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Limnology

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THE DYNAMICS OF ACCUMULATION OF PHOSPHORUS BY THE SEDIMENTS OF THE LAKE SYSTEM OF THE WATER QUALITY MANAGEMENT PROJECT AT MICHIGAN STATE UNIVERSITY

By

Thomas Charles Young

A DISSERTATION

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

DOCTOR OF PHILOSOPHY

Department of Fisheries and Wildlife

1977

ABSTRACT

THE DYNAMICS OF ACCUMULATION OF PHOSPHORUS BY THE SEDIMENTS OF THE LAKE SYSTEM OF THE WATER QUALITY MANAGEMENT PROJECT AT MICHIGAN STATE UNIVERSITY

By

Thomas Charles Young

The lake system of the Michigan State University Water Quality Management Project received secondary effluent from the wastewater treatment plant in East Lansing. Phosphorus dynamics in the sediments of Lakes 1 and 4 of the system were investigated in terms of transport of phosphorus to the sediments by sedimentation of seston, accumulation of phosphorus in the sediments, and partitioning of phosphorus in seston and sediments.

Lake 1 had higher phosphorus loadings than Lake 4 and was dominated by phytoplankton, while Lake 4 was dominated by macrophytes. The absence of macrophytes in Lake 1 permitted resuspension of particulates from the lake bottom and resulted in rates of sedimentation of seston which were six times greater than those in Lake 4.

Resuspension affected the pattern of phosphorus accumulation in sediments. In Lake 4, phosphorus accumulation was greatest in shallow water since macrophytes minimized

resuspension. In Lake 1, accumulation was greatest in deep water and areas of eddy formation where less resuspension occurred.

Phosphorus content of seston from Lake 4 averaged 1.81 mg P/g and varied by insignificant amounts. Phosphorus in seston from Lake 1 was 3.49 mg P/g prior to and 20.27 mg P/g after a permanent increase in the phosphorus concentration of secondary effluent from an average of 1.4 to 4.1 mg P/l which occurred as a result of a change in wastewater plant operation. Rate of sedimentation of phosphorus by seston was greater than the rate of phosphorus loading in both lakes.

Most of the phosphorus transported to the sediments by seston in both lakes was bound to organic matter by adsorption. In sediments from Lake 1, most of the phosphorus was partitioned by adsorption to organic matter which occurred predominantly as an iron-organic complex. In sediments from Lake 4, most of the phosphorus was partitioned by adsorption to inorganic iron colloids.

Accumulation of phosphorus in sediments was greater at higher loading rates than lower rates, but growth of macrophytes permitted greater accumulation of phosphorus in sediments than phytoplankton at the loading rates observed in Lake 1. Macrophytes reduced oxygen demand on the sediments which permitted accumulation of iron-bound phosphorus. Loss of phosphorus from sediments of Lake 1 was associated with resuspension, while macrophyte growth accompanied losses from the sediments in Lake 4.

At the stage of development of the lake system at the time of this investigation, permanent accumulation of phosphorus in the sediments was 6.6 and 10.5 percent of incoming phosphorus to each lake. On the basis of these values, it is postulated that permanent accumulation of phosphorus by the sediments of this lake system will not be effective for withdrawing phosphorus from secondary effluent.

ACKNOWLEDGMENTS

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I thank my wife, Suella, for her patience, perseverance, understanding, and participation during the period of our lives required for this work.

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INTRODUCTION

The Michigan State University Water Quality Management Project is a pioneering effort in wastewater recycling. Through application of scientific understanding of aquatic and terrestrial ecosystems, the project strives to meet societal needs for wastewater disposal and desires for clean water. However, achievement of these goals requires a realistic management plan which cannot be derived from current knowledge of these systems. Mechanisms which bring about renovation of wastewater in natural systems must be defined and assessed for inclusion in such a plan.

Phosphorus is a wastewater component of concern, since it promotes aquatic plant growth. Thus, a major goal for the project is reduction of phosphorus concentrations by the system. In the lake system, biological uptake of phosphorus represents a temporary storage compartment, the size of which depends on standing crop. In contrast, permanent phosphorus removal can occur in lake sediments.

Phosphorus in sediments has been studied by limnologists for the past 40 years. According to Hutchinson (1957), Einsele (1936, 1938) was the first to suggest the existance of a relationship between iron and dissolved phosphorus in hypolimnetic waters. Mortimer (1941, 1942) observed release of phosphorus and iron when anaerobic conditions developed in sealed water-sediment systems.

Early interpretations of the iron-phosphorus association (Hutchinson, 1957; Ruttner, 1963) described a cycle of precipitation and dissolution involving an hypothesized insoluble ferric phosphate and a soluble ferrous phosphate. The ferric compound was said to be formed under aerobic conditions and displaced to the sediments where reduction of the iron occurred, allowing loss of phosphorus by dissolution and diffusion.

No direct evidence has been given for the formation of discrete ferric or ferrous phosphate compounds during annual phosphorus cycles in lakes (Armstrong _et al_., 1971). Golterman (1975) reported that Thomas (1965) demonstrated that ferric phosphate in activated sludge was not solubilized in passage through anaerobic digestion. Still, the ferric phosphate model has formed the basis for design of phosphorus removal facilities in wastewater treatment and has worked in practice (EPA, 1976).

Currently, the iron-phosphorus relationship is thought to involve adsorption of inorganic phosphorus to oxides and hydrated oxides of iron in the water column (Stumm and Morgan, 1970; Stumm and Leckie, 1971; Golterman, 1975) as has been demonstrated under laboratory conditons (Gastauche _et al_., 1963; from Syers _et al_., 1973).

After reaching the sediments, two mechanisms have been postulated for the relationship between iron and phosphorus. Inorganic phosphorus was shown to be bound by amorphous iron oxides and hydroxides in calcareous and non-calcareous lake sediments using analytically defined phosphorus fractionation procedures (Williams *et al*., 1971a; Williams *et al*., 1971b; Williams *et al*., 1971c; Shukla *et al*., 1971). The second mechanism involved formation of a humic-iron-phosphorus complex, wherein iron was bound to phosphorus and this complex was bound secondarily to a decay-resistant organic molecule (Golterman, 1975).

Binding of phosphorus by calcium has been shown to depend on the amount of calcium in the lake water. Golterman (1973) presented evidence for hydroxyapatite control of phosphorus concentrations in Lake Geneva. Stumm and Morgan (1970) and Stumm and Leckie (1971), based on solubility, considered hydroxyapatite to control the distribution of phosphorus between water and sediments in most natural lakes. Lee (1970), however, did not believe that hydroxyapatite played a major role in the chemistry of phosphorus in water or sediments (from Syers *et al*., 1973). Williams *et al*. (1976) presented evidence that apatite phosphorus was an important contributor to the sedimentary phosphorus of surficial sediments of Lake Erie, but concluded that it was due to erosion from terrestrial sources.

Stumm and Leckie (1971) demonstrated the conversion of calcite to hydroxyapatite but indicated the process was very slow. Williams and Mayer (1972) presented evidence that diagenic formation of hydroxyapatite in deep sediments of Lake Ontario was widespread in that lake.

Williams *et al*. (1971a) found little evidence for apatite in non-calcareous sediments, but gave evidence that it formed a major portion of inorganic phosphorus in calcareous sediments (Williams *et al*., 1971b).

White and Wetzel (1975) showed a direct relationship between phosphorus and calcium carbonate in seston from a hardwater lake. In this same lake, Otsuki and Wetzel (1972) demonstrated co-precipitation of phosphorus with calcium carbonate using radioisotope methods.

Zoltek (1976) analyzed data concerning pH and phosphorus concentration in wastewater treated with lime for phosphorus removal. He interpreted his results to mean octacalcium phosphate solubility controlled phosphorus concentration rather than that of hydroxyapatite or co-precipitation with calcium carbonate.

Adsorption of dissolved phosphorus by sediment samples taken from the Roanoke River and Chesapeake Bay was studied by Carritt and Goodgal (1954). Their results suggested phosphorus sorption reduced regeneration of phosphorus under anaerobic conditions.

Harter (1968) studied phosphorus adsorption by eutrophic lake sediments and concluded that two mechanisms were involved: one involved a tightly bound aluminum phosphate, and a second involved a more loosely bound iron phosphate.

Williams *et al*. (1970) found non-calcareous lake sediments adsorbed and retained more added organic phosphorus than calcareous sediments, and that the adsorption reactions were not reversible over the period of observation. Shukla et al. (1971) confirmed these results and found that chemical removal of the hydrated iron oxide gel from the sediments eliminated the phosphorus adsorption capacity of both calcareous and non-calcareous sediments. They stated that the adsorption capacity was inversely related to the calcium carbonate content of the calcareous sediments.

Patrick and Khalid (1974) studied adsorption of phosphorus by terrestrial soils under aerobic and anaerobic conditions. Their results showed anaerobic conditions permitted greater adsorption from solutions higher in phosphorus, and greater desorption to solutions lower in phosphorus than occurred under aerobic conditions. They interpreted their results as meaning the hydrated iron oxide gel gained in surface area during anaerobic periods as a result of chemical reduction of iron.

Adsorption of phosphorus to aluminum clays in natural systems was considered important by Stumm and Leckie (1971). However, a study of phosphorus adsorption by standard clay minerals (Edzwald et al., 1976) demonstrated that acid extractable iron and calcium content of clays was more closely related to phosphorus adsorption capacity than acid extractable alumnium or the aluminum:silicon atomic ratio.

After sophisticated statistical manipulation, phosphorus fractions in sediment samples taken from several lake types (Williams et al., 1971c) showed no relationship between total phosphorus and any alumninum fraction. However, extractable aluminum was related to organic phosphorus.

Williams et al. (1971c) found no relationship between organic carbon and total phosphorus in sediments, but found that organic phosphorus was closely related to organic carbon. A similar finding was made by Sommers et al. (1972) who concluded that organic phosphorus levels in sediments were related to organic matter dynamics, rather than differences in the kinds of organic phosphorus present.

Golterman (1975) believed that phosphorus reaching the sediments by particulate sedimentation was organic-bound and that mineralization resulted in secondary binding by a mineral component, probably iron hydroxide. However, he presented no data to substantiate this hypothesis. Based on radioisotope studies, Hutchinson and Bowen (1950) concluded that sedimentation of phytoplankton was responsible for vertical displacement of phosphorus in stratified lakes.

Autolytic release of phosphorus by sinking phytoplankton was shown to recycle up to 80 percent of algal phosphorus prior to cell movement out of the epilimnion (Golterman, 1973). However, the phosphorus content of growing algae was shown to depend on that of the growth medium and percent losses would reflect these conditions (Sievers, 1972; Young, 1972). Foree et al. (1971) showed losses of 50 to 60 percent of cell phosphorus under prolonged aerobic and anaerobic conditions. They concluded that the extent of phosphorus loss was dependent on the length of degradation period and the initial nutrient concentration of the algal culture. Thus, there is less autolytic regeneration of phosphorus from cells grown in lakes under low phosphorus concentrations that in lakes with high phosphorus concentrations.

Phosphorus in lake sediments occurs as a result of interactions between the biology, physics, and chemistry of the lake and its watershed. The current state of understanding of sedimentary processes involving phosphorus permit qualitative prediction of phosphorus binding mechanisms in sediments. However, these mechanisms lack quantitative details which relate them to interactions with lake biota and phosphorus loading. Consequently, prediction of permanent losses of phosphorus to the sediments is unreliable with present knowledge.

This investigation endeavors to characterize and quantify the mechanisms involved in permanent and temporary storage of phosphorus in the sediments of the lakes of the Water Quality Management Project. The approach employed to meet these objectives involved consideration of levels of phosphorus loading, and growth and decay of dominant aquatic plants as influences on (1) sedimentation of seston as a means for transporting phosphorus to the sediments, (2) accumulation of phosphorus in the sediments, (3) partitioning of phosphorus in seston and sediments, and (4) the dynamics of the sediments of the lake system as a compartment for phosphorus.

METHODS AND MATERIALS

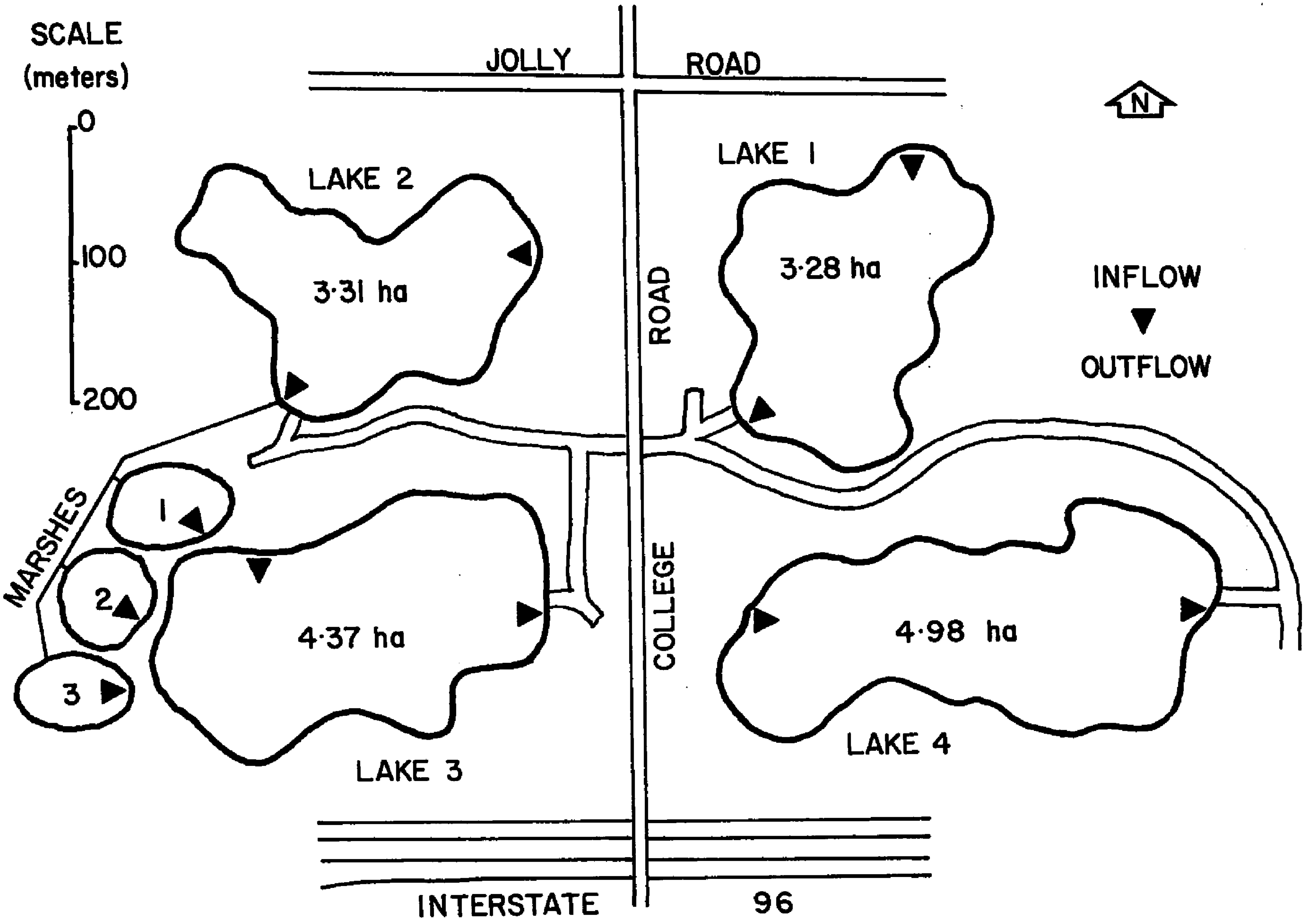
Description of the Study Area

The Michigan State University Water Quality Management Project provided the field setting for this investigation. A detailed description of the project plan, facilities, and objectives can be found elsewhere (Institute of Water Research, 1976). A brief description is given here. The facility consists of an activated sludge wastewater treatment plant, which is part of the East Lansing municipal treatment works; a transmission line, for transport of treated wastewater; four lakes in series, for detention of the treated wastewater; and a spray irrigation area, consisting of a woodlot and open fields.

The lake system, illustrated in Figure 1, has a combined surface area of 16 ha, and each lake has a mean depth of 1.8 m. The lakes are unprotected from wind due to the lack of surrounding trees and terrain contour, with the exception of the west end of Lake 4, which is protected by a road grade. Fluorescent dye studies of water movement in these lakes during May, 1976, showed each lake was well mixed with mixing times of 10 to 20 percent of detention time. The circulation pattern of each lake depended on wind direction and had the following characteristics: (1) wind shear produced a surface current

Figure 1: Lake System, Michigan State University Water Quality Management Project

FIGURE 1


SCALE
(meters)
0
100
200
JOLLY
ROAD
LAKE 2
3·31 ha
LAKE 1
3·28 ha
ROAD
COLLEGE
INFLOW
▼
OUTFLOW
MARSHES
1
2
3
4·37 ha
LAKE 3
4·98 ha
LAKE 4
INTERSTATE
96
N

which ran in the same direction as the wind; (2) at the lee shore, a subsurface return current formed which ran windward; (3) the subsurface return current originated at lee shoreline angularities.

