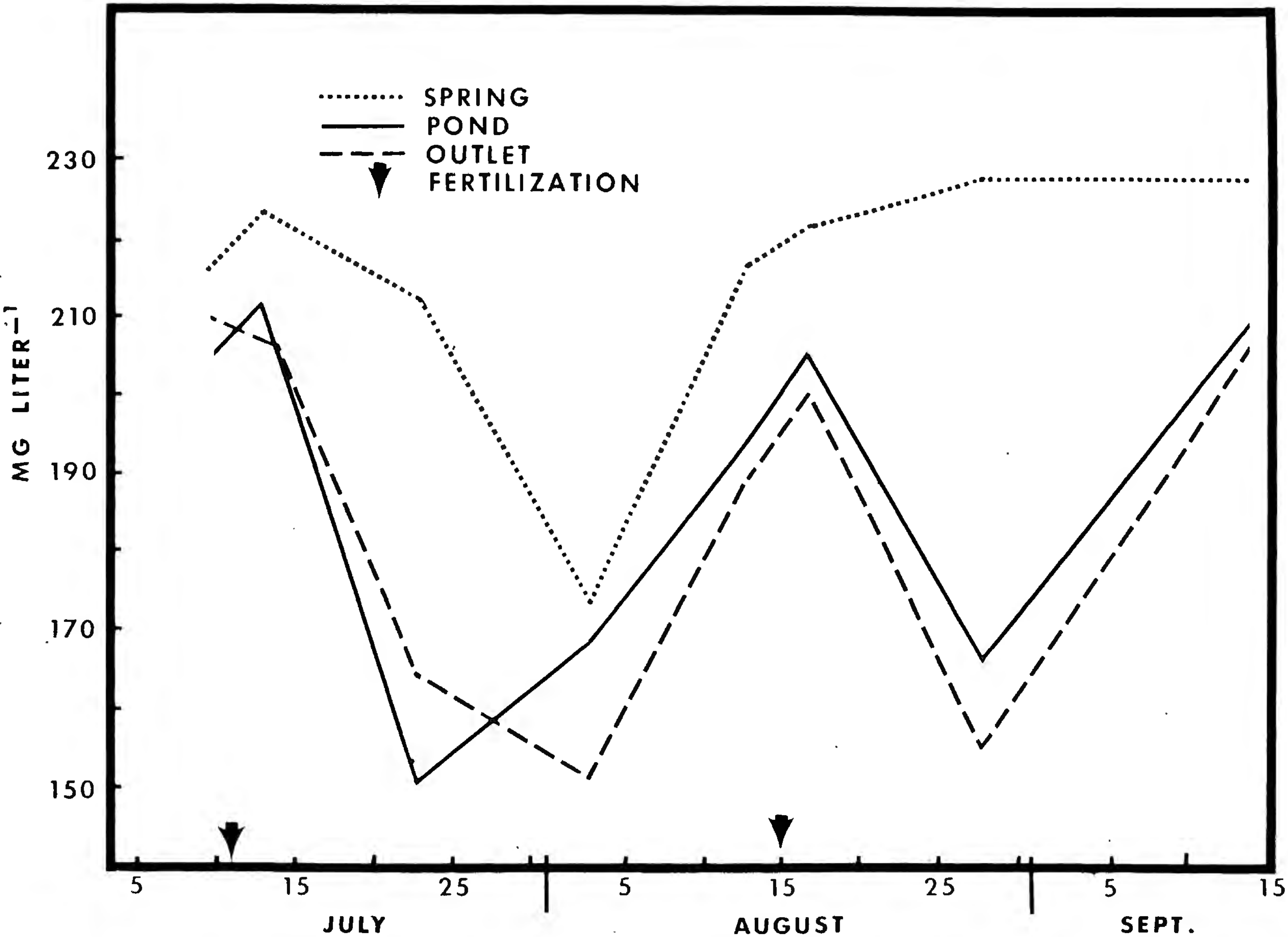
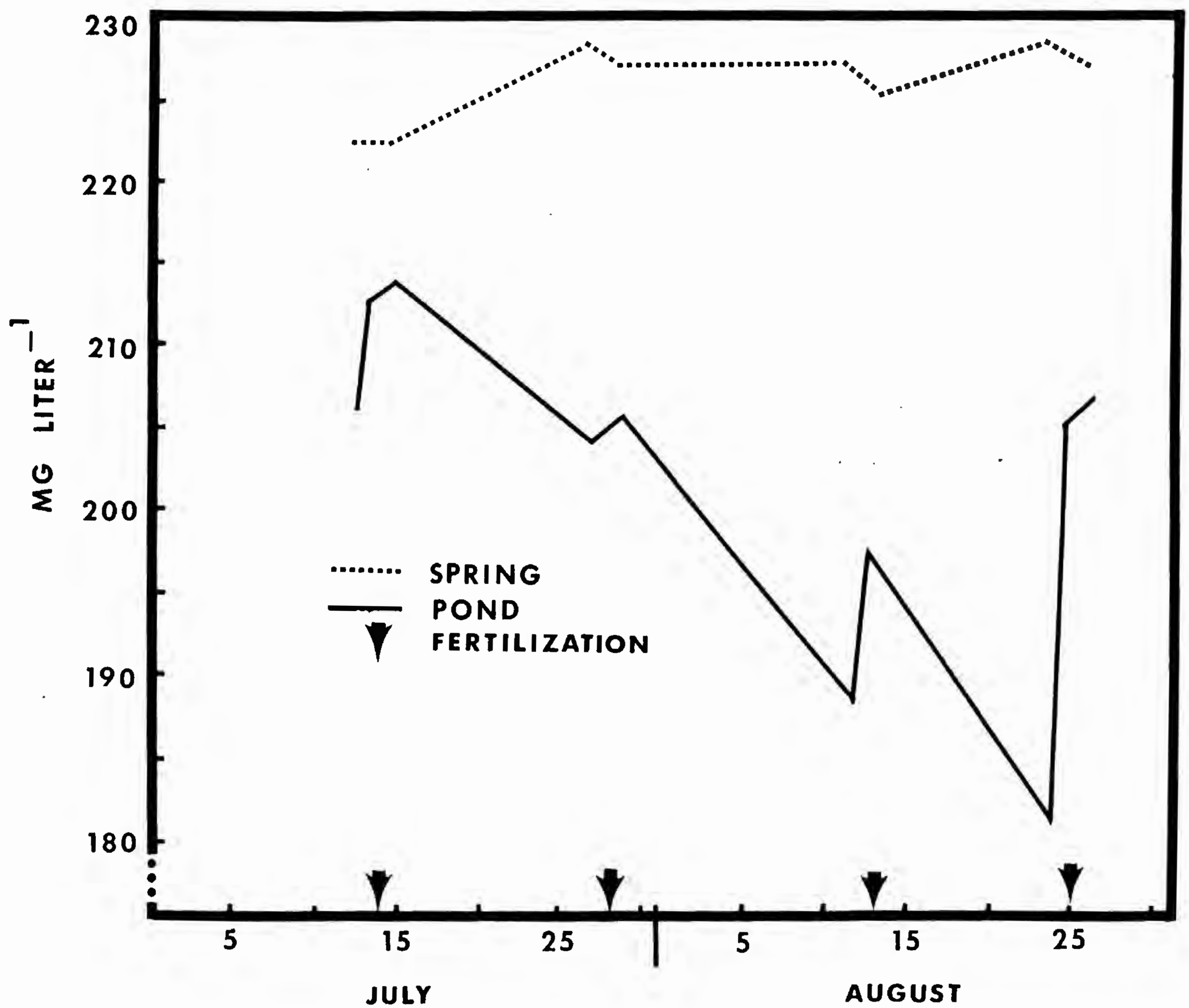

SPRING
POND
OUTLET
FERTILIZATION
230
210
190
170
150
MG LITER^{-1}
5
15
25
5
15
25
5
15
JULY
AUGUST
SEPT.

Fig. 20. Calcium-magnesium hardness of Pintail Spring and Pond Water the second year (1953). Increases in hardness after each fertilizer application (See also Fig. 19) resulted from the re-solution of the calcium carbonate substrate (See text, p. 110 and 115). The general decline of hardness in the pond water from July 15 - Aug. 25 is attributed to the increases in phytoplankton (See text p. 81).


230
220
210
200
190
180
MG LITER^{-1}
SPRING
POND
FERTILIZATION
5
15
25
5
15
25
JULY
AUGUST

fertilizer and the increase in hardness which followed the application of the fertilizer. Adding fertilizer increased the calcium-magnesium carbonate hardness and the non-carbonate hardness of pond water. Thus the fluctuations in calcium-magnesium hardness of Pintail Pond water may be attributed to rainfall, phytoplankton volume, and the addition of chemical fertilizer (See text p. 78, 81, 110).

Calcium trends during the two years were not materially different from those for total hardness.

Hydrogen Ion Concentration

The pH of spring water averaged about 7.3 and did not cause the changes in pH of the pond water. Pond pH normally ranged between 8.1-8.4 with highest measurements occurring in August. The pH of Pintail Pond water showed a large decrease immediately after fertilizer application (Table 32, July 28), probably a result of the ionization of the fertilizer and the formation of phosphoric acid. The effect remained for a few minutes but was quickly nullified by the highly buffered pond water and thick deposits of calcium-magnesium carbonate substrate. The pH then increased to a point above the pre-fertilization measurements (Table 32). This increase in pH is attributed to the re-solution of substrate materials which is also indicated by the increases in the conductivity and calcium-magnesium hardness of the pond water (Table 32). Pintail Outlet pH trends were similar to pond pH trends but fluctuated over a wider range (7.9-8.5). The data are shown in Appendix II.

TABLE 32.--The Hydrogen Ion Concentration and Conductivity (25°C-10^{-6}) of the Water of Pintail Pond Before and After Artificial Fertilization (1953)

Date	pH	Conductivity (25°C-10^{-6})	Hardness (mg $liter^{-1}$)
7/13*	8.10	332	206
7/15**	8.15	368	214
7/27*	8.10	300	204
7/29**	8.25	351	206
8/12*	8.10	267	188
8/13**	8.20	294	198
8/24*	8.35	298	181
8/26**	8.25	368	206

7/28	Before fertilizer applied- - - - - -	8.10
	Immediately after fertilizer applied	7.70
	100 minutes after fertilizer applied	8.10

* before fertilizer added

**after fertilizer added

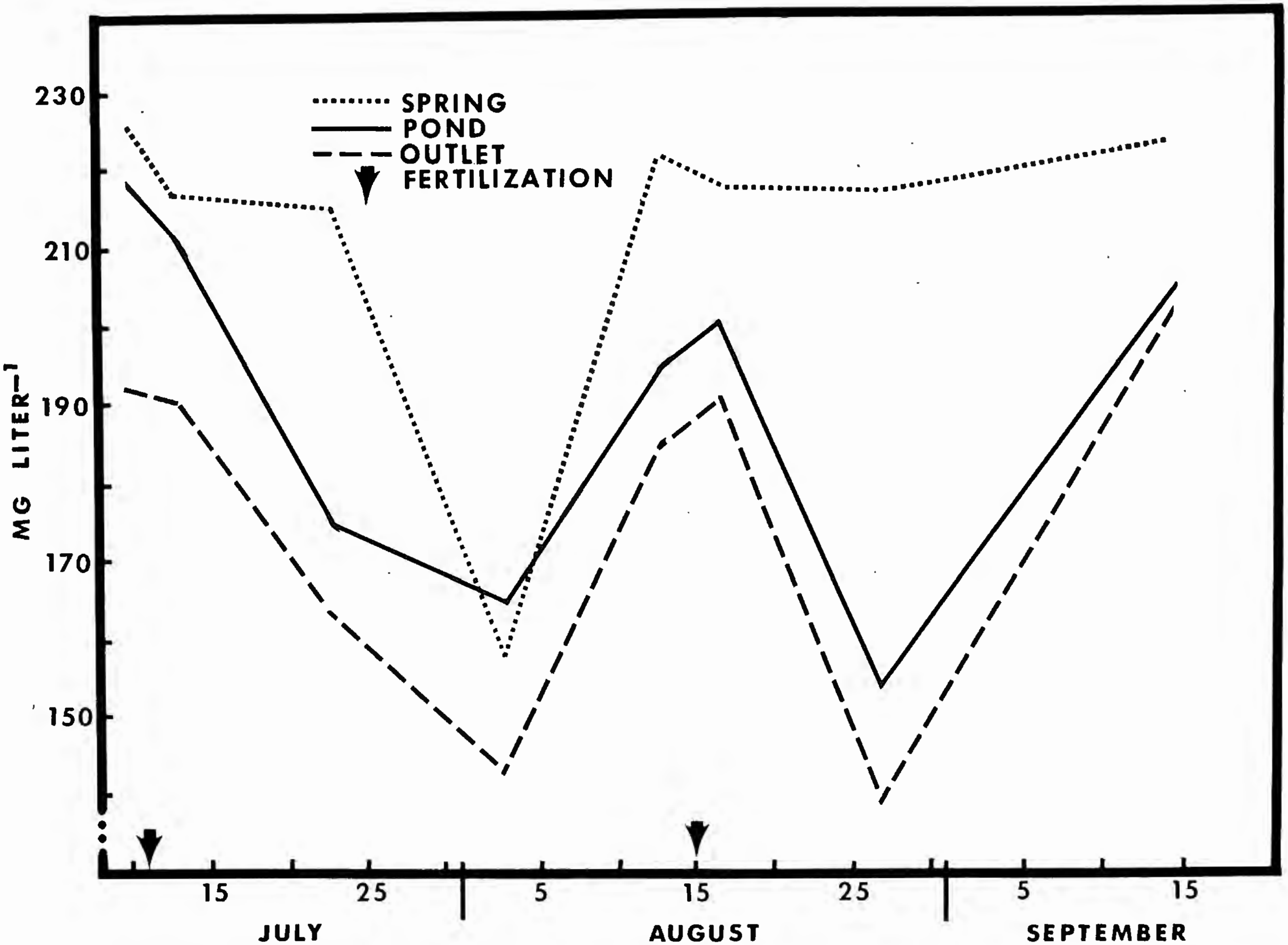
Alkalinity

Trends in the total alkalinity of the spring and pond water throughout the first and second year of study are indicated in Figs. 21 and 22.

The alkalinity of the spring water varied between 158 - 226 mg $liter^{-1}$. Lowest values occurred during rainy periods.

