THE UNIVERSITY OF MICHIGAN

SCHOOL OF NATURAL RESOURCES
Department of Wildlife and Fisheries

Technical Progress Report

NUTRIENT CYCLING AND PRODUCTIVITY OF DYSTROPHIC LAKE-BOG SYSTEMS (Part A)
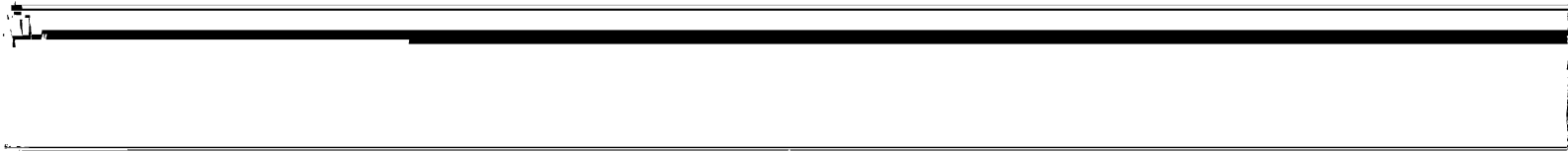
Frank F. Hooper

ORA Project 01644

LIST OF ILLUSTRATIONS

To begin work it was first necessary to develop field laboratory facilities and to construct an experimental area on a bog lake selected for experimental studies. During April, The University of Michigan constructed laboratory facilities to house the project at The University of Michigan forestry camp (Camp Filibert Roth, Iron River, Michigan). Two existing buildings were remodeled. The first was designed as a chemical laboratory and was provided with the necessary sinks, hood, shelves, cabinets, gas heat, plumbing, and hot water. The second building was remodeled for use as a counting laboratory and for microscopy. A third building was used for equipment storage. Buildings were supplied with fluorescent lighting, heat, cabinets, and bench work space. We were able to occupy these quarters on May 15.

The work reported in this report is that proposed in subproject B of the original proposal. Other phases of the work (subproject A and portions of subproject E) are reported in Part B to be submitted by Professor T. C. Griffing of The University of Notre Dame.

The work on subproject B consisted of the following: (1) An analysis of the salient features of the phosphorus cycle of a bog system and its relationship to the geochemical events of the region. A major segment of this phase of the project was completed. The results are reported in a preliminary draft of a manuscript included within Appendix A of this report. (2) Studies of the kinetics of phosphorus exchange in bog lakes. This phase of the work is in progress. Data on phosphorus exchanges were collected in late summer after suitable apparatus had been built and tested. These data have not been adequately analyzed at the time of preparing this report. Only a general discussion of the progress made on this phase of the project is given below.

IN SITU MEASUREMENTS OF THE KINETICS OF PHOSPHORUS EXCHANGE IN BOG LAKES

Analyses of the phosphorus in the North Gate bog system show sizable quantities of phosphorus in the soluble organic form and the soluble reactive state within the lake water. Even larger resources of these two forms, as well as particulate phosphorus, are present within the bog mat (see Appendix A). It also appears that the mat phosphorus may become available to the open lake water under certain hydrological conditions and water levels in bog-lake systems.

Unanswered questions regarding the significance of these materials are: (1) The precise physical and chemical state of phosphorus designated as "soluble reactive" and "dissolved organic"; (2) the orgin of these phosphorus compounds; (3) their fate; and perhaps most important, (4) the relationship of

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these phosphorus resources to the photosynthetic process, that is, their availability to algae and the processes whereby they are made available.

These unanswered questions are not unique to bog-lake systems. They apply to most freshwater and marine environments. Bog systems offer unique possibilities of analyzing these problems. They make good systems for developing an experimental approach and certain analytical problems may be simplified because bog environments appear to be relatively simple and stable systems.

A major guideline in considering the approach to be made to these problems has been the belief that field experimentation has many advantages over laboratory microcosms. One goal has been to find in situ systems which can be manipulated and within which certain variables can be controlled while retaining many if not most of the qualities and the population structure of natural systems.

In our initial thinking of in situ systems which could be used to study the phosphorus cycle, we envisioned using small microcosms of lake water which could be floated on the bog surface, but which could be manipulated in various ways, and in which a flow of labeled materials through the system could be monitored. This design offered the possibility of control and replication and such microcosms would be exposed to some of the natural environmental changes taking place in the lake itself.

In our initial experiments we used three floating plastic wading pools 8 feet in diameter and approximately 16 inches deep. These containers were filled with lake water, floated on the surface of the lake, and observations were made of biological and physical changes within these systems as compared to events in the open water. Preliminary data indicated that each pool became a new and unique microcosm that differed qualitatively and quantitatively from the lake and other pools. Heavy growth of filamentous algae developed on the walls of these containers and unique aggregations of aquatic insects populated these waters. Lack of control and replication made such systems less desirable than laboratory microcosms. It appeared that random colonization and innoculation as well as differences in enrichment by atmospheric debris led to the development of variations in quality. Lack of water exchanges with the lake produced chemical changes even when gaseous exchange was facilitated and water movement maintained by bubbling compressed air at a uniform rate through the three pools.

Some work has continued with experimental pools but our main interest has shifted to flow-through type systems, viz., a system which enables manipulations of lake water while it is in transit through a container in which experimental populations and/or materials are isolated.

EXPERIMENTAL APPARATUS

An experimental apparatus was constructed during the early part of the summer and tested in August. It consisted of (1) a clear plastic box made up of four compartments (Figure 1), (2) two fixed baffles, each containing an opening that can be sealed with a rubber stopper, which separate the compartments, and (3) a removable filter-holder panel which fits tightly into machined grooves in the bottom and sides of the box, between the two fixed baffles, and which supports four 2-inch filter membranes. The apparatus is designed to be suspended in the lake with the lake level approximately 1 inch below the top of the box. An opening at one end allows lake water to enter the upstream end of the compartment. Water then passes through the three filter panels to reach the compartment at the opposite end of the box. From the end compartment it is pumped out by an air-lift mechanism (Figure 1). The rate of water flow through the system is controlled by the rate at which air is supplied to the air-lift mechanism. By stoppering the baffles, filter panels can be removed and the filters changed without mixing the water of adjacent compartments.

The apparatus was attached to a large Styrofoam float and anchored adjacent to our floating work platform on North Gate Lake (Figure 2). The apparatus was designed to use radioactive isotopes without contaminating the lake environment.

Isotopes were introduced from a Marriotte bottle in the upstream compartment and were collected for disposal in a bottle which received the outflow of the air-lift apparatus.

TESTING OF APPARATUS

Using a 0.45 μ filter we found an average flow of 50 ml/min could be maintained for 2 hours without a change of filters. After this time, a sizable head developed between the upstream two compartments. The length of time the system could be operated without changing filters depended, of course, upon the amount of suspended material in the lake water.