Wastewater Flow History

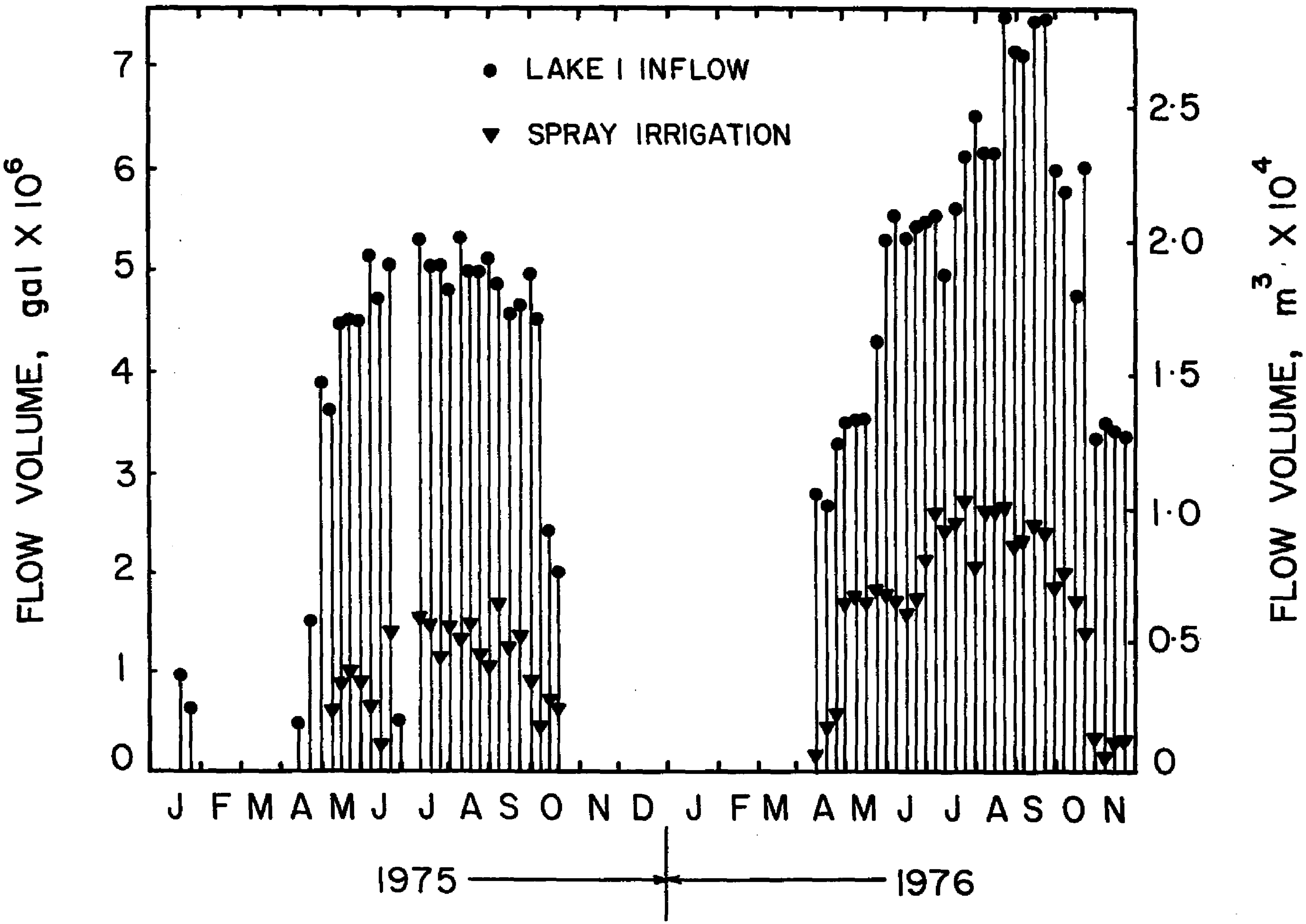
The lake system was filled first during the fall of 1973, and this water was allowed to stand until the summer of 1974. Pumping was resumed for a short period during the fall of 1974 at the nominal rate of 1.9×10^3 m^3/day (0.5 MGD). Beginning in April, 1975, the lake and spray systems were ready for continuous operation, and water was taken from the East Lansing Wastewater Treatment Plant at a rate of approximately 1.9×10^3 m^3/day (0.5 MGD). Hydraulic loading to the first lake was greater than that to the other lakes during this period, since water for irrigation was taken from the outlet of Lake 1, during 1975.

Lake system inflow and irrigation volumes for 1975 and 1976 are shown in Figure 2. Flow to the lake system was interrupted for approximately two weeks beginning about the end of June, 1975, to permit a change in pump location from the old to a new clarifier at the wastewater treatment plant. Pumping then resumed and continued through October, 1975.

In December, 1975, East Lansing began operation of a new wastewater treatment facility; and from April to about mid-May, 1976, water from the new facility was pumped to the lake system. All of the secondary effluent pumped to the lake system from

Figure 2: Weekly volumes of secondary effluent introduced to the lake system and pumped to the spray irrigation site, Michigan State University Water Quality Management Project, from January 1975 through November 1976

FIGURE 2



● LAKE I INFLOW
▼ SPRAY IRRIGATION
FLOW VOLUME, gal X 10^6
0
1
2
3
4
5
6
7
FLOW VOLUME, m^3 X 10^4
0
0·5
1·0
1·5
2·0
2·5
J F M A M J J A S O N D J F M A M J J A S O N
1975
1976

the fall of 1973 to mid-May of 1976, had been treated with ferric chloride and organic polymer to remove phosphorus. By that time part of the old East Lansing wastewater facility had been put into operation by Michigan State University, and it was operated without a phosphorus removal step. Beginning about mid-May, water coming to the lake system was secondary effluent with its normal complement of phosphorus, and for the remainder of this investigation, sufficient secondary effluent was pumped to provide approximately 1.9×10^3 m^3/day (0.5 MGD) of water to the lake system exclusive of water for spray irrigation. During 1976, irrigation water was taken from the transmission line, upstream from the inlet to Lake 1 which resulted in occasional back-siphoning of water from Lake 1.

Given in Table 1 are mean values and coefficients of variation (CV) for selected water quality parameters for the secondary effluent pumped to the lake system, during periods of flow. While these data do not indicate it directly, the raw wastewater treated at the East Lansing facility is relatively weak. East Lansing has no industry besides small retail businesses, and wastewater from Michigan State University receives treatment from the East Lansing plant. As a result, the East Lansing plant treats wastewater consisting, principally, of sanitary domestic waste and urban runoff. A detailed characterization of East Lansing municipal wastewater, before, during, and after treatment, can be found in other sources (Institute of Water Research, 1976).

Table 1. Characteristics of East Lansing and and MSU secondary effluent, April 1975 to October 1976

Time Period	Total Phosphorus (mg P/l)	Total Iron (mg Fe/l)	Total Calcium (mg Ca/l)	Filterable Residue (mg/l)	pH
1975					
1-30 Apr*					
mean	1.05	0.11	65.4	47.3	7.32
CV	0.48	0.29	0.38	1.28	0.04
1 May to 5 Jul*					
mean	1.38	0.14	49.97	24.6	7.68
CV	0.85	0.92	0.21	2.18	0.03
13 Jul to 26 Oct*					
mean	1.58	0.25	74.82	18.4	8.00
CV	0.49	0.67	0.19	1.64	0.04
1976					
12 Apr to 18 May*					
mean	1.38	0.34	85.8	12.0	7.97
CV	0.37	0.92	0.04	--	0.07
27 May to 31 Oct**					
mean	4.22	0.30	73.87	6.6	7.41
CV	0.29	0.42	0.07	0.59	0.03

* East Lansing Secondary Effluent

** Michigan State University Secondary Effluent

Primary Production

Studies of primary production in Lake 1 and 4 were made concurrently with this investigation (Schloesser, 1975). Production by phytoplankton, macrophytes, and associated epiphytes was estimated by oxygen measurements taken at dawn, dusk, and dawn in plexiglass enclosures. Identification and counting of phytoplankton were performed using membrane filtration techniques, and chlorophyll-a was measured by acetone extraction, corrected for phaeophytins. Macrophyte standing crop was estimated in all lakes by McNabb *et al*. (1975, 1976).

Sediments

Sediment cores were obtained in plastic tubes with the device illustrated in Figure 3 which was built from a prototype designed by Robert P. Glandon, a graduate student in Fisheries and Wildlife at Michgan State University. Sediment cores were obtained from Lake 1 and 4 at the permanently marked sampling stations shown in Figures 4 and 5. Sediment cores from Lakes 2 and 3 were taken from the locations shown in Figures 6 and 7. Dates for core sampling are given in Table 2.

Cores were returned to the laboratory intact, and the water overlying each was aspirated to within 1 cm of the sediment-water interface. Each core was examined visually and depth of accumulation of sediment over the native clay seal was determined. Coring tubes were marked with a felt tipped pen to indicate demarcation of the core into three or more strata: (1) an upper stratum, the accumulation zone; (2) a middle

Figure 3: Device used to obtain cores of lake sediment

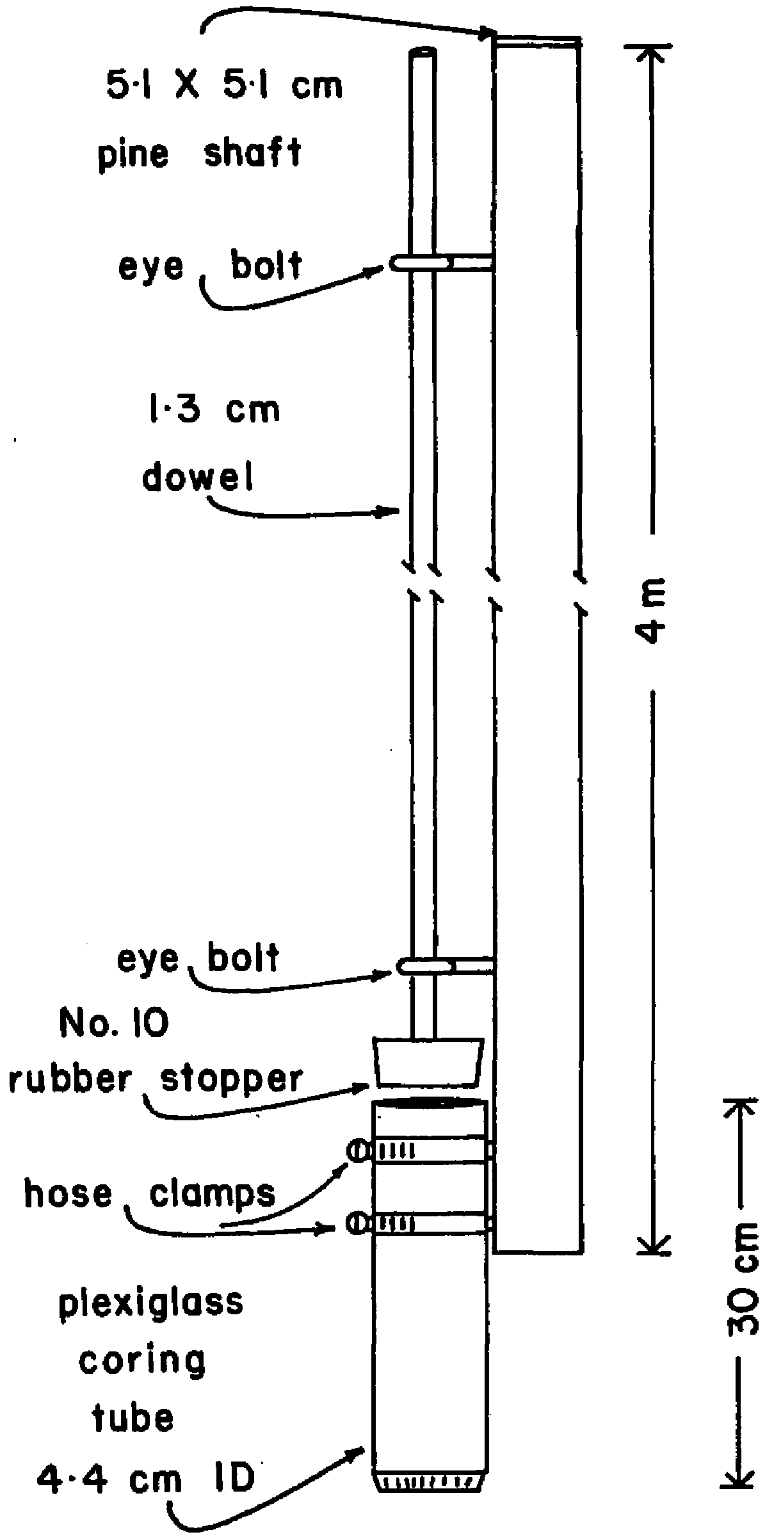

5·1 X 5·1 cm
pine shaft
eye bolt
1·3 cm
dowel
4 m
eye bolt
No. 10
rubber stopper
hose clamps
plexiglass
coring
tube
4·4 cm ID
30 cm

FIGURE 3.

Figure 4: Location of sampling stations for sediment cores and sediment traps, Lake 1, Michigan State University Water Quality Management Project

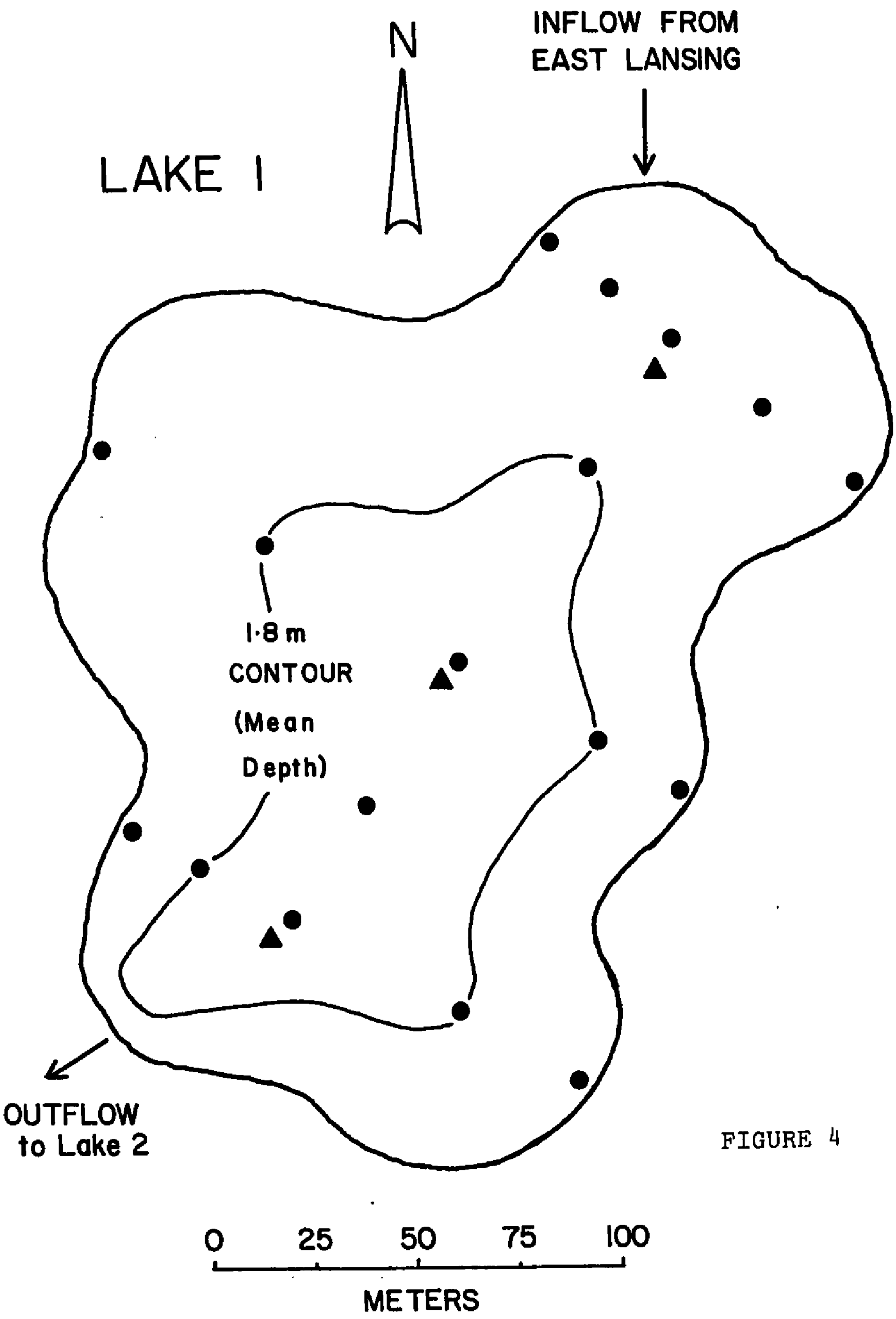

LAKE 1
N
INFLOW FROM EAST LANSING
1·8 m CONTOUR (Mean Depth)
OUTFLOW to Lake 2
0
25
50
75
100
METERS

FIGURE 4

Figure 5: Location of sampling stations for sediment cores and sediment traps, Lake 4, Michigan State University Water Quality Management Project