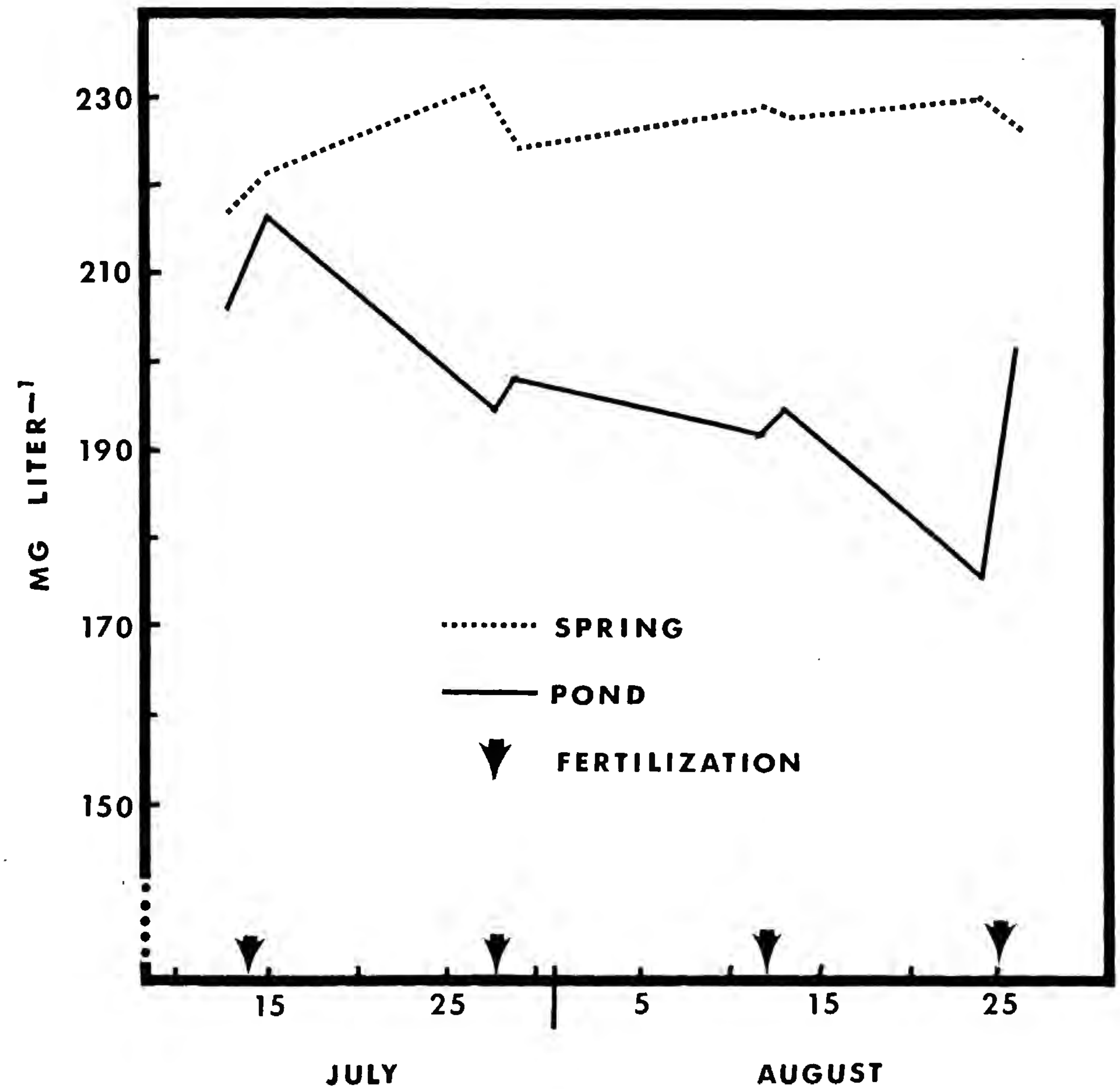
Pond alkalinity varied from 152 - 211 mg $liter^{-1}$. Increases in the pond carbonate and bicarbonate alkalinity occurred after 5 of the 6 fertilizer applications. Ball (1950) reported an increase in alkalinity from 48 to 58 mg $liter^{-1}$ in South Twin lake that had received numerous applications of fertilizer. The single exception in the Pintail tests (July 10-13 of the first year) is attributed to the heavy rainfall which

Fig. 21. Total Alkalinity in Pintail Spring, Pond and Stream water the first year (1952). Low alkalinity in the spring water between July 24 - Aug. 15 is the result of heavy rainfall. Low alkalinity in pond and stream water between July 17 - Aug. 10 and Aug. 20 - Sept. 10 is attributed to the metabolic activities of the phytoplankton (See text p. 81).



SPRING
POND
OUTLET
FERTILIZATION
230
210
190
170
150
MG LITER⁻¹
15
25
5
15
25
5
15
JULY
AUGUST
SEPTEMBER

Fig. 22. Total alkalinity in Pintail Spring and Pond Water (1953) Increases in alkalinity after each fertilizer application resulted from the re-solution of the calcium carbonate substrate (See text p. 110, 115 and 116). The general decline of alkalinity in the pond water from July 15 - Aug. 26 is attributed to the increases in phytoplankton (See text p. 81).


230
210
190
170
150
MG LITER⁻¹
SPRING
POND
FERTILIZATION
15
25
5
15
25
JULY
AUGUST

counteracted the usual increases in alkalinity following application of the fertilizer. Fluctuations in the alkalinity of Pintail Pond water, at times other than those immediately following the application of fertilizer, have been shown dependent upon variations in local rainfall or phytoplankton volume. The quantitative relationships between these three ecological factors have been shown previously.

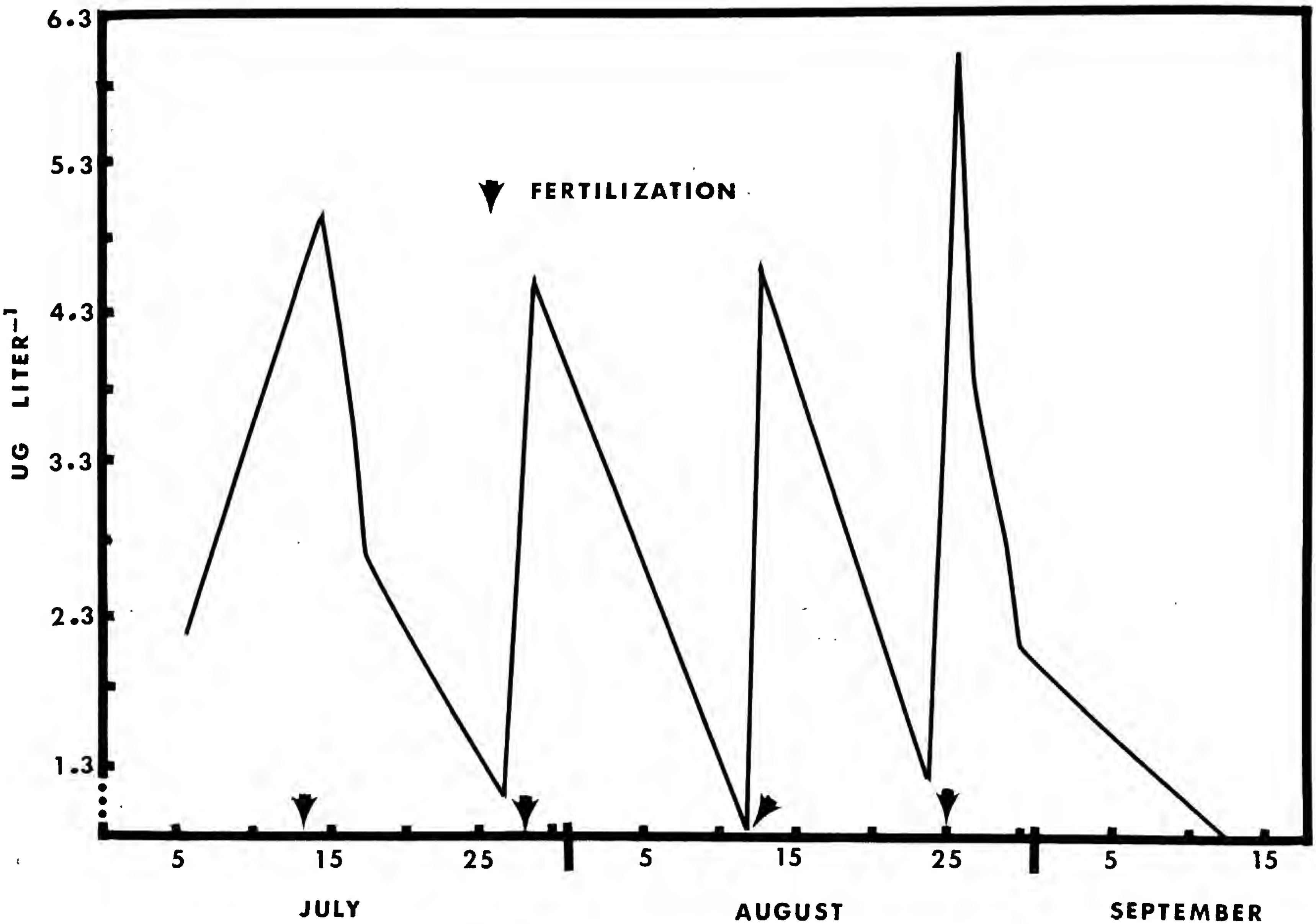
Alkalinities of the stream waters were about 10 mg liter^{-1} less than the pond alkalinities.

Nitrogen in the Water

Total nitrogen of Pintail Spring water averaged .74 mg liter^{-1}, organic nitrogen about .61 mg liter^{-1}, and ammonia nitrogen (NH_4) about .13 mg liter^{-1}.

Total nitrogen of pond waters before applications of fertilizer averaged about 1.00 mg liter^{-1}, except for the July 6th pre-fertilization sample which was considerably higher. This unusually high pre-fertilization concentration was associated with abnormally heavy rainfall during the week preceding the sample date. Theoretically, about 4 mg liter^{-1} nitrogen was added to the pond with each fertilizer treatment. Thus one would expect the total nitrogen concentration in the waters of the pond to be about 5.00 mg liter^{-1} after fertilization if the nitrogen were not immediately adsorbed or precipitated. Since the post-fertilization total nitrogen concentrations averaged nearly 5.00 mg liter^{-1} (Fig. 23), it is concluded that very small quantities of the nitrogen were lost within the 24 hrs subsequent to fertilization. Normal pond organic nitrogen fluctuated from .60 to 1.20 mg liter^{-1} and doubled after fertilizer applications. The normal concentration

Fig. 23. Concentration of total nitrogen in Pintail Pond water the second year (1953). The increase and then the decline of the nitrogen concentrations in the water of the Pond for the first and last treatments with fertilizer are based on daily nitrogen determinations. Maxima and minima resulting from the other treatments are shown.


6.3
5.3
4.3
3.3
2.3
1.3
UG LITER⁻¹
FERTILIZATION
5
15
25
5
15
25
5
15
JULY
AUGUST
SEPTEMBER

of ammonia in the pond averaged about .25 mg liter^{-1} although heavy rains brought increases to more than 1.00 mg liter^{-1}. The fertilizer applications raised ammonia progressively with each successive treatment the second year, indicating progressively less interaction with the marl substrate. The increases averaged 3.72 mg liter^{-1}. Dissipation of the ammonia to normal concentrations occurred within 6 days after fertilizer application. The data are shown in Appendix II.

Addition of Earthern Materials to the Marl Substrate

Relationships of plant growth to the substrate in marl lakes have received little attention. Wohlschlag (1950) performed experiments using three rooted aquatic plants and four Wabee Lake substrate soil types. These experiments suggested the efficacy of marl-soil mixtures in supporting plant growth on marl substrates. Surveys of several marl lakes showed that the macrohydrophytes grew in the darker marl soils. Hutchinson (1957) has referred to the littoral vegetation and the organic matter as the major storage place for phosphorus. If it could be established that the lack of organic matter was a limiting factor in plant growth, lake production could be increased by adding organic materials to the substrate.

Experiments were designed to test (i) the hypothesis that organic materials added to the North Lake substrate would be an effective and feasible means for increasing the productivity, (ii) the comparative effectiveness of several easily obtainable organic materials, (iii) the comparative growth responses of several hydrophytes, and (iv) methods for planting and placement of organic materials on marl substrates in lakes.

Test of Substrates

Two Latin Square experiments (method of Fisher, 1947) totaling 72 cells were placed in North Lake in water 4-6 ft deep near the AA experimental area (Fig. 3). This is the shallow, protected bay area near the outlet of North Lake where disturbances by wave action and shore currents were minimized. Although an area barren of plants was selected for the experiments, a few aquatic plants grew in the peat-marl substrate nearby. The types of containers and the retrievable racks designed for the experiments are shown in Fig. 24. The containers were filled with marl, peat, sand, sand over peat, sod, and sewage sludge and planted with two 6 in. shoots of *Myriophyllum spicatum*. The first and second experiments were placed in the lake in October (1953, 1954) and retrieved in August (1954, 1955), respectively. The data are shown in Tables 45 and 46 of Appendix I.

The analysis of variance for the combined data of the two experiments is given in Table 33, and the significance of individual treatments based on the "Multiple Range and Multiple F" tests of Duncan (1955) are shown in Table 34. Conclusions from these two experiments are: (i) some substrate materials produced significantly more plant growth than others; (ii) the two experiments did not differ significantly from each other; (iii) the rows and columns within the experiments did not produce significantly different plant growth and no significant interaction between treatment and experiment, rows and experiment, or columns and experiment was detected. Therefore, it is concluded that the directional orientation of the experiments, the depth of water, sunlight, and currents affected all containers equally; (iv) substrate materials arranged in increasing order of effectiveness in

Fig. 24. Retrievable racks and attached containers used in the Latin Square experiments of substrate materials.

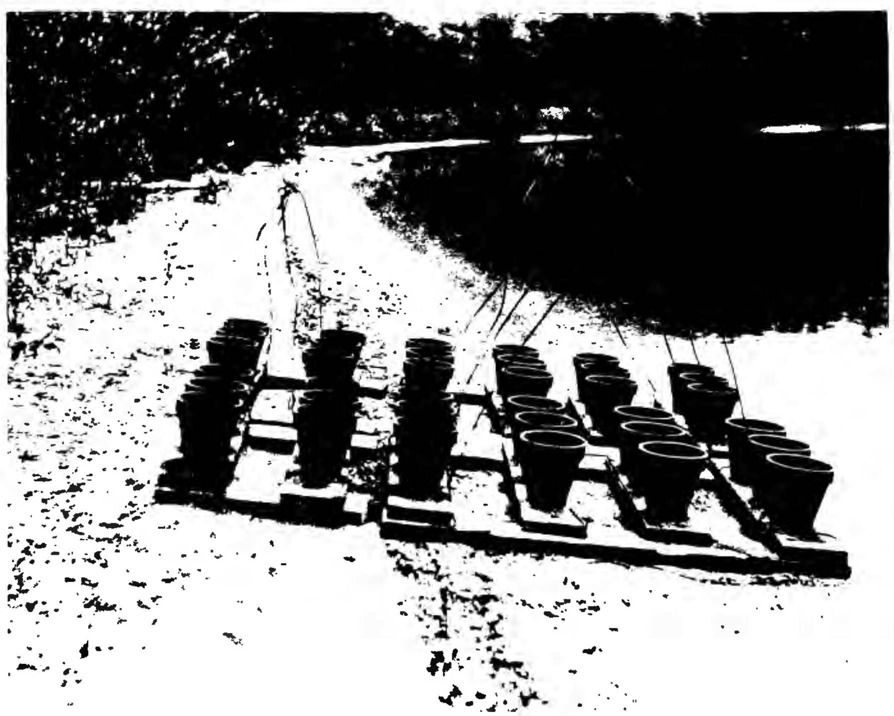


TABLE 33.--Analysis of Variance for Combined Latin Square Tests No. 1 and No. 2

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Total	71	92.877	--	40.000
Treatment	5	64.619	12.924	31.139**
Treatment x Experiment	5	2.848	.570	1.373
Experiments	1	.042	.042	.101
Rows	5	1.193	.238	.573
Experiments x Rows	5	1.556	.311	.749
Columns	5	4.881	.976	2.351
Columns x Experiments	5	1.101	.220	.530
Error	40	16.637	.475	

(Correction term = 10.418)

**significant to 1% level.

Data are shown in Tables 45 and 46 of Appendix I.

TABLE 34.--The Growth of *Myriophyllum spicatum* on Several Substrate Materials*

Substrates Producing Significantly Greater Quantities of *Myriophyllum*

Substrates Producing Significantly Less Quantities of *Myriophyllum*	Sewage	Marl	Sand	Sand/Peat	Peat	Sod
Sewage	—	+	+	+	+	+
Marl		—	+	+	+	+
Sand			—	+	+	+
Sand/Peat				—	Not sig.	Not sig.
Peat					—	Not sig.
Sod						—

*After the method of Duncan (1955)

producing *Myriophyllum* growth were sewage sludge, marl, sand, sand over peat, peat, and sod. Significant differences between sand over peat, peat, and sod were not demonstrated.

Experimental Plots

Three series of plots were established in North Lake (AA, BB, CC, Fig. 3) to test the effects of adding earthen materials to a marl lake substrate on plant growth and bottom fauna populations. The areas selected for the plots had a uniform, white marl, substrate and scant plant coverage. The plots measured 10 x 15 ft, and earthen materials were applied to form a cover 1-1/2 inches in depth. Each series of plots included the following treatments: sand over peat, peat, a sod plot and a control (the unaltered North Lake marl substratum). The AA series included a sand treatment in addition to the others. Plots were subdivided into 2 x 2 ft sample squares, leaving a narrow unsampled area around the perimeter of the plot. Estimates of plant populations were based on a complete harvest of 21 per cent of each plot (8 samples). Seven bottom fauna samples were collected from each plot by Petersen dredge.