Using a fluorescent dye we found that all the water passed through the filters and that there was no leakage between compartments during normal operations and during filter changes. Further testing showed that we could sustain populations of lake algae and zooplankton at different densities within a given compartment under varying flow conditions. Plankton densities several fold greater than those of the lake water appeared to sustain themselves.
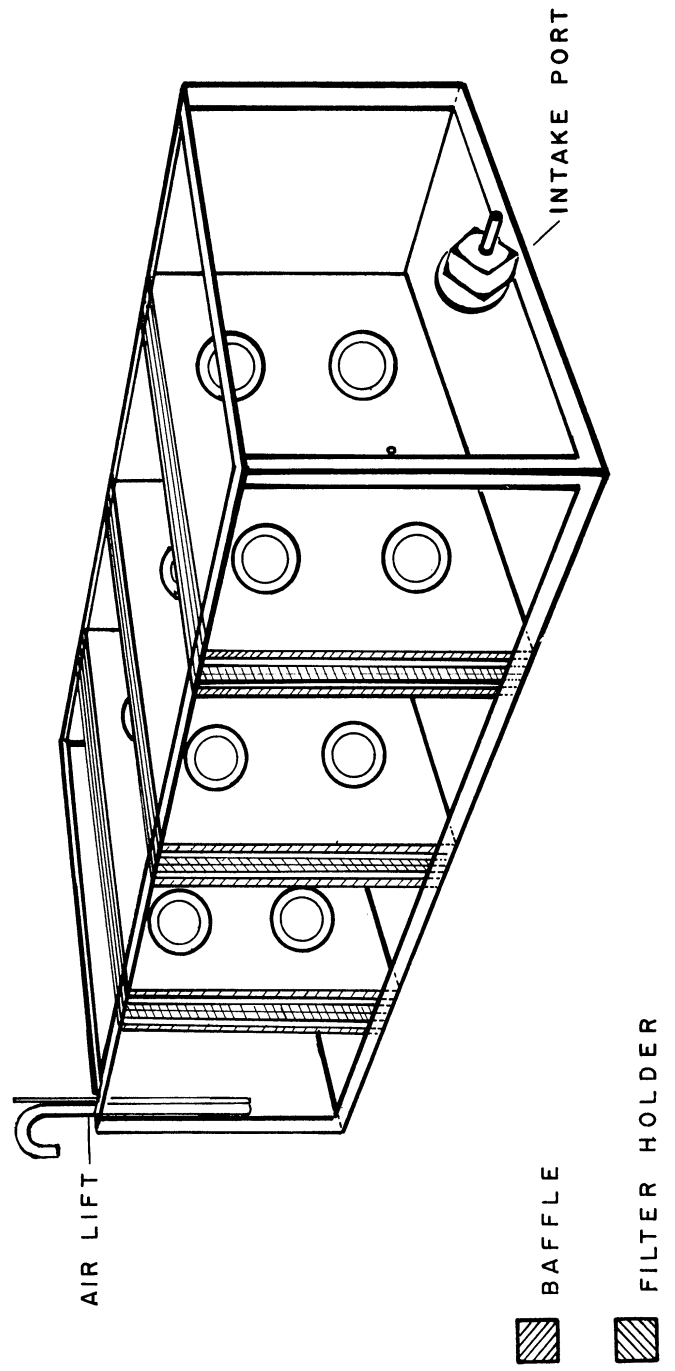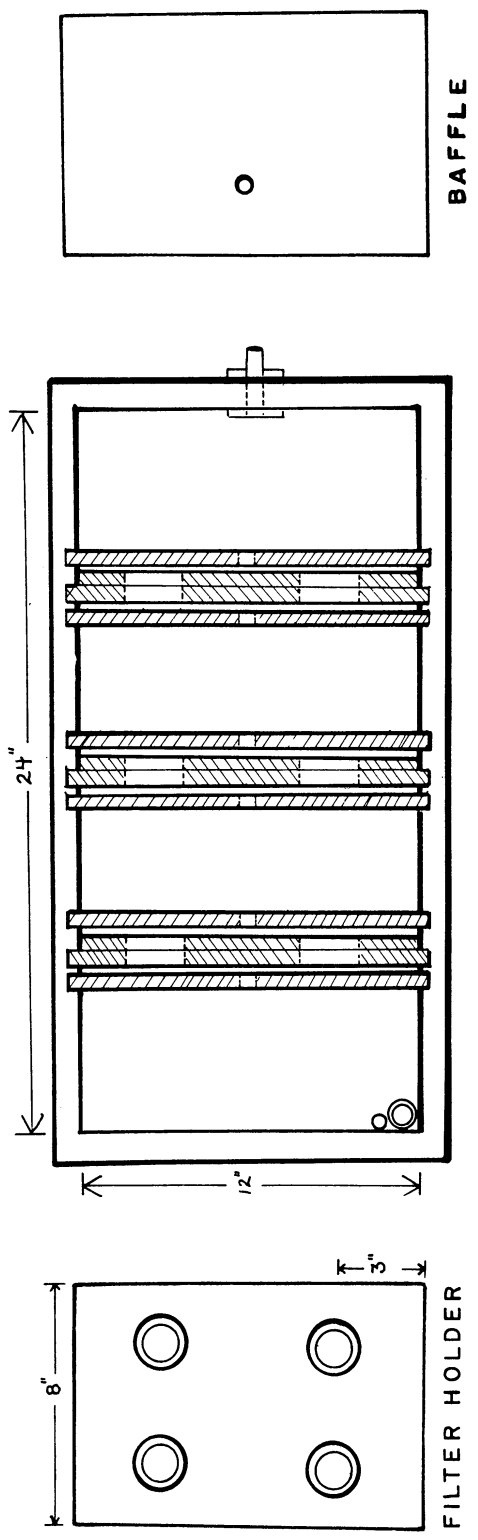
PLAN VIEW

BAFFLE

24"

12"

FILTER HOLDER

8"

3"

INTAKE PORT

AIR LIFT

BAFFLE

FILTER HOLDER

Figure 1. Design of experimental flow-through apparatus.

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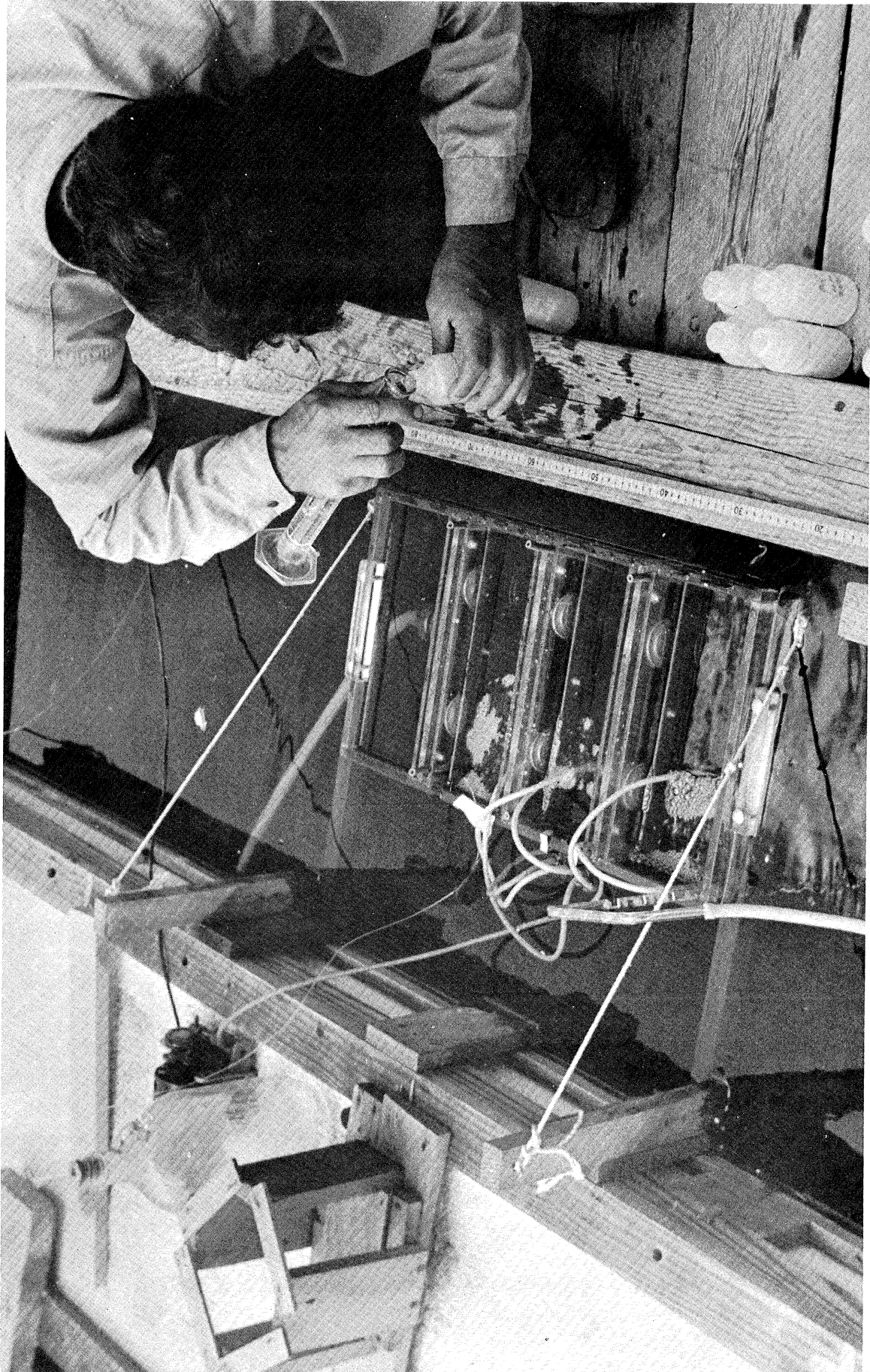
Figure 2. Flow-through system in place in North Gate Lake.