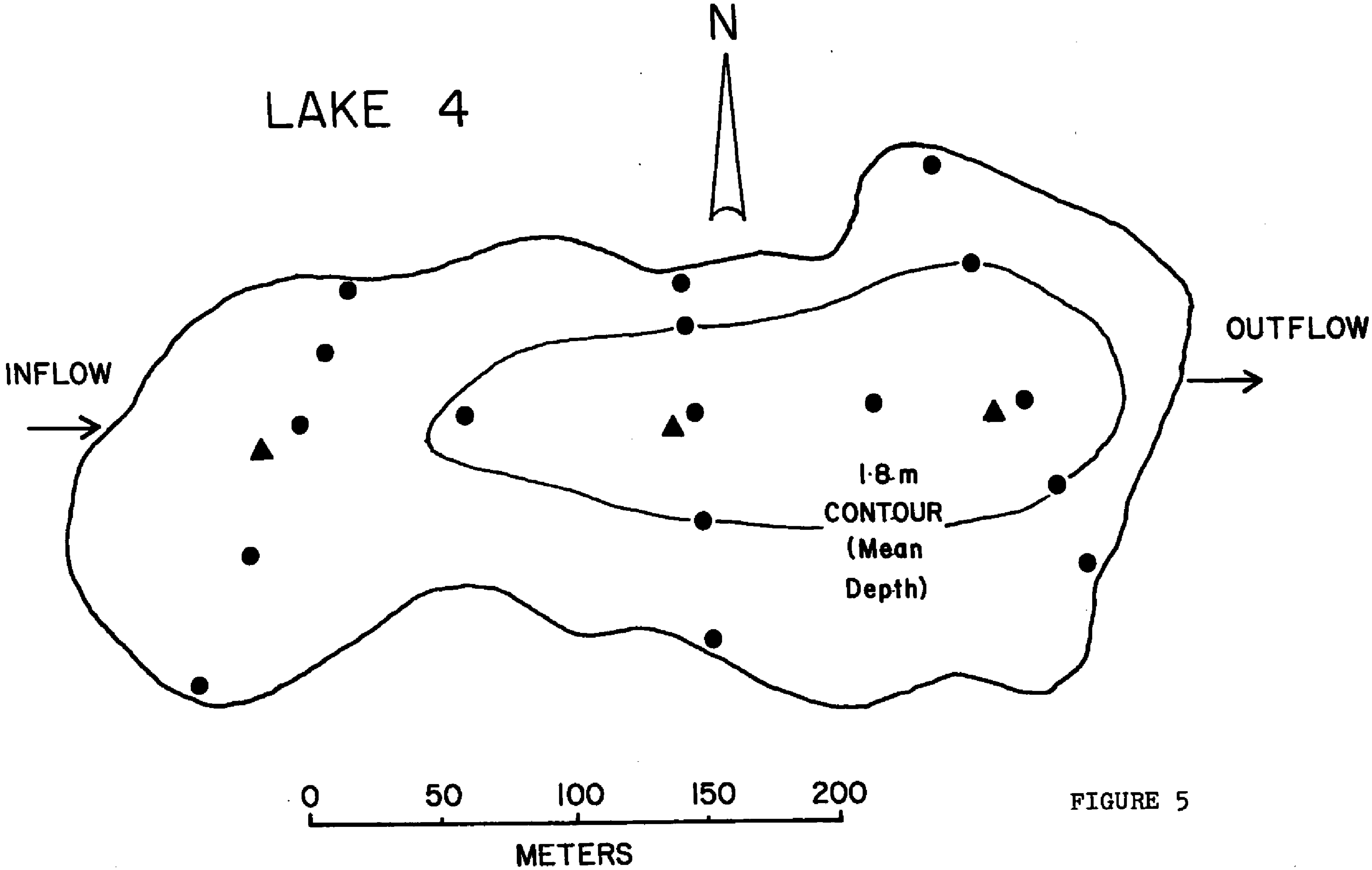

LAKE 4
N
INFLOW
OUTFLOW
1·8 m
CONTOUR
(Mean
Depth)
0
50
100
150
200
METERS

FIGURE 5

Figure 6: Location of sampling stations for sediment cores, Lake 2, Michigan State University Water Quality Management Project

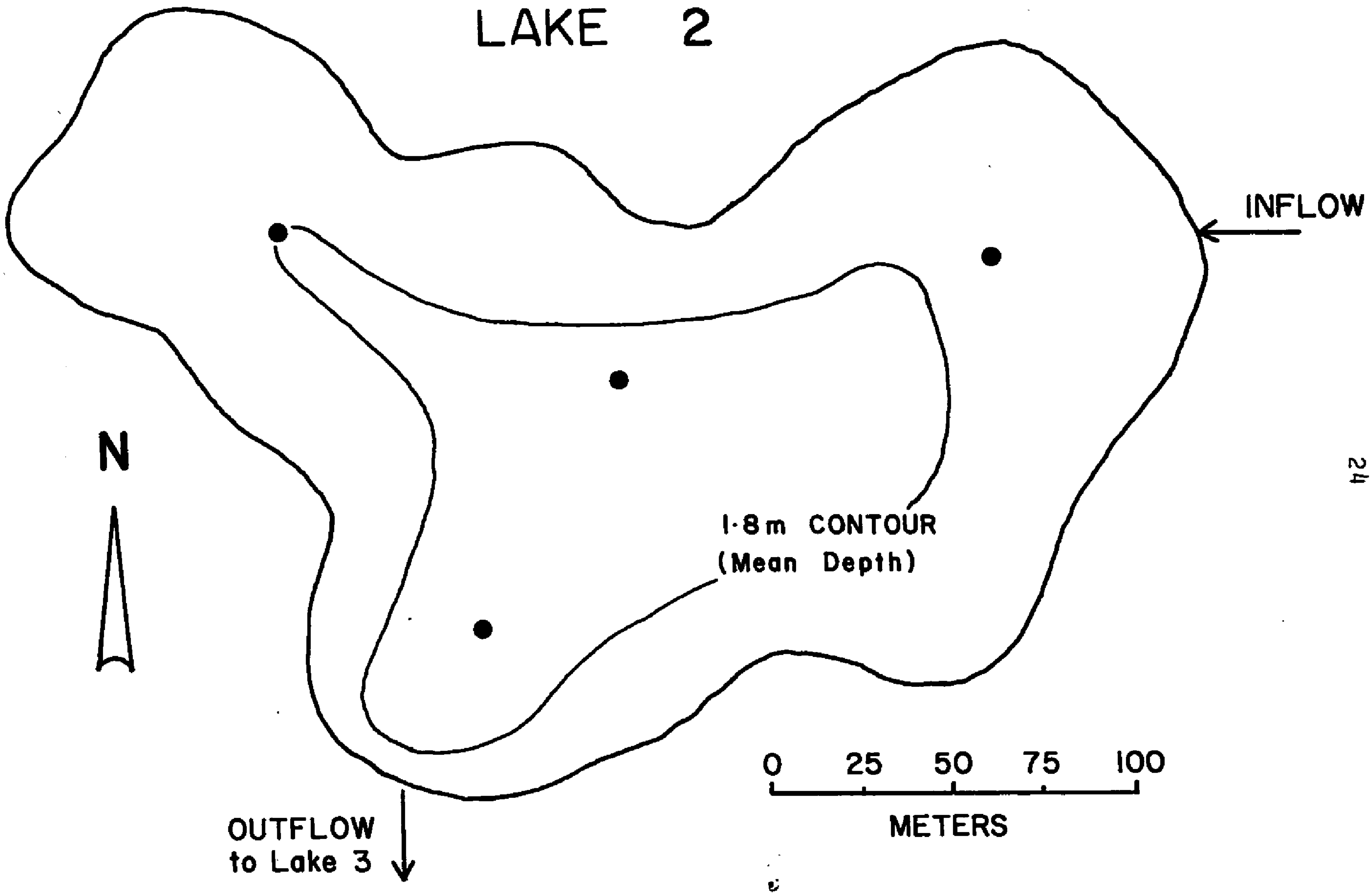

LAKE 2
INFLOW
N
1·8m CONTOUR
(Mean Depth)
0
25
50
75
100
METERS
OUTFLOW
to Lake 3

FIGURE 6

Figure 7: Location of sampling stations for sediment cores, Lake 3, Michigan State University Water Quality Management Project

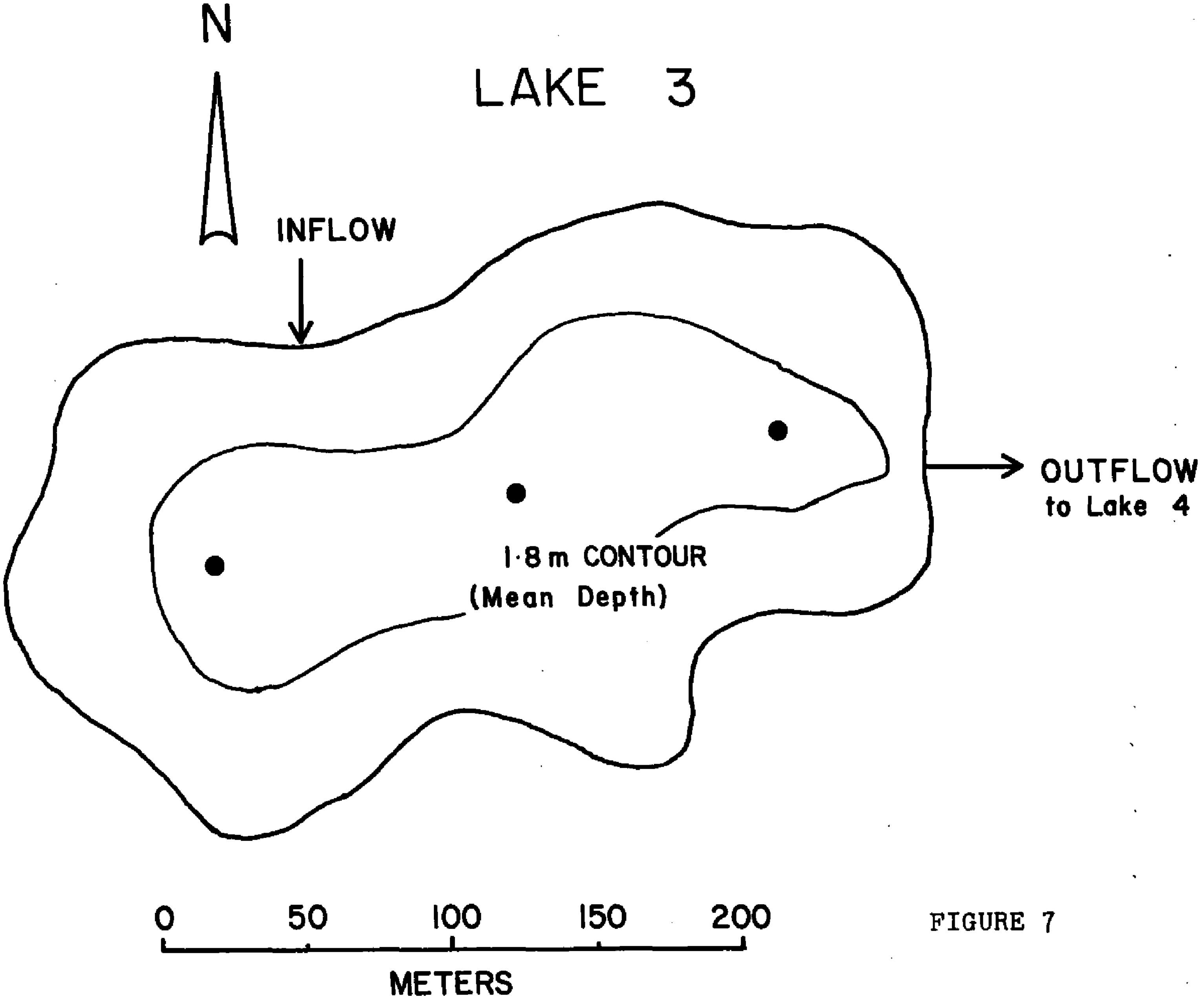

N
LAKE 3
INFLOW
OUTFLOW
to Lake 4
1·8 m CONTOUR
(Mean Depth)
0
50
100
150
200
METERS

FIGURE 7

Table 2. Sediment core sampling dates for Lake 1, 2, 3, and 4 of the Water Quality Management Project, 1975-1976

Lake 1	Lake 2	Lake 3	Lake 4
2, 3 May 1975			9, 19 May 1975
16 September 1975			9 October 1975
10 January 1976			
			1 April 1976
2 June 1976	30 June 1976	30 June 1976	11 June 1976
2 September 1976			
25 October 1976	25 October 1976	25 October 1976	25 October 1976

stratum, a transition zone, which often contained small amounts of upper stratum material carried down by the shearing action of coring; and (3) a lower stratum, which was clay from the lake seal.

The cores were frozen and sectioned with a metal saw. The sections were dried for approximately 48 hours at 110°C, cooled, and weighed. Dried sections were hand ground by mortar and pestle to pass a Number 35 Standard Sieve (maximum diameter = 0.5 mm), and stored in glass containers.

Ground sections of sediment cores were chemically analyzed and accumulation of phosphorus was determined by the amount of phosphorus in the sectioned cores. For each sampling station the value for accumulation was calculated as the difference between the total phosphorus in the core and the total which would have been present had the levels of phosphorus in upper and transition strata been equal to that of the underlying clay seal.

Seston

Seston was collected in sediment traps, one of which is illustrated in Figure 8. Six 50 ml glass centrifuge tubes were held upright by means of an inverted plastic bucket which had holes drilled in the bottom to hold the tubes securely. The buckets were fitted with lead weights at the open end to provide negative buoyancy. An inverted bucket assembly was suspended at depths of 0.5, 1.0, and 1.5 m from eyebolts at the corners of a 2 m equilateral wooden triangle which was anchored

Figure 8: Sediment Trap, drawn in plan and side views, details in text

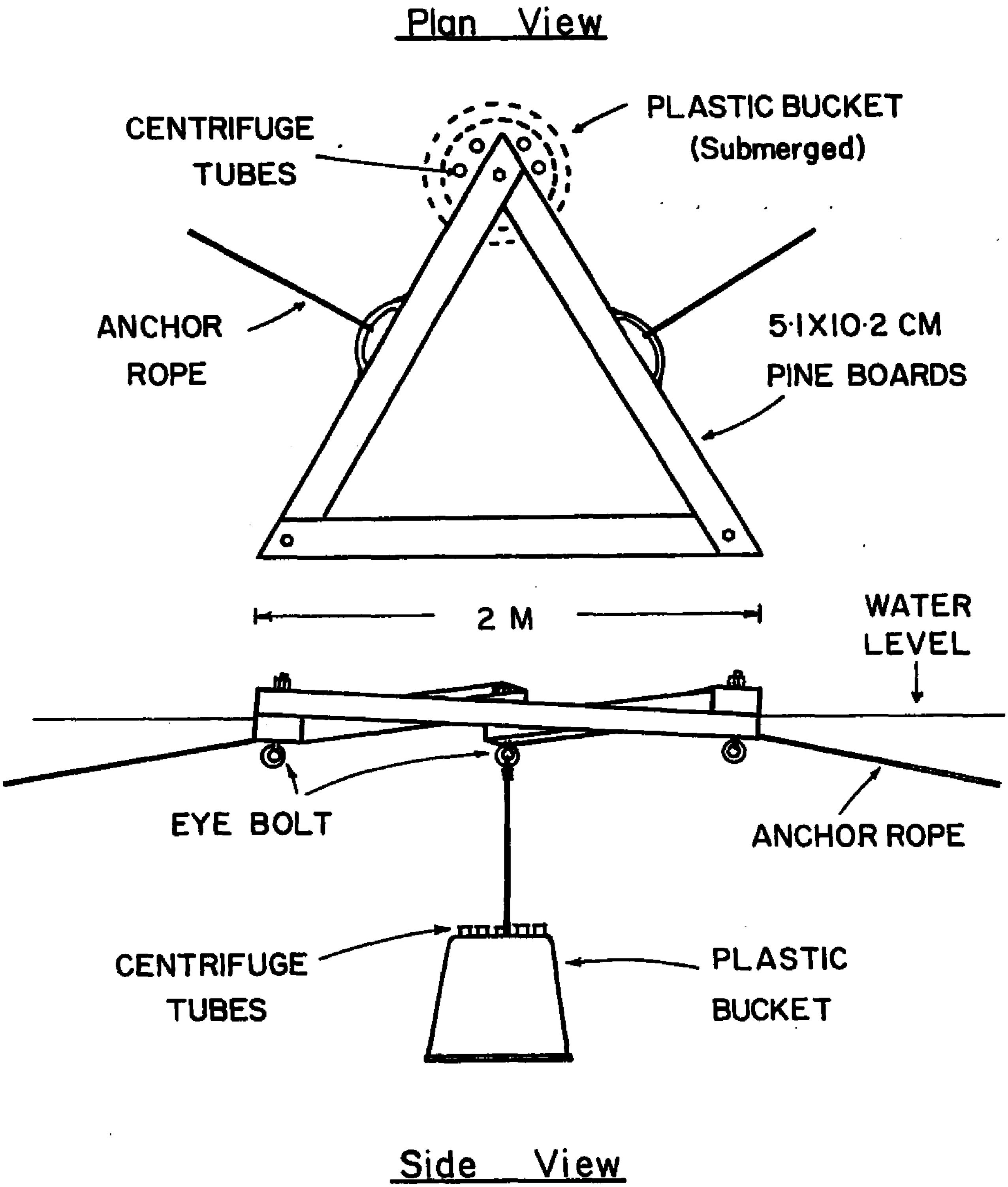

Plan View
CENTRIFUGE TUBES
PLASTIC BUCKET (Submerged)
ANCHOR ROPE
5·1X10·2 CM PINE BOARDS
2 M
WATER LEVEL
EYE BOLT
ANCHOR ROPE
CENTRIFUGE TUBES
PLASTIC BUCKET
Side View

FIGURE 8

from two sides and allowed to float on the surface. These triangles plus bucket assemblies were positioned in Lakes 1 and 4 in open water at the locations indicated in Figures 4 and 5.

The tubes of each bucket were assigned to one of three replicate groups for sampling. For each sampling, two tubes of a specified replicate group at each depth were removed and replaced with fresh tubes. Replicate groups were sampled in order which allowed estimation of sedimentation of seston over long overlapping periods. The long periods were found necessary to provide sufficient material in a manageable number of samples.

Seston samples were returned to the laboratory and examined qualitatively for algae, macrophyte fragments, zooplankton, macroinvertebrates, and detritus. Volume measurements after centrifugation at 1000 g for 10 minutes were taken. The solids from both replicates were combined and dried for 48 hours at 110°C, cooled, and weighed. Samples were ground by hand using a mortar and pestle and stored in glass containers.

Methods of Chemical Analysis

Standard analytical methods were employed for the determination of phosphorus, iron, calcium, and carbon in core and seston samples. Total carbon and carbonate carbon were determined gravimetrically by the wet oxidation and acid extraction procedures described by Allison _et al_. (1965), and Allison and Moodie (1965). The digestion reagent used in the carbonate digestion was modified to 0.5 N HCl from 2 N H_2SO_4, and the

$FeSO_4 \cdot 7 H_2O$ recommended as a reductant was not included. A paired data analysis showed no significant difference between the results obtained by the two methods ($P > 0.1$), for estimating inorganic carbon.