BB and CC Experimental Series

The BB and CC series of plots were established in 1953 on the slopes of the main basin of North Lake (Fig. 3) where they were subjected to the usual wave and shore current action. Neither area originally supported hydrophytes. The depth of the water over the plots varied from 2 - 10 ft; the substrate was gray-white marl. The only detectable difference in the two areas was the basin slope. The BB plots were established on a steep basin slope having a drop of

5-8 in. ft^{-1} while the CC series of plots were established on a more gradual substrate which dropped 3 in. ft^{-1}. A standing crop of Chara, Najas and Sago averaged .8 g ft^{-2} on the two areas before treatments. Although the bottom fauna in the BB and CC series were not sampled before treatment, marl control plots showed an average of 18 organisms ft^{-2}. Hydrella and Hexagenia were most numerous.

In addition to earthen materials, each plot in the two series received similar plantings of the following plants: *Ruppia maritima*, *Salicornia Virginica*, *Sagittaria Rigida*, *Nelumbo Lutea*, *Potamogeton americanus*, *Vallisneria spiralis*, *Myriophyllum spicatum*, *Elodea Canadensis*, *Potamogeton perfoliatus*, *Potamogeton pectinatus* and *Zannichella sp*.

After one year estimates were made of the standing crop of plants (g ft^{-2}) on all plots in both series (Table 35). Tables 47 and 48 of Appendix I show the weight of the plants found in each sample. A statistical comparison of the plant sample weights collected on the two series of plots is shown in Fig. 25 (BB) and Fig. 26 (CC). The data show: (i) plant growth on the marl substrate of the two series of plots was similar (averaged 1.0 g ft^{-2}) and significantly less than for the other treatments, (ii) plantings on the unaltered marl substrate did not increase production, (iii) plant growth response to the treatments was similar in both areas, (iv) the sod treatment produced significantly greater plant growth than plots receiving other treatments, and (v) after one year the plant growth by weight was not significantly different on the plots receiving the peat and sand over peat treatments.

Adding peat and sand to the marl substrate caused increases in

TABLE 35.--Weight of Hydrophytes (g ft^{-2}) Collected from The BB and CC Experimental Plots in North Lake (1953-54)

BB Series

Plot No.	1	3	1	2	3	4
Year	1953	1953	1954	1954	1954	1954
Treatment	Control	Control	Control	Peat	Sand/Peat	Sod
g ft^{-2}	1.2	.4	1.7	25.5	36.5	183.4

CC Series

Plot No.	1	2	1	2	3	4
Year	1953	1953	1954	1954	1954	1954
Treatment	Control	Control	Control	Peat	Sand/Peat	Sod
g ft^{-2}	.8	.9	1.2	34.2	39.8	169.9

Fig. 25. Comparison of plant sample size from the BB experimental plots. Means and two standard errors of the means were plotted. Eight samples were collected from each plot. The symbols # and * show the plots sampled in consecutive years.

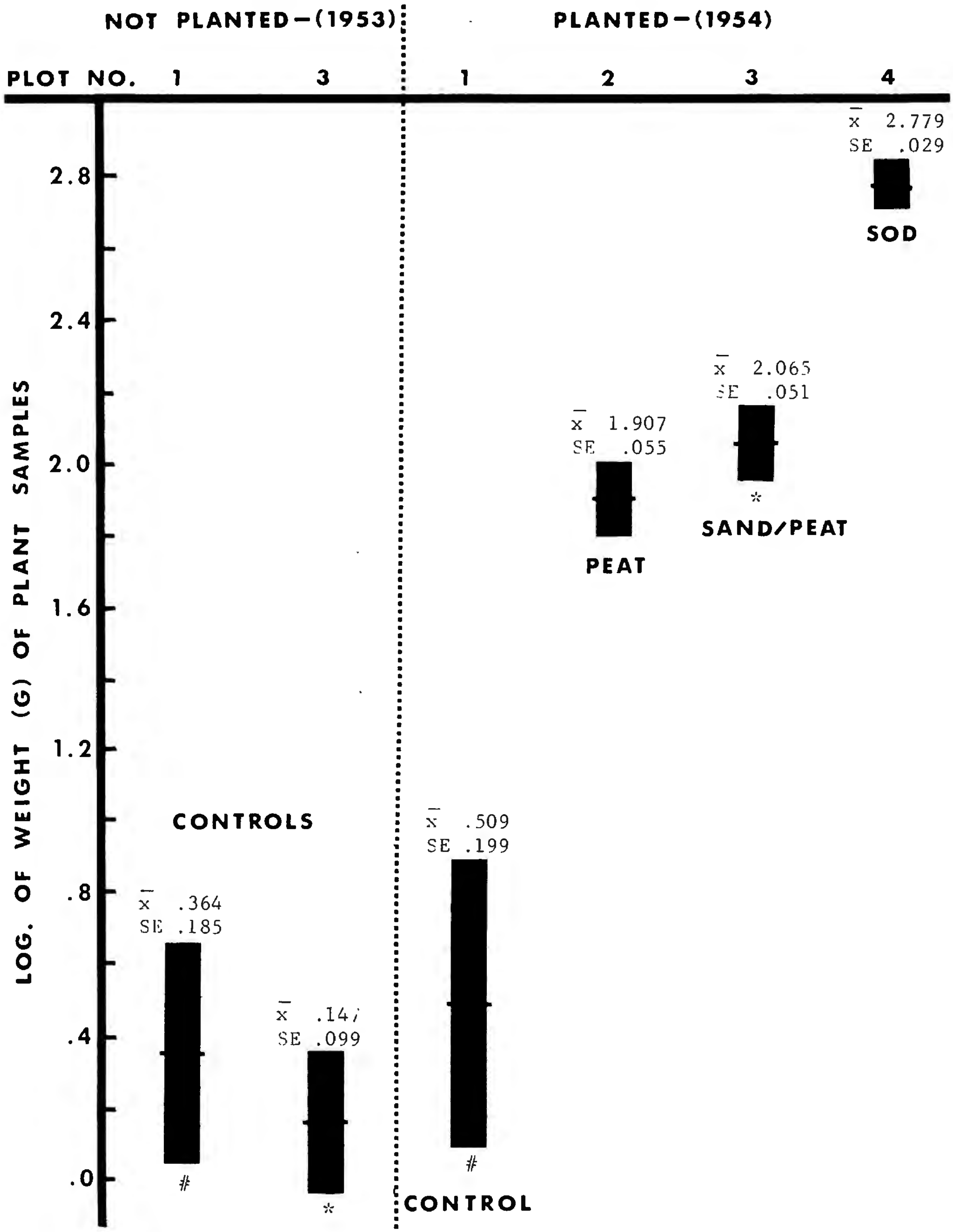
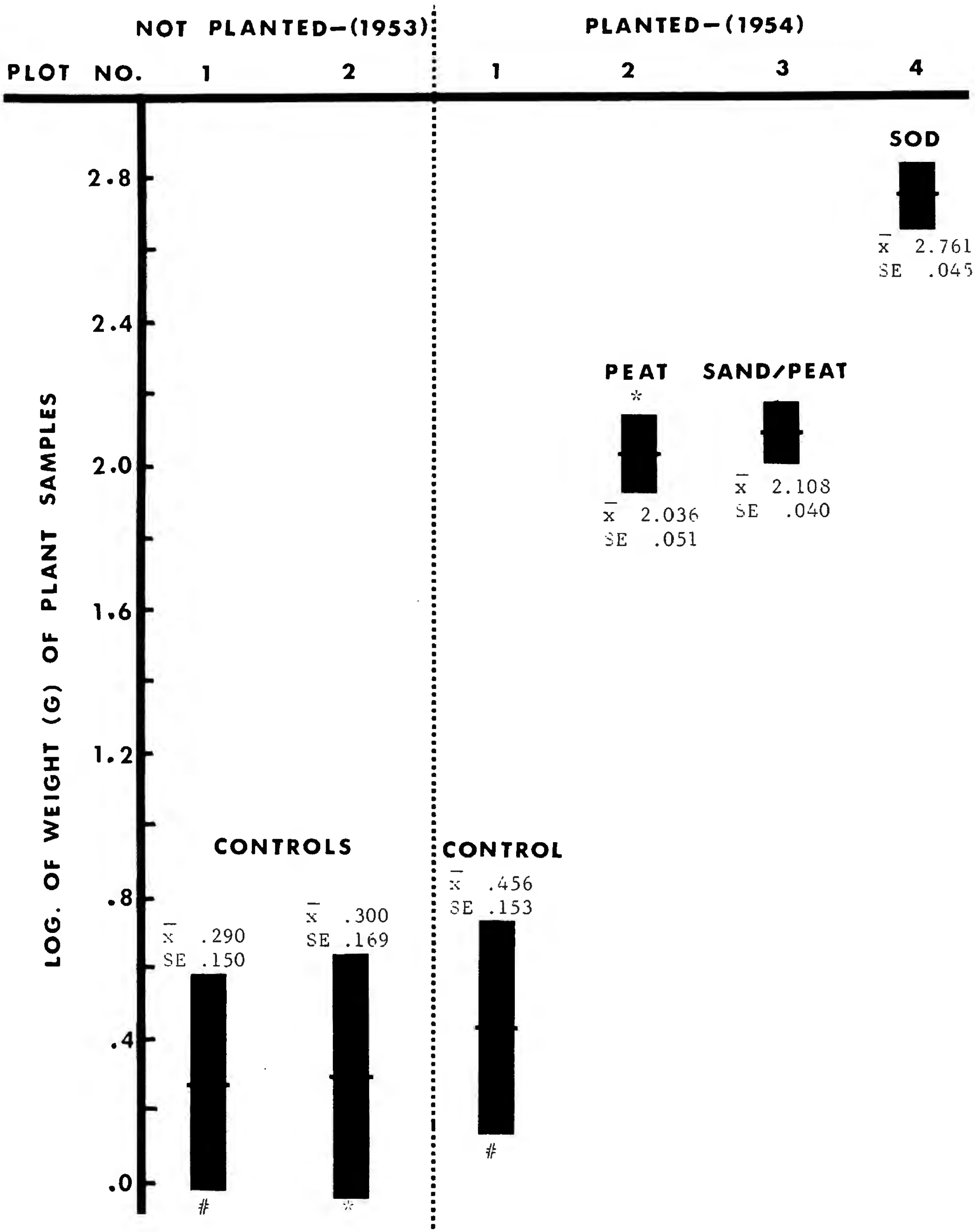

NOT PLANTED—(1953)
PLANTED—(1954)
PLOT NO. 1 3 1 2 3 4
x̄ 2.779
SE .029
SOD
x̄ 2.065
SE .051
x̄ 1.907
SE .055
SAND/PEAT
PEAT
CONTROLS
x̄ .509
SE .199
x̄ .364
SE .185
x̄ .147
SE .099
CONTROL
LOG. OF WEIGHT (G) OF PLANT SAMPLES
2.8
2.4
2.0
1.6
1.2
.8
.4
.0
#
*

Fig. 26. Comparison of plant sample size from the CC experimental plots. Means and two standard errors of the means are shown. Eight samples were collected from each plot. The symbols # and * show the plots sampled in consecutive years.


NOT PLANTED—(1953)
PLANTED—(1954)
PLOT NO. 1 2 1 2 3 4
LOG. OF WEIGHT (G) OF PLANT SAMPLES
2.8
2.4
2.0
1.6
1.2
.8
.4
.0
SOD
x̄ 2.761
SE .045
PEAT
SAND/PEAT
x̄ 2.036
SE .051
x̄ 2.108
SE .040
CONTROLS
x̄ .290
SE .150
x̄ .300
SE .169
CONTROL
x̄ .456
SE .153

production 35 fold. Adding sod caused increases in production of plants 175 fold (Fig. 27). The marl substrate of the control areas supported a scant growth of Najas, Chara and Sago. The peat, sand over peat, and sod treatments supported large standing crops of Myriophyllum, Elodea, Valisneria and Potamogeton americanus.

The CC plots were sampled for bottom fauna one year after the substrate was treated and planted with hydrophytes. Samples from the marl control plot contained Hexagenia, Caenis, and Hydrella. The standing crop was about 13 organisms ft^{-2}. The application of peat, and sand over peat, to the marl substrate increased standing crops of bottom fauna 2.6 fold. Sod applied to the marl substrate increased bottom fauna populations 20 fold and provided a suitable habitat for 17 genera. Paraleptophebia, Hydrella, Chromagrion, Polycentropus, and Hyalella were the most numerous organisms on plots receiving organic matter. A statistical comparison of bottom fauna sample sizes is shown in Fig. 28. The data may be found in Table 49 of Appendix I.

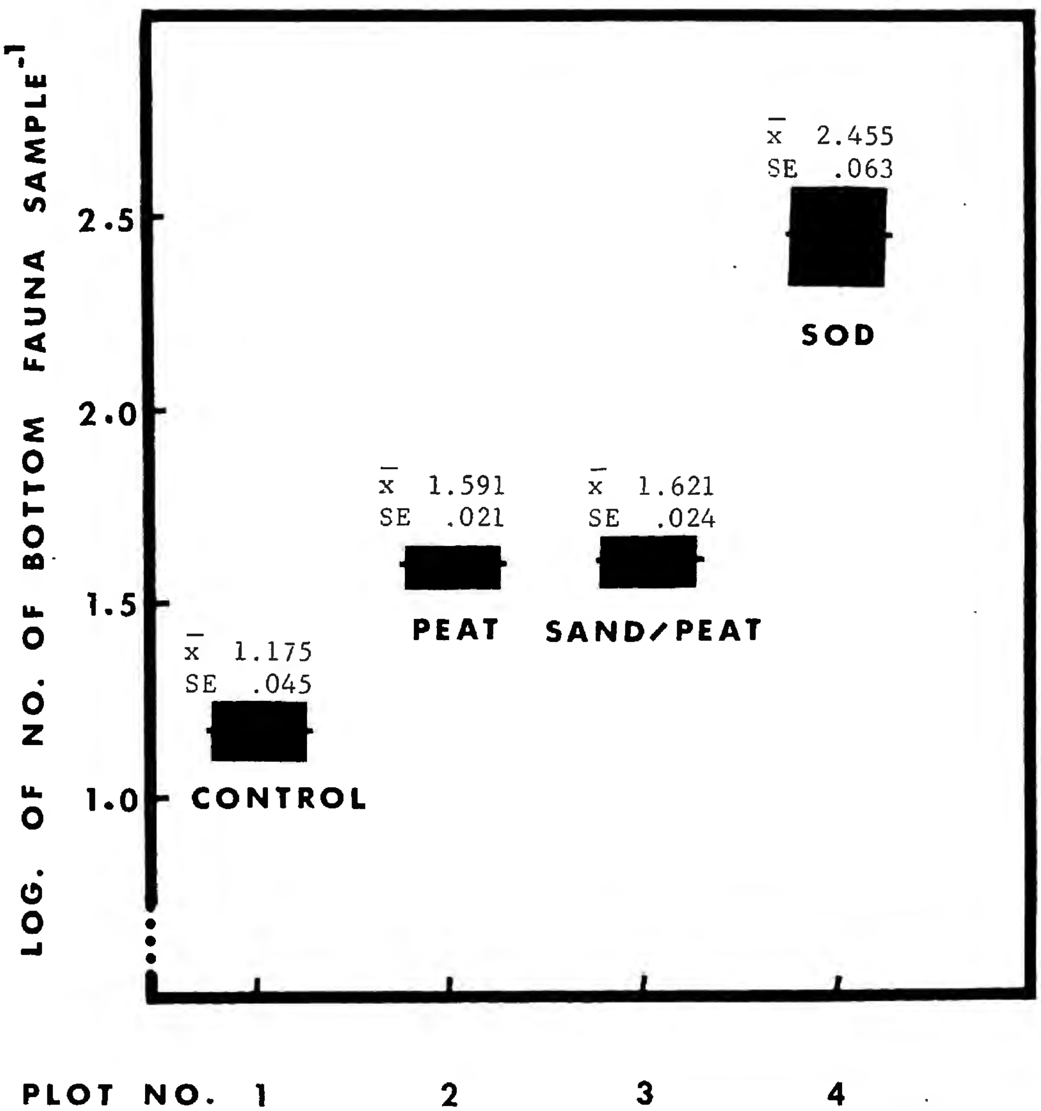
AA Experimental Series

The AA series of plots were established in the shallow, protected bay of North Lake near the outlet in 1952. The depth of the water for each plot varied from 2-6 ft; the substrate was gray-white marl with a slope of 1.6 in. ft^{-1}. Before treatment, the standing crop of plants (Chara, Najas) on the area averaged about 1.5 g ft^{-2}; the number of bottom fauna averaged 17 ft^{-2} and consisted mostly of Hexagenia and Calopsectra.