During August, four flow-through experiments were attempted with the above apparatus. The objective was to see if we could detect a net change in the quantity of the various phosphorus components within bog water during its passage through a compartment containing a bog lake phytoplankton community. The experimental procedure was as follows:

1. 0.45 μ filters were installed in the three filter holders and the box was placed in the lake and allowed to fill to the proper level. When full, the upstream compartment at the inlet (compartment A) contained unfiltered water while three downstream compartments (in order B, C, and D) contained 0.45 μ filtered water.

2. We then added 32P to compartments B, C, and D to give a water activity in each compartment of approximately 30 pc/ml.

3. Air-stone circulators were installed in each compartment so that the water was circulated gently (approximating natural movements at the lake surface).

4. The air-lift mechanism was adjusted to give a flow through the system of approximately 40 ml/min.

5. 32P was bled into compartment B from a Marriotte bottle at a rate which supplied the inflowing water with an activity of 30 pc/ml. Thus the total activity in compartment B (and the system) remained approximately constant.

6. The system was allowed to run for approximately 2 hours to equilibrate and obtain base-line phosphorus measurements. During this period we measured: (a) stable soluble reactive phosphorus and total stable phosphorus of filtered and unfiltered samples from compartments B, C, and D; (b) the activity associated with the soluble reactive and dissolved organic phosphorus of these three compartments. To measure the activity of the soluble reactive phosphorus, hexanol extracts were made of filtered and unfiltered samples. The color that developed was read in a colorimeter and extracts were then evaporated to dryness and transferred to a planchet and counted. To measure activity of total phosphorus, samples of filtered and unfiltered water were digested. After measuring color development, they were extracted with hexanol, evaporated to dryness and transferred to a planchet and their activity measured.

7. After 2 hours' equilibration period we introduced the plankton concentrated from approximately 50 liters of water into compartment C and continued the experiment three additional hours. During this period we continued all measurements described in step 6.

Through the above procedure we hoped to detect differences in labeled

and stable phosphorus components in passing through the cell containing net plankton. At the time of preparation of this report, all data have not been completely analyzed but it appears that in at least one experiment differences did develop. It also appears that in three of the experiments large and un-explained differences in specific activity arose in the soluble reactive phos-phorus component during passage through the compartment containing plankton.

Although it is too early to evaluate the effectiveness of this in situ technique in studying phosphorus exchanges within water of the bog lake, we feel that preliminary results are encouraging and we plan to continue these studies during 1969.

APPENDIX A

OBSERVATIONS ON THE PHOSPHORUS CYCLE OF
SOME NORTHERN MICHIGAN BOG LAKE SYSTEMS*

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Bog-lake ecosystems may be more or less completely isolated from the mineral and nutrient resources of ground water and from mineral supply arising from the run-off of surrounding soil. This isolation is provided by the vegetational complex surrounding the open water. In this paper we wish to describe measurements of various components of the phosphorous resources of northern Michigan bog-lake systems and to discuss the relationship of these resources to the allochthonous supply and to the metabolism of phosphorous within the system.

Waters of bog-lakes of the north temperate zone typically show a low level of primary productivity. Low production may be related to the impoverished mineral resources of these waters which in turn is related to the extent to which these waters are isolated from ground and surface drainage. A number of other factors, however, have been suggested as major influences. The brown organic stains characteristic of these waters must affect light penetration and these stains may regulate availability of nutrients and thereby influence the production process (Hasler, et al., 1951). Other factors that have been suggested are low pH and a deficiency of alkaline earth metals which are needed to fix and maintain a sufficient supply of bound carbon dioxide (Waters, 1957). The supply of phosphorus in the lake water and the lake sediments as well as its availability to algae must be considered as possible limitations upon the production process.

There may be little uniformity in the mineral supply and the mineral resources among bog-lakes of various areas. Even within a relatively uniform area, the levels of minerals and nutrients appear to be related to the extent of isolation from the surrounding ground water (Bay, 1966). Those lakes maintaining a low pH, low alkalinity, and having a high concentration of organic stains are lakes which have a high degree of isolation. On the other hand, lakes of an intermediate or neutral pH range are supplied by ground water

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and/or surface drainage. As judged by pH and alkalinity data (Griffing, 1968) lakes considered in the present study appear well isolated. Thus mineral exchanges are in large part regulated by the surrounding vegetational complex and perhaps by atmospheric sources, e.g., rain and/or windblown debris. As a first step in the analysis of the processes regulating production in this series of bog-lakes, we first wished to investigate the total phosphorus resources of these systems and thereby evaluate the possible role of phosphorus as a limiting factor. Such an evaluation must consider not only the total quantity and various forms of phosphorus present throughout the year within the open water and the water within the surrounding bog-mat, but also the exchanges that take place between these two components. It is also essential to evaluate and attempt to test the extent to which various forms of phosphorus in the open water are available to species of algae and microorganisms found within these lakes.

The four bog-lakes considered in this paper are located within section 36 of T 45 N, R 42 W and section 1 of T 44 N, R 42 W, Gogebic County, Michigan. They are part of a 5500 acre reserve owned by the University of Notre Dame. Certain of the lakes on this preserve were studied by Juday, Birge, and their associates in their exploration and inventory of the lakes of the northeastern counties of Wisconsin (Juday, Birge, Kemmerer, and Robinson, 1928; Juday and Birge, 1931; Juday and Birge, 1932; Juday, Birge, and Meloche, 1938). Two of the smaller lakes of the preserve (Peter and Paul) have been utilized in a variety of experiments dealing with fish population dynamics (Johnson and Hasler, 1954) and the influence of lime upon lake metabolism (Stross and Hasler, 1960; Stross, Neess, and Hasler, 1961). These two lakes (Peter and Paul) are within the same watershed but are not connected with two of the lakes considered in this report (North Gate and Tuesday).