Total elemental analyses for phosphorus, iron, and calcium involved acid decomposition of the sample using a HNO_3-H_2SO_4 digestion, as described in Standard Methods (APHA, 1971) for heavy metals in polluted waters. Care was taken to avoid excessive fuming of SO_3 during digestion to avoid volatilization of phosphorus (Maxwell, 1968). The digestate was diluted to approximately 50 ml with H_2O, boiled, and filtered through Number 3 Whatman filter paper, supported by a Buchner funnel. Digestates from the carbonate carbon analysis were filtered in a similar manner for determination of acid extractable phosphorus, iron, and calcium.

The total element digestions render a near complete decomposition of the samples, leaving a residue consisting chiefly of quartz sand and some occluded metal oxides, including iron (Maxwell, 1968). Percent recoveries of incremental additions of phosphorus, iron, and calcium, and their standard errors were 101.4 ± 0.7, 100.9 ± 9.6, and 99.9 ± 2.7, respectively, for the total element analysis. The results of recovery trials for iron and calcium using the acid extraction procedure were 97.9 ± 2.6 and 101.9 ± 1.6 percent, respectively. Recovery of phosphorus by the acid extraction procedure was not performed.

Wentz and Lee (1969) and later, Cowen and Lee (1976) described an acid extraction procedure for "plant available" phosphorus, similar to that used here, with the exception of the heating step. The latter authors suggested that their procedure extracted calcium-bound phosphorus, much of the iron and aluminum-bound phosphorus, surface-bound or adsorbed phosphorus, but not phosphorus occluded in oxides of iron, or appreciable phosphorus from hydrolysis of carbon-oxygen-phosphorus linkages of organic phosphorus. Further, Cowen and Lee (1976) failed to show effective acid hydrolysis of inositol (phytic acid) phosphate, after boiling for 1 hour at 100°C with 0.09 N H_2SO_4. Wentz and Lee (1969) found their cold extraction had no hydrolytic action on adenosine monophosphate and minimal hydrolysis of calcium phytate. Sommers et al. (1972) found that extraction with 1 N HCl (no time or temperature given) removed both in calcareous and non-calcareous sediments. Mehta et al. (1954) found no hydrolysis of organic phosphorus in terrestrial soil samples extracted with 12 N HCl after heating for 10 minutes on a steam table. While no recovery experiments with organic phosphorus were conducted in the present investigation, the results reported by others indicate that most of the phosphorus in the acid extractable fraction was physically or chemically bound inorganic phosphorus and that discrete organic phosphorus contributed little to this fraction.

A colorimetric finish was used for both total and extractable phosphorus determinations. The procedure employed the Automated Colorimetric Ascorbic Acid Method (EPA, 1974). These analyses were performed by the technical staff of the Michigan

State University Institute of Water Research Water Quality Laboratory using a Technicon Auto-Analyzer.

All iron and calcium final determinations were obtained by atomic absorption spectroscopy according to standard procedures (EPA, 1974).

Virtually all physical and chemical data for lake water and secondary effluent were furnished by the Water Quality Laboratory, Institute of Water Research.

Statistical Methods

Statistical reduction of data was by analysis of variance. Univariate split-plot designs were employed for analysis of phosphorus accumulation and seston sedimentation to remove correlations resulting from sequential sampling of the same locations.

Phosphorus partitioning in sediment and seston samples was estimated by multiple regression analysis. It was assumed that the phosphorus in these samples was bound to either iron, calcium, or organic matter by physical mechanisms such as occlusion or adsorption, or by chemical mechanisms such as ionic or covalent bonding or chemisorption. By multiple regression, the amount of phosphorus in sediments and seston was compared to amounts of iron, calcium and organic carbon. When phosphorus levels were related to levels of these other elements, it was concluded that a causal relationship existed and was a result of binding of phosphorus by the related elements.

Amounts of phosphorus which were shown by the analysis to be bound by either iron, calcium or organic carbon in samples of sediment and seston were calculated from the regression equation. Average amounts of phosphorus bound by each element were expressed as percentages of total phosphorus or extractable phosphorus in the samples. Phosphorus not bound by any of these elements was assumed to be equal to the constant term in the regression equation, and where significant ($P < 0.05$), this term was included as an unidentified form of phosphorus.

Loading Estimates

Hydraulic loading during the period 1 May 1975 to 31 October 1976 was estimated for each lake by stepwise application of the hydrologic balance given by the following equation.

$$V_{in} + V_{atm} = V_{out} + V_{exf}$$

Where: V_{in} = Volume of water flowing to a lake, m^3

V_{atm} = Volume of water gained or lost to the atmosphere, m^3

V_{out} = Volume of water flowing from a lake, m^3

V_{exf} = Volume of water lost through exfiltration, m^3

Recorded volumes of flow to the lake system from East Lansing were used as inflow volume (V_{in}) for Lake 1. Outflow volume (V_{out}), calculated from the balance equation, was used as V_{in} for Lake 2 on the next step. Water for spray irrigation was taken from the outflow of Lake 1 in 1975, and from the inlet pipe to Lake 1 in 1976. In either case, the calculation was modified for the irrigation volume for Lake 1 calculations. Atmospheric gains and losses (V_{atm}) were estimated from data reported by the U.S. Weather Bureau, Capitol City Airport, Lansing, Michigan. Precipitation was taken directly from monthly totals, and evaporation was estimated after an empirical method suggested by Fair and Geyer (1963). Exfiltration volume (V_{exf}) was calculated as the difference between estimated and measured total discharge from the lake system for 1976. The estimate of V_{exf} for the system was 0.11 to 0.22 cm/day; and for loading calculations, a median of 0.165 cm/day was used. The results of a direct estimate of lake seal exfiltration gave a value of 0.18 cm/day (Bahr et al., 1977).

Assumptions required for use of the hydrologic balance equation were: (1) exfiltration was constant and uniform; (2) meterologic data from the U.S. Weather Bureau, Capitol City Airport, Lansing, Michigan, represented conditions at the Water Quality Management Project site; and (3) lakes were always full.

Hydraulic loading was verified two ways. The first method was a comparison of estimated and measured volumes of discharge from the lake system. The results of this comparison are illustrated in Figure 9. The mean difference between measured and calculated values was not significant ($P > 0.5$), indicating a strong relationship, and that calculated flows closely predict field measurements.

The second verification involved use of the hydraulic loadings in a chloride mass balance for each lake, and comparison of predicted chloride concentrations with those obtained by analysis of water samples. The chloride balance gave the results shown in Figure 10. The hydrologic balance permitted prediction of chloride concentration with a standard error of estimation of 9 percent of the mean measured concentration for 1975 data, and of 5 percent for 1976 data. Additional assumptions required for the chloride balance were: (1) the lakes were completely and instantaneously mixed; (2) chloride was conservative; (3) irrigation water taken upstream from Lake 1 was secondary effluent, with no back siphoning; and (4) the volume and chloride content of runoff entering the lakes were neglegible.

Phosphorus loading was estimated as the product of flow estimates and measured concentrations of phosphorus in East Lansing effluent and the lake system.

Figure 9: Comparison of measured and predicted monthly discharges of water from Lake 4, Michigan State University Water Quality Management Project

FIGURE 9

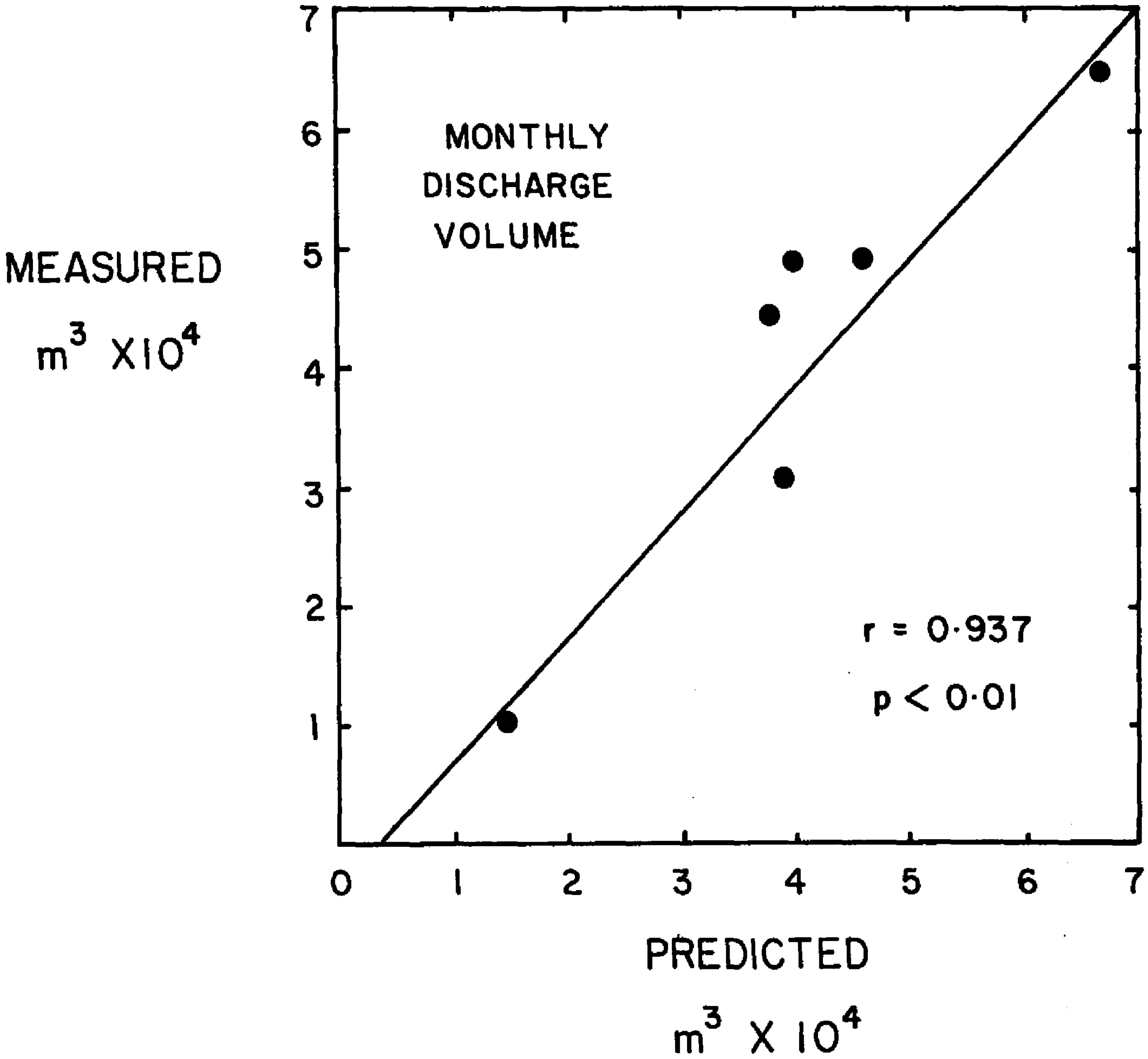

MEASURED
$m^3 \times 10^4$
MONTHLY DISCHARGE VOLUME
r = 0·937
p < 0·01
PREDICTED
$m^3 \times 10^4$
0
1
2
3
4
5
6
7

Figure 10: Comparison of measured chloride concentrations with concentrations estimated by hydraulic balance, lake system, Michigan State University Water Quality Management Project, 1975 and 1976

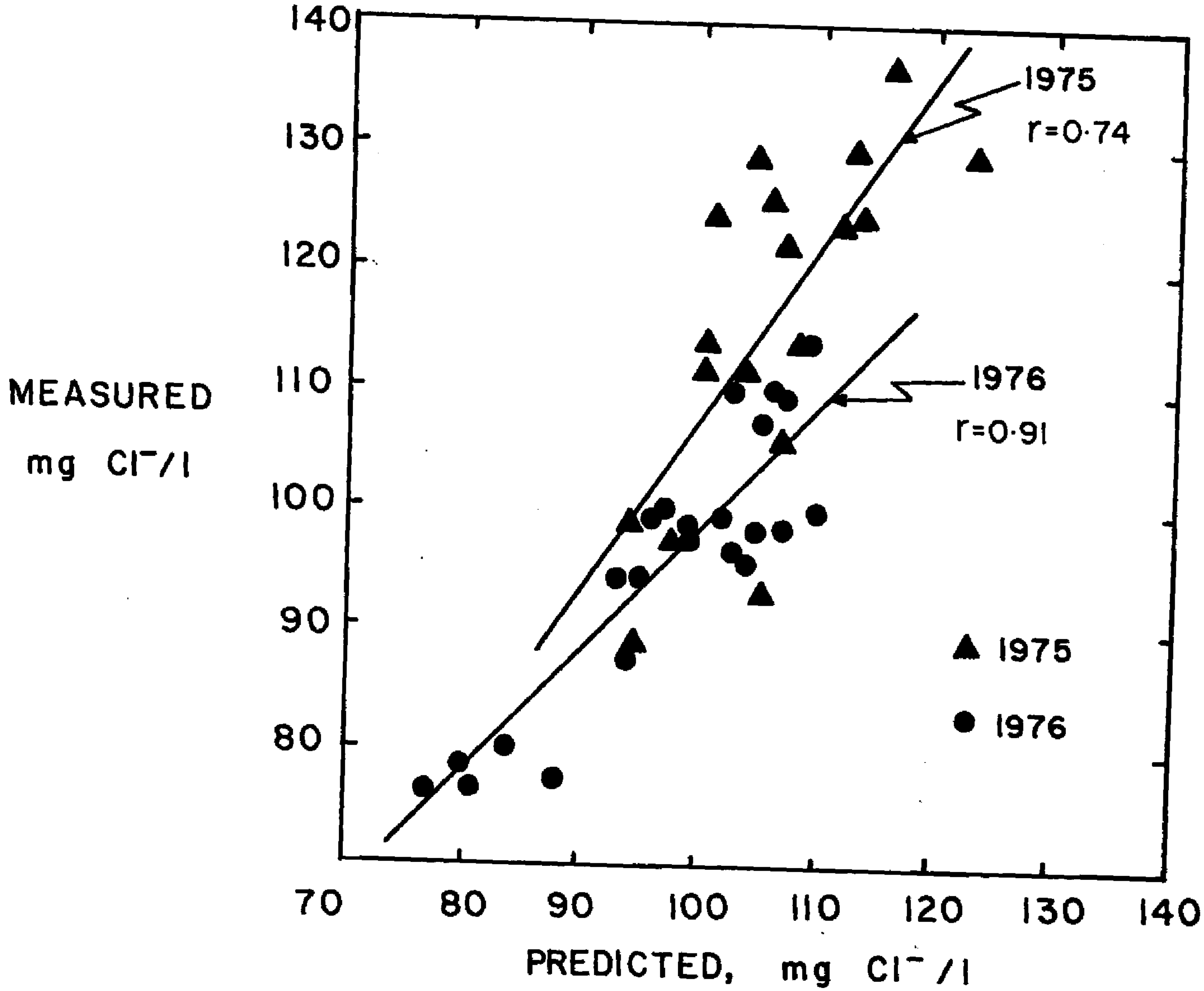

MEASURED
mg Cl⁻/l
140
130
120
110
100
90
80
70
80
90
100
110
120
130
140
PREDICTED, mg Cl⁻/l
1975
r=0·74
1976
r=0·91
▲ 1975
● 1976

FIGURE 10

RESULTS AND DISCUSSION

Phosphorus Loading

Phosphorus concentrations in East Lansing effluent are shown in Figure 11. From May, 1975, through May, 1976, concentrations averaged 1.45 mg P/l. During this period iron chloride was used for phosphorus removal in the East Lansing plant. Iron additions were discontinued after May, and from June through October, 1976, phosphorus concentrations averaged 4.09 mg P/l.

Phosphorus loadings to individual lakes are summarized in the Appendix and illustrated in Figure 12. Time intervals for these values are approximately one month, either 4 or 5 weeks, since East Lansing flow data were in weekly summaries. Downstream lakes received less phosphorus than lakes immediately upstream in the system due to phosphorus retention by succeeding lakes, and loss of volume from exfiltration and evaporation. Annual loadings for each lake of the system are summarized in Table 3.

Loading values for the lakes of the Water Quality Management Project can be compared with those which Vollenwieder (1968) recommended to avoid eutrophic conditions. As a guideline, Vollenwieder set the critical level at 0.10 g P/m^2-year for lakes with a mean depth less than 2 m. This value is less

Figure 11: Concentrations of total phosphorus in East Lansing effluent pumped to lake system, May 1975 through October 1976

FIGURE 11

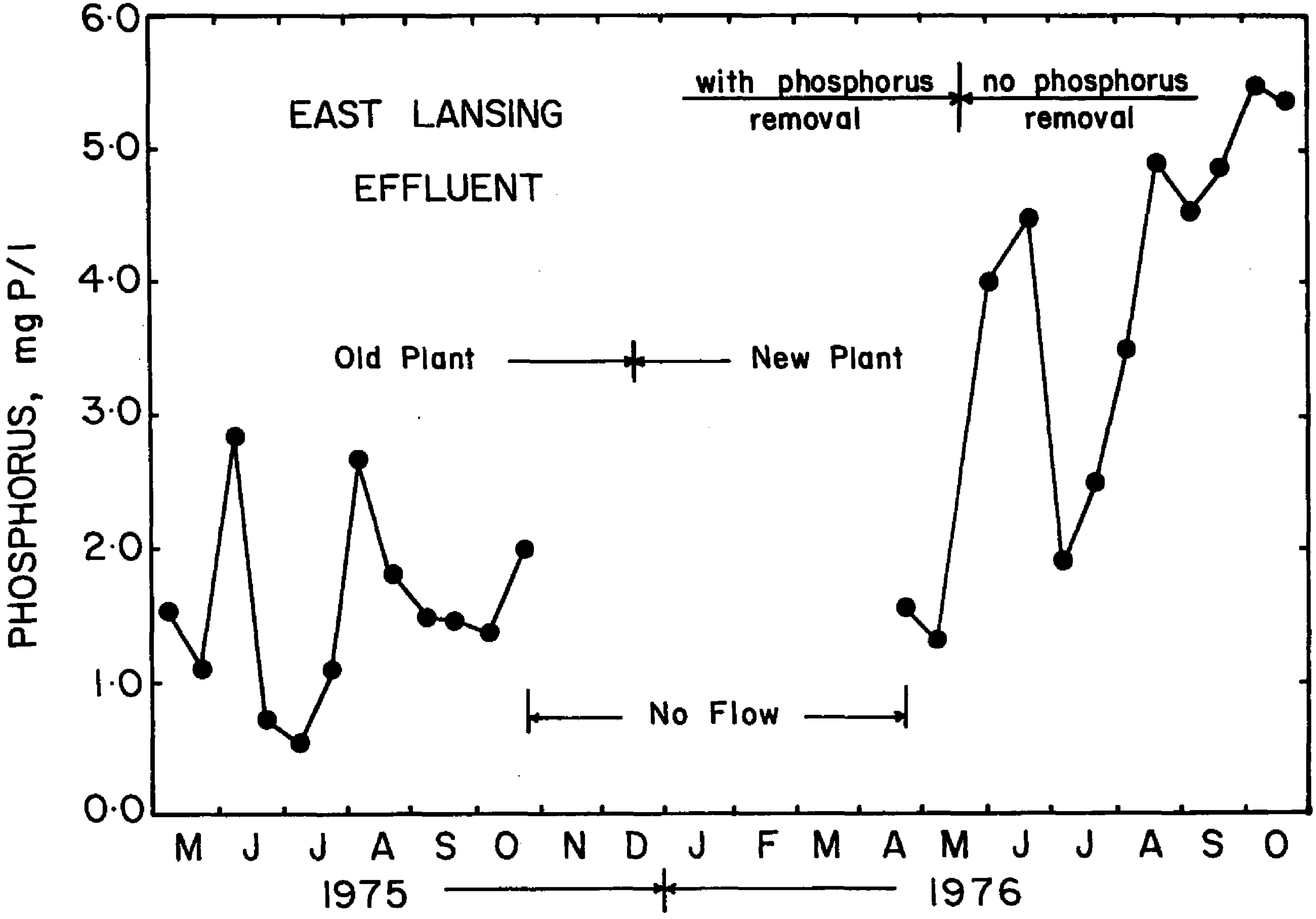
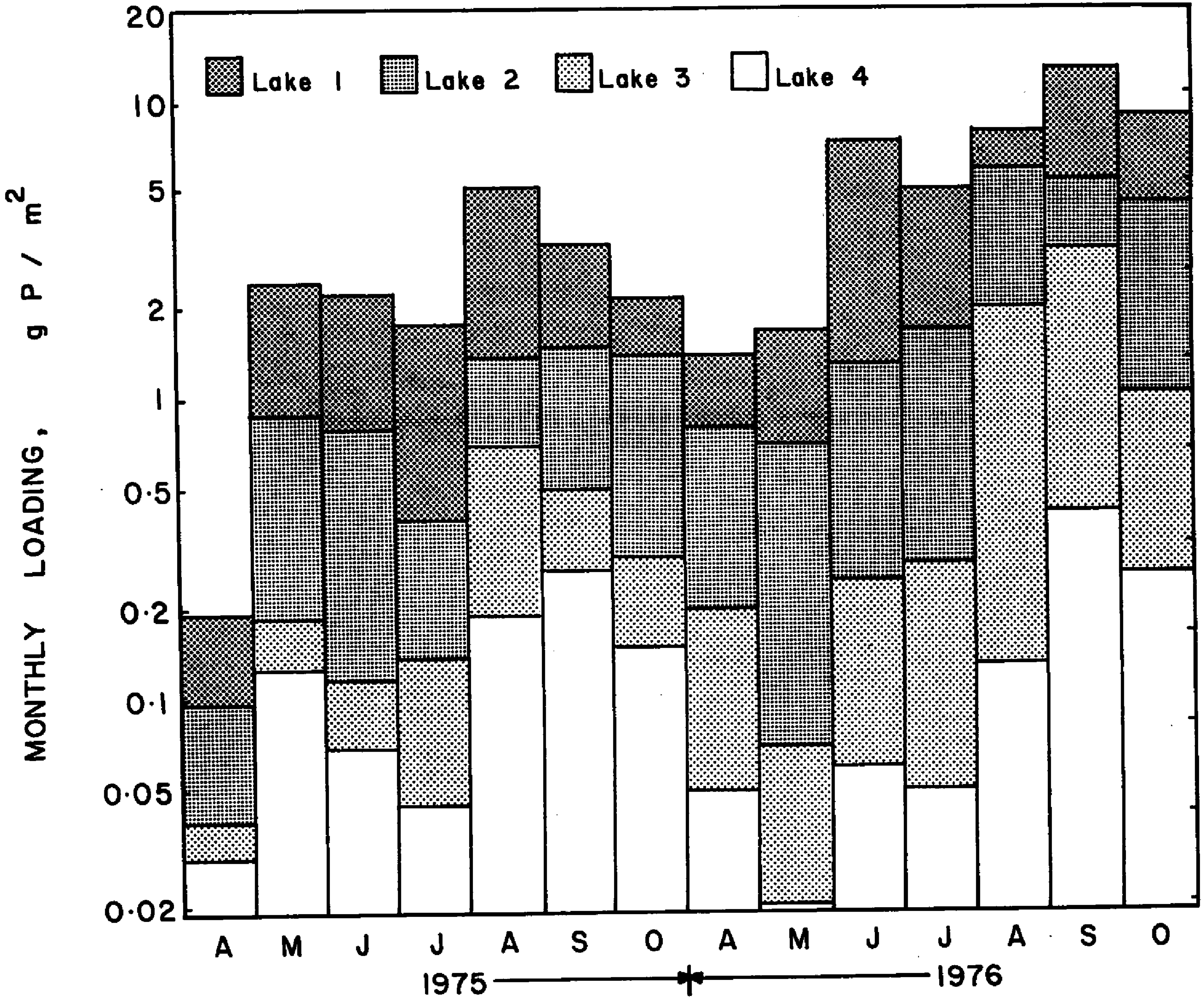

6·0
5·0
4·0
3·0
2·0
1·0
0·0
PHOSPHORUS, mg P/l
EAST LANSING
EFFLUENT
with phosphorus removal
no phosphorus removal
Old Plant
New Plant
No Flow
M J J A S O N D J F M A M J J A S O
1975
1976

Figure 12: Monthly loading of phosphorus to the lakes of the Michigan State University Water Quality Management Project, April 1975 through October 1976

FIGURE 12



MONTHLY LOADING, g P / m^2
20
10
5
2
1
0·5
0·2
0·1
0·05
0·02
Lake 1
Lake 2
Lake 3
Lake 4
A
M
J
J
A
S
O
A
M
J
J
A
S
O
1975
1976

Table 3. Loading of phosphorus to lake system May 1975 to October 1976 (g P/m^2-yr)

Lake	1975	1976
1	17.4	44.8
2	6.45	20.37
3	1.94	6.93
4	0.89	0.98

than the annual loading received by any lake in the system during this investigation. The lakes in this study each received sufficient phosphorus to be classed as eutrophic by Vollenwieder's criteria.

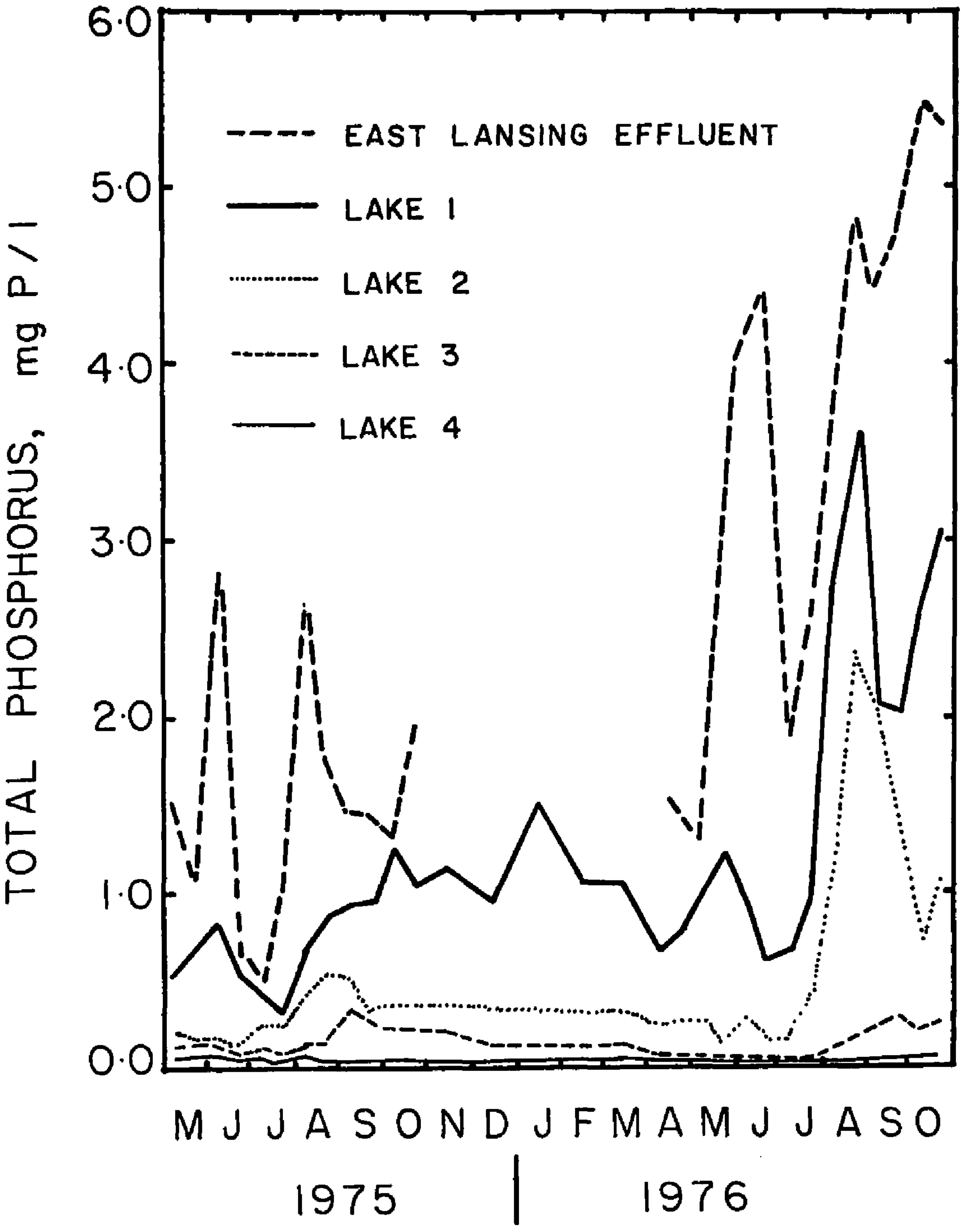
Phosphorus concentrations in successive lakes were less as loading diminished as shown in Figure 13. Total phosphorus in Lake 1 averaged 0.86 mg P/l from May, 1975, through July, 1976, and 2.68 from August through October, 1976. In Lake 4 the average for the entire period was 0.05 mg P/l. Lakes 2 and 3 showed concentrations intermediate to those of Lakes 1 and 4.

Primary Production

The primary producer communities of Lakes 1 and 4 were dissimilar. Lake 1 was dominated by phytoplankton (diatoms, unicellular green algae, cryptomonads, and blue-green algae), and filamentous green algae. Macrophytes (*Elodea canadensis* and *Potamogeton foliosus*) were present in significant numbers in Lake 1 only during late summer, 1975, when a combined

Figure 13: Concentration of total phosphorus in East Lansing effluent and lakes of the lake system, Michigan State University Water Quality Management Project, May 1975 through October 1976

FIGURE 13


6·0
5·0
4·0
3·0
2·0
1·0
0·0
TOTAL PHOSPHORUS, mg P/l
EAST LANSING EFFLUENT
LAKE 1
LAKE 2
LAKE 3
LAKE 4
M J J A S O N D J F M A M J J A S O
1975
1976

standing crop of 54 g dry weight/m^2 was observed (McNabb *et al*., 1975). In contrast, Lake 4 was dominated by macrophytes (principally *Elodea*) in 1975, and 1976, with maximum standing crops of 208 and 499 dry weight/m^2, in each year, respectively (McNabb *et al*., 1975, 1976).

Phytoplankton chlorophyll-a was higher in Lake 1 than in Lake 4. During the period 5 May to 1 October 1975, chlorophyll-a ranged between 2.7 and 52.1 mg/m^3 in Lake 1, with an average value of 17.4 mg/m^3. In Lake 4 values ranged from 0.0 to 5.9 mg/m^3, with an average of 2.5 mg/m^3 (Schloesser, 1975). Gross primary production by phytoplankton as determined by oxygen measurements was higher in Lake 1 than in Lake 4 during this period. Lake 1 averaged 1.97 g C/m^2-day, while Lake 4 averaged 0.69 g C/m^2-day (Schloesser, 1975).

Seston

Microscopic examination of seston from Lake 1 revealed the presence of phytoplankton and zooplankton. However, seston from Lake 1 showed more decomposition than that from Lake 4, and the predominant component was unidentifiable detrital material. Lake 4 seston contained detritus as well, usually fecal pellets. Seston from Lake 4 predominantly contained macrophyte fragments and identifiable phytoplankton, which included: *Cosmarium* sp., *Scenedesmus* sp., *Chlorella* sp., *Spirogyra* sp., *Mougeotia* sp., *Gomphosphaerium* sp., *Chroococcus* sp., *Merismopaedia* sp., *Spirulina* sp., *Oscillatoria* sp.

Clay and other inorganic materials, which were scoured from the lake edge and bottom by wind-driven currents, were present in greater amounts in seston from Lake 1 than Lake 4. Analysis of the relationship between the volume and dry weight of seston showed that the weight of a volume of wet seston from Lake 1 was twice that of an equal volume from Lake 4. Regression coefficients relating seston dry-weight to volume were 0.44 ± 0.02 g/ml ($P < 0.001$) for Lake 1 and 0.22 ± 0.03 g/ml ($P < 0.001$) for Lake 4. Organic content of seston from the two lakes was similar, because production and sedimentation of phytoplankton in Lake 1 tended to balance clay from resuspension. Average content of organic carbon in seston from Lakes 1 and 4 was 72.8 and 79.7 mg C/g.

Relative differences in amount of resuspension between Lakes 1 and 4 were estimated by assuming that the principal source of organic carbon in seston was sinking or resuspended phytoplankton in both lakes. The ratio of phytoplankton production to sedimentation of organic carbon in seston averaged 0.85 in Lake 1 and 1.71 in Lake 4. A value less than 1.0 for this ratio indicates either phytoplankton were not the source of organic carbon in seston, or resuspension of settled organic material was occurring. Since phytoplankton were the dominant primary producer group in Lake 1, and a major contributor to seston in Lake 4, these values indicate resuspension was at least twice as extensive in Lake 1 as in Lake 4.

Movement of fluorescent dye showed the extent to which macrophytes reduced current velocities and resuspension in the lakes of the Project. A standing crop of 150 g dry weight/m^2 of macrophytes, which were 98 percent Elodea, plus 200 g dry weight/m^2 of filamentous algae (McNabb et al., 1976), reduced current velocities in Lake 2 to one-half of those observed in Lake 1 under similar wind conditions but with no macrophytes. From differences in macrophyte abundance between Lakes 1 and 4, it is concluded that the greater resuspension measured in Lake 1 was due to greater current velocities resulting from low macrophyte density as compared to Lake 4.

Rates of sedimentation of seston were higher in Lake 1 than Lake 4, due to greater resuspension and production of phytoplankton in Lake 1, and suspended solids in water entering Lake 1 from East Lansing. The average value for all samples was 31.8 g/m^2-day for Lake 1 and 4.9 g/m^2-day for Lake 4.

Low standing crop of macrophytes during the spring of 1975 in Lake 4 as well as Lake 1 permitted edge erosion and resuspension in both lakes. Erosion and resuspension during that period resulted in the highest rates of sedimentation observed. Rates of sedimentation of seston averaged for all depths and locations are given in Figures 14 and 15 and illustrate the high rates of sedimentation which occurred that spring. In April of that year, the standing crop of macrophytes in Lake 1 was too low to quantify, while Lake 4 had a combined macrophyte-filamentous algae biomass of 31 g dry weight/m^2.