The AA series of plots received similar substrate treatments as the BB and CC series, but in addition included a plot receiving sand.

Fig. 27. Sod plot in CC series showing an abundant crop of aquatic plants. Similarly planted but barren Marl Control plot lies just beyond.

Fig. 28. Comparison of bottom fauna sample size from the CC experimental plots after one year of plant growth. Means and two standard errors of the means are shown. Seven samples were collected from each plot.



LOG. OF NO. OF BOTTOM FAUNA SAMPLE-1
2.5
2.0
1.5
1.0
x 2.455
SE .063
SOD
x 1.591
SE .021
PEAT
x 1.621
SE .024
SAND/PEAT
x 1.175
SE .045
CONTROL
PLOT NO. 1
2
3
4

Myriophyllum spicatum, *Najas flexilis*, *Elodea Canadensis*, *Ruppia maritima*, *Potamogeton perfoliatus*, *Potamogeton pectinatus* and *Potamogeton natans* were similarly planted on each plot. Standing crops of plants were measured after the growing season in 1953 and 1954. Standing crops of bottom fauna were measured in 1954.

All plants were removed from the AA plots and weighed at the end of the first growing season after treatment. The planted marl plots averaged about 2.0 g ft^{-2}, indicating that planting alone did not materially increase the production of plants. Sand suppressed plant production while applications of peat and sod to the marl caused increases in plant production of 22 and 82 fold, respectively. Table 36 shows a comparison of the plant production by weight on the experimental plots.

TABLE 36.--Production of Macrohydrophytes (g ft^{-2}) on the AA Experimental Plots at the End of the First Growing Season (1953) after Substrate Alteration Based on a Complete Harvest of the Plants

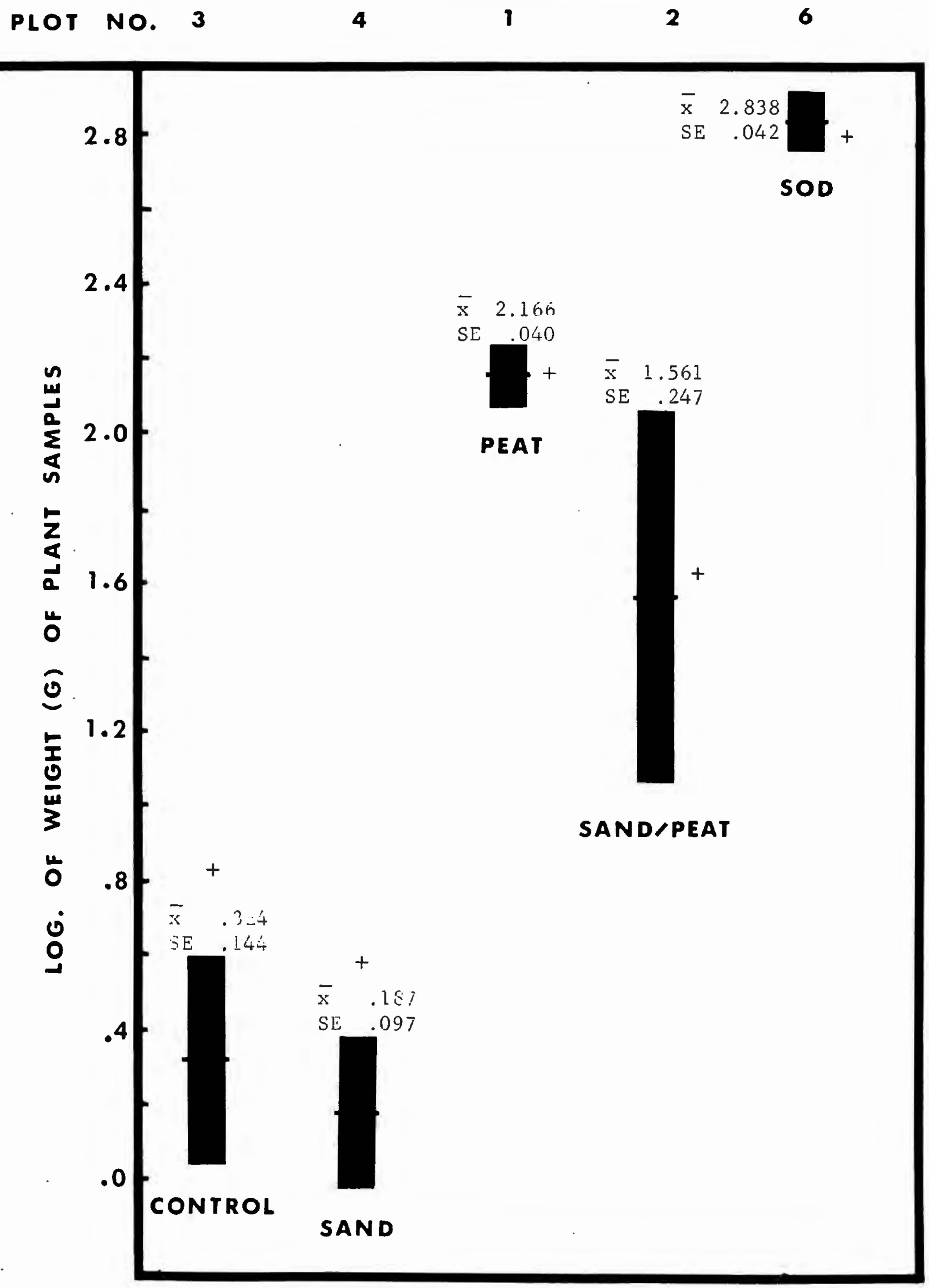
Treatment	Marl Plots		Sand	Peat	Sand/Peat	Sod
Plot No.	3	and 5	4	1	2	6
g ft^{-2}	2.68	1.29	1.01	44.36	13.14	164.22

The estimates of the standing crops of plants at the end of the second growing season (1954) were based on a harvest of 21% of each plot. The standing crops of plants the second year were about the same as for the first (Fig. 29, Table 50 Appendix I).

The AA plots were sampled for bottom fauna before substrate treatments were begun (1952), and a second series of samples was collected two years after treatment (1954).

Fig. 29. Comparison of plant sample size from the AA experimental plots after two years. Means and two standard errors of the means are shown. Eight samples were collected from each plot. The symbol + represents the standing crops of plants at the end of the growing season the first year.

SECOND YEAR'S PLANT GROWTH (1954)



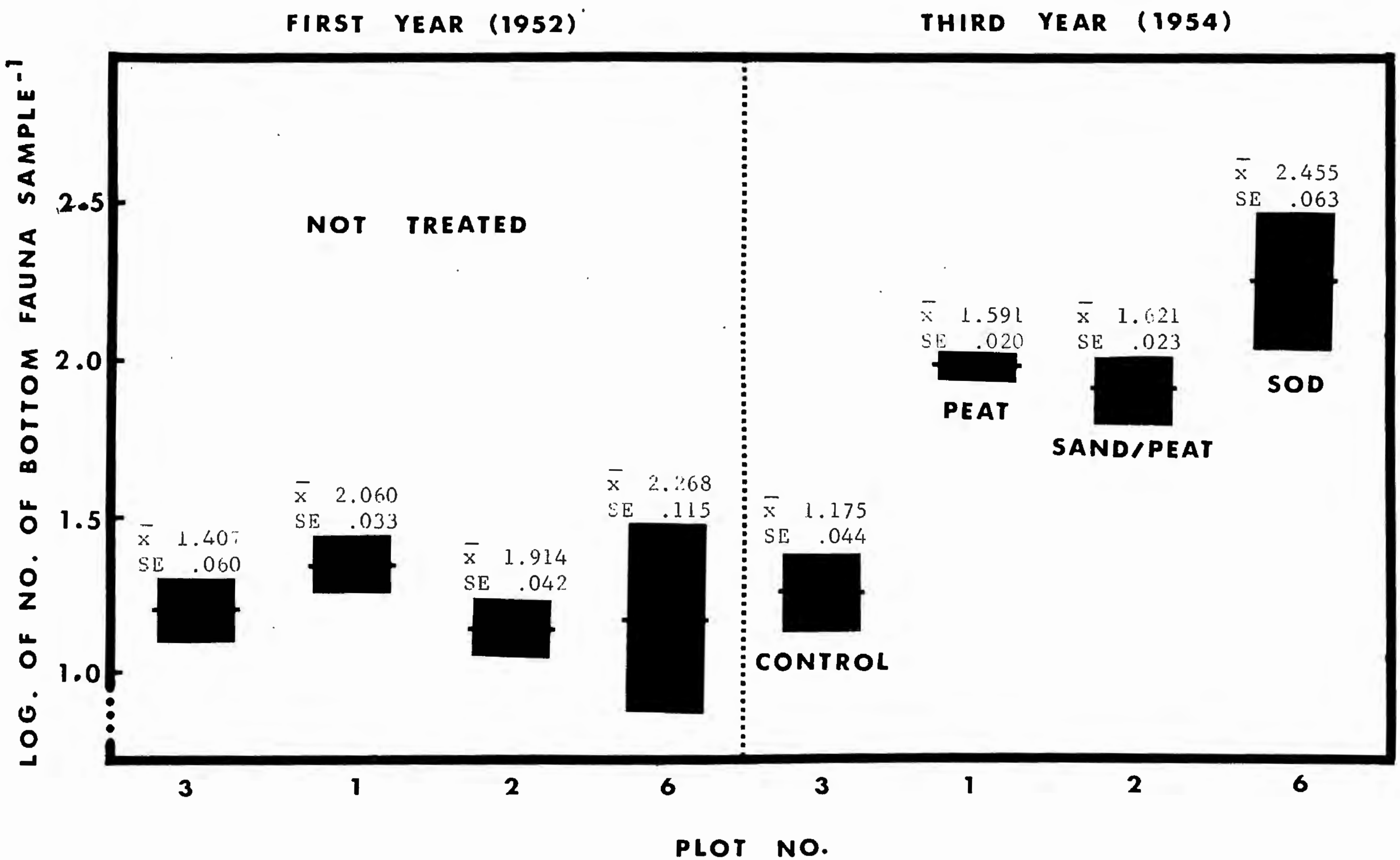
A statistical comparison of sample sizes (Fig. 30) shows: (i) the numbers of bottom fauna on the various plots before treatment did not vary significantly, (ii) no significant change in population numbers occurred on the control plots between years and (iii) peat, sand over peat, and sod treatments produced significantly larger numbers of bottom fauna than the unaltered marl substrate.

Statistical differences in numbers of bottom fauna between peat, sand over peat, and sod plots were not found for the AA series. However, it should be noted that the numbers of bottom fauna in samples from the sod plot are much larger than those taken from other plots (Fig. 30). The lightly weighted Petersen dredge used to sample the AA series failed to close completely on the sod and parts of some samples were lost. A heavily weighted dredge was used satisfactorily on the sod plot of the CC series, and significant differences in bottom fauna between plots receiving sod, peat, or sand over peat were shown.

The bottom fauna samples from the unaltered marl substrate supported 23 organisms ft^{-2}. _Hydrella_, and _Hexagenia_ were the most numerous organisms. The application of peat and sand over peat to the marl substrate increased standing crops of bottom fauna 3.7 fold. Sod applied to the marl substrate increased bottom fauna populations 8.5 fold. _Caenis_, _Paraleptophebia_, _Hydrella_, _Chromagrion_ and _Hyalella_ were numerous on plots receiving organic matter as a treatment.

An analysis of plant and bottom fauna samples collected from the AA, BB, and CC series of plots shows conclusively that adding organic matter to the marl lake substrate increases the basic productivity many fold. Table 37 is a summary of the findings.

Fig. 30. Bottom fauna sample size from the AA plots before and after substrate alteration. Means and two standard errors of the means are shown. Seven samples were collected from each plot.



FIRST YEAR (1952)
THIRD YEAR (1954)
LOG. OF NO. OF BOTTOM FAUNA SAMPLE-1
2.5
2.0
1.5
1.0
NOT TREATED
x̄ 1.407
SE .060
x̄ 2.060
SE .033
x̄ 1.914
SE .042
x̄ 2.268
SE .115
x̄ 1.175
SE .044
CONTROL
x̄ 1.591
SE .020
PEAT
x̄ 1.621
SE .023
SAND/PEAT
x̄ 2.455
SE .063
SOD
3
1
2
6
3
1
2
6
PLOT NO.

TABLE 37.--Standing Crops of Hydrophytes and Bottom Fauna on the Three Series of Experimental Plots in North Lake

AA Series

Treatment	Before Plots	Control	Peat	Sand/Peat	Sod
Plants g ft^{-2}	1.3	1.1	45.4	26.1	213.2
Bottom Fauna					
No. ft^{-2}	--	23.2	100.7	72.5	198.1
Species	--	6	11	10	16

BB Series

Treatment	Before Plots	Control	Peat	Sand/Peat	Sod
Plants g ft^{-2}	.8	1.7	25.5	36.5	183.4

CC Series

Treatment	Before Plots	Control	Peat	Sand/Peat	Sod
Plants g ft^{-2}	.9	1.2	34.2	39.8	169.9
Bottom Fauna					
No. ft^{-2}	--	13.1	33.8	36.4	259.7
Species	--	3	9	11	17

Bagged Organic Substrates

Difficulty was experienced in placing the organic matter accurately on the lake bottom and wildlife disturbed the newly planted areas. Bagged organic material containing aquatic plant seeds or root stocks was a possible solution.

Three series of burlap bags (Fig. 3 AA, BB, CC) were filled with peat and sewage sludge. Valisneria spiralis, Sagittaria rigida, Nymphaea ordorata, Potamogeton americanus, Potamogeton perfoliatus, and Potamogeton natans were the aquatic plants placed in the bags. Each experiment was triplicated at each of the three locations. The entire aquatic plant growth from each bag was harvested and weighed at the end of one year. Table 51 of Appendix I shows the data.

The statistical analysis of plant production on the three experimental series is presented in Table 38. In a final appraisal, however, the BB sewage sludge series was omitted because the basin slopes were too steep and some of the sludge was dispersed from rotted bags which split open decreasing plant production. With this exclusion Fig. 31 shows a comparison of plant production by species on bagged sewage sludge and peat substrates.

Conclusions from the analyses are as follows:

(i) Within the sewage series.--Production (wt) in order of decreasing magnitude was Potamogeton americanus, Valisneria spiralis, Potamogeton perfoliatus, Sagittaria rigida, Nymphaea odorata and Potamogeton natans. Increases in plant production over the unaltered marl substrate ranged between 39 and 615 fold.