<div align="center">METHODS</div>

PHOSPHORUS

Approaches made to measure the various states of phosphorus have been limited by the absence of methods which differentiate between various forms on the basis of physical state, chemical characteristics, and biological origin. Separation of "forms" is limited to that obtained by way of filtration (unfiltered versus 0.45 μ membrane) and that which will react with an acid molybdate solution with and without digestion by concentrated acid. Strickland and Parsons (1965) review the methodology of measurement of various forms of phosphorus in freshwater and marine systems. The terminology employed in this report is that given by these authors. The forms of phosphorus are as follows: (1) soluble reactive phosphorus (SRP); this is the phosphorus measured by reaction with molybdate after filtration with a 0.45 μ filter and without digestion. (2) Particulate unreactive phosphorus (PUP); this is the phosphorus in-

corporated into solids (not absorbed) which is measured by subtracting the particulate reactive phosphorus from the difference between the total phosphorus of an unfiltered sample and the total phosphorus of a filtered sample. (3) Particulate reactive phosphorus (PR); this is the phosphorus absorbed on solids and precipitated which reacts with molybdate. It is obtained by subtracting the reactive phosphorus of a filtered sample from that of an unfiltered sample. (4) Soluble unreactive (SUP); this is the organic phosphorus in solution that will not react with molybdate without digestion. It is determined by subtracting the reactive phosphorus of a filtered sample from the total phosphorus of a filtered sample.

Procedures adopted in this study utilize features of methods given by a variety of authors including Strickland and Parsons (1965), Mackereth (1963), Heron (1962), Jones and Spencer (1963), Murphy and Riley (1962), and Stephens (1963). The glassware used was "aged" Pyrex which was stored in 1% H_2SO_4 when not in use and was never used in other determinations. To filter samples, at least 100 ml of 1% H_2SO_4 was drawn through 0.45 µ membranes which had been stored in distilled water. A field filtration assembly enabled us to filter samples within 15 minutes after being removed from the lake. Collection containers used were polyethylene and had been washed with concentrated sulfuric acid before use in the field.

PROCEDURE FOR MEASUREMENT OF SOLUBLE REACTIVE PHOSPHORUS (SRP)

Lake water samples were collected in 200 ml iodinated polyethylene containers and were filtered immediately through a 0.45 µ membrane. Twenty ml of "mixed reagent" were then added and mixed with the sample. "Mixed reagent" consisted of a mixture of ammonium molybdate, ascorbic acid and potassium antimonyl tartrate, and sulfuric acid prepared as recommended by Stephens (1963). The blue color developed by ammonium molybdate in the presence of antimony and phosphorus is stable for at least 24 hours. Thus, we were able to transport samples from the field to the laboratory for measurement of color. In all cases color was measured within 3 hours after samples were collected. In the laboratory the 200-ml sample was put in a separatory funnel and 20 ml (or 10% of the sample volume) of n'-hexanol was added and the funnel was shaken vigorously for 1 minute and allowed to stand for 5 minutes. The aqueous phase was separated and discarded and the hexanol fraction was transferred to a 20-ml volumetric flask, and the volume was brought up to 20 ml with ethanol. Maximum color absorption was measured in a Klett-Summerson colorimeter using a red filter (640 to 700 millimicrons) and a 50-ml absorption cuvette.

DIGESTION OF SAMPLES FOR TOTAL PHOSPHORUS

The digestion procedure was essentially that given by Strickland and Parsons (1965) and consists of digestion of samples with fuming perchloric acid. We collected 50-ml samples in the field, filtered them immediately and returned

them to the bottle in which they were collected. Perchloric acid was added to the sample and the collecting vessel was rinsed with a small quantity of the acid. Samples were boiled to a volume of approximately 15 ml. The heat was then reduced and two or three drops of potassium iodide reagent were added and a cover glass was placed over the flask. Digestion was continued at a lower temperature until all of the H_2O and HCl were removed and the perchloric acid was allowed to reflux in the flask at a temperature above 400° for at least 10 minutes. The flask was removed, cooled, dilute ammonia solution was added and the flask was returned to the hot plate and evaporated to dryness. Samples then were made up to a 50-ml volume with distilled water and the samples analyzed for soluble reactive phosphorus utilizing the above procedure except that in most instances it was not necessary to make an n-hexanol extraction in order to obtain sufficient sensitivity.

PHOSPHORUS OF LAKE WATER

Phosphorus data for the water of North Gate bog cover the period from May 21 to August 14 (Table 1). The range of total phosphorus concentration was from 51 mg/m^3 (July 16) to 92.7 mg/m^3 on June 6. Somewhat higher levels were probably present in the samples collected May 21 to May 31. These series had exceptionally high concentrations of soluble phosphorus but particulate phosphorus data were not included. The lake water of North Gate bog was unstratified in May and the highest plankton populations noted during the year were present at this time. Levels of soluble unreactive phosphorus were lower on June 4. At this time thermal stratification had appeared and there was an indication of accumulation of particulate unreactive phosphorus in the bottom water. The high values of the total phosphorus on June 6 arose from the large concentration of particulate unreactive phosphorus in the surface waters. In all other sets of samples the major portion of the water phosphorus was in the soluble unreactive form. From 60 to 80% of the total phosphorus was in this fraction in samples for which complete data are available. Soluble reactive phosphorus was present at all times and varied between 5.8 and 16.9 parts per billion. Particulate reactive phosphorus was detected in only four samples. Values range from 0.1 to 3.5 mg/m^3. Levels of all fractions of phosphorus averaged higher in May and June than in July and August. During the latter period, strong thermal stratification developed and prevented transport of phosphorus to the surface water from lower strata.

Data were collected from other bog-lakes of the area only during late May (Table 2). Values for Hummingbird and Ralph's bog appeared to be somewhat higher than those for North Gate. Tuesday had smaller amounts of soluble unreactive phosphorus than North Gate. On May 29 Ralph's bog had 160 mg/m^3 soluble phosphorus; of this, 34 mg/m^3 was soluble reactive phosphorus. This and other high values encountered in bog-lakes in middle and late May were associated with high water levels. At this time surface drainage from the upland areas reached the bog forests and the raised water levels may have caused flow of mat water into the lake.

Values for these bog-lakes appear considerably higher than previously reported values for other lakes of the area and for ground water (Table 2). Total phosphorus values for Peter and Paul lakes in 1956 (Stross and Hasler, 1960) ranged between 23 and 35 mg/m^3. These values are similar to those for a well adjacent to Tenderfoot Lake, 36 mg/m^3. It would appear from these data that the isolated bogs and bog lakes have higher phosphorus content than adjacent waters or other seepage and drainage lakes of this area (Juday and Birge, 1931; Juday, et al., 1928). Highly stained waters tend to have the highest total phosphorus concentration (Juday and Birge, 1931).

Table 1. Phosphorus fractions of lake water from North Gate Bog, 1968. Particulate phosphorus is that retained by a 0.45μ membrane. (Averages of 2 samples unless otherwise indicated).

Date	Depth (meters)	Soluble Reactive	Soluble Unreactive	Particulate Reactive	Particulate Unreactive	Total
				mg/m^3		
May 28	sfc					89.0
29	sfc					78.0
31	sfc					74.0
June 4[a]	sfc	5.8	58	3.5	0.0	67.3
	2	5.8	50	3.4	2.0	61.2
	7	8.2	49	0.0	13.0	60.2
June 6[b]	sfc	9.7	61	2.7	19.3	92.7
10	sfc	10.6	42	---	10.0	
24[c]	sfc	16.9	50			
27	sfc	7.8	54			
July 16[b]	sfc	9.0	40	0.1	1.9	51.0
29	sfc	12.0	62			
Aug. 6	sfc	10.0	51			
14	sfc	11.1	49			

[a]Blank reading on colorimeter estimated on this date.

[b]Average of 4 samples.

[c]Average of 5 samples.