Figure 14: Average rates of sedimentation of seston, Lake 1, Michigan State University Water Quality Management Project, May 1975 through October 1976

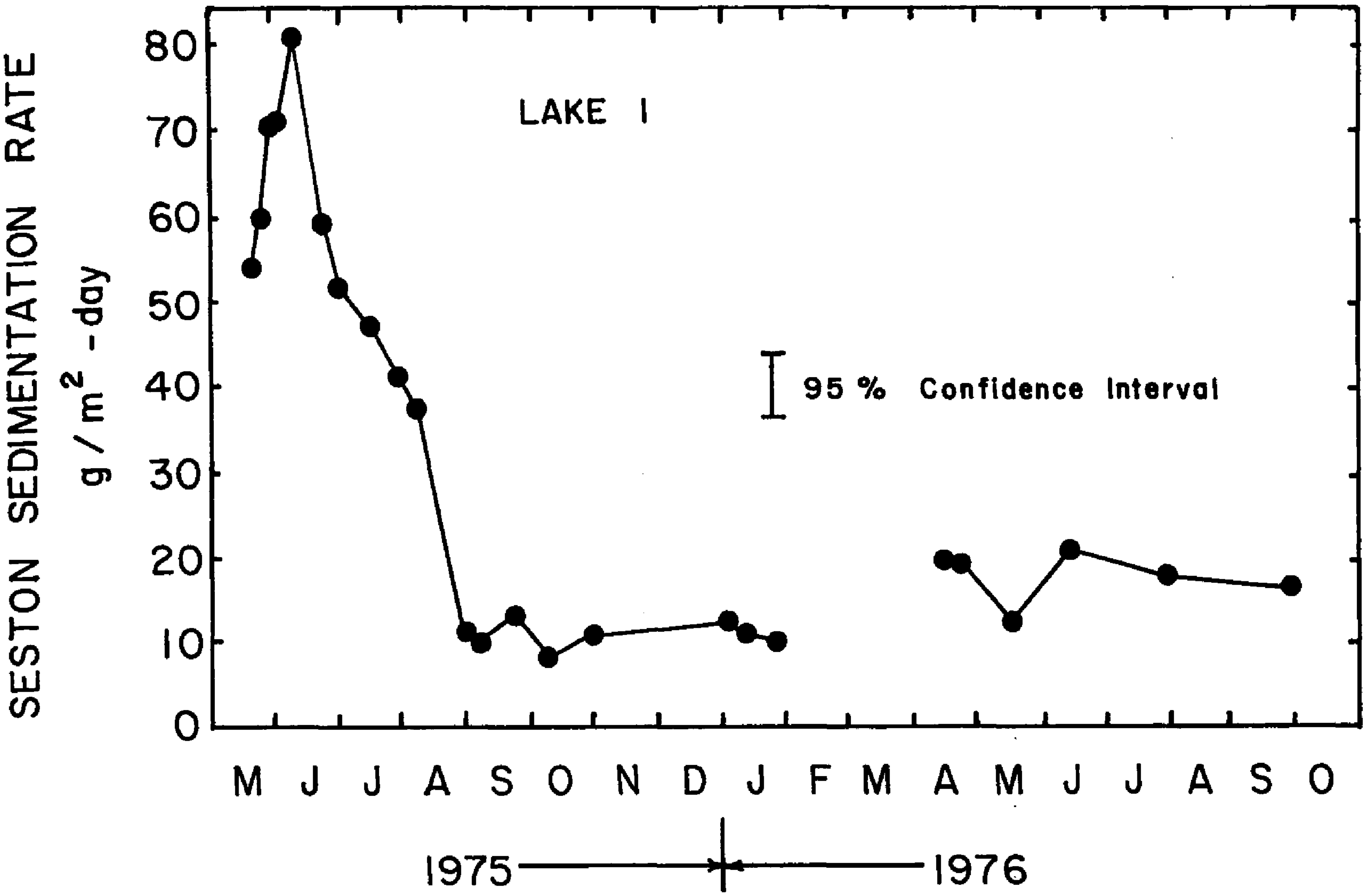

SESTON SEDIMENTATION RATE
g / m^2 -day
LAKE I
95 % Confidence Interval
0
10
20
30
40
50
60
70
80
M J J A S O N D J F M A M J J A S O
1975
1976

FIGURE 14

Figure 15: Average rates of sedimentation of seston, Lake 4, Michigan State University Water Quality Management Project, May 1975 through October 1976

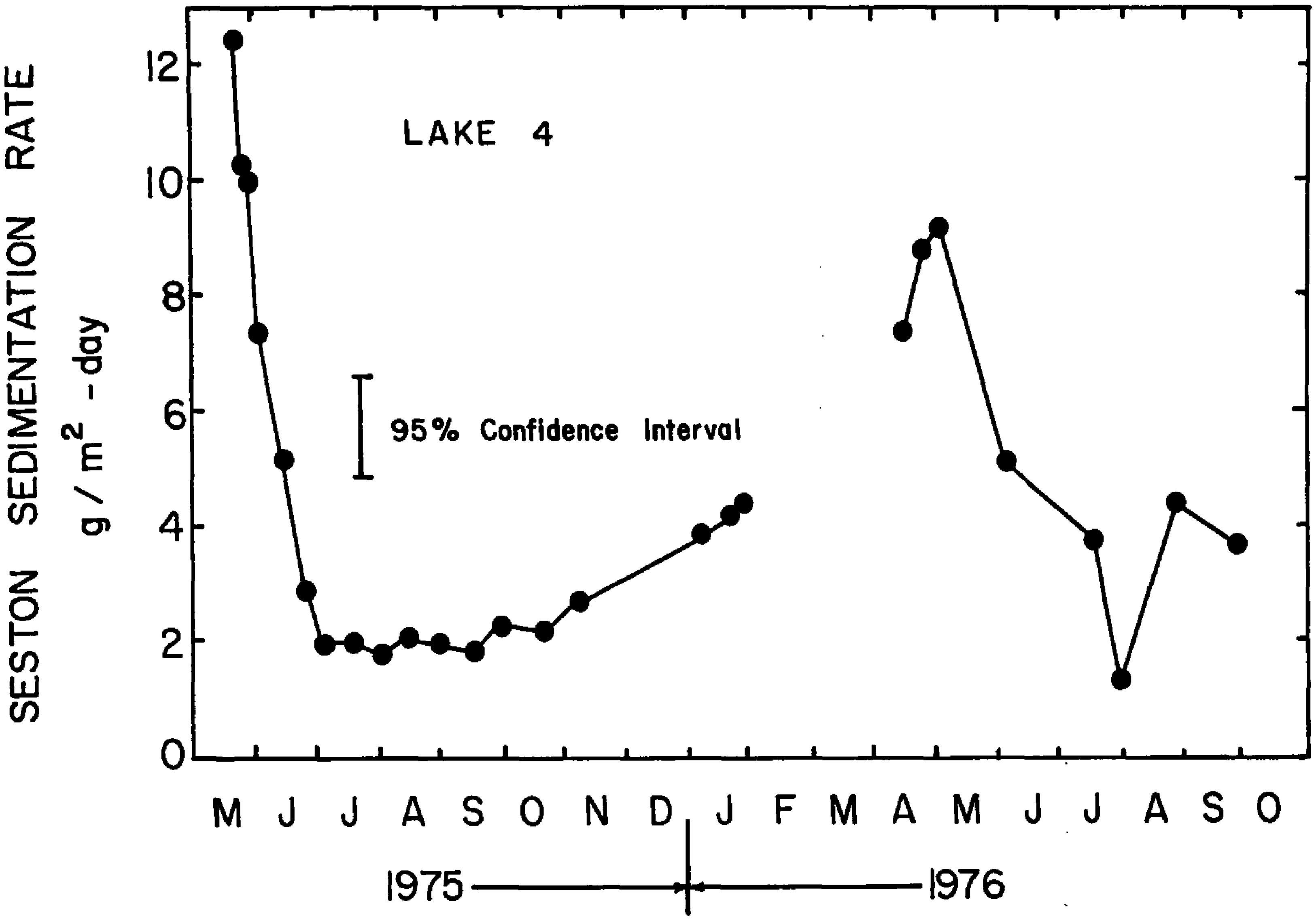

SESTON SEDIMENTATION RATE
g / m^2 -day
LAKE 4
95% Confidence Interval
0
2
4
6
8
10
12
M
J
J
A
S
O
N
D
J
F
M
A
M
J
J
A
S
O
1975
1976

FIGURE 15

Suspended solids in East Lansing effluent entering Lake 1 increased sedimentation throughout Lake 1 between April and June of 1975. Peak effluent residue coincided with peak sedimentation in Lake 1, during June of that year and occurred when the East Lansing effluent had a filterable residue as high as 305 mg/l.

Sedimentation rates were greater near the inlet of Lake 1 (Figure 4) and the outlet to Lake 4 (Figure 5) than at other locations within each lake. Figures 16 and 17 illustrate vertical profiles of average rate of sedimentation at different locations in each lake. In Lake 1 near the inlet, Station 1, rates of sedimentation at 1.5 m averaged 250 percent more than those at any other location. In Lake 4 near the outlet, Station 3, rates of sedimentation were 30 percent greater at all depths than those measured at other locations.

The higher values found near the inlet to Lake 1 resulted from suspended solids in East Lansing effluent, and the circulation pattern which depended on wind direction. Dye tracing studies revealed formation of an eddy in the inlet of Lake 1 (Figure 4) during periods when wind was from the west or northwest. Suspended solids in the East Lansing effluent entered this eddy and settled to the bottom, which resulted in higher sedimentation rates near the inlet.

Higher rates of sedimentation of seston at the outlet of Lake 4 (Figure 5) resulted from deeper water and greater water circulation at that location. Macrophytes did not grow to the surface in deeper water near the outlet, and it is

Figure 16: Average rates of sedimentation of seston on a function of depth at Station 1 (near inlet), Station 2 (mid-lake), and Station 3 (near outlet), Lake 1, Michigan State University Water Quality Management Project

FIGURE 16

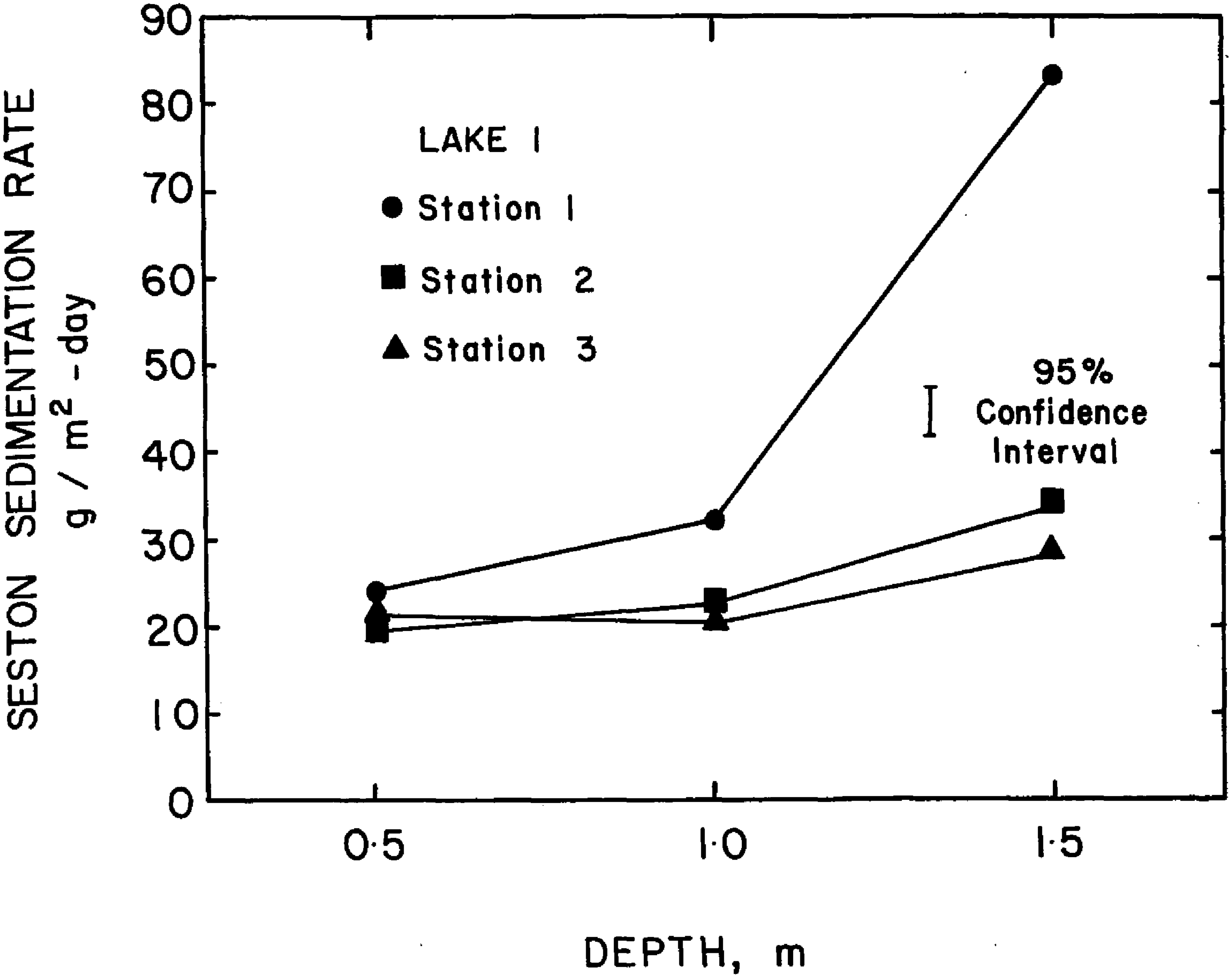
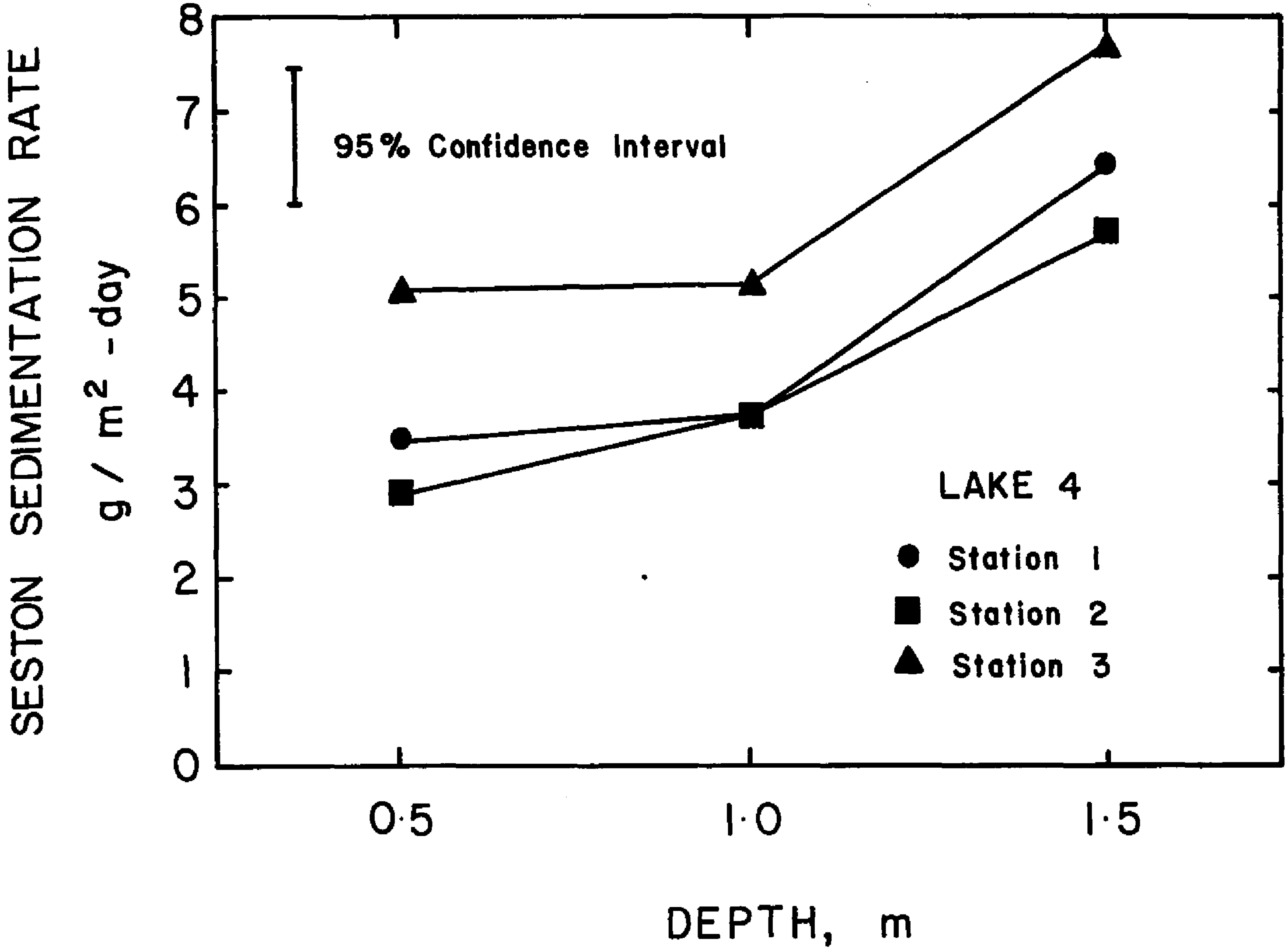

SESTON SEDIMENTATION RATE
g / m^2 -day
90
80
70
60
50
40
30
20
10
0
LAKE 1
● Station 1
■ Station 2
▲ Station 3
95%
Confidence
Interval
0·5
1·0
1·5
DEPTH, m

Figure 17: Average rates of sedimentation of seston as a function of depth at Station 1 (near inlet), Station 2 (mid-lake), Station 3 (near outlet), Lake 4, Michigan State University Water Quality Management Project

FIGURE 17


SESTON SEDIMENTATION RATE
g / m^2 -day
0
1
2
3
4
5
6
7
8
95% Confidence Interval
LAKE 4
● Station 1
■ Station 2
▲ Station 3
0·5
1·0
1·5
DEPTH, m

presumed that this resulted in reduced competition and permitted more phytoplankton production and sinking. Additionally, winds from the prevailing west and southwest set up windward subsurface currents, which caused resuspension of bottom deposits. Resuspended material was carried to the sampling location, since macrophytes were not present to retard water movement.

Transport of phosphorus to sediments by sedimentation of seston was greater in Lake 1 than Lake 4. Average rates of transport by seston were 0.171 g P/m^2-day in Lake 1 and 0.005 g P/m^2-day in Lake 4. The difference between rates in Lake 1 and Lake 4 resulted from greater sedimentation of seston and greater amounts of phosphorus in seston in Lake 1 than Lake 4. The phosphorus content of seston averaged 1.81 mg P/g in Lake 4 and did not change proportionately to changes in phosphorus concentration of lake water which occurred between sampling periods. Prior to the flow of unmodified secondary effluent in May, 1976 (Figure 12) phosphorus content of seston from Lake 1 did not change between sampling periods in proportion to changes in lake concentration. However, after the flow from East Lansing began, the concentration of phosphorus and phosphorus content of seston increased in Lake 1. Phosphorus content in seston from Lake 1 averaged 3.49 mg P/g prior to the flow of unmodified secondary effluent and 20.27 mg P/g after the flow began. Phosphorus content of samples taken from different depths was similar within both lakes.