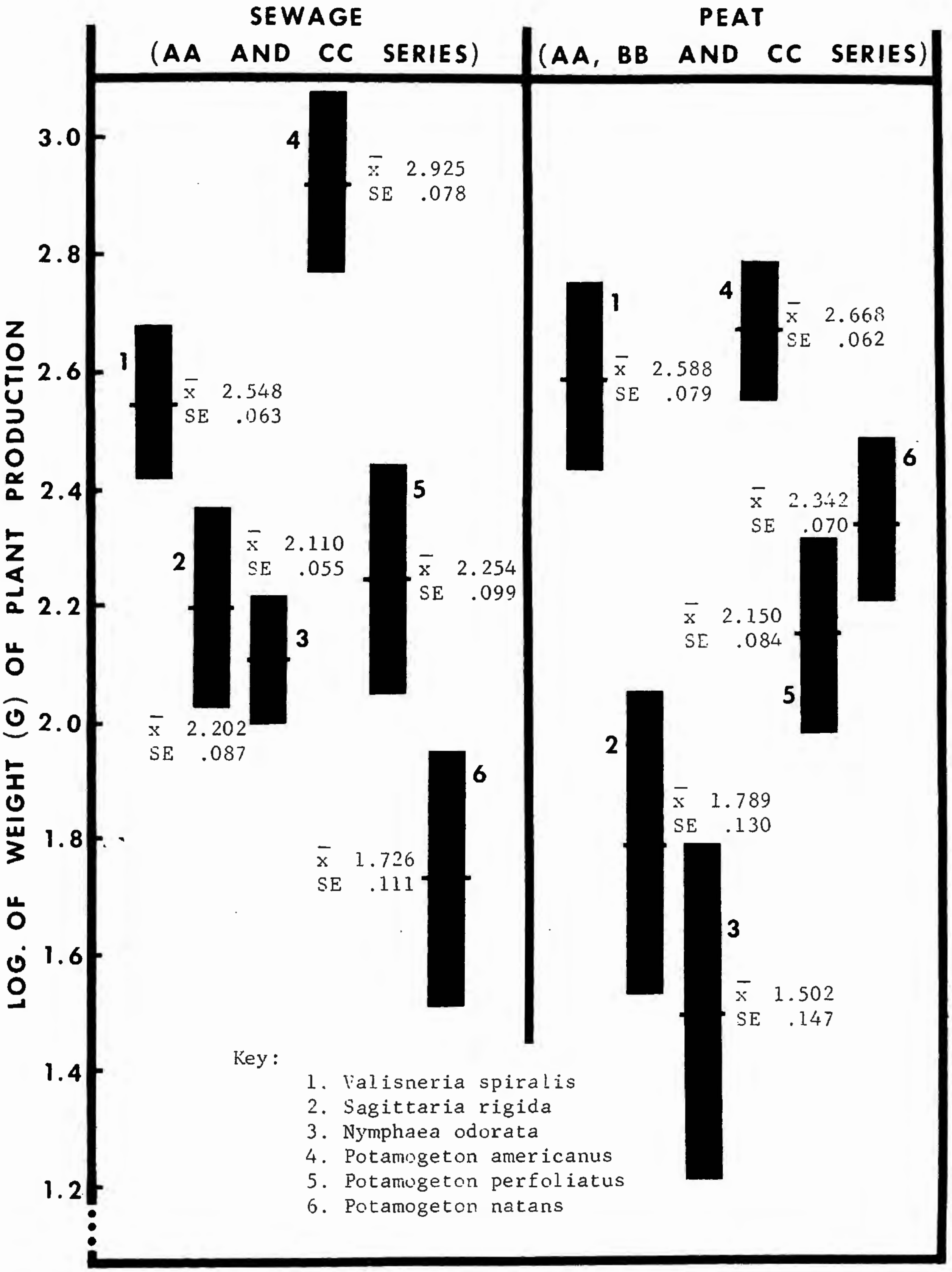
(ii) Within the peat series.--Production (wt) of the plants in order of decreasing magnitude was the same as within the sewage series

TABLE 38.--Significant differences in plant production on bagged sewage and peat substrates.*
(1. *Valisneria spiralis* 2. *Sagittaria rigida* 3. *Nymphaea odorata* 4. *Pot. americanus* 5. *Pot. perfoliatus* 6. *Pot. natans*).

CC Experimental Area	AA Experimental Area	BB Experimental Area
(a) Within the Sewage Series 4 is > 5, 1, 2, 3, 6 5 is > 1, 2, 3, 6 1 is > 2, 3, 6	(a) Within the Sewage Series 4 is > 1, 2, 5, 3, 6 1 is > 3, 5, 6 2, 5 are > 6	(a) Within the Sewage Series 4 is > 1, 2, 3, 5, 6 1 is > 3, 5, 6 2, 5 are > 6
(b) Within Peat Series 4 is > 5, 2, 3 1 is > 5, 2, 3 5, 6 are > 3	(b) Within Peat Series 4 is > 6, 2, 3 1, 2, 5, 6 are > 3	(b) Within Peat Series 4 is > 6, 2, 3 1, 5, 6, 2 are > 3
(c) Between Sewage and Peat Sewage 4 is > Peat 4, 1, 6, 5, 2, 3 Sewage 5 is > Peat 6, 5, 2, 3 Sewage 1 is > Peat 5, 2, 3 Sewage 2 is > Peat 3	(c) Between Sewage and Peat Sewage 4 is > Peat 5, 6, 2, 3 Sewage 1, 2, 5 are > Peat 3	(c) Between Sewage and Peat Sewage 4 is > Peat 5, 6, 2, 3 Sewage 1, 2, 5 are > Peat 3
Peat 4 is > Sewage 2, 3, 6 Peat 1 is > Sewage 3, 6 Peat 6 is > Sewage 3, 6 Peat 5, 2 are > Sewage 6	Peat 4 is > Sewage 1, 2, 5, 3, 6 Peat 1 is > Sewage 5, 3, 6 Peat 5, 6, 2 are > Sewage 6	Peat 4 is > Sewage 2, 5, 3, 6 Peat 1 is > Sewage 5, 3, 6 Peat 5, 6, 2 are > Sewage 6

*T test significance to the 1% - 5% level. The analyses are based on 108 cases (nine for each treatment). Numbers representing plant species are listed in order of decreasing yields (increasing significant differences).

Fig. 31. A comparison of plant production by weight (g) of species from sewage and peat filled bags in North Lake. Means and two standard errors of the means were plotted.


SEWAGE
(AA AND CC SERIES)
PEAT
(AA, BB AND CC SERIES)
LOG. OF WEIGHT (G) OF PLANT PRODUCTION
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1
x̄ 2.548
SE .063
2
x̄ 2.202
SE .087
3
x̄ 2.110
SE .055
4
x̄ 2.925
SE .078
5
x̄ 2.254
SE .099
6
x̄ 1.726
SE .111
1
x̄ 2.588
SE .079
2
x̄ 1.789
SE .130
3
x̄ 1.502
SE .147
4
x̄ 2.668
SE .062
5
x̄ 2.150
SE .084
6
x̄ 2.342
SE .070
Key:
1. Valisneria spiralis
2. Sagittaria rigida
3. Nymphaea odorata
4. Potamogeton americanus
5. Potamogeton perfoliatus
6. Potamogeton natans

except that *Potamogeton natans* was third highest in the peat series. Increases in plant production over the unaltered marl substrate ranged between 36 and 375 fold.

(iii) Between Sewage and Peat.--*Potamogeton americanus* growing on sewage sludge produced significantly more than any other treatment. Roots grew out 4 ft from the bags and supported healthy shoots (Fig. 32). *Valisneria spiralis* did about the same on both substrates and treatment resulted in a 288 fold increase in plant production. *Sagittaria rigida* and *Nymphaea odorata* grew significantly better on sewage sludge while *Potamogeton perfoliatus* responded about the same to both substrates. *Potamogeton natans* grew significantly better on the peat substrate.

Comparisons of plant production from plot type treatments and bagged organic matter treatments must be made with some reservations since the latter formed a thicker substrate and was planted differently. However, the data seem to justify the conclusion that the most effective bagged organic matter and plant treatments were about 3.5 fold greater than the most effective plot type treatments on a ft^{-2} basis. Stabilizing peat in bags was much more effective in stimulating plant growth (73-750 g ft^{-2}) than peat applied directly to the marl substrate (44 g ft^{-2}). The experiments show that lake management techniques devised and tested during this study increased North Lake plant production from less than 2.0 g ft^{-2} to 1,230 g ft^{-2}, a 600 fold increase.

Fig. 32. Large bed of *Potamogeton americanus* growing from bagged organic material.

DISCUSSION

The chemical and biological features of a Michigan hypermarl temperate second-order lake and a hypermarl temperate third-order lake were studied. There are three noticeable differences between marl and non-marl lakes. The first relates to the composition and the mechanisms of deposition of the deposits around the margin of a marl lake and within the lake basin. Secondly, deep hyper-marl lakes have precipitous basin slopes and a marl terrace which are not exhibited by shallow marl lakes or non-marl lakes. Finally, marl forming lakes characteristically support a sparse biota.

The Marl Deposits

A hypothesis which explains the development of marl lakes, the source for the material of the marl deposits, and the method of entry of the material into these lakes was found in a study of the region's geology, physiography, soil types and drainage patterns.

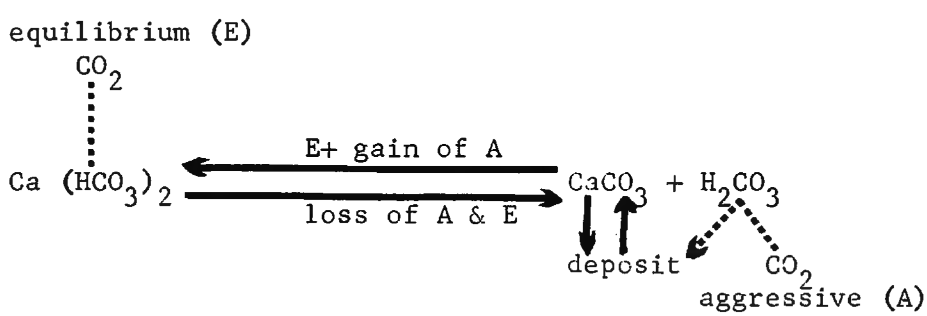
The underlying rocks in the region are sedimentary limestones, and overlying soils and moraines are partially structured of the fragments and glacial "rock flour" from these formations. The lakes (North Lake and Pintail Pond) have basins cradled in a glacial outwash valley between higher moraines. Drainage of the ground water is rapid through the upland soils, the high moraines and along the glacial outwash into the basins of the lakes. Rainwater percolating through the upper portion of the glacial drift of the moraines becomes weakly acid and carbon dioxide is absorbed from the soils. The carbonic acid thus formed dissolves minerals from the rock debris. According to Ruttner (1953), the following reactions take place:

(1) $H_2O + CO_2 \rightarrow H_2CO_3$ carbonic acid,

(2) H_2CO_3 + limestone $\rightarrow$ Ca $(HCO_3)_2$ soluble bicarbonate.

Some of the calcium bicarbonate and carbonic acid ionizes in reaction 2 so that the solution contains CO_2, H_2CO_3, HCO_3^-, H^+, Ca^{++}, HCO_3^- and OH^-. The quantity of OH^- is greater than the H^+ ions arising from the dissociation of H_2CO_3, making the solution alkaline. When compared to other Michigan lakes (Hooper, 1956), the waters entering North Lake and Pintail Pond contain large quantities of calcium and magnesium bicarbonate alkalinity.

The deposition of marl from a calcium carbonate solution results if the quantity of dissolved carbon dioxide in the solution is depleted. For calcium bicarbonate to be stable, free CO_2 must remain in the solution and disproportionately larger increases in CO_2 are required as alkalinity increases. This free CO_2 is labeled the "CO_2 of equilibrium." Quantities of free carbon dioxide in excess of that required for the equilibrium are designated "aggressive" since solution of calcium carbonate within a marl lake takes place. A carbon dioxide deficiency exists when quantities of free CO_2 decrease below the requirement for the calcium bicarbonate equilibrium. The system, described by Ruttner (1953), may be diagrammed as follows:



Most carbonate (marl) formed in the upper waters of North Lake as the carbon dioxide was lost to the atmosphere. Various mechanisms in the upper waters dissipate the carbon dioxide causing the calcium carbonate precipitation.

In agitated solutions, carbon dioxide is desaturated in proportion to the concentration in solution (Quinn et al., 1936), and wind is sometimes a cause of carbonate formation.

Temperature is a factor in carbonate formation. In North Lake where hydrophytes were not abundant, the carbonates of upper waters were directly correlated with summer temperatures. Increases in temperature decreased the solubility of carbon dioxide and increased evaporation over North Lake, causing a 9.55 mg $meter^{-2}hr^{-1}$ concentration of carbonate in the water and subsequent deposition of marl.

Where phytoplankton was abundant (Pintail Pond), photosynthetic activity was the most effective mechanism for CO_2 depletion and calcium carbonate precipitation. Standing crops of rooted vegetation in North and Pintail are very small and the decalcification by the rooted vegetation is negligible to that brought about by phytoplankton. Decalcification rates in Pintail Pond were four times those in North Lake where hydrophytes were sparse.

In North Lake and Pintail Pond, temperature is the primary cause of carbon dioxide depletion and subsequent carbonate formation. Temperature affects the metabolic rate of hydrophytes and produces wind; the wind-temperature relationship determines the evaporation rate. The mechanisms are additive in total effect while the comparative effectiveness of each varies in depth and time. Presumably warming and wind-induced agitation have the largest effect on surface waters. Photosynthetic activity is often diminished in surface waters (Edmondson, 1956; Strickland, 1960), but determines the lower limits of CO_2 uptake and carbonate formation. Although the factors causing carbon dioxide depletion are all operative within the trophogenic zone, not all are related to photosynthesis.

The composition of the marl deposits in the lakes reflects the chemistry of local ground water and the rocky materials within the local moraines. The "parent" material of the local moraines is probably Traverse limestone outcropping on the north-east rim of Michigan near Alpena. A comparison of the analyses of North Lake marl and the Traverse limestone is given in Table 39.

TABLE 39.--The Composition of Marl from North Lake and Traverse Limestone*

	North Lake Marl	Traverse Limestone (near Alpena)
Calcium Carbonate	94.62%	95.91%
Magnesium Carbonate	2.38%	3.63%
Silica	.25%	.31%
Alumina & Iron Oxide	.14%	.13%
Sulfuric Acid	.18%	Traces

*Analyses of Traverse limestone--after Eckel (1913). Analyses of North Lake marl--courtesy of the Michigan Department of Public Health.

The extent of basin seal is presumed to be a fundamental factor in the development of marl lakes in addition to local soils, the chemistry and physiography of the surrounding glacial deposits and drainage patterns. The presence of materials in the original glacial basin depression or the development of an organic filter around the basin may form a basin seal which excludes the ground water or some of its components before the water enters or leaves the lake.

Probably few lakes are completely sealed, but Hooper (1954) found evidence that the basin of Weber Lake was sealed against the alkalinity of the ground water of the area. The glacial debris in Michigan is mostly sand and gravel (Leverett and Taylor, 1915). Therefore, few if any of the water-filled depressions in the newly-formed drift left by the retreating glacier were effectively sealed. Under such conditions and without well-developed drainage systems, nearly all lakes, ponds, and waterways in Michigan must have received very large quantities of calcium bicarbonate in the ground water. The existence of many shallow, marsh covered, upland beds of marl in Michigan lend support to the contention that marl formed from these waters.

In deeper basins, with the passage of time, sedimentation of autochthonous and especially the various local allochthonous materials may have resulted in varying degrees of basin seal. Progressive accumulations of carbon dioxide in the hypolimnion of these deep lakes developing a basin seal would transform the $CaCO_3$ substrate to the soluble bicarbonate and while circulating, there would be uptake by the biota. Thus many glacial lakes in North America may have been marl-forming in the earliest stages of their development even though basin probes at present show no evidence of marl deposits. In many cases the original marl substrate is not all dissolved and recirculated. Hale (1903) reports many instances in Michigan where a marl deposit rests on glacial debris and is covered by peat.

In contrast to non-marl lakes, the basins of marl lakes are not sealed from excessive quantities of calcium bicarbonate in ground waters. When the factors of soil, glacial deposits, drainage systems and basin seal are optima, hypermarl lakes such as North and Pintail Pond develop. Such lakes ultimately fill, becoming marsh covered marl beds, or a change in one of the above factors leads to a modification of the hypermarl condition and an eventual shift from alkalitrophism toward eutrophism.