Table 2. Phosphorus of surface water of lakes, Notre Dame property Gogebic County, Michigan.

| Lake | Year | Date | Phosphorus (mg/m^3) | | | Reference |
			Soluble Reactive	Soluble Unreactive	Total	
Tuesday	1968	May 28				Present Study
		29	21	46		
		31	10			
Hummingbird	1968	May 29	33			Present Study
		31	26	87		
Ralph's Bog	1968	May 29	34	126		Present Study
		31		96		
Tenderfoot (well)	1968	Aug. 27			32	Juday and Birge (1931)
Peter	1955-1956	Dec.-June			14-35	Stross and Hasler (1960)
Paul	1955-1956	Dec.-June			23-34	Stross and Hasler (1960)

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MAT WATER

Water within the mat was collected by inserting a 2-inch well point 0.2 meter into the sphagnum. Water entering the well point was transferred by suction into a 100 ml sample bottle. The screen of the well point removed the larger debris from the mat water, however, the unfiltered samples were highly variable in color and in quantity of suspended material. Stable phosphorus determinations were made on samples filtered through a 0.45 μ membrane. Samples were collected at four stations around the lake. Locations varied somewhat as regards proximity of the lake water (Figure A-1).

Among the four stations, there was significant variability in both the soluble reactive and total soluble phosphorus concentrations. Stations 1 and 2 differed significantly from Stations 3 and 4 in total soluble phosphorus concentrations. Station 1 differed from Stations 3 and 4 in soluble reactive phosphorus. Considerable sample variability was apparent particularly in the case of the samples collected for analysis of total phosphorus. Total phosphorus values followed closely the amount of suspended debris and color which in turn may have been related to the amount of disturbance created in the mat by insertion of the well point. Total soluble phosphorus averaged 2.1 times greater than the total reactive phosphorus. The average total soluble phosphorus at Stations 3 and 4 on June 24-26 was 4.3 times the average total soluble phosphorus of the open surface lake water on June 24-27. Soluble reactive phosphorus values of the mat water, June 24-26, were from 4- to 12-fold greater than the soluble phosphorus of the open lake water June 24-27.

Even larger quantities of phosphorus existed as particulate matter. (Table 3). Concentrations in most instances were at least twice concentrations of soluble material. Suspended materials within the samples of unfiltered bog water remain suspended for several days, suggesting that the particulate material was of small size and perhaps possessed some mobility within the mat-water system.

DIALYSIS EXPERIMENT

To further explore the physical characteristics of the phosphorus included in the soluble fractions we introduced 10 ml of a solution containing 10 μ of $H_3{}^{32}PO_4$ dissolved in distilled water into the mat at two stations (3 and 4). The radioactive solution was injected into the mat water with a 10 ml pipette at a depth of 0.2 meter below the mat surface. The solution was allowed to equilibrate with the solids and water of the mat system for 27 days. At the end of this period duplicate 100 ml samples of mat water were collected from each location. Samples were filtered and placed in dialysis tubing. The tubing was suspended in 1 liter of distilled water for 48 hours. Activity was

NORTH GATE BOG
GOGEBIC COUNTY, MICHIGAN

T 45 N R 42 W SEC. 36

STATION 3

2
4
6

PLATFORM

STATION 1

STATION 2

STATION 4

DEPTHS IN METERS

0   5   10   15
METERS

N

OPEN SPHAGNUM MAT

SPHAGNUM — LEATHERLEAF — SPRUCE
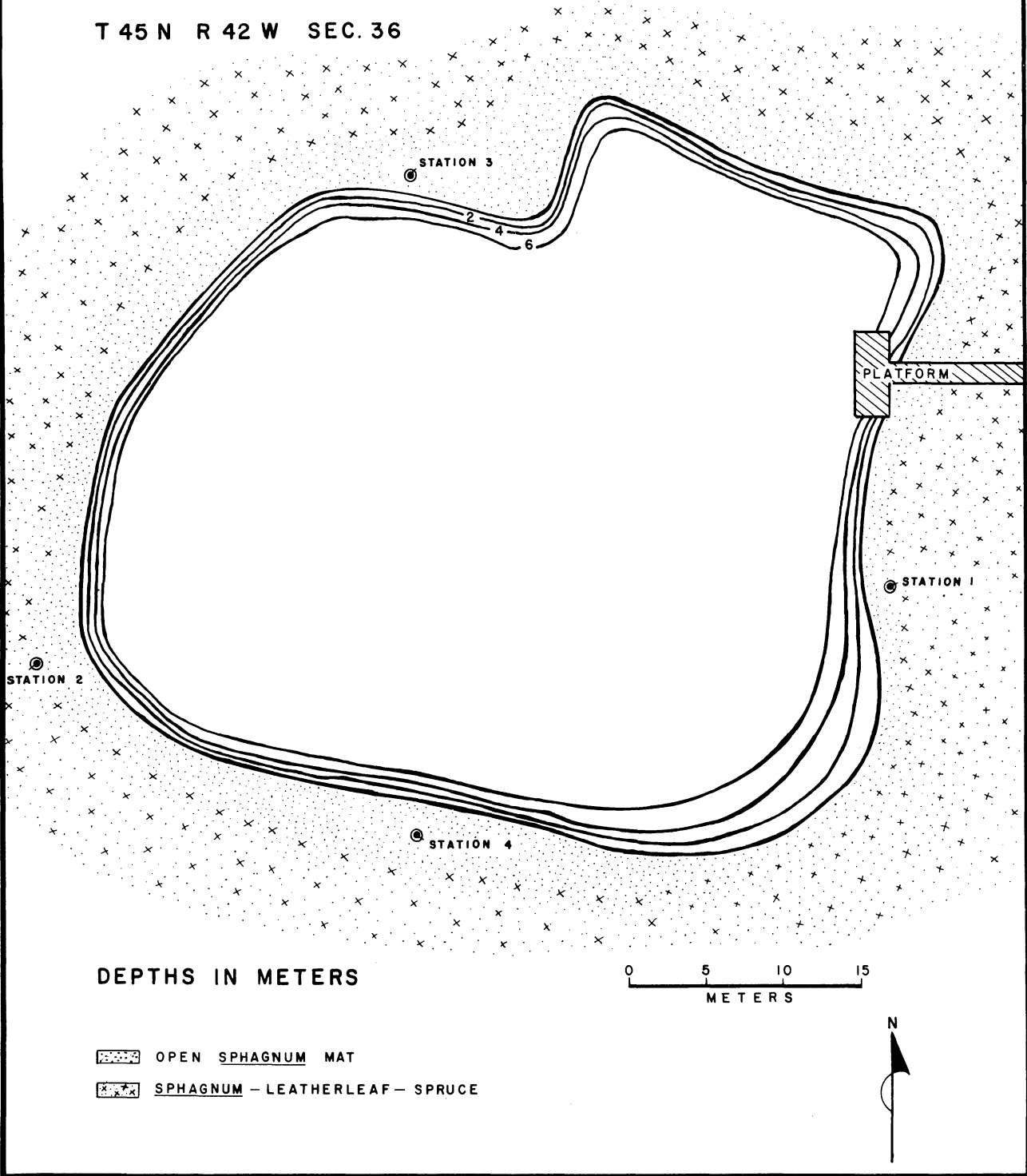
Figure A-1. Hydrographic map—North Gate Lake.

Table 3. Phosphorus of water within _Sphagnum_ mat of North Gate Bog, 1968. Particulate phosphorus is that retained by a 0.45μ membrane.

Date	Station	Depth Below Surface (Meters)	Phosphorus, mg/m^3					
			Soluble Reactive		Total Soluble		Total (Particulate + Soluble)	
			No. of Samples	Mean	No. of Samples	Mean	No. of Samples	Mean
June 24-26	1	0.2	4	174	1	313	4	1077
	2	0.2			2	353		
	3	0.2	4	60	2	287	4	1069
	4	0.2	4	44	2	262	4	336
	4	0.5					1	600
July 7	3	0.2	2	240				
	4	0.2	2	195	2	390		
11	4	0.2	4	160	4	274		

measured inside and outside the tubing after 1 hour and after 48 hours (Table 4).