Increased phosphorus content of seston in Lake 1 resulted in part from greater amounts of phytoplankton in seston, as shown by changes in the organic carbon content of seston after the flow began. Presented in Table 4 are data concerning dominant algal type, rate of sedimentation of seston, and phosphorus and organic carbon content of seston, during the period after the flow began. As diatoms replaced filamentous algae, sedimentation of seston increased, as did the phosphorus and organic carbon content of seston. When diatoms gave way to other phytoplankton, sedimentation of seston decreased, but phosphorus and organic carbon content continued to increase. These data indicate phytoplankton quality as well as quantity influenced levels of phosphorus in seston, and modified rates of transport of phosphorus to sediments.

Most of the phosphorus transported to the sediments of Lakes 1 and 4 by sedimentation of seston was bound by organic matter, and the principal binding mechanism was adsorption. Partitioning of total and the extractable fraction of phosphorus by iron, calcium, and organic matter is illustrated in Figure 18 for seston samples from the two lakes.

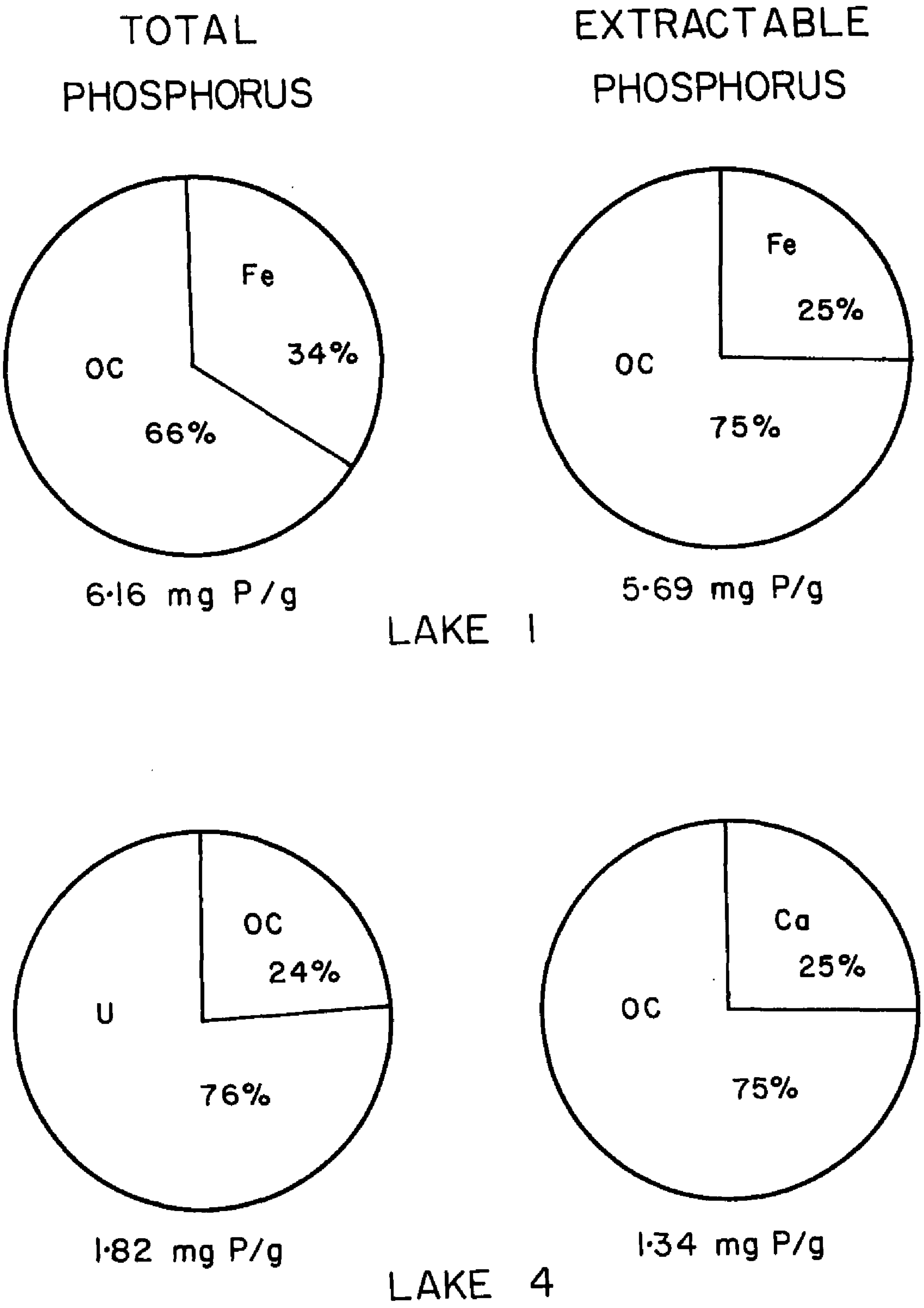
The importance of adsorption as a mechanism for binding phosphorus to settleable particulate matter is shown by the amounts of extractable phosphorus in seston from both lakes. Extractable phosphorus, which was mostly adsorbed to organic matter averaged 92 percent of all the phosphorus in seston from Lake 1 and 74 percent of that in samples from Lake 4.

Table 4. Changes in dominant algal group, rate of sedimentation of seston and seston content of phosphorus and organic carbon following introduction of unmodified secondary effluent, 1975-1976

Period	Dominant Algal Group	Rate of Seston Sedimentation g/m^2-day	Seston	
			Phosphorus mg P/g	Organic Carbon mg C/g
April-May	Filamentous Algae	12.8	3.17	75.9
June	Diatoms	20.8	15.34	91.7
July-August	Unicellular Green and Cryptomonads	17.5	17.42	121.3
September-October	Green and Blue-Green	16.1	26.1	144.9

Figure 18: Phosphorus partitioning in seston from Lake 1 and 4, Michigan State University Water Quality Management Project; circle sections proportional to percent and phosphorus bound by iron (Fe), calcium (Ca), organic carbon (OC), and unidentified (U)

FIGURE 18


TOTAL PHOSPHORUS
EXTRACTABLE PHOSPHORUS
Fe
34%
OC
66%
6·16 mg P/g
Fe
25%
OC
75%
5·69 mg P/g
LAKE 1
OC
24%
U
76%
1·82 mg P/g
Ca
25%
OC
75%
1·34 mg P/g
LAKE 4

Total phosphorus in seston from Lake 4 occurred predominantly in an unidentified form, while extractable phosphorus was bound predominantly by organic matter. Considering the small number of samples of seston which were analyzed from Lake 4 (20), this discrepancy indicates total phosphorus was bound predominantly by organic matter, but that the variability in the amount of non-extractable phosphorus which was bound by organic matter, relative to the amount of organic matter present, was too great to allow resolution of the state of total phosphorus as efficiently as that of extractable phosphorus alone.

Sediments

Measurements of amounts of phosphorus which accumulated in sediments of the lake system showed a gradient of declining accumulation through the sequence of lakes (Table 5). Lake 1 had the greatest amount of accumulated phosphorus, Lake 4 had the least, and Lakes 2 and 3 were intermediate to these.

The effects of lake inlet location, macrophyte beds, currents, and depth of water resulted in the patterns of accumulation of phosphorus illustrated in Figure 19 for Lakes 1 and 4. While Lakes 2 and 3 were as essential to the results of this investigation as Lakes 1 and 4, time requirements did not permit a detailed study of all lakes. Lakes 2 and 3 were sampled to determine amounts of phosphorus which accumulated in sediments, but the sample size was not sufficient to describe patterns of accumulation in these lakes.

Table 5. Phosphorus accumulation in the sediments of the lake system, 1975-1976

Lake	Date of Sampling	Number of Samples	Phosphorus Accumulation	
			g P/m^2 ± $S_{\bar{y}}$*	kg P/lake
1	3 May 1975	15	10.67 ± 1.63	349.87
	16 Sep 1975	17	18.25 ± 2.04	598.15
	10 Jan 1976	17	17.82 ± 1.79	584.07
	2 Jun 1976	17	13.21 ± 1.36	433.35
	2 Sep 1976	5	17.18 ± 1.41	563.50
	25 Oct 1976	5	14.70 ± 2.82	482.16
2	30 Jun 1976	4	8.30 ± 3.81	275.44
	25 Oct 1976	4	10.13 ± 2.69	336.00
3	30 Jun 1976	3	6.93 ± 1.51	303.04
	25 Oct 1976	3	4.73 ± 2.80	206.88
4	9 May 1975	15	4.3 ± 0.41	214.14
	9 Oct 1975	17	4.5 ± 0.41	222.41
	1 Apr 1976	17	4.3 ± 0.41	213.65
	11 Jun 1976	17	5.9 ± 0.41	294.24
	25 Oct 1976	5	4.5 ± 0.62	224.10

* Standard error of mean

Figure 19: Pattern of phosphorus accumulation in sediments of Lakes 1 and 4, Michigan State University Water Quality Management Project

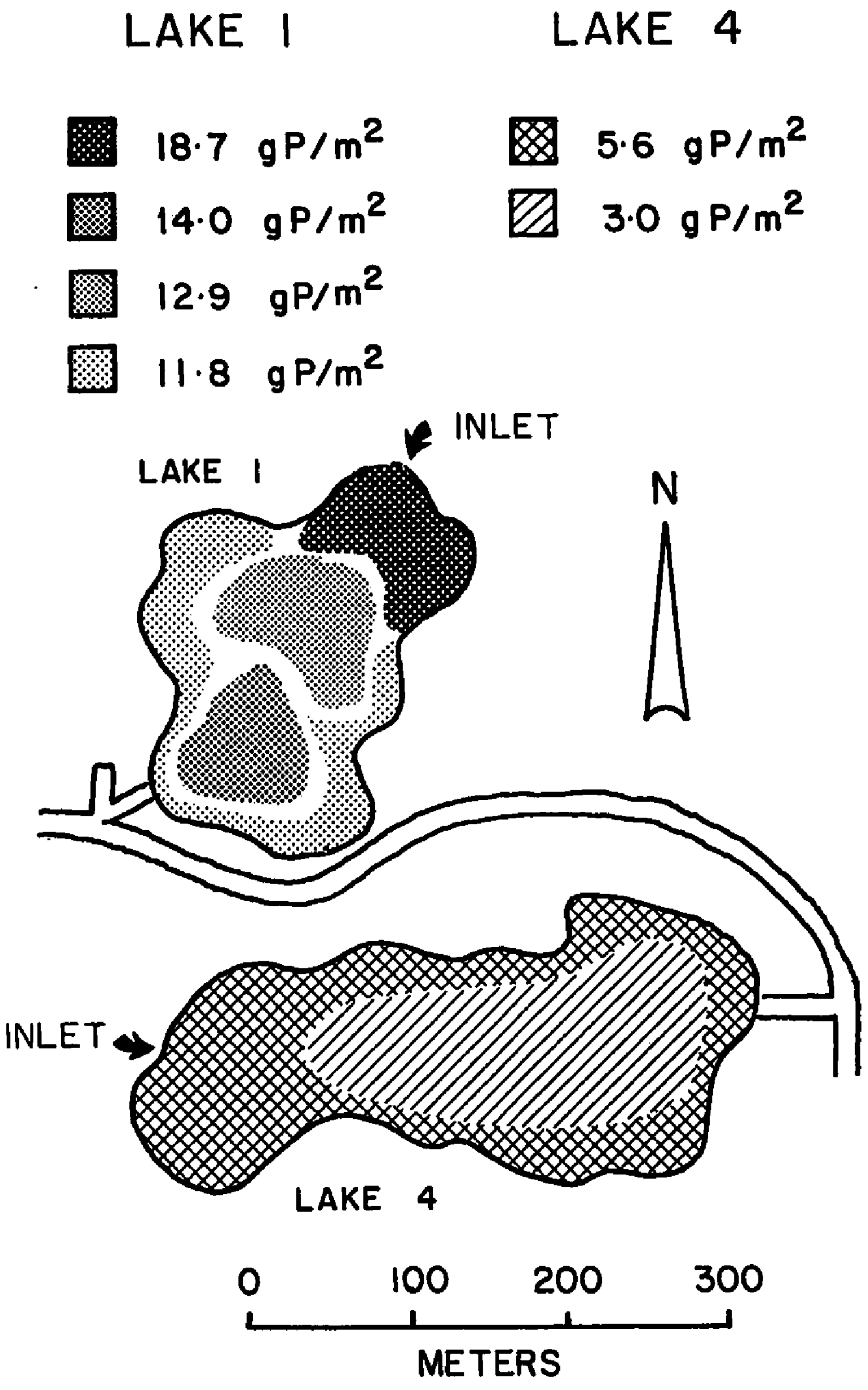

LAKE I
LAKE 4
18·7 gP/m²
14·0 gP/m²
12·9 gP/m²
11·8 gP/m²
5·6 gP/m²
3·0 gP/m²
INLET
LAKE I
N
INLET
LAKE 4
0
100
200
300
METERS

FIGURE 19

In Lake 1, more phosphorus accumulated in shallow-water sediments near the inlet than in other areas. The accumulation near the inlet was greater due to the combined effects of suspended solids entering in the East Lansing effluent, and the eddy which formed in the inlet cove. As discussed earlier, these factors allowed greater amounts of phosphorus to be carried to the bottom by sedimentation of seston near the inlet than at other locations.

Accumulation of phosphorus in Lake 1 was least in shallow water around the southern two-thirds of the lake due to the scouring action of subsurface, wind-driven currents. Resuspended phosphorus from shallow-water sediments was deposited in deep water, where resuspension was less effective. As indicated earlier, rooted macrophytes were not abundant in Lake 1, which resulted in more resuspension in Lake 1 than in Lake 4 with its heavy aquatic weed beds.

In Lake 4, more phosphorus accumulated in shallow rather than deep-water sediments. This pattern resulted from the occurrence of heavy beds of macrophytes which grew to the surface in shallow areas before doing so in deeper water. The effect of these plants was to reduce water movement, which hindered resuspension and allowed deposition in shallow areas.

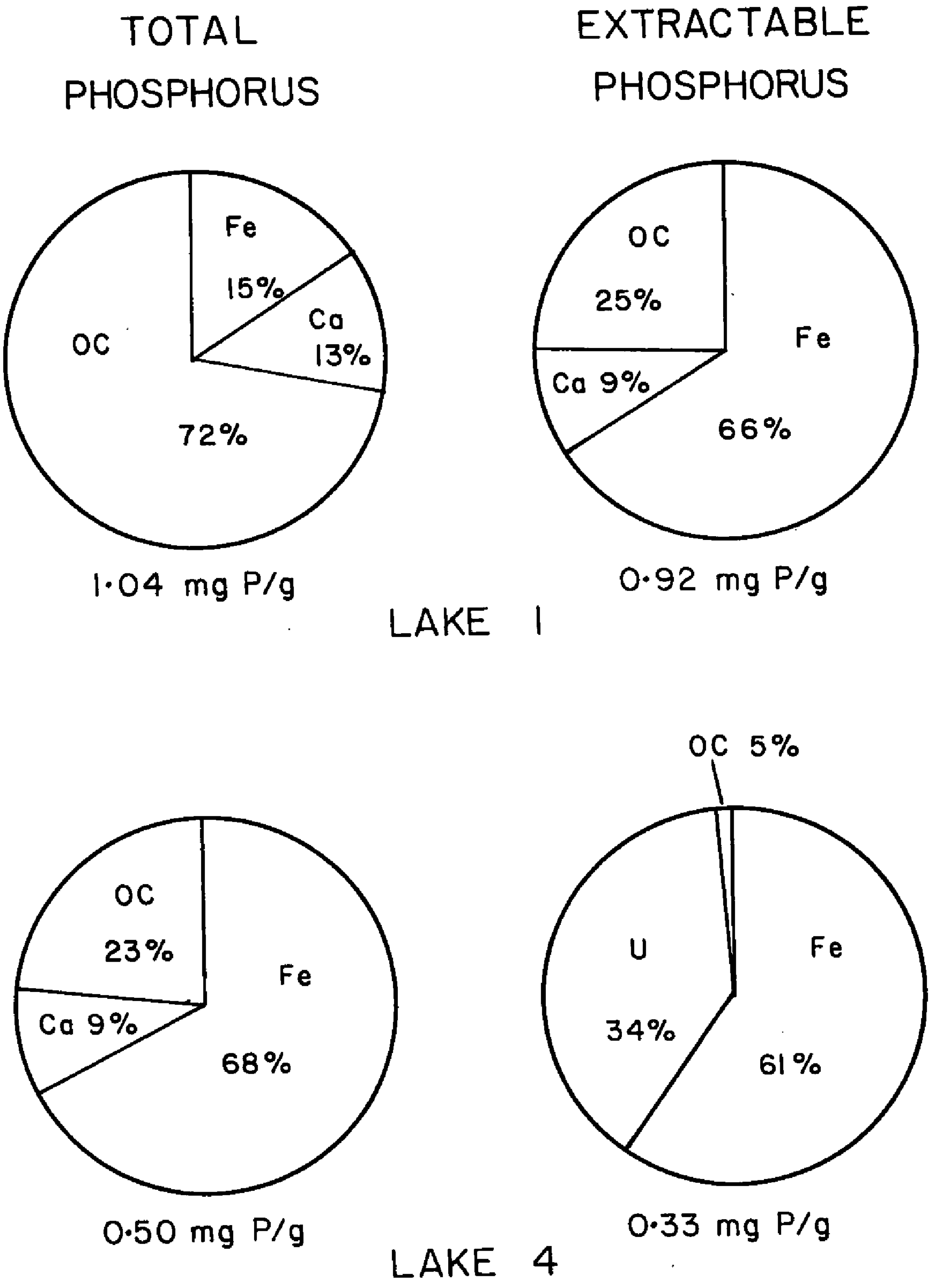
Phosphorus partitioning occurred by different mechanisms in the sediments of the two lakes. In Lake 1, organic-bound phosphorus was the main form retained in sediments and occurred as phosphorus adsorbed to organic matter. In Lake 4, inorganic phosphorus predominated and occurred as phosphorus adsorbed to inorganic iron. Partitioning of phosphorus by iron, calcium, and organic matter in sediment samples from Lakes 1 and 4 are illustrated in Figure 20.