Marl Lake Basin Physiography

Many studies have shown that basin physiography affects the chemistry of lake water (Rawson, 1939; Ruttner, 1953; Hooper, 1956; Hutchinson, 1959).

In North Lake, the chemistry of the water determines the basin physiography. The typical terraces and abrupt slopes of deep hypermarl lakes are a result of vertical differences in carbon dioxide deficiency. Calcium carbonate forms in the upper waters and settles. Carbonate sediments, reaching that part of the basin which lies above water masses containing accumulations of aggressive carbon dioxide, become marl substrate. Sediments sinking into deeper water may be transformed to bicarbonate, or become marl substrate for a time, and then be transformed to calcium bicarbonate and recirculated throughout the lake. Several cycles of deposition, transformation, and precipitation may occur before the material becomes a permanent part of the marl terrace. Filling of a deep lake by marl deposition thus takes place more rapidly from the shore outward than from the bottom upward. The organic detritus within the lake fills the deeper basin depressions forming a substrate which increases in organic content as depth from surface to basin increases.

The lower limits of the purest marl deposits within deep lake basins are the average upper limits for the accumulation of aggressive carbon dioxide. Since aggressive carbon dioxide does not accumulate in marl lakes too shallow to stratify thermally or those in the final stages of filling, carbonate is deposited uniformly and basins with gradual slopes develop. All factors that influence the warming of surface waters and affect thermal stratification in lakes are significant in explaining variations of marl deposits in lakes or in old dry upland basins.

Other physical features found commonly in deeper hypermarl lakes such as bars, hooks, and emerging islands are constructed of marl materials from the terrace. The terrace is easily eroded by waves since the material is flocculant and barren of plants. Eroded sediments are carried by the shore currents and deposited wherever current velocities are slowed.

Conditions Limiting Basic Productivity in Marl Lakes

Dice (1952) states that, "The ultimate limit of productivity of a given ecosystem is governed by the total effective solar energy falling annually on the area, by the efficiency with which the plants in the ecosystem are able to transform this energy into organic compounds, and by those physical factors of the environment which affect the rate of photosynthesis".

Ruttner (1953) and others have shown that hydrophytes can grow at depths of water receiving about .4-1.5% of surface light intensity. When wind velocities are high, penetration of solar energy into marl-forming waters is diminished and becomes a limiting factor to productivity. Under normal wind conditions, light penetration of the water is not decreased enough either quantitatively or qualitatively to prevent the growth of hydrophytes and other factors within the ecosystem have larger deleterious effects on productivity.

The formation of H_2S in North Lake may have limited the productivity of hydrophytes. Hydrogen sulfide formed in basin muds and accumulated in the hypolimnion indicating that some H_2SO_4 formed. Brooks (1943) has shown that small concentrations of H_2SO_3 almost completely inhibits respiration, decreases photosynthesis at all light intensities, causes reduced development of plastid pigments and slows growth in Elodea. The productivity of the fauna may also have been reduced by H_2S since Doudoroff (1950) has shown that low concentrations are toxic to aquatic animals.

The calcium carbonate incrustations forming around all plants diminishes plant growth in marl lakes. The photosynthetic processes use dissolved carbon dioxide from the water causing the incrustations to form. The effects of the incrustations are mechanical and physiological. Plants encased in the calcium carbonate sheath are less pliable. The cells are injured when waves and strong currents bend the plants breaking the encasement. In hypermarl lakes, plants with heavy incrustations are weighted down to the bottom decreasing the hours of effective sunlight in the day and season. The incrustations interfere with photosynthesis by directly blocking the solar energy from reaching the plastids, i.e., incrustations removed in tact from the leaves of Potamogeton angustifolius and placed over a photometer showed that up to 24% of the total light was held back by the incrustations. Incrustation may also reduce the diffusivity of CO_2 and O_2 in the metabolic processes and diminish proportionately the efficiency of carbon fixation.

The productivity of marl lakes is low because the water and substrate are deficient in elements required for plant growth. Adding phosphorus, nitrogen, and potassium to a marl pond significantly increased the productivity of plankton, vascular aquatic plants, bottom fauna, and periphyton. Eyster (1958) showed that phosphorus and potassium were limiting factors in the growth of the alga Nostoc muscorum in a marl lake near Ann Arbor, Michigan. Schelske (1962) has shown that iron deficiency limited primary productivity in Blind Lake. The reddish brown deposits on marl near small springs indicate that iron may also be a limiting factor in the productivity in North Lake.

The quantity and distribution of organic matter in lake basins influence the distribution of plants and affects the productivity. Misra (1938) found a relationship between the distribution of plants and organic matter in the soils of several eutrophic lakes in England. The vascular plants in North Lake were found only in sheltered places where small quantities of organic matter had become mixed with the marl substrate. Roelofs (1944) and Wohlschlag (1950) made similar observations in marl lakes. Since adding organic matter to marl substrates in North Lake increased plant production 600 fold and bottom fauna 13 fold, it can be concluded that lack of organic matter in marl substrates is a major factor limiting productivity.

The sources of organic matter to North Lake and Pintail Pond are meager. The allochthonous organic material is almost entirely air-transported leaves from timbered shores in autumn; the autochthonous material is mostly $CaCO_3$ with a few animal and plant corpses. As a consequence, organic matter does not progressively enrich the littoral zone; therefore, plant succession is retarded.

The unique physiography of hypermarl second-order lakes decreases the efficiency of the ecosystem for converting solar energy to organic compounds. It is an accepted principal (Rawson,1939) that a small, shallow basin with gentle slopes is conducive to productivity and eutrophy while a large, deep, and steeply sloped basin is comparatively less productive. This is true because in the latter case the area of the littoral region is smaller in proportion to the size of the lake. Hypermarl lakes have littoral regions that are unusually small and steeply sloped. The scant organic matter synthesized in the littoral zone is carried down the steep slope into the depression of the basin. Thus the productive zone loses organic matter at rates equal to its formation. Alternate settling and erosion of the flocculant substrate by shore currents with changes in wind direction preclude the establishment of plants on the steep slopes. The gently sloping terrace top is even less suitable for plant growth. Waves, shore currents, and ice action continually bring shifts in the substrate. Thus the only part of the basin receiving solar energy sufficient for photosynthesis is not suitable for colonization by vascular aquatic plants. Organic hydrosols and a basin slope suitable for plant colonization exist in most hypermarl lakes but lie below the compensation level.

Although each of the several limiting conditions to basic productivity in marl lakes mentioned here is significant, the effects are additive and together explain the sparse biota. In North Lake, the basin physiography, diminished light penetration, calcium carbonate incrustations on plants, deficiency of plant nutrient elements, and a deficiency of organic matter are secondary causes of low productivity, since each of these is a result of the high calcium bicarbonate content of ground waters entering the lake basin.

Experiments of Lake Management Techniques in Marl Lakes

Fertilization

Ball (1948, 1949) and Ball and Tanner (1951) added fertilizer to Michigan ponds and trout lakes to increase productivity. Alexander (unpbl. ms.) added fertilizer to a marl lake and concluded that there were increases in periphyton but found no evidence of increases in plankton or bottom fauna.

Barrett (1952) concludes that there is an equilibrium between the fixed-exchangeable-soluble phases of the phosphate system in lakes containing marl. According to Barrett, phosphate ions become effectively and relatively rapidly "fixed" when added to lakes in which alkalinities and concentrations of homogeneous marl are high. Theoretically phosphate ions added to a marl lake in excess of those fulfilling the fixed phase become exchangeable. The concept of a fixed-exchangeable-soluble system is meaningful from the standpoint of phosphorus availability to aquatic organisms; however, experiments with radioactive phosphorus (Hutchinson and Bower, 1950; Hayes and Coffin, 1951; Hayes, McCarter, Cameron, and Livingstone, 1952) indicate that the exchange equilibrium involves the rapid movement, uptake and regeneration of phosphate ions within all the phases of Barrett's system.

In terrestrial soils, the organic and carbonic acids from the organic matter tend to decrease phosphate fixation in noncalcareous soils; in calcareous soils the effect is not noticeable as long as solid phase $CaCO_3$ remains to control pH and Ca^{++} concentration (Bear, 1948). However, the data of Barrett (1952) and Bear (1958) suggest in general, the overall effect of the organic phase in soil is to decrease phosphorus fixation.

Harvey (1953, 1955) has shown that some plankton organisms absorb phosphate quickly, even in darkness, and can build up a reserve product for further synthesis later. If the phosphorus in the fertilizer were not immediately immobilized or if first immobilized and subsequently recycled, one would expect that the hydrophytes might absorb and store enough phosphorus from the fertilizer to effect significant increases in productivity in a marl lake. It was hypothesized that increases in basic productivity would occur when fertilizer was added to a hypermarl lake as a result of (i) rapid uptake and storage of phosphorus by the hydrophytes before it became immobilized in the substrate and (ii) cation-anion exchange mechanisms in the microcosm of plant root systems may be operative since the distribution of vascular aquatic plants in hypermarl lakes seems limited to substrates containing some organic matter. Positive response of hydrophytes to fertilizer application would lend support to the hypothesis and as a consequence, Pintail Pond received six applications of fertilizer over a two year period.

The data show that neither all the total nor soluble phosphorus were immediately adsorbed by the substrate or precipitated, but much remained in the water for 6-8 days and large increases in phytoplankton followed each treatment. The plankton volume the second year before fertilization exceeded that of the first by a factor of 5.7 indicating a fertilizer carry-over effect between years. Thus it appears that the phytoplankton absorbed phosphorus from the water before it became fixed in the substrate. Vascular aquatic plants also increased significantly as a result of the fertilizer applications. The general response in growth was correlated with the amounts of fertilizer added.

Increases in the flora of these marl lakes were soon followed by large increases in the bottom fauna, i.e., a direct relationship existed. Since there appears to be a definite relationship between the production of bottom fauna and the production of fish (Ball, 1948), ultimately the increases in the biota shown to occur in a marl lake receiving fertilizer would be reflected in fish growth and the fishing quality of a lake. Ball (1949) has reported that a 10-6-4 fertilizer application of 100 lb acre^{-1} every three weeks increased the standing crop of bottom fauna of hatchery ponds 21-68%. The heavier rate of 130 lb acre^{-1} applied to Pintail Pond produced increases of 88% and 212% at non-vegetated and vegetated stations respectively. A justifiable conclusion would seem to be that applications of fertilizer to this marl lake were as effective in raising standing crops of fish food organisms as similar treatments have been to small non-marl-forming bodies of water.

Hutchinson (1957) states that "the artificial addition of phosphorus in a single or even two consecutive years has no permanent effect on the biochemistry of the lake, which evidently acts as a self-regulatory system returning to a steady-state condition determined by all the variables that operate within it, after one of these variables has been temporarily disturbed." The effects on a marl lake of continued treatment with fertilizer are problematical although some data exist from which tentative conclusions can be drawn.

Hutchinson (1957) in a review of Einsele's study of the phosphorus cycle in the Schleinsee states that "the fall in the inorganic fraction was not quite so rapid", after a third application of superphosphate.

The data of Pintail Pond show that the last four of a series of six successive applications of fertilizer produced successively higher levels of phosphorus in the water (Fig. 18). Laboratory tests with stirred samples have shown that phosphate adsorption by substrates may occur within a period of five minutes (Fatchichina, 1939), but the Pintail data show that the removal of added phosphorus (third application) under natural hypermarl third-order lake conditions is actually a much slower process (.44 ug $liter^{-1} hr^{-1} acre^{-1}$). Thus there is some evidence to support the conjecture that the adsorptive capacity of substrate materials for phosphorus decrease as larger quantities of the nutrient are added. Continued treatment of Pintail Pond with fertilizer would probably shift the balance of the entire ecosystem to one in which the deposits of organic matter in the shallow lake basin would be greater than the deposits of calcium carbonate. This study shows that additions of organic matter to the littoral zone of a marl substrate are followed by large increases in the flora. As a consequence, a shift in the ratio of organic matter and $CaCO_3$ deposited would speed eutrophic processes.

Increasing the Basic Productivity of Marl Lakes by Adding Organic Matter

It has been shown that a deficiency of organic matter limits basic productivity in marl lakes. The organic material in most lakes is initially derived almost wholly from the plankton and other hydrophytes that have grown within it. In turn, all plants with their residues become a part of the organic matter of lake soils and, directly or indirectly, the food supply for a host of organisms which have no power to utilize inorganic carbon. Many of these organisms provide metabolic channels through which the mineralized nutrients become available cyclically to green plants. Organic matter, then, consists of plant residues at various stages of decomposition together with the corresponding products of decomposition and excretion of all organisms living on it.

Organic matter is of fundamental physical importance to the texture and structure of the soil. The cohesion, porosity, reaction, and ion exchange capacity are related to the organic matter content (Bear, 1958). The retention of available nutrients is particularly dependent upon the colloidal nature of the organic matter.

The fundamental importance of organic matter to plant growth and the lack of organic matter in marl substrates led to the conjecture that basic productivity of marl lakes could be increased if organic matter were added. Wohlschlag (1950) and the Latin Square tests of substrate materials performed in North Lake had shown that organic matter in small containers was more effective than marl in promoting plant growth. Such tests were indicative but not considered an adequate basis for concluding that organic matter could be added to marl substrates as an effective lake management technique. If additions of organic matter to marl lakes were to become a lake management method, it was essential to test several inexpensive, easily available organic materials by establishing large replicated plot type experiments which would (i) exclude the effects of small containers, (ii) include the effects of lake basin slope, (iii) include the effects of water currents and shifting substrates, (iv) reveal problems encountered in organic matter placement, (v) reveal problems encountered in aquatic planting of large areas, (vi) reveal responses of bottom fauna to treatment, (vii) permit testing the growth responses of a number of species of aquatic plants simultaneously, (viii) permit observation of disturbance and usage of such plantings by fish and wildlife, and (ix) permit adequate sampling which allowed greater confidence in the conclusions drawn. The study has shown that adding organic matter to large areas of the marl substrate significantly increases the basic productivity and is feasible as an effective lake management technique.

Plant growth increased 114 fold when organic matter was added to the marl substrate. The effectiveness of an organic substrate in producing plants seems to be dependent on two characteristics: (i) the stability of the substrate formed, and (ii) the quantity of humus in the material which is directly related to the soil colloids present. Although the colloidal content of peat was high, the substrate was unstable and plant production comparatively low. When sand was applied as a "top dressing", the peat was held in place and plant production remained a little higher for a longer time. Sod provided a firm, stable substrate with a high colloidal content and plant production was high even on steep lake basin slopes.

Misra (1938) has described a series of events within the organic matter of lake substrates that provides elements for plant growth. As plant residues containing nitrogen are decomposed, the ammonia formed tends to be adsorbed on the surface of the soil colloids and replaces other ions from colloidal surfaces. The cations exchanged in this way go into the solution around the organic particles and gradually diffuse into the aqueous system above the mud. Larger quantities of ammonia, phosphate, exchangeable iron and manganese are associated with soils containing more organic matter. The less productive inorganic and peat soils contained less exchangeable bases and more replaceable hydrogen.

The productivity of the bottom fauna increased 13 fold with application of organic matter to marl substrates. Bottom fauna population size on the experimental plots was shown to be dependent on standing crops of aquatic vascular plants. The largest and most varied bottom fauna populations were found in association with the densest stands of plants.

Seeded Organic Material in Bags
as a Lake Management Technique

The method of establishing vegetation on marl substrates by seeding organic matter in sealed burlap bags and dropping them into the lake was very successful. The method provided solutions to several problems. Wildlife did not disturb the seed stock until plant shoots appeared through the bags; positioning, stabilizing and prevention of erosion of semi-bouyant materials were accomplished with little difficulty. Compaction of the peat and sewage materials in bags provided more suitable substrata for vascular aquatic plants and production was higher than on similar, non-bagged material. The productivity of marl substrates receiving the bag treatments increased 340 fold. In general, sewage sludge produced more plant growth, but production on peat was almost as high. Potamogeton americanus, Potamogeton perfoliatus, and Valisneria spiralis responded well to both substrates.