Table 4. Dialysis of membrane-filtered water removed from bog-mat after 27 days incubation with $H_3{}^{32}PO_4$. Bog water dialyzed against distilled water.

| Station | CPM/ml (Average of 2 Samples) | | | |
| | Initial (1 hr) | | Final (48 hr) | |
	Inside Tubing	Outside Tubing	Inside Tubing	Outside Tubing
3	7.6	1.3	4.8	2.6
4	170.0	5.4	17.0	19.0

In the case of water from Station 4 activity levels were slightly higher outside the tubing than inside after 48 hours. However, the difference was not statistically significant. At Station 3, activity was exceedingly low after 27 days presumably because of dilution by water flowing through the mat. After 48 hours of dialysis the mean concentration inside remained slightly higher than the concentration of activity outside. This difference however, was barely significant at the 95% level. The greater activity present at Station 4 made these data somewhat more reliable. Thus there appeared to be little evidence to indicate that ^{32}P had been incorporated into nondialysable fractions during the period incubated.

To further explore the form of the ^{32}P activity introduced into the bog-mat at Station 4, we collected 10 additional 100 ml samples from the site of the ^{32}P injection. Samples were filtered through a 0.45 μ membrane. Five of the samples were then treated with the "mixed" reagent and extracted with hexanol. The color of the hexanol extract was read in the colorimeter. The hexanol was evaporated to dryness in a planchet and the residue counted. These samples gave five measurements of the stable phosphorus concentration and associated ^{32}P activity. The other samples were digested with perchloric acid, after which the reactive phosphorus and its associated activity was analyzed in the manner described above.

The mean concentration of stable phosphorus of undigested samples was 160 mg/m³ and the corresponding mean activity was 283 cpm/ml. Digested samples had a mean stable phosphorus concentration of 219 mg/m³ and a mean activity of

340 cpm/ml. These data indicate that a sizable fraction (approximately 22%) of the soluble stable phosphorus was nonreactive. Approximately 17% of the activity was associated with nonreactive phosphorus. Since the dialysis data indicate that all labeled phosphorus was dialysable, the dialysable phosphorus must consist of reactive and nonreactive components.

MOBILITY OF PHOSPHORUS COMPONENTS WITHIN THE MAT-WATER SYSTEM

The addition of ^{32}P to the mat-water in the dialysis experiment offered an opportunity to study movement of labeled fractions of phosphorus within the mat. One day after introduction of the label we collected samples in a circular pattern around the point of injection. This series not only indicated movement of the labeled material, but also indicated that the movement was directional. We therefore collected additional samples 3 days and 4 days after the release of the isotope. Samples with radioactivity significantly greater than the background level of activity of each bog station were considered positive indication of movement. In cases where there was some question as to whether the level was significantly above background we shielded the planchet with an aluminum absorber. Thus we were able to judge whether the activity was beta or gamma. A previous study of bog radiation had indicated a large fraction of gamma activity (Appendix B).

Location of samples that were above background level are plotted in Figures A-2 and A-3. The position of readings above background compared to those at or below average background indicated that movement at Stations 3 and 4 was away from the open lake water. At Station 4 the direction is somewhat more oblique to the lake shore than at Station 3. At the time, the mat vegetation was partially submerged indicating that the water level was high and flow away from the open water might be expected.

The quantity of activity in bog water was too small to attempt analysis of the physical state of the phosphorus moving through the mat. Data taken at the sight of injection indicate mobile elements must be dialysable phosphorus and must contain reactive and nonreactive components.

ATMOSPHERIC ALLOCHTHONOUS PHOSPHORUS

Sources of phosphorus input to the lake water other than that entering from the mat and the surrounding vegetational complex must be atmospheric in origin. Some estimates of the extent of atmospheric phosphorus input were compiled by (1) collection of samples of rainfall and (2) measurement of the net change in the phosphorus content of lake water within plastic pools floating on the lake surface.

Station 3

OPEN WATER

Submerged
Kalmia, Sedge

Kalmia,
Sedge

Sphagnum,
Leatherleaf

Spruce
Hummocks

Sphagnum,
Leatherleaf,
Spruce

Mat
Pool

LEGEND

⊗ Site of ^{32}P Introduction
(July 4)

☐ July 4, Background

■ July 4, Above Background

○ July 6, Background

● July 6, Above Background

△ July 7, Background

▲ July 7, Above Background

1 2 3 4 5 6
Scale in Feet

N
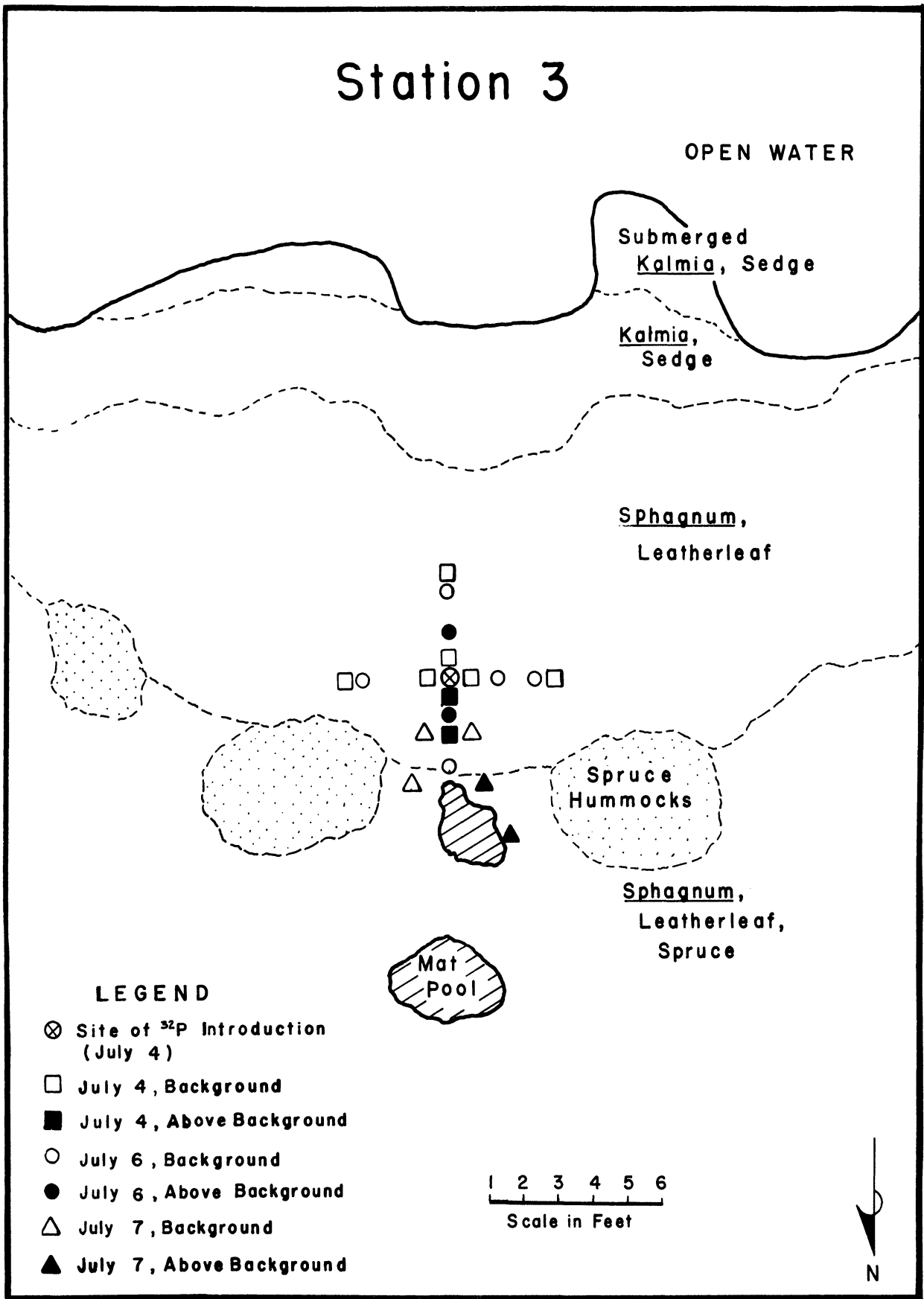
Figure A-2. Map showing location of samples collected
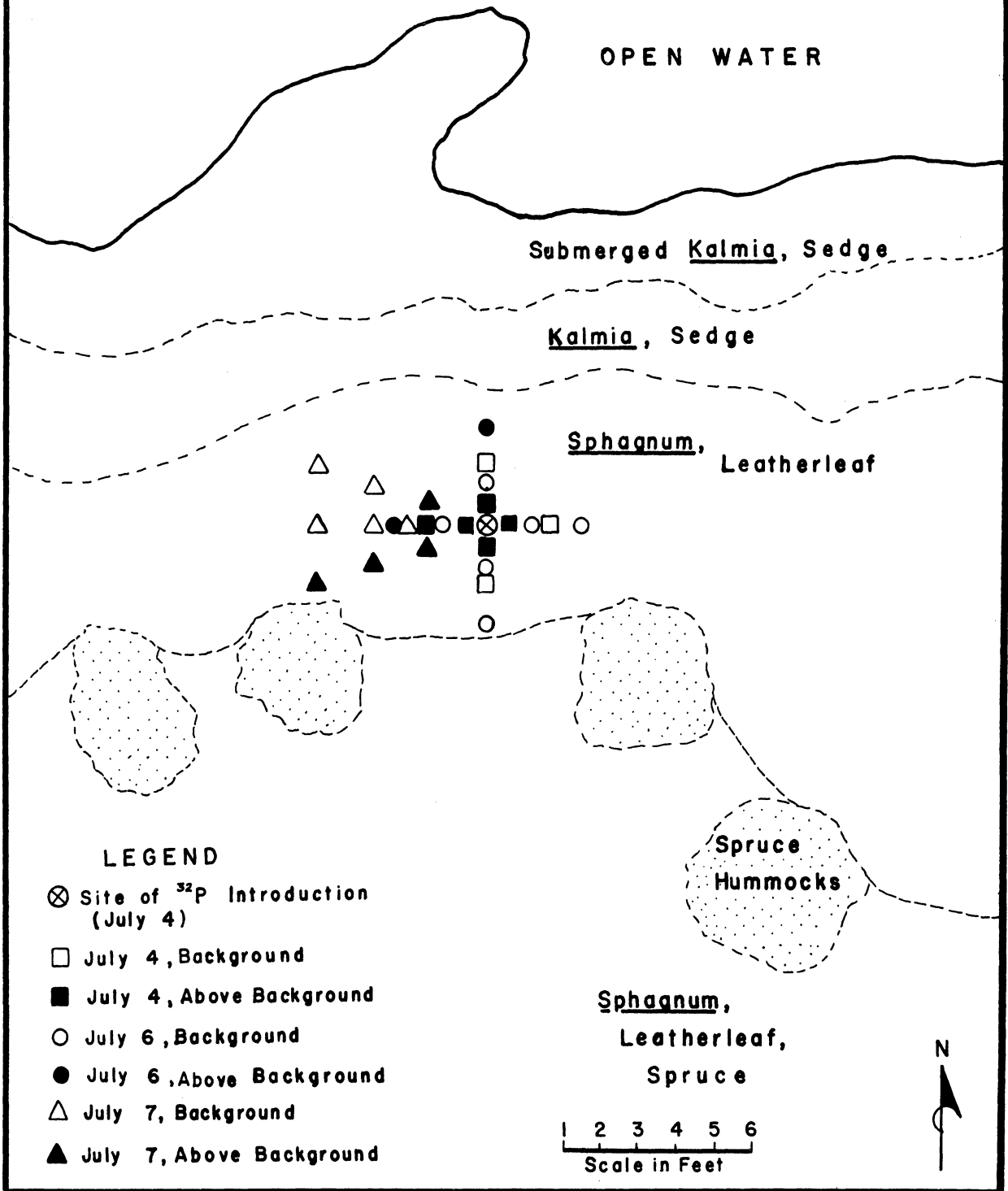in vicinity of Station 3.

Figure A-3. Map showing location of samples collected in vicinity of Station 4.

Few data are to be found in the literature on the phosphorus content of rainwater. Lee, et al. (1966), summarized existing data in the literature and used certain of these data to compute the phosphorus falling directly on Lake Mendota and the phosphorus that could enter the lake by falling on the watershed. No systematic study of the pattern of "rainout" phosphorus has been made and the sources of this material cannot be identified with certainty, although atmospheric contamination from industrial sources is a prime suspect. Quantities reported by Tamm (1951, 1953) and by Miller (1953) on occasions reach levels as high or higher than the concentrations of surface waters of many lakes.

Upon finding higher levels of phosphorus in rainwater than were to be found in the surface lake water in two samples collected on June 11, we began a systematic program of collection of rainwater for phosphorus analyses (Table 5). Samples collected between June 11 and June 27 were taken from the small plastic rain gauge located on our working platform at the margin of the lake. Samples collected from June 30 to July 26 were from a series of collection units located on a raft in the center of the lake. Each unit consisted of a 10-inch polyethylene funnel inserted into the mouth of a 500-ml polyethylene bottle. To avoid contamination we analyzed only water which had not been exposed to the atmosphere for an extended period during which the rain was not actually falling.

Table 5. Phosphorus of rain water collected at North Gate Lake during summer of 1968.

Date	Rainfall Previous 48 Hours (inches)	No. of Samples	Phosphorus Soluble Reactive (ppb)		Total (ppb)	Standard Error
			Mean	Range	Mean	
June 11	0.3	2	110	97-114		
13	0.8	1			14.6	
24	1.65	2	4	2-6		
27	1.35	1			48	
30		4			30	±1.0
July 21		6			126	±5.1
26		5			47	±3.4

The range of the total phosphorus concentrations in these samples was from 14.6 mg/m³ on June 6 to 126 mg/m³ on July 21 (Table 3). Only two of the collections had concentrations less than the existing surface values for lake water. Two collections were approximately the same as the open lake water (48 mg/m³). Two collections (June 11 and June 21) had more than twice the total phosphorus of the open lake water. Most samples were digested giving total phosphorus values. However, data on June 11 were on undigestive samples and indicated that a large fraction (perhaps all), of "rainout" phosphorus may be in soluble reactive form. Since samples were collected in open water some distance from marginal vegetation, it would appear that little of this phosphorus came from adjacent trees and vegetation. The variability in "rainout" phosphorus from storm to storm indicated by these data suggests differences between air masses and provide further support to the belief that industrial or domestic air pollution is a major source. The magnitude of the values clearly suggests that this source may be of considerable significance in the geochemical cycle of phosphorus, particularly in the case of bog lakes where input from surface drainage is minimized.

The three plastic pools used in the estimation of total atmospheric input were approximately 2.4 meters in diameter and were filled with water to a depth of 0.5 meter. They were filled with lake water on June 29. At this time the phosphorus concentration was 78 mg/m³. Pools were anchored on the lake surface, 5-7 meters from the edge of the mat. After 16 days' exposure samples were collected from each pool and were analyzed for total phosphorus. The mean increase during the 16 days was 24 mg/m³ or 31%. During exposure we noted an input of atmospheric debris consisting of plant material and terrestrial and aquatic insects. The aquatic insects noted (whirligig beetles and water bugs) do not represent input sources to be found over the lake as a whole. However, these forms utilized the pools temporarily; it is doubtful if they contributed a sizable amount of phosphorus other than that from their metabolic wastes. The rainfall of June 11 contained high soluble phosphorus "rainout" and other rains that were not monitored during the period may have contributed phosphorus. However, the total rainfall during the period was less than 2 inches, and even if all rain had the level of the June 11 rainfall, only a small fraction of the accumulated phosphorus would have been accounted for by rain.

Table 6. Allochthonous phosphorus accumulated by pools containing North Gate Lake water between May 29 and June 13, 1968.

Total Phosphorus						
Initial Concentration, May 29, mg/m³	Final Concentration (Mean of 2 Samples, mg/m³)				Estimated Input	
	Pool 1	Pool 2	Pool 3	Mean	mg/cm²/day	Entire Lake, mg/day
78	95	104	107	102	0.65	1323

DISCUSSION

FLOW OF PHOSPHORUS THROUGH THE NORTH GATE BOG-LAKE ECOSYSTEM

From the above data and from other observations made during the spring and summer of 1968, the general features of phosphorus flow through the ecosystem can be deduced, and the function of these small isolated bog lakes in the overall conservation of phosphorus in the watershed can be considered.

Phosphorus levels of the bog waters studied appear to be greater than the levels of ground water, other lakes of the Notre Dame property, and most of the lakes in this area (Table 1). The levels of organic phosphorus in the bog lakes studied fall within the upper 21 of the 454 lakes included by Juday and Birge in their 1931 report. Many of the lakes included in this group are within a short distance of the Notre Dame property and all are within 30 to 50 miles.

The higher levels reported in our studies are perhaps in part the results of different techniques. The acid digestion procedure used and the procedure used to develop the molybdate color reaction appear to be somewhat more efficient than the acid digestion procedure and the modification of the Deniges method used by Juday and Birge. Addition of color—producing reagents in the field would tend to give higher soluble reactive phosphorus values since losses by absorption and biological uptake are minimized.

Although the differences between our values for the small bog lakes and the values for the larger drainage and seepage lakes of this area may in part be due to techniques, two other possibilities present themselves: (1) headwater bog lakes because of their isolation, conserve phosphorus and therefore maintain levels above those in the surface and ground water drainage. A second and somewhat less likely possibility is that phosphorus of all these waters has increased since the earlier studies by Birge and Juday because of increased atmospheric "rainout." An increase in atmospheric yield might perhaps be conserved more effectively by bog systems than by drainage lakes of the watershed.

The level of the water table of bog systems may be completely independent of the level of water table of surrounding soils. Cases in which the bogs have been (1) separated and (2) connected with regional tables have been discussed by Bay (1966-1967). Using criteria of Bay (pH, conductivity, and diversity of flora) North Gate bog falls in the type that are completely independent of the regional water table. These bogs receive no recharge from the regional aquifer and their levels fluctuate considerably in various seasons.

This appears to have been the situation in the case of North Gate bog. In 1968 the lowest lake levels observed were in mid March when the lake was ice—covered. In mid-May at the height of the spring thaw levels were 4 to 6 inches higher. At this time water levels reached the surface of the mat, much of the

bog forest was flooded, and there was considerable surface drainage of the lowland bog forest complex. Observed changes in water levels would indicate that the only period of time there was a flow of water from the upland through the mat complex toward the lake was during the transition between the low winter levels and the flooded condition noted in mid-May. Between May 20 and June 25, precipitation fell in the area on all except 4 or 5 days. During this period the bog remained in essentially a flooded condition. There may have been some drainage of water through the lake at this time since the entire bog and lowland complex was drained by surface drainage. In late June and throughout July temperatures were much higher and rain was intermittent. During this period the water table fell below the level of the mat surface but fluctuated somewhat depending upon the amount of precipitation. This is the condition that existed at the time of the ^{32}P labeling experiment. Because of the high transpiration rates of the open mat and the bog forests, water moved peripherally away from the lake into the surrounding vegetation.

The hydrological changes have implications regarding the phosphorus cycle and phosphorus transport between the mat and open water. Since a large reservoir of water rich in mobile phosphorus compounds exists in the mat, enrichment of the lake must occur when there is a positive flow toward the open water. This must occur at the onset of spring thaw in early May and continue in part through early and mid-June when there was a net outflow from the lowland bog area due to the excess of precipitation over evaporation and transpiration. High phosphorus levels in all of the bogs studied were noted during this period. Phosphorus levels fell during July when drainage was away from the open water. However, even during this period atmospheric input appeared to be high judging from the pool data and levels noted in "rainout". These atmospheric sources alone might be sufficient to sustain a relatively high level of productivity within the shallow photosynthetic zone of these lakes.

PHOSPHORUS AS A LIMITING FACTOR

The abundant phosphorus resources present in the face of the low level of biological productivity raises the question as to what extent phosphorus might be considered a limiting or regulating element. Although the above considerations tend to indicate that there is an abundant standing crop of dissolved reactive and unreactive phosphorus, virtually nothing is known as to the availability of various phosphorus components to the photosynthetic organisms and rates of turnover in the lake water. Data on physiological availability of phosphorus compounds as well as the ease of metabolic breakdown by microorganisms are key data needed to understand the dynamics of phosphorus in these systems.

SUMMARY

Levels of phosphorus found in the lake water and mat water of a series of bog-lakes in northern Michigan were much higher than levels of surrounding drainage and seepage lakes. This suggested that these bog systems, because of their isolation, tend to conserve phosphorus. All phosphorus fractions in water retained by the mat were considerably higher than the corresponding fractions in the lake water. Soluble phosphorus fractions labeled by allowing ^{32}P to equilibrate with the phosphorus of the mat water for 29 days were dialysable indicating that little fixation of activity in a filterable (0.45 μ) but non-dialysable form had occurred within the mat. Both the reactive and unreactive components of the filterable phosphorus of mat water had dialysable fractions.

Phosphorus movement in the mat was away from the lake in July when transpiration by the bog vegetation was high, but the phosphorus—rich water of the mat may move from the mat into the lake when mat water levels rise during the spring run-off and during prolonged periods of heavy rainfall.

Allochthonous input of phosphorus from rain varied from storm to storm, but total phosphorus in rain was at times over twice the concentration in surface lake water. Total phosphorus of lake water isolated in pools on the lake surface and exposed to the atmospheric sources increased by 31% in a 16-day period, indicating a sizable input of allochthonous phosphorus from rain, wind blown materials, and flying insects. The relationship of the phosphorus resources of the bog system to primary production of the lake water is discussed.

BACKGROUND RADIATION OF LAKE WATER AND MAT WATER, NORTH GATE BOG, JULY 3-4, 1968.
(Unfiltered Samples Were Evaporated to Dryness and Counted.)

Station	Location Distance From Lake (Meters)	Location Vegetation Type	Samples No.	Samples Vol (ml)	Mean Background Radiation (pc/ml x 10^2) Unshielded	Shielded Density-Thickness mg/cm^2 6.7	13.4
1	0	Lake Water	2	100	4.7		
	1	Sphagnum	2	100	8.20		
	2	Sphagnum	2	100	5.4		
	4	Sphagnum	2	100	6.5		
2	1	Sphagnum Kalmia	2	100	37.0	30.3	30.0
	2	Sphagnum	2	100	14.0		
	4	Sphagnum Spruce	2	100	13.0		
3	1-3	Sphagnum	12	5	21.1		
	2	Sphagnum	2	100	6.6		
4	1-3	Sphagnum	12	5	28.0		

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