Phosphorus in sediment samples from Lake 1 was bound predominantly by organic matter which occurred as an iron-organic complex. Partitioning of the total phosphorus in sediments of Lake 1 showed most of the phosphorus as an organic-bound form. However, partitioning of the extractable phosphorus, which was 88 percent of the total, indicated most of the phosphorus was bound by iron by adsorption. Based on the occurrence of high amounts of iron and organic matter with high levels of phosphorus and the degree of relationship found between iron and organic matter ($P < 0.001$) in sediment samples from Lake 1, it is concluded that most of the phosphorus retained by the sediments of Lake 1 was bound by adsorption to an iron-organic complex.

The predominant form of phosphorus retained by sediments in Lake 4 was iron-bound. Extractable phosphorus was 66 percent of the total and occurred mainly adsorbed to inorganic iron colloids. Little phosphorus was found adsorbed to organic matter. However, some phosphorus was present as discrete organic compounds as shown by the occurrence of organic-bound phosphorus in the partitioning of total phosphorus. From this analysis, it is concluded that phosphorus adsorbed to inorganic iron colloids was the predominant form of phosphorus in sediments of Lake 4.

Figure 20: Phosphorus partitioning in sediment samples from Lakes 1 and 4, Michigan State University Water Quality Management Project; circle sections are proportional to percent of phosphorus bound by iron (Fe), calcium (Ca), organic carbon (OC), and unidentified (U)

FIGURE 20


TOTAL PHOSPHORUS
EXTRACTABLE PHOSPHORUS
Fe 15%
Ca 13%
OC 72%
1·04 mg P/g
OC 25%
Fe 66%
Ca 9%
0·92 mg P/g
LAKE 1
OC 23%
Fe 68%
Ca 9%
0·50 mg P/g
OC 5%
U 34%
Fe 61%
0·33 mg P/g
LAKE 4

Process of Phosphorus Accumulation in Sediments

Data concerning sedimentation and accumulation of phosphorus in sediments, phosphorus components of seston and sediments, and composition of primary producer communities provide a mechanism to account for the presence and state of phosphorus in sediments of the lakes of the Water Quality Management Project.

When phytoplankton dominate primary production, algal biomass sinks to the sediments and decomposes by the activities of bacteria and macroinvertebrates. When oxygen levels in accumulated sediments become insufficient to satisfy aerobic decomposition, anaerobic conditions and lower pH values occur. Autolysis, bacterial action, and ingestion by macroinvertebrates release phosphorus from phytoplankton and detritus. Organic material produced by algal decay and resistant to further decomposition adsorbs the phosphorus released by decomposers. Phosphorus in sediments under these conditions exists as organic phosphorus of undecayed organic matter and is also bound to organic and inorganic detritus by adsorption.

At pH values less than 6-7, organic matter adsorbs iron as well as phosphorus (Koenigs, 1976). When the sediment surface is aerobic and pH is greater than 7, iron, bound to decay-resistant organic matter, desorbs to form hydrated ferric oxides. These inorganic iron colloids adsorb phosphorus and increase the capacity of the sediments to bind phosphorus. The pH dependent adsorption of iron to organic matter is a mechanism by which sediments are buffered against loss of iron as conditions change from aerobic to anaerobic, thus retaining phosphorus binding capacity if aerobic conditions return.

By retaining biomass in the water column, macrophytes reduce oxygen demand in sediments and assist in creating conditions which favor accumulation of phosphorus by adsorption to inorganic iron. However, during periods of macrophyte decomposition, the amount of organic material in sediments increases. If sufficient oxygen is not available for decomposition, anaerobic conditions occur and result in loss of iron-bound phosphorus and an increase in phosphorus bound to organic matter by adsorption.

Examples from Lake 1 and 4 illustrate the mechanisms of phosphorus accumulation in sediments. From May to September, 1975, a change occurred in the primary producer community of Lake 1. In May, macrophytes were too sparse for quantification, but developed a standing crop of 56 g dry weight/m^2 between late July and mid-August. The lowest of daily oxygen measurements during this period was 2.2 mg O_2/l and occurred during July. Oxygen was not found lower than 5.2 mg O_2/l during August or lower than 9.4 mg O_2/l during September. Accumulation of phosphorus increased by 7.6 g P/m^2 during this period. Data concerning phosphorus partitioning in sediment samples taken during May and September are given in Table 6. Phosphorus in the sediments changed from an organic-bound to an iron-bound form, and some of the phosphorus adsorbed to organic matter was lost, presumably resorbed by inorganic iron. These data support the hypothesis that growth of macrophytes

Table 6. Phosphorus bound by iron and organic matter in sediment samples from Lake 1, May and September 1975

Sample Date	Phosphorus Fraction	Phosphorus Content (mg P/g)	Iron-Bound (%)	Organic-Bound (%)
May	Total	0.93	4.2	74.4
	Extractable	0.76	0.0	89.4
September	Total	1.13	71.1	28.9
	Extractable	0.87	100.0	--

assists accumulation of phosphorus by reducing oxygen demand on sediments, which allows accumulation of phosphorus by inorganic iron.

In Lake 4, a period of declining macrophyte biomass occurred between April and June, 1976. During the decline, daily measurements of dissolved oxygen averaged 10.8 mg O_2/l. Sediments accumulated 1.6 g P/m^2 of new phosphorus between early April and mid-June. Phosphorus forms, given in Table 7, showed an increase in organic phosphorus relative to other components, no change in phosphorus adsorbed to organic matter, and a gain in inorganic iron-bound phosphorus. These observations support the hypothesis that aerobic decomposition of macrophytes assists accumulation of phosphorus as organic phosphorus in decay-resistant organic matter and phosphorus adsorbed to inorganic iron colloids.

With reduced concentrations of phosphorus in downstream lakes, total loadings of phosphorus decreased (Figure 12) and less phosphorus accumulated in sediments (Table 5) through the lake sequence. The correlation between phosphorus loading and accumulation indicates the lake system responded to higher loading rates by increased accumulation in sediments. However, measurements of accumulation of phosphorus in the sediments of Lake 1, taken after the lake system began to receive unmodified secondary effluent, showed accumulation of phosphorus did not increase in proportion to the increased loading. Phosphorus accumulation, loading and sedimentation of phosphorus by seston are summarized in Table 8. Accumulation of phosphorus in

Table 7. Phosphorus bound by iron and organic matter in sediment samples from Lake 4, April and June 1976

Sample Date	Phosphorus Fraction	Phosphorus Content (mg P/g)	Iron-Bound (%)	Organic-Bound (%)
April	Total	0.51	72.3	20.5
	Extractable	0.34	60.9	12.2
June	Total	0.48	66.7	28.5
	Extractable	0.30	88.2	11.8

Table 8. Accumulation, loading, and sedimentation of phosphorus in Lakes 1 and 4

Sediment Sampling Date	Phosphorus Accumulation (g P/m^2)	Change in Accumulation (g P/m^2)	Phosphorus Loading		Total Phosphorus Sedimentation by Seston (g P/m^2)
			Average Daily (g P/m^2-day)	Total (g P/m^2)	
Lake 1					
May, 1975	10.7	+7.6	0.09	11.7	30.2
September, 1975	18.2	-0.4	0.05	5.5	4.9
January, 1976	17.8	-4.6	0.02	3.1	6.2
June, 1976	13.2	+4.0	0.22	20.1	26.6
September, 1976	17.2	-2.5	0.36	21.7	25.1
October, 1976	14.7				
May, 1975 to October, 1976		+4.1	0.12	62.1	93.0
Lake 2					
May, 1975	4.3	+0.2	0.005	0.7	0.37
October, 1975	4.5	-0.2	0.001	0.2	0.84
April, 1976	4.3	+1.6	0.002	0.1	0.45
June, 1976	5.9	-1.4	0.008	0.9	1.97
October, 1976	4.5				
May, 1975 to October, 1976		+0.2	0.004	1.9	3.55

sediments increased periodically rather than continuously and alternated with periods of loss. The intervals of gain and loss correspond to activities in the aquatic plant community and not to changes in phosphorus loading.

In Lake 1, increased accumulation in sediments was found only during summer months. A greater increase occurred during the summer of 1975, at a lower rate of phosphorus loading, than the summer of 1976. The increase of 1975 was in an iron-bound form and was associated with growing macrophytes as discussed earlier. During the following summer, phosphorus loading increased over two-fold, with the flow of unmodified secondary effluent, but the increase in accumulation of phosphorus in sediments was half as great as that which occurred the previous summer. The smaller increase in accumulation occurred as organic-bound phosphorus, was associated with production of phytoplankton, and was less than that of 1975 presumably because of decay of algae and release of phosphorus. A comparison of phosphorus loading, accumulation in sediments, and primary producers for 1975 and 1976 indicates that quality of primary production had a greater effect on accumulation of phosphorus in sediments than level of loading.

Increased accumulation of phosphorus in the sediments of Lake 4 occurred only during the spring of 1976 and was not related to increased loading. From April to June of that year, phosphorus was stored in sediments as inorganic iron-bound phosphorus and organic phosphorus, and coincided with aerobic decay of macrophytes.

Periods of loss of phosphorus accumulation were associated with aquatic plant activities in both lakes. The greatest of three periods of loss in Lake 1 (Table 8) occurred during the spring of 1976. At mid-winter, filamentous green algae were present at the sediment-water interface. After the ice left the lake at the end of February and water temperatures began to rise, these algae began to increase and float to the surface in mats. Based on high ash and phosphorus content found in samples of algae taken during this period (McNabb *et al.*, 1976; King, personal communication), it is hypothesized that mats of filamentous algae trapped resuspended particles which contained phosphorus, and thus, were indirectly responsible for the loss of phosphorus from sediments.

The greater loss of phosphorus from sediments of Lake 4 occurred during the summer of 1976 and was associated with an increase in standing crop of *Elodea*. Phosphorus loading during the period was insufficient to provide more than 55 percent of phosphorus present in plant biomass, based on analysis of samples of plant tissue taken during the period (King, personal communication). Accordingly, it is concluded that the remainder of the plant phosphorus was derived from phosphorus accumulation in sediments and was a major cause of loss of accumulation of phosphorus from sediments in Lake 4.

Transport of phosphorus to the sediments by sedimentation of seston increased as loading increased. As shown in Table 8, sedimentation of sestonic phosphorus was greater than phosphorus loading for most periods in Lakes 1 and 4. Thus, loss of phosphorus from sediments as a result of resuspension, decomposition of organic matter, and aquatic plant production reduced the capacity of Lakes 1 and 4 to store phosphorus in sediments, rather than insufficient rates of transport in particulate form.

During the first year of this investigation, iron was added for phosphorus removal at the East Lansing wastewater treatment plant. Increased accumulation of phosphorus in the sediments of Lake 1 during the summer of 1975 in an iron-bound form indicates the iron in East Lansing effluent enhanced the process of phosphorus accumulation in sediments during that summer. However, this investigation has shown the mechanism of phosphorus accumulation in sediments in the lake system to be dependent on the composition of the primary producer community. Accordingly, it is concluded that the macrophyte production which occurred in Lake 1 during 1975 resulted in conditions which permitted utilization of iron in East Lansing effluent for retaining phosphorus in the sediments of Lake 1.

SUMMARY AND CONCLUSIONS

The lake system of the Water Quality Management Project showed an impressive capacity to reduce aquatic plant nutrients in wastewater during this investigation. Secondary effluent entering the lake system contained 3 to 4 milliequivalents of carbonate-bicarbonate alkalinity and was super-saturated with carbon dioxide; 20 to 25 mg/l total nitrogen, mostly as nitrate; and 1 to 5 mg/l total phosphorus. Plant utilization of these nutrients had a broad impact on water quality. Reduction of carbon dioxide concentration, as a result of photosynthesis and atmospheric loss, caused pH to increase from an average of 7.5 in East Lansing effluent to values exceeding 10.5 occasionally.

Increased pH resulted in higher carbonate concentrations which precipitated with calcium and caused a loss of inorganic carbon from the water. As nitrogen was converted from the nitrate form in the East Lansing effluent to proteins and amino acids by the aquatic plants, and finally to ammonia through decomposition of these plants, elevated pH shifted the ammonia-ammonium equilbrium toward ammonia and resulted in the loss of large quantities of ammonia nitrogen to the atmosphere. Phytoplankton and macrophytes removed phosphorus from the water through uptake and growth and transported it to lake sediments. In the sediments phosphorus was released through decomposition and returned to the water or accumulated as adsorbed or organic phosphorus. By facilitating ecological interactions between biology, physics, and chemistry, the lake system reduced phosphorus and nitrogen concentrations to less than 5 percent of those in East Lansing effluent.

This investigation was conducted while the lake system was maturing ecologically. As the investigation progressed, aquatic plant communities evolved and established dominance, deposition of sediments occurred and covered the native clay bottoms, and a pool of organic detritus formed which did not consolidate with sediments, but was resuspended frequently as seston. As phosphorus was channeled from East Lansing effluent into these compartments, phosphorus was retained by the lake system.

This investigation has attempted to clarify the mechanisms underlying the dynamics of phosphorus in the sediments of the lake system by relating levels of phosphorus loading and dominant aquatic plant growth and decay to (1) sedimentation of seston as a means for transporting phosphorus to the sediments, (2) accumulation of phosphorus in the sediments, and (3) partitioning of phosphorus in sediments and seston.

The presence or absence of macrophytes affected the rate of sedimentation of seston and the pattern of accumulation of phosphorus in lake sediments. Sedimentation of seston was greater in Lake 1, which was dominated by phytoplankton, because wind-driven currents had the capacity to resuspend and redistribute particulate matter from lake bottoms, in the absence of macrophytes. In Lake 1, phosphorus accumulated in sediments in greater amounts near the outlet and near the inlet since resuspension of phosphorus was less effective in deeper water and in the inlet eddy. In Lake 4, where macrophytes were abundant, resuspension was reduced and greater amounts of phosphorus accumulated in the sediments of areas with heaviest beds of macrophytes.

The phosphorus content of seston was higher at the higher levels of phosphorus loading in Lake 1 than in Lake 4. However, in Lake 1, the phosphorus content and rate of sedimentation of seston increased or decreased as changes in phytoplankton dominance occurred with diatoms resulting in greater rates of sedimentation and lower phosphorus content of seston than other groups of algae. Rates of phosphorus loading to both lakes were less than the rates of transport of phosphorus to lake sediments by sedimentation of seston.

Amounts of phosphorus which had accumulated in the sediments of the lake system were greater at higher levels of phosphorus loading than at lower levels. However, accumulation of phosphorus in sediments at the higher loading levels of Lake 1 was greater when macrophytes were part of the aquatic plant community than when they were absent. Growth of macrophytes rather than phytoplankton increased amounts of phosphorus accumulation in sediments by reducing the demand for oxygen in sediments and allowing accumulation of iron-bound phosphorus.

Transport of phosphorus to the sediments of Lakes 1 and 4 occurred principally through partitioning of phosphorus by organic matter, either as phytoplankton or organic detritus, while phosphorus in the sediments was partitioned to either organic or inorganic matter. In Lake 1, where phytoplankton dominated primary production, adsorption of phosphorus to organic matter predominated in sediments, while in Lake 4, with abundant macrophytes, adsorption of phosphorus to inorganic iron was the principal form.

Storage of phosphorus in sediments was seasonal and largely temporary in Lakes 1 and 4, whether storage occurred by partitioning to either an organic or an inorganic form. Periods of loss alternated with periods of gain in both lakes. Resuspension resulted in the greatest loss of phosphorus from the sediments of Lake 1, while direct uptake by growing macrophytes resulted in the greater loss of phosphorus from the sediments of Lake 4.

At the stage of ecological development attained in Lakes 1 and 4 at the time of this investigation, amounts of phosphorus permanently retained by sediments were small compared to total amounts entering the lakes. From May, 1975, to October, 1976, accumulation of phosphorus in the sediments of Lakes 1 and 4 amounted to 6.6 and 10.5 percent of phosphorus loading to each lake (Table 8). On the basis of data collected during this investigation, it is postulated that retention of phosphorus by the sediments of the lake system of the Water Quality

Management Project is not an effective means for permanently withdrawing phosphorus from secondary effluent.

APPENDIX

APPENDIX

A1. Monthly phosphorus loading to lake system, Michigan State University Water Quality Management Project, g P/m^2 and kg P/lake

Time Interval*	Lake 1		Lake 2		Lake 3		Lake 4	
	g P/m^2	kg P/lake	g P/m^2	kg P/lake	g P/m^2	kg P/lake	g P/m^2	kg P/lake
1975								
13 Apr to 3 May	0.2	7.8	0.1	4.2	0.04	1.9	0.03	1.6
4 May to 31 May	2.5	83.0	0.9	30.2	0.19	8.9	0.13	6.5
1 Jun to 28 Jun	2.3	75.6	0.8	26.6	0.12	5.1	0.07	3.7
29 Jun to 2 Aug	1.8	58.6	0.3	11.0	0.14	6.0	0.04	2.0
3 Aug to 30 Aug	5.1	166.1	1.4	45.8	0.7	29.3	0.19	9.3
31 Aug to 27 Sep	3.3	108.1	1.5	50.6	0.5	21.4	0.27	13.6
28 Sep to 25 Oct	2.2	73.7	1.4	45.0	0.3	13.0	0.15	7.6
1976								
1 Apr to 9 May	1.4	47.4	0.8	25.5	0.2	8.9	0.05	2.4
10 May to 30 May	1.7	55.3	0.7	24.8	0.07	3.3	0.02	1.2
31 May to 27 Jun	7.2	237.5	1.3	43.2	0.25	11.1	0.06	3.1
28 Jun to 1 Aug	5.0	164.5	1.7	55.6	0.28	12.2	0.05	2.3
2 Aug to 29 Aug	7.9	257.7	5.9	196.2	2.0	85.7	0.13	6.5
30 Aug to 3 Oct	12.8	418.7	5.4	178.7	3.1	136.3	0.41	20.4
4 Oct to 31 Oct	8.9	293.2	4.5	150.2	1.0	45.2	0.26	12.7

*Four or five continuous weeks, discussed in text.

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