Bags placed on gradual basin slopes in checkerboard pattern form pockets which trap and hold the organic matter produced in the area. Stabilization of the organic matter takes place as the area is colonized by plants.

Wildlife Utilization of the Experimental Areas

The newly established beds of aquatic vegetation attracted wildlife immediately. The developed areas became the spawning places for bluegills, bass, minnows and other fish. Small fish foraged on the bottom fauna and found protective cover in the vegetation. Larger fish congregated to feed, improving fishing. Waterfowl, as well as other aquatic animals, frequented the areas for food.

Lake Management Considerations

It has been shown in this study that adding inorganic fertilizer and organic matter to marl lakes significantly increases basic productivity.

Ball (1950) concludes that "it does not seem that fertilization, especially the warm-water lakes, can be justified under present conditions. The adequate harvesting and proper balancing of the fish crop are perhaps more pressing questions of management than is an increase of the standing crop of fish." Applications of fertilizer to some shallow soft water lakes (alkalinity 42-47 mg liter^{-1}) may also produce objectionable filamentous algae and a severe winter kill (Ball and Tanner, 1951). However, problems of marl lake management are somewhat different from those of most warm-water lakes. The major problem here is not one of harvesting fish, but rather increasing the basic productivity and subsequently the standing crops of fish. Since hypermarl lakes are deficient in organic matter, winterkill would probably not occur. Thus, adding fertilizer to a marl lake as a means of increasing productivity seems feasible providing: (i) the marl lake is of the temperate third-order type, (ii) fertilizer is added to the water when phytoplankton populations are normally highest, (iii) eutrophication is desirable, and (iv) the cost of the program can be measured against the increased sport and not the pounds of fish harvested. The fertilizer applications will be most effective in lakes with substrates containing some organic matter and supporting some vascular aquatic plants.

Temperate second and third-order marl lake productivity may be increased most effectively by adding organic matter to lake substrates. Lumpy or semi-bouyant materials should be bagged to prevent erosion and provide a firm substrate for plants. In large lakes, only the gradual basin slopes between 4-16 ft which are protected from waves and currents should be selected for development. The organic materials may be added to lakes during the winter season when trucks or manure spreaders can unload their cargoes onto the ice directly above the littoral zone. The success or failure of this lake management technique may depend on (i) acquiring acclimatized aquatic seed stock, (ii) care and storage of the seeds until used, (iii) the proper planting of the seed, and (iv) care in the placement of the organic matter on the marl substrate. Bags placed on gentle slopes in checkerboard pattern provide pockets between the bags which trap and tend to hold organic matter in the area. Colonization by the plants stabilizes the organic matter.

SUMMARY

North Lake

1. North Lake is a marl pit lake lying in a glacial outwash plain. The glacial matrix of the area has abundant fragments of limestones and is characterized by good drainage. The ground water contains comparatively large quantities of calcium and magnesium bicarbonate.

2. Bottom deposits are marl or marl concretions. The calcium content of the substrate samples increased from lake to shore. Soils were deficient in phosphorus, nitrogen, potassium and organic matter.

3. Light penetration of the marl forming water was not usually a limiting factor to plant growth although high winds changed the spectral quality and increased light extinction coefficients. Beds of vegetation reduced light extinction coefficients.

4. North Lake total alkalinity was higher than usually found in Michigan Lakes. The ecology of North Lake and Pintail Pond is the result of carbonate alkalinity. Most carbonate occurred in the epilimnion during July - September when fluctuations were directly related to temperature. Higher temperatures resulted in increases in evaporation and greater physiological activity of phytoplankters decreasing the CO_2. About ninety per cent of the carbonate deposition occurred on the lake basin above the hypolimnion.

5. The formation of marl and the unique physiography of the North Lake basin may be directly attributable to the vertical differences in carbon dioxide deficiency and the vertical differences in carbonate

deposition. Features, such as hooks and bars, are constructed of marl particles eroded from the shore and terrace by waves and ice. The lake annually becomes smaller when some of the marl deposited on the terrace is pushed shoreward by ice.

6. North Lake hardness was about all carbonate hardness. The calcium maximum occurred in the deeper water just before fall turn-over and in the upper water during the winter under ice. The maxima are associated with large increases in aggressive carbon dioxide which transformed the calcium carbonate (marl) substrate to soluble calcium bicarbonate. The calcium minimum occurred during summer stagnation. Net calcium losses occurred during summer stagnation, fall turn-over, and toward the end of winter stagnation. The magnesium of the water showed little variation with depth or season. The magnesium-calcium ratio decreased with depth. Non-carbonate hardness was due to sulphates.

7. The oxygen-carbon dioxide relationship in the hypolimnion is inverse and of biogenic origin. When compared to other lakes, the hypolimnetic areal relative oxygen deficit, the estimates of productivity and production show North Lake productivity to be quite low.

8. Hydrogen sulphide accumulated in the deeper water of North Lake during summer stagnation. Toxic quantities to plants and animals were found in the thermocline and hypolimnion by mid October. Sulphide was not chemically detectable in the water after the fall turn-over but emanated from basin muds throughout the year.

9. The dry marl flats around North Lake were characterized by *Thuja occidentalis*, *Betula sp.*, *Myrica Gale var. subglabra*, *Alnus incana* and *Potentilla fruticosa*. The aquatic vegetation belonged to seven plant families and eleven plant species. All aquatics, including *Chara*,

were rigidly suppressed in growth and development by heavy incrustations of calcium carbonate. Plankton was sparse. The principal marl concretion "builders" were *Schizothrix fasciculata*, *Lyngbya Martensiana*, and *Phormidium sp*.

10. The littoral benthic fauna consisted of a few gastropods, amphipods, and insects. The mayflies *Hexagenia* and *Caenis* were the most common members of the community.

11. The fish population of North Lake was composed of eight families, twenty species, and hybrids of two sunfishes. The fishing quality of North Lake is poor in comparison to non-marl lakes in the locality having the same species of fish but supporting abundant stands of aquatic vegetation. Eight times as many fish and three to five times as many pounds of fish per fishing hour were taken from the non-marl lakes in the vicinity of North Lake.

The Pintail System (a marl forming water)

1. Water samples for chemical analyses were taken from Pintail Spring, Pond and Outlet to measure changes in the quality of the water as it flowed through the system. Within the system, CO_2, calcium, magnesium, and conductivity decreased; CO_3, phosphorus, nitrogen and pH increased. Compared to other lakes, phosphorus, nitrogen, and potassium were present in small quantities.

2. Fluctuations in alkalinity, hardness, calcium hardness, and magnesium hardness of the spring water entering the lake were correlated inversely with rainfall. Chemical characteristics in the pond were inversely correlated with phytoplankton volume.

3. The calcium content of the water was about 2-1/2 times greater

than magnesium but was deposited in the marl in quantities 10 times greater. The rate of decalcification varied from 9.2 - 66.5 mg hr^{-1} $meter^{-2}$.

Addition of Inorganic Fertilizer to a Marl Pond

1. Inorganic fertilizer was applied in six applications over a two year period to a 2.3 acre marl pond located in northern Michigan. Chemical and biological changes were studied.

2. The pH of the pond water decreased and the calcium ion increased immediately after each application of fertilizer. This response was attributed to the ionization of the fertilizer, the greater reabsorption of carbon dioxide from the atmosphere resulting from the increases in phosphorus, and the transformation of the calcium carbonate (marl) substrate to the soluble calcium bicarbonate.

3. Each fertilizer application increased the phosphorus about 1500%, nitrogen 700%, and potassium 300%. The increases in phosphorus the second year, became progressively higher with successive treatments indicating that there may be a decreasing exchange capacity for substrate and water.

4. Applications of the fertilizer increased the productivity of the pond. The average plankton volume increased after each treatment and there was a carry-over effect from the first to the second year. Standing crops of macrohydrophytes increased 4-6 fold. Numbers of bottom fauna and numbers of species of bottom fauna increased from 100-200% and 50-100% respectively.

5. Significant decalcification of pond waters was correlated with peaks in phytoplankton volume.

Experiments with Substrate Materials

1. Replicated Latin Square experiments testing the growth of *Myriophyllum spicatum* on various substrate materials within the marl lake disclosed the following order of effectiveness (least to most: sewage sludge, marl, sand, sand over peat, peat, and sod.

2. Aquatic plants were planted on experimental plots to test growth on marl, sand, peat, sand over peat, and sod substrates in North Lake. The planting of marl substrates did not increase plant production. Sand substrates were no more effective than the marl controls. Peat and sand over peat substrates were 25 times as effective as marl in the production of plants. Sod substrate was about 138 times as effective as marl in the production of plants.

3. Bottom fauna populations on the North Lake experimental plots varied directly with amounts of vegetation produced by the different substrates. Peat and sand over peat were 3-1/3 times as effective as marl in supporting bottom fauna organisms. The sod substrate was 12-1/2 times as effective as marl in supporting bottom fauna organisms.

4. Burlap bags filled with sewage sludge or peat were seeded with 6 different species of plants. *Potamogeton natans* produced best on peat substrates and *Nymphaea odorata* did better on sewage. *Valisneria spiralis* and *Potamogeton perfoliatus* grew well on both substrates. *Potamogeton americanus* did significantly better on sewage sludge and grew better on both substrates than other plants used in the experiments. These treatments were about 3 times as effective as the plot type treatments on a ft^{-2} basis.

North Lake Appendix I

TABLE 40.--Chemical Characteristics of North Lake Water (1953)

Date	Depth	Temp.	O_2	H_2S	pH	Hardness Ca	Hardness Mg	Total Hard.	Total Alk.
3/1	0'	39.0	11.0	0.0	8.0	99.4	62.1	161.5	143.2
	15'	39.3	9.7		8.0	100.5	62.1	162.6	152.0
	25'	39.1	8.7		8.0	102.9	62.1	165.1	160.0
	35'	38.8	7.5		7.8	111.7	69.6	181.3	175.0
	45'	38.9	6.6	0.0	7.9	119.0	73.5	192.5	187.6
			(Secchi Disc 15')						
5/9	0'	60.8	10.8	0.0	8.2	110.7	67.7	178.4	165.0
	6'	58.0	11.1		8.2	107.2	72.8	180.0	177.2
	13'		11.0		8.2	108.0	72.0	180.0	167.3
	25'	45.2	11.0		8.2	110.3	69.7	180.0	168.0
	45'	44.4	10.5	0.0	7.9	111.2	67.6	178.8	167.9
			(Secchi Disc 11'1")						
6/30	0'	73.4	7.7	0.0	8.3	114.9	61.7	176.6	160.1
	8'		7.5		8.3	108.0	64.2		151.0
	12.5'	69.1			8.3	105.7	65.7	171.4	151.1
	20'	52.0				111.8	67.2	179.0	161.0
	23'	48.6	7.0		8.2	114.0	67.5		165.0
	25'	48.4				115.5	67.5	183.0	168.0
	45'	45.3	2.8	0.0	7.6	117.4	68.2	185.6	174.7
			(Secchi Disc 13'7")						

TABLE 41.--Chemical Characteristics of North Lake Water (1953)

Date	Depth	Temp.	O_2	H_2S	pH	Hardness Ca	Mg	Total Hard.	Total Alk.
7/13	0'	78.1	8.6	0.0	8.4	98.9	66.5	165.4	166.2
	10'	71.1	8.9		8.4	99.6	64.3	163.9	164.9
	21.5'	49.5	9.6		8.2	108.5	67.5	175.9	173.1
	25'	48.2	8.5		7.8	103.7	70.0	173.7	172.5
	45'	45.0	2.0	0.0	7.3	111.8	71.7	183.5	183.6
			(Secchi Disc 14'3")						
8/3	0'	74.6	8.9	0.0	8.4	92.6	75.0	167.6	167.0
	13'	72.6	9.1	0.0	8.3	95.9	72.5	168.4	168.3
	25'	49.0	8.0	0.0	8.0	105.6	76.0	181.6	178.3
	45'	44.7	0.2	0.0	7.3	117.6	79.0	196.6	193.8
			(Secchi Disc 5'2")						
8/11	0'	73.0	8.9	0.0	8.4	95.8	74.3	170.0	164.4
	14'	67.0	8.5	0.0	8.3	100.8	74.0	174.8	169.2
	25'	51.0	8.7	0.0	8.2	125.6	61.4	187.0	177.3
	45'	44.8	0.7	0.0	7.3	121.7	81.8	203.4	194.4
			(Secchi Disc 11'6")						

TABLE 42.--Chemical Characteristics of North Lake Water (1953)

Date	Depth	Temp.	O_2	H_2S	pH	Hardness Ca	Hardness Mg	Total Hard.	Total Alk.
8/31	0'	77.5	8.9	0.0	8.4	83.8	83.3	167.0	165.2
	13'	73.5	8.9		8.4	87.4	85.0	172.4	168.8
	28'	49.5	3.2		7.7	103.9	88.7	192.6	187.5
	45'	45.1	0.0	1.0	7.3	116.5	90.5	207.0	208.1
			(Secchi Disc 11'3")						
9/15	0'	64.2	8.5	0.0	8.3	97.4	76.0	173.4	164.8
	20'	62.8	8.6		8.3	101.4	74.2	175.6	168.5
	28'	47.3	2.5		7.4	92.7	83.7	176.4	188.3
	45'	45.3	0.0	1.0	7.3	123.6	88.0	211.6	209.3
			(Secchi Disc 12')						
10/31	0'	51.6	9.1		8.2	104.3	74.7	179.0	172.1
	25'	51.3	9.1		8.1	118.5	74.5	193.0	170.5
	30'		6.5		7.9	125.0	75.7	200.7	178.8
	36'		3.8		7.7	137.5	78.0	215.5	187.0
	45'	45.5	0.0	1.0	7.3	143.8	82.0	225.8	218.9
			(Secchi Disc 13'9")						
11/11	0'	45.5	9.5		8.0	112.0	75.0	187.0	182.0
	25'	45.5	9.6		8.0	108.2	75.2	183.4	182.7
	45'	45.5	9.2	0.0	7.9	110.2	75.0	185.2	183.8
			(Secchi Disc 12'6")						

TABLE 43.--Chemical Characteristics of North Lake Water (1954)

Date	Depth	Temp.	O_2	H_2S	pH	Hardness Ca	Hardness Mg	Total Hard.	Total Alk.
1/23	0'	32.0	13.1		8.2	121.7	79.9	201.6	185.5
	25'	37.5	11.4		8.1	119.1	77.1	196.2	183.1
	45'	39.0	6.4	0.0	7.8	121.5	79.3	200.7	191.8
		(Secchi Disc 11'6" - ice)							
2/28	0'	33.8	13.6		7.9	100.2	71.1	171.3	158.2
	25'	37.9	11.3		7.9	118.4	74.4	192.8	172.4
	45'	39.2	3.4	0.0	7.4	120.1	81.5	201.6	187.5
		(Secchi Disc 4'13" - ice and snow)							

TABLE 44.--Hydrogen Sulfide in North Lake Water (1953)

No H_2S at any level August 11

No H_2S at any level November 11

Depth	Date		
	8/31	9/15	10/31
34			0.0
35	0.0		T
36			.03
37			.10
38	0.0	0.0	
39		T	
40	0.0	.03	.60
41	T	.10	
42	.17	.25	.75
43	.55	.75	
44	.85		
45	1.0	1.0	1.0
46			
47	1.0	1.5	
48			
49			
50	1.5	3.0	2.5

TABLE 45.--Latin Square Tests of Substrate Materials

Yields (g*) of *Myriophyllum spicatum* Grown in Various Substrates--North Lake, Test No. 1

Rows	Column 1	2	3	4	5	6
1	B: 50.0	D:25.0	C:24.0	A: 1.0	C: 1.0	F: 1.0
2	A: 00.2	B: 25.0	F: 0.2	C: 1.0	D: 27.0	E: 18.0
3	C: 11.0	F: .02	D: 32.0	E: 20.0	B: 32.0	A: 1.0
4	E: 12.0	C: 2.0	B: 17.5	F: 0.5	A: 3.0	D: 25.0
5	D: 7.0	E: 30.0	A: 0.5	B: 5.0	F: 0.2	C: 5.0
6	F: 0.5	A: 0.5	C: 3.0	D: 3.0	E: 27.0	B: 20.0

TABLE 46.--Latin Square Tests of Substrate Materials

Yields (g*) of *Myriophyllum spicatum* Grown in Various Substrates--North Lake, Test No. 2

Rows	Column 1	2	3	4	5	6
1	B: 3.0	D: 8.0	E: 24.0	A: 0.5	C: 6.0	F: 3.0
2	A: 1.0	B: 12.0	F: 2.0	C: 2.0	D: 8.5	E: 28.0
3	C: 9.0	F: .02	D: 10.0	E: 17.0	B: 12.0	A: 3.5
4	E: 10.0	C: 3.0	B: 4.0	F: .02	A: 6.0	D: 7.0
5	D: 4.0	E: 13.0	A: 5.5	B: 21.0	F: .02	C: 6.0
6	F: .02	A: 3.0	C: 3.5	D: 12.0	E: 11.0	B: 18.0

*Weights less than .5 of a gram were estimated.

Treatments: A = Marl; B = Peat; C = Sand; D = Sand/Peat;
E = Sod; F = Sewage.

TABLE 47.--Weight of Hydrophytes (g ft^{-2}) Collected from BB Experimental Plots in North Lake (1953 - 1954)

Plot No.	1	3	1	2	3	4
Year	1953	1953	1954	1954	1954	1954
Treatment	Control	Control	Control	Peat	S/Peat	Sod
Sample No.	g ft^{-2}	g ft^{-2}	g ft^{-2}	g ft^{-2}	g ft^{-2}	g ft^{-2}
1	.0	1.5	2.1	17.0	34.7	268.3
2	.0	.9	.0	39.2	56.6	159.5
3	1.5	.0	.0	14.6	38.3	153.5
4	.0	.3	6.0	37.1	41.9	149.6
5	.0	.0	.0	19.1	24.8	186.2
6	5.4	.0	.0	25.7	46.1	181.7
7	.0	.0	3.6	24.8	29.3	201.5
8	2.7	.3	2.1	27.2	20.9	166.7

Total Samples - 48

TABLE 48.--Weight of Hydrophytes (g ft^{-2}) Collected from CC Experimental Plots in North Lake (1953 - 1954)

Plot No.	1	2	1	2	3	4
Year	1953	1953	1954	1954	1954	1954
Treatment	Control	Control	Control	Peat	S/Peat	Sod
Sample No.	g ft^{-2}	g ft^{-2}	g ft^{-2}	g ft^{-2}	g ft^{-2}	g ft^{-2}
1	.0	.0	1.2	52.0	34.9	208.2
2	.9	2.7	2.4	49.3	36.1	106.8
3	.3	.0	3.0	21.1	38.8	227.6
4	2.1	.0	.0	21.7	31.6	171.6
5	3.0	.0	.0	37.0	27.1	185.4
6	.0	.6	2.1	28.5	44.8	245.4
7	.0	4.2	.6	31.3	38.5	164.1
8	.0	.0	.0	33.1	66.1	122.98

Total Samples - 48

TABLE 49.--Numbers of Bottom Fauna Ft^{-2} Collected from the CC Experiment Plots in North Lake (1954)

Plot No.	1	2	3	4
Treatment	Control	Peat	Sand/Peat	Sod
Sample No.				
1	1.7	5.1	4.3	16.4
2	2.2	4.0	5.4	36.4
3	2.3	4.9	4.2	59.4
4	1.4	4.3	5.7	34.9
5	2.0	5.2	6.1	38.2
6	2.4	4.4	5.9	34.4
7	1.2	5.8	4.8	39.8

TABLE 50.--Weight of Hydrophytes (g ft^{-2}) Collected from AA Experimental Plots in North Lake (1952 - 1954)

Plot No.	5	3	3	4	1	2	6
Year	1952	1952	1954	1954	1954	1954	1954
Treatment	Control	Control	Control	Sand	Peat	S/Peat	Sod
Sample No.	g ft^{-2}	g ft^{-2}	g ft^{-2}	g ft^{-2}	g ft^{-2}	g ft^{-2}	g ft^{-2}
1	.0	.0	3.8	.0	45.8	24.0	189.0
2	.8	.0	.0	.0	33.0	27.8	212.3
3	.0	.0	.0	.0	69.0	14.3	180.8
4	5.3	.0	.0	.0	54.0	8.3	231.8
5	.0	.0	.8	.0	39.0	6.0	162.8
6	.0	10.5	.8	.8	36.0	42.8	321.1
7	2.3	4.5	.0	.8	51.8	.0	267.1
8	.8	.0	1.5	1.5	34.5	33.8	141.0

Plot No.	5	3	4	1	2	6
Year	1953	1953	1953	1953	1953	1953
Treatment	Control	Control	Sand	Peat	S/Peat	Sod
g ft^{-2}*	1.3	2.7	1.0	44.4	13.1	164.2

*Total standing crop of plants harvested and weighed in 1953.
Standing crops of plants for 1952, 1954 and 1956 based on samples.

TABLE 51.--Production (g) of Six Species of Aquatic Plants on bagged sewage and Peat substrates in North Lake

	AA Area		BB Area		CC Area	
	Total Wt (3 bags)	Av/bag	Total Wt (3 bags)	Av/bag	Total wt (3 bags)	Av/bag
			Sewage Series			
Valisneria	968	322	742	247	1250	417
Sagittaria	467	155	516	172	585	195
Nymphaea	425	142	208	69	378	126
P. americanus	2121	707	1971	657	3287	1096
P. perfoliatus	402	134	360	120	809	269
P. natans	276	92	87	29	102	34
			Peat Series			
Valisneria	1414	371	1224	408	1320	440
Sagittaria	210	70	326	109	375	125
Nymphaea	259	86	54	18	126	42
P. americanus	1115	372	1761	587	1623	541
P. perfoliatus	279	93	658	219	511	170
P. natans	923	308	429	143	820	273

Pintail Pond Appendix II

TABLE 52.--Chemical Characteristics of Pintail Spring Water (1952)

Date	Temp.	O_2	pH	Hardness Ca	Hardness Mg	Total Hard	Total Alk.
7/8	52.0	2.8	7.2				
7/11	52.0		7.2	146.4	70.0	216.4	226.0
7/13	45.0		7.2	150.7	72.3	223.0	217.0
7/23	50.0		7.2	139.7	71.9	211.6	214.5
8/3	54.0		7.3	102.8	71.3	174.0	158.0
8/13	50.0		7.3	141.6	75.0	216.6	220.5
8/17	50.0		7.3	140.7	80.3	221.0	217.5
8/28	48.0		7.3	150.9	73.5	227.3	217.0
9/14	55.3		7.5	150.5	76.0	226.5	223.3

TABLE 53.--Chemical Characteristics of Pintail Pond Water (1952)

Date	Secchi Disc	Temp.	O_2	pH	Hardness Ca	Hardness Mg	Total Hard.	Total Alk.
7/8		74.0	6.7	8.2				
7/11		74.0		8.2	132.6	73.0	205.6	219.0
7/13	6'6"	79.0		8.0	137.1	73.7	210.8	212.0
7/23	2'4"	84.0		8.3	89.1	67.5	156.6	174.9
8/3	2'6"	69.0		8.2	106.3	61.3	167.6	164.7
8/13		78.0		8.2	123.7	70.5	194.2	193.5
8/17	1'9"	78.0		8.3	128.4	76.0	204.4	199.5
8/28	1'0"	81.0		8.3	98.5	67.9	166.4	150.4
9/14	0'10"	75.0		8.3	130.3	76.6	206.9	201.3

TABLE 54.--Chemical Characteristics of Pintail Outlet Water (1952)

Date	Temp.	O_2	pH	Hardness Ca	Mg	Total Hard.	Total Alk.
7/8		7.1	8.2				192.0
7/11				137.3	72.3	209.6	
7/13	84.0		8.0	132.2	74.0	206.2	191.0
7/23	88.0		8.2	94.9	69.3	164.2	162.7
8/3	70.0		8.1	94.8	55.8	150.6	142.5
8/13	74.0		8.3	116.4	72.8	189.2	184.3
8/17	74.0		8.3	130.7	69.3	200.0	189.7
8/28	80.0		8.3	90.0	64.7	154.7	138.0
9/14			8.3	135.4	70.5	205.9	199.3

TABLE 55.--Potassium in Pintail Water
(mg liter^{-1}, 1952)

Date	Spring	Pond	Stream
7/11	.3	.7	.3
7/13	.7	2.7	2.4
7/23	.2	.5	.3
8/3	.3	.2	.2
8/13	.3	.2	.2
8/17	.5	2.0	2.2
8/27	.3	.7	.7
9/14	.4	.5	.5
9/15	.4	.7	.7

TABLE 56.--Chemical Characteristics of Pintail Spring Water (1953)

Date	Temp.	O_2	pH	Hardness Ca	Mg	Total Hard.	Total Alk.
7/1	47.5		7.3	89.0	66.0	155.0	138.6
7/6	53.0	2.6	7.3	88.8	65.8	154.6	140.0
7/13		4.5	7.4	147.1	78.3	222.2	217.1
7/15			7.3	147.1	75.3	222.4	221.4
7/27	48.5		7.3	139.4	88.8	228.2	230.1
7/29	48.0		7.3	140.4	86.8	227.2	224.0
8/12	51.6	3.4	7.3	138.0	89.0	227.0	228.6
8/13	49.5		7.2	142.2	83.0	225.2	228.3
8/24			7.3	140.8	88.0	228.8	223.2
8/26	49.0		7.3	141.9	85.5	227.4	220.6
3/2	42.8	3.5	7.3	159.5	64.5	224.0	202.0
5/10	43.3	3.7	7.6	159.6	62.4	222.0	212.9

TABLE 57.--Chemical Characteristics of Pintail Pond Water (1953)

Date	Secchi Disc	Temp.	O_2	pH	Hardness Ca	Hardness Mg	Total Hard.	Total Alk.
7/1	3'2"	79.0		8.0	101.2	68.8	170.0	167.4
7/6	3'2"	67.0	6.7	7.9	97.4	66.0	163.4	160.4
7/13	2'11"		6.7	8.1	134.4	72.0	206.4	206.1
*7/14					139.7	73.3	213.0	206.2
7/15	4'4"				141.7	72.5	214.2	216.2
7/27	2'1"	73.5		8.1	126.9	77.3	204.2	195.9
7/28				7.9				195.0
7/29	2'1"	71.5		8.3	122.7	83.3	206.0	197.6
8/12	1'10"	69.5		8.1	111.1	77.3	188.4	192.1
8/13	2'2"			8.3	118.8	78.8	197.6	195.1
8/24	1'0"			8.4	106.0	75.0	181.0	176.2
*8/25				8.2	120.1	85.5	205.6	
8/26	1'0"	78.0		8.3	120.9	85.5	206.4	200.1
5/10	1'0"	70.7	8.1	8.2			200.0	199.5

*Samples collected immediately after fertilizer application.

TABLE 58.--Chemical Characteristics of Pintail Outlet Water (1953)

Date	Temp.	O_2	pH	Hardness Ca	Hardness Mg	Total Hard.	Total Alk.
7/1	75.0		7.9	100.1	70.5	170.6	165.8
7/16	66.0	3.9	7.6	84.1	59.1	143.2	135.6
7/13		8.8	8.1	128.0	71.3	199.2	198.5
7/15			8.2	135.0	75.3	210.6	210.0
7/27	70.0		8.1	117.0	77.3	194.2	184.8
7/29	77.0		8.2	101.8	81.8	183.6	173.9
8/12	71.0		7.9	117.2	77.8	195.0	190.3
8/13	73.0		8.1	103.7	76.3	180.0	170.9
8/24			8.5	79.4	82.0	162.2	
8/26	68.0		8.3	101.3	82.5	183.8	

TABLE 59.--Phosphorus in Pintail Water (ug liter^{-1}, 1952)

	SPRING			POND			OUTLET		
Date	Total	Organic	Soluble	Total	Organic	Soluble	Total	Organic	Soluble
7/8	11.0	8.0	3.0	14.0	13.0	1.0	17.0	17.0	0.0
7/13	6.0	4.0	2.0	211.0	39.0	172.0	50.0	31.0	19.0
7/23	8.0	7.0	1.0	20.0	19.5	.5	14.0	13.5	.5
8/3	10.0	9.0	1.0	12.0	10.0	2.0	11.0	10.0	1.0
8/13	6.0	4.0	2.0	12.0	11.0	1.0	8.0	8.0	0.0
8/17	5.0	3.0	2.0	125.0	124.0	1.0	80.0	79.5	.5
8/28	8.0	7.5	.5	31.0	31.0	0.0	40.0	40.0	0.0
9/14	6.0	5.0	1.0	118.0	118.0	0.0	32.0	32.0	0.0

TABLE 60.--Phosphorus in Pintail Water
(ug liter^{-1}, 1953)

	SPRING			POND			OUTLET		
Date	Total	Organic	Soluble	Total	Organic	Soluble	Total	Organic	Soluble
7/6	23.0	16.0	7.0	19.0	7.0	12.0	20.0	10.0	10.0
7/13	11.0	9.0	2.0	17.0	7.0	10.0	11.0	7.0	4.0
7/15	9.0	7.0	2.0	144.0	63.0	81.0	53.0	20.0	33.0
7/16				106.0	26.0	80.0			
7/17				69.0	25.0	44.0			
7/18				61.0	34.0	27.0			
7/19				54.0	50.0	4.0			
7/20				44.0	21.0	23.0			
7/27	10.0	8.0	2.0	24.0	8.0	16.0	21.0	12.0	9.0
7/29				139.0	74.0	65.0	139.0	74.0	65.0
8/12	9.0	7.0	2.0	26.0	14.0	12.0	20.0	15.0	5.0
8/13				186.0	52.0	134.0			
8/24	9.0	4.0	5.0	40.0	24.0	16.0	28.0	12.0	16.0
8/26				273.0	103.0	170.0	158.0	77.0	81.0
8/27				207.0	75.0	132.0	154.0	54.0	100.0
8/28				202.0	132.0	70.0	148.0	88.0	60.0
8/29				196.0	122.0	74.0	130.0	75.0	55.0
8/30				178.0	94.0	84.0	108.0	67.0	41.0
8/31	10.0	6.0	4.0	137.0	52.0	85.0	72.0	34.0	38.0
9/13				9.0	4.0	5.0			

TABLE 61.--Nitrogen in Pintail Water
(ug liter^{-1}, 1953)

	SPRING			POND			OUTLET		
Date	Total	Organic	Ammonia	Total	Organic	Ammonia	Total	Organic	Ammonia
7/1	.64	.64	.00	-	-	-	.85	.67	.18
7/6	1.07	1.00	.07	2.22	1.10	1.12	.46	.46	T
7/13	.64	.54	.10	-	.97	-	1.65	.87	.78
7/15	1.22	.70	.52	4.96	1.54	3.42	3.76	1.06	2.70
7/16				4.02	.94	3.08			
7/17				3.61	1.15	2.46			
7/18				2.72	1.18	1.54			
7/27				1.05	.85	.20	1.57	1.21	.36
7/29				4.51	1.06	3.45			
8/12	.40	.40	T	.83	.82	T	.85	.85	T
8/13				4.65	.95	3.70			
8/24	.80	.60	.20	1.20	1.20	T	.80	.80	T
8/26				6.10	1.80	4.30	3.30	1.50	1.80
8/27				3.90	1.50	2.40	3.40	1.50	1.90
8/28				3.30	2.20	1.10	2.50	1.60	.90
8/29				2.80	2.00	.80	2.10	1.70	.40
8/30				2.10	1.70	.40	1.80	1.50	.30
8/31	.40	.40	T	2.00	1.70	.30	1.60	1.40	.20
9/13				.81	.60	.21			

T = Trace

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