United States
Environmental Protection
Agency

Environmental Research
Laboratory
Corvallis OR 97330

EPA-600/3-79-046
April 1979

Research and Development

Watershed and Point Source Enrichment and Lake Trophic State Index

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EPA-600/3-79-046
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WATERSHED AND POINT SOURCE ENRICHMENT AND LAKE TROPHIC STATE INDEX

by

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This study shows that diffuse sources of nutrients within a watershed may be as important as a municipal wastewater treatment plant effluent in affecting the trophic quality of a lake.

James C. McCarty
Acting Director, CERL

ABSTRACT

Water in the permeable soils of the upper Pelican River watershed, Minnesota, requires slightly more than a year to move generally out of the phreatic zone into surface channels and basins. Its nutrient content seems mainly responsible for the load borne in surface waters above entrance of a wastewater effluent, and groundwater changes have been followed a year later by similar ones in surface water. In 1975 P load from non-point sources markedly exceeded that from the wastewater effluent. Nutrients in groundwater are assumed to result from soil surface application, but only quantities supplied by precipitation have been measured. The most noxious conditions in surface waters have been occasioned by heterocystous blue-green phytoplankters, but the greatest plant mass has been produced by rooted and attached vegetation. Blue-green algae have not been predominant in some water bodies and only intermittently in most others. Their occurrence appeared controlled by environmental conditions other than nutrient loading in the ranges encountered here. Groundwater seepage into these lakes contributed more nutrients than precipitation, but the latter supplied what may be significant amounts to watershed soils. A trophic state index based on change in Mg/Ca quotient relative to water residence time has reliably depicted relative total productivity levels in 6 lakes or ponds, and its general applicability, at least to natural lakes, now appears likely.

This report was submitted in fulfillment of Grant R800490 by the University of North Dakota under sponsorship of the U.S. Environmental Protection Agency. This report covers the period January 1, 1973, to December 5, 1975, and work was completed as of August 18, 1976.

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ACKNOWLEDGMENTS

Lakeside (Lake Sallie) laboratory and storage facilities were provided by the Minnesota Department of Natural Resources and local cooperation by Manferd Branby, Coleman Nordhausen, Donald Olson, and Walter Wiese is gratefully acknowledged.

The Pelican River Watershed District and the City of Detroit Lakes continued the fine cooperation they began with Project No. 16010 DFI in 1968, and special recognition is again due Winston C. Larson, of Larson-Peterson and Associates, Inc., and Dr. T.A. Rogstad, Chairman, Pelican River Watershed District.

Surface water discharge measurements were performed by the U.S. Geological Survey, Charles Cornelius, Montevideo, Minnesota, in cooperation with Albert M. Ungerecht, Research Assistant on this project, who also measured water elevations in groundwater sampling wells.

Sampling and analyses were performed by Research Assistants David F. Brakke, Jayce L. Lahlum, Richard S. McVoy, Stanley J. Miekicki, Arlene P. Moran, Michael Pfeifer, John W. Stambaugh, Jr., and William M. West.

SECTION 1

INTRODUCTION

This report covers the second phase of a study program designed to learn methods that may be applied to reversal or alleviation of cultural lake eutrophication. Phase 1 (1) evaluated the possibility of critical nutrient reduction through harvest of aquatic weeds and associated organisms and led to the conclusion that removal of all organisms from the lake under consideration (Lake Sallie, Minnesota) would decrease annual nutrient increments by a very small fraction and would alone contribute little or nothing toward the lake's recovery. Harvest did markedly reduce the growth of aquatic weeds in succeeding years.

Soon after the results of Phase 1 were known (1971) a conference, attended by project personnel, representatives of the EPA, U.S. Geological Survey, the Minnesota Department of Natural Resources, and consultants, led to the opinion that a more profitable approach toward solution of these lake eutrophication problems was reduction or removal of nutrients in influent waters. It was recommended that what then appeared the major nutrient inflow, wastewater effluent from the City of Detroit Lakes, Minnesota, be subjected to additional treatment procedures to remove nutrients, especially phosphorus. Methods approved by the group were: (1) chemical precipitation, (2) intermittent application to grassed adsorption galleries, and (3) spray irrigation. These procedures had previously been applied singly to individual wastes at other locations, and it was agreed that their relative efficiency could better be learned by applying all 3 to the same effluent.

Meeting the directives of this conference required, in addition to construction of treatment facilities, (1) expansion of the analytical program to cover groundwaters in the Pelican River watershed above Lake Sallie, especially in the region to receive applications of wastewater effluent, (2) continuation of the Lake Sallie program involving study of water, bottom sediments, surface and groundwater inflow, plankton, chlorophyll, primary production, etc., (3) expansion of these procedures to include water bodies traversed by the wastewater effluent enroute to Lake Sallie, and (4) sampling of the Pelican River at key locations to ascertain conditions in the watershed above entrance of the wastewater effluent.

This program began in 1972. Early phases were reported in MS theses by Miekicki (2), and Brakke (3); watershed plankton studies were carried out in 1974-75 by Stambaugh (17), and chlorophyll-phytoplankton relations were considered by West (18). Abstracts of these 4 MS theses appear in the Appendix. Dissertations dealing with Phase 1 investigations were written by Peterson (6) and Smith (7); Lee (8) was author of an MS thesis dealing with nutrients entering Lake Sallie in groundwater.

SECTION 2

CONCLUSIONS

1. Lakes in the upper Pelican River watershed are situated in permeable soils and are subject to considerable groundwater flow-through.

2. The general trend of groundwater movement in the western part of the upper basin is south toward Long Lake, the waste treatment area, Lake St. Clair, and Lake Sallie.

3. Surface discharge in the western area, which includes wastewater effluent from the City of Detroit Lakes, amounted to 22% of the total reaching Lake Sallie via the Pelican River and 28% of the surface discharge from Detroit Lake, which represents the eastern part of the upper basin.

4. Chemical data indicated both a spatial and seasonal non-uniformity of groundwater quality. Phosphorus and nitrogen varied from year to year (1973-74, 1974-75); phosphorus was markedly less concentrated the second year and nitrogen slightly so.

5. Most groundwater nitrogen was present as NH_3-N or NO_3-N, their relative abundance apparently dependent on oxygen level. Neither was noted to be absent, but NH_3-N was most concentrated when oxygen was very low or absent and NO_3-N when oxygen was in middle or upper groundwater ranges.

6. Slightly more than 12 months has been required for groundwater to make a general appearance in watershed surface waters; and high groundwater P concentrations in 1973-74 were followed by increased P values in surface water in 1975, and lower groundwater P concentrations in 1974-75 were transmitted to surface water in 1976.

7. Project resources limited groundwater study to the area within and adjacent to the wastewater treatment facilities, but this region was assumed, with a high confidence level, to be diagnostic of the upper watershed when surface water changes in other parts coincided in time and character with those attributable to groundwater in the study area. Screen casings permitted groundwater to pass through wells at the levels it occupied in surrounding soils.

8. Although groundwater varied chemically at different sites and depths in the water table, it was quite distinct in character from surface water present at the same time.

9. In 1973 and 1974, the major share of the P load entering Lake Sallie via the Pelican River was in the wastewater effluent from the City of Detroit

Lakes, but in 1975 most P going into Lake Sallie came from non-point sources in the drainage area above Detroit Lake. No groundwater sampling was carried out in that area, but similarities in annual surface water changes to those in the area with groundwater records strongly suggest that higher surface water P values in 1975 came from water that had been underground the preceding year.

10. Sources of P in the phreatic zone are unknown. Quantities brought to water surfaces by precipitation are inadequate to account for non-point loads any year, but P in summer precipitation to the 12,821 hectare upper watershed has amounted to 29 - 43% of the annual P load from Detroit Lake. Summer rains have provided a rather uniforn percentage of total precipitation from year to year, but the fate of rain borne P in soils and the constancy of P concentration in precipitation over the seasons are quite speculative at this time. If atmospheric P is notably involved in amounts carried in groundwater, it appears that 2 or more years are required for it to travel from soil surface to phreatic zone.

11. Phosphorus in groundwater was assumed to come from surface application in some form, precipitation, fertilizers, manure, etc., but detailed records of farm practices, precipitation chemistry, etc., over a period of a few years seem necessary to establish its sources, and studies to ascertain its travel time through soil to the water table would seemingly require a like amount of time.

12. Heterocystous blue-green phytoplankters were not observed in the 2 sewage ponds (see study area description); they became predominant for all or a major part of the growing season in lakes receiving some share of the wastewater effluent, were dominant for 8 weeks spread through July, August and October in discharges from the 2 Floyd Lakes in the upper watershed (Figure 1), practically disappeared from the Pelican River before it reached Detroit Lake, and were never more than a minor component of the plankton leaving that lake.

13. Heterocystous blue-green algae never amounted to more than a small percentage of the total mass of photosynthate produced in any lake but were responsible for the most offensive conditions observed. Rooted and attached vegetation produced physical nuisances.

14. Nitrogen fixation by blue-green algae was detectable by aberrant oxygen-pH relationships when they dominated the phytoplankton.

15. Groundwater seepage brought in significant quantities of water, phosphorus, and nitrogen in lakes where it was measured and analyzed, conspicuously more nutrients than they received directly from precipitation.

16. Precipitation was the lowest ranking contributor of P and N directly to lakes, but amounts so supplied in summer to the upper 12,821 hectare watershed ranged from 1.39 to 2.88 metric tons P and 15.3 to 58.82 metric tons N.

17. Lake St. Clair, a small shallow natural lake, first in line to receive effluent from the stabilization pond, became crowded with macrophytes and attached vegetation each year but produced also quantities of blue-green

phytoplankters that affected water chemistry. Marl composed 80-85% of sediments in the lake's central area but only 30% or less of those in the littoral zone. In 1974 its sediments contained 9.82 and 35.37 metric tons, respectively, of P and N. Its blue-green dominated phytoplankton fixed nitrogen from the atmosphere over most of the growing season, and primary production by this plankton population ranged from 2 to 4.25 grams of C fixed per hour over the period 8:30 a.m. to 2:30 p.m. CDT.

18. Lake Sallie exhibited intermittent thermal stratification in summer, and total time it was in this condition was very short in 1974 and 1975. Distribution of P in its bottom sediments suggests that conditions leading to calcium deposition reduce P availability and that CO_2 production enhances it. In 1974 the bottom loads, in metric tons, were nitrogen 208, total P 45.06, and SRP 9.74. Weeds accessible to the available harvester declined each year following initial harvest in 1970 and were not considered worthy of harvester effort in 1973 and 1974. In 1975 higher lake level permitted harvesting in areas previously too shallow to enter, and 41 metric tons wet weight were removed. Phosphorus taken out with weeds also declined progressively. Some qualitative changes in the macrophyte population followed weed harvest. Some photosynthesis occurred under ice and snow cover. Primary production by phytoplankton was lower than in Lake St. Clair.

19. A trophic state index, based on increase in the Mg/Ca quotient relative to water residence time and developed from records on 4 watershed lakes and the stabilization pond, has indicated relative status of each with regard to total photosynthate production. Experience to date suggests that this index will probably be generally applicable to those standing water bodies whose major inflow and outflow may be sampled, except possibly reservoirs that have a large share of discharge from their hypolimnions. In these watershed lakes it has provided a precise mathematical statement that has denoted the relative productivity status of each and has proved much more descriptive of individual situations than terms, mesotrophic, eutrophic, etc., currently applied.

20. Calculation of the above trophic state index (TSI) requires measurement of (1) lake volume, (2) annual outflow volume, and (3) calcium and magnesium (preferably as $CaCO_3$) concentration of inflow and outflow at regular intervals (probably biweekly) over 12 consecutive months. The formula for calculation appears in the body of this report. Since this TSI reflects total photosynthate production, it may hardly be expected to be exceptionally reliable in predicting nuisance conditions that may develop from accelerated growth of a restricted group or biotic segment. Such irruptions may be influenced by environmental factors not especially related to over-all productivity, and their occurrence at times may actually have a negative effect on total plant growth. This index has proved very helpful in conduct of these studies. It has (1) established total productivity rankings among the varied lakes under prevailing conditions, (2) demonstrated that nuisance conditions due to blue-green algae are not necessarily indicative of highest trophic state, (3) indicated that attached algae and vascular plants produce greater masses of photosynthate than phytoplankton, (4) reaffirmed that nutrient loading and lake conditions control productivity, and (5) pointed out rewarding study routes. Experience here shows it to be unaffected by lake size

from 3 to 38,602 hectare meters capacity, by total hardness concentration up to 1,045 mg/l, or by wide variation in the carbonate/noncarbonate hardness ratio. Several other details appear in the body of this report.

SECTION 3

RECOMMENDATIONS

1. This study demonstrated that a wastewater effluent does not always overshadow non-point sources in supplying nutrients to a small watershed; and it appears that in many cases non-point sources will need be sought and evaluated for meaningful appraisal of areal eutrophication problems.

2. It has been shown here that groundwater can have a delayed but very marked effect on phosphorus load in surface waters and that the strength of subterranean waters differs from year to year; but these data shed very little light on sources of groundwater P, and other nutrients, and the mechanics of their transport through soil. Data on these aspects, including any organisms involved, would be very helpful to eutrophication study and control.

3. The most noxious condition appearing in these water bodies arose through heavy development of heterocystous blue-green phytoplankters. The occurrence of prevalent growths of these organisms was apparently not controlled by nutrient loading in the ranges encountered; they were not conspicuous in all lakes nor throughout the growing season in most lakes in which they at times achieved dominance. These facts suggest that investigation into their natural energizing and limiting factors would be quite relevant, as their control may prove to be a workable approach to improvement of lake conditions stemming from non-point enrichment.

4. The trophic state index used here accurately indicated the relative productivity of 6 standing water bodies, and its testing on other waters in varied geographic areas is advocated. If it proves generally applicable, it should simplify eutrophication assessment and terminology.

SECTION 4

STUDY AREA

PELICAN RIVER WATERSHED

The upper Pelican River is a rather slow stream traversing a number of lakes (Figure 1). It begins with Campbell Creek ((1) , Figure 1) and acquires the name of the river when it leaves Little Floyd Lake. Just below Detroit Lake it is joined by a ditch that carries discharges from Long and St. Clair Lakes, which include effluent residuals from waste treatment facilities at the City of Detroit Lakes (see below). The river is dammed just above Lake Sallie, forming 26-hectare (65-acre) Muskrat Lake, which discharges to Lake Sallie over 2 adjustable weirs at the heads of 2 concrete-lined flumes. Monson and Fox Lakes have small, the latter intermittent, discharges to Lake Sallie.

The Pelican River watershed represented in this sampling program extends from Campbell Creek to the outlet of Lake Sallie and includes final sewage treatment facilities for the City of Detroit Lakes and the lake and stream they pass through enroute to the Pelican River. Layout of the treatment area appears in Figure 2.

Sampling stations shown in Figure 1 are as follows:

A. Aerated pond following secondary (biofiltration) sewage treatment
B. Stabilization pond receiving effluent from A, outlet
E. Long Lake outlet
F. Lake St. Clair outlet
G. Drainage ditch above Highway 6
H. Drainage ditch above Pelican River
I. Campbell Creek above Floyd Lake
J. Floyd Lake outlet
K. Little Floyd Lake outlet
L. Pelican River at Highway 34
M. Pelican River above Detroit Lake
N. Detroit Lake outlet
P. Pelican River above Muskrat Lake
1. Muskrat Lake outlet to Lake Sallie
8. Lake Sallie outlet

Discharge data have been available for Stations A, B, F, M (January-June, 1975, only), N, 1, and 8.

Areas, depths, and volumes of the lakes involved (Figure 1) appear in Table 1 and total annual discharges are listed in Table 2.

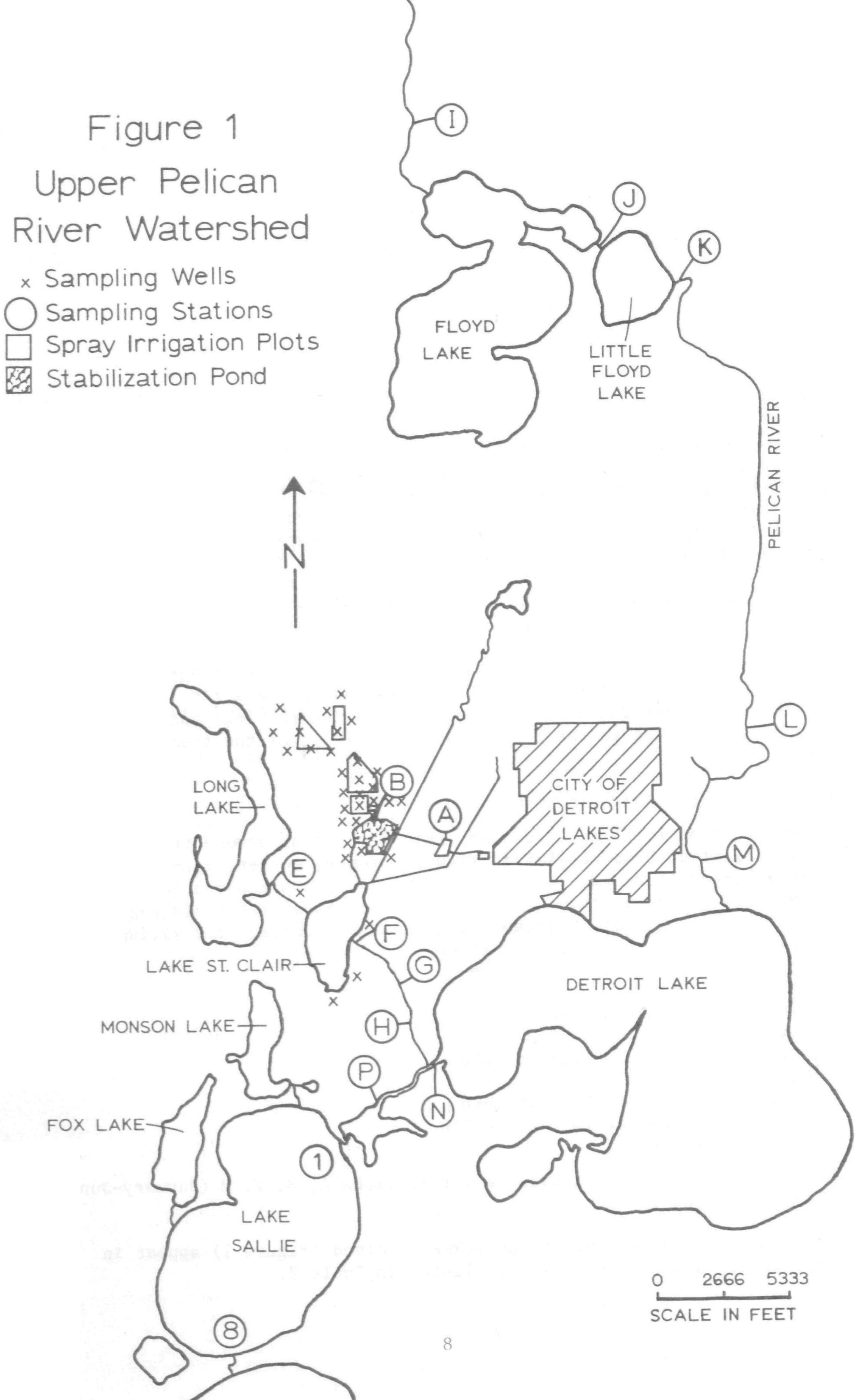
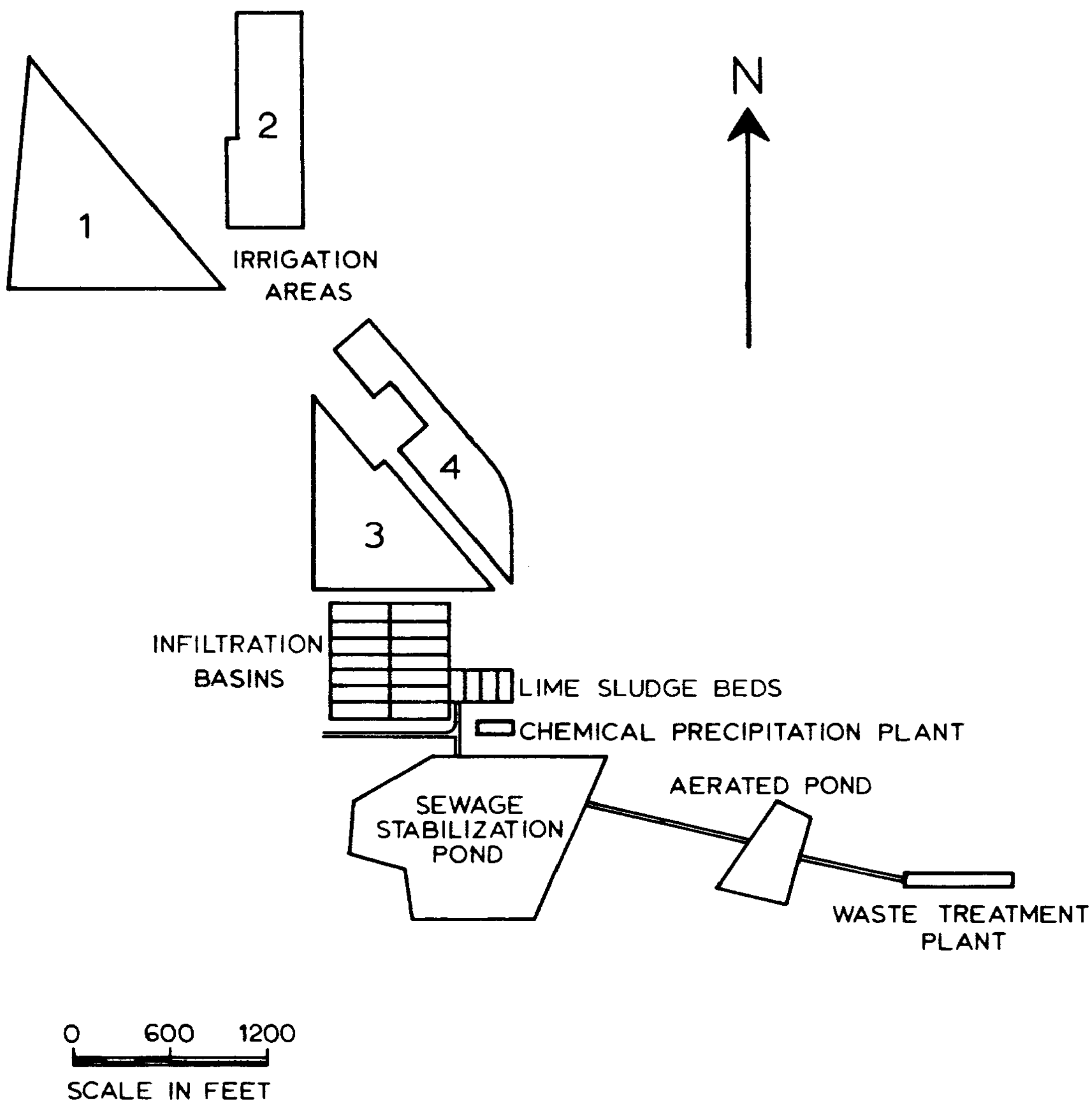


Figure 1
Upper Pelican River Watershed

Figure 2. Details of Treatment Area



Flow is regulated at the Muskrat Lake dam, and discharge at Station 1 is not considered representative of natural conditions. Losses indicated for F + N discharges at Station 1 in 1973 and 1974 may reflect control exercised at the weirs in the Muskrat Lake dam, as may the gain indicated for 1975.

Mean water residence times in those water bodies with discharge records over the period 1973-75 were:

Detroit Lake	2.17 years
Lake St. Clair	0.10 years
Muskrat Lake	0.012 years
Lake Sallie	0.70 years
Aerated pond	0.02 years
Stabilization pond	0.03 years

As reference to Table 3 will demonstrate, soils in the upper Pelican River watershed are composed of permeable materials, sand, gravel, glacial till, etc., at least down into the phreatic zone. Lakes in this area are interposed in groundwater flow, receiving all or significant amounts of their inflow from this source and returning varied quantities. There have been no direct measurements of water volumes going from ground to lake to ground, but in some instances surface water discharge records show changes that may be attributed to gain from or loss to groundwater. Long Lake has no surface inlet, and it appears that its major outflow is to the ground. From December, 1974, to June, 1975, Detroit Lake, as estimated from surface inflow and outflow records and evaporation losses, gained about 560 hm (4,520 af) from the ground. Mann and McBride (11) indicated that Lake Sallie gained 19 and 22% of its total inflow in 1969 and 1970, respectively, from ground sources. Over 1973-75 an estimated 13% of water entering Lake Sallie was from the ground.

Miscellaneous Lake Features

The only observations on the 2 Floyd Lakes relate to water chemistry and plankton of their discharges. In other lakes autotrophic populations have been dominated by rooted, floating, and attached plants; and these forms have been reduced in Lake Sallie by weed harvest.

The aerated pond is continuously oxygenated by a tethered floating mixer that drives air into the water. It has had very little attached or rooted vegetation, and its ice cover has never been complete. Volume varied in the stabilization pond in 1974-75 largely due to construction of advanced waste treatment facilities. Dense accumulations of duckweed have covered most of its surface during growing seasons of the 3 year period.

SECTION 5

METHODS

SAMPLING

Surface and groundwater samples were collected with Kemmerer samplers. Groundwater was obtained from 15.25 cm (6") diameter wells, with PVC casings, that were drilled down to gray till, which occurred at varying distances below the soil surface. The lower part of each casing was formed by a plastic screen that extended from the well bottom up to near the upper limit of the saturated zone or water table. It was hoped that this screen would permit normal lateral passage of water through each well, and analytical results suggest that water moved through wells at the level it occupied in the surrounding earth formations. Details of each well appear in Table 3. Where water depth permitted, surface and bottom samples were taken from well water columns.

Groundwater seepage into lakes was collected in evacuated plastic bags connected to a cap (the cut-off end of a steel drum) that isolated a 0.325 m^2 area of bottom. This collector was developed for seepage studies in Lake Sallie and is described by Lee (6 and 7) in some detail. As groundwater head declined, it was necessary to move these collectors farther into the lake; and they sometimes were partially or completely clogged by algae, fungi, or benthic animals. Lee (7) lists problems he encountered.

Sediment samples were collected with an Ekman dredge which drove to a depth of 15 cm (6"). Plankton was taken with a Kemmerer sampler and concentrated by settling. Sampling of lakes was omitted during periods of ice formation in early winter and ice melt in spring.

Precipitation samples were collected in enamel pans that were placed on stands to avoid surface splash and located beyond the reach of eave and tree drip.

ANALYSIS

Most chemical methods were according to Standard Methods, 13th edition (8). Total phosphorus was by the method of Krawczyk (9) and NO_3 as described by Strickland and Parsons (10). Field measurement of oxygen was usually with a galvanic cell oxygen analyzer that was calibrated every 2 hours.

Water analyses were conducted on the date of collection and phosphorus for groundwater samples within 3 hours. Tests showed that longer periods of storage generally resulted in grossly exaggerated P values.

MISCELLANEOUS

Primary production by phytoplankton was measured with the light and dark bottle technique with 2-hour incubation periods from 8:30 a.m. to 2:30 p.m., CDT. Weed harvest was with the same apparatus listed in the 1973 report (1), and weeds removed were hauled out of the drainage basin. Weighing of harvested weeds was limited to Lake Sallie.

SECTION 6

RESULTS AND DISCUSSION

CLIMATOLOGICAL DATA

Air temperature and precipitation data from U.S. Weather Bureau records over 1973-75 appear in Table 4. Mean annual air temperature declined over the 3-year period, but some months were contrary to this trend as may be noted in the table. Precipitation declined 24.37 cm (9.6") below the 1973 amount in 1974, but 1975 received 14.55 cm (5.73") more than 1974. The heaviest monthly total was in June, 1975, which was followed by severe flooding of local streams extending into July. This, in turn, produced the highest water level observed in Lake Sallie over the 7 years (since 1968) this study has continued and permitted weed harvest in areas previously too shallow for the harvester to enter.

Discharge records for the Pelican River in the study area end with June, 1975, but measurements at a site near Fergus Falls, Minnesota, about 30 miles downstream from the study area, show unusually high discharges in July and August, 1975 (Table 5).

WATER QUALITY

Watershed Nutrients

Surface Waters--

Concentration--Mean annual concentrations of total P and total inorganic N (NH_3- + NO_2- + NO_3-N) varied over the watershed (Table 6) and at individual sites over the seasons (Tables 7 and 8). The aerated and stabilization ponds were most heavily endowed in these respects, and their influences carried through Lake St. Clair and into the ditch below, but P was diluted noticeably when the ditch joined the Pelican River (see Muskrat Lake inlet). All lake and stream sites above entrance of the wastewater effluent showed marked increases in total P concentration in 1975 that could only result from general watershed conditions. Only a minor share of this phosphorus was brought in by precipitation (see precipitation section); and it appears that these increases must be attributed to the soil. Reference will be made to this matter again in the groundwater section. High phosphorus levels from non-point sources may have been produced by unknown, unusual phenomena in 1975, and there is no certainty that they will be continued over later years.

Total nitrogen was most concentrated in water containing 10% or more of the wastewater effluent (Station A down to Station H in the ditch).

Total P and soluble reactive phosphorus (SRP) were generally higher in 1975 than in 1974 (Figures 3 and 4). This trend was evident in both wastewater effluent and land drainage. There was a basin-wide increase in phosphorus content of runoff in 1975; it was most concentrated in wastewater in winter and declined as aeration and stabilization ponds supported photosynthesis during the growing season (Figures 3a, b and 4a, b). A low record frequency makes 1974 values prior to June invalid for comparison with 1975 data, but in summer and late autumn variation at Station A was much greater in 1974. Greater uniformity and concentration of P in 1975 may both reflect influences of higher P levels in general runoff.

These data (Figures 3 and 4) were plotted chiefly to illustrate that phosphorus control was exercised either by conditions restricted to individual water bodies or by phenomena common to the entire watershed. Reference to Figures 3a and 3b will show that in 1974 phosphorus patterns at Stations A and B were each largely due to events in each pond. In 1975 (Figures 4a and 4b) peaks at Station B in late January and mid-March could be interpreted to represent transmission from Station A, since there is an 11-day detention period between Stations A and B. However, the January and March peaks occurred at Station F (Figure 4c) on the same dates they were evident at Station B, and time of passage between those 2 points was 37 days. The March high was also present on the same date, albeit to a lesser degree, at Stations P, 1, and 8, where similar patterns also occurred in April. Farther up the Pelican River, Stations M and N had closely corresponding P peaks and lows in March, April, and May, 1975 (Figures 4e and 4f), despite their being separated by a 792-day time interval. Phosphorus dynamics usually seemed a function of individual water bodies, and it is assumed that basin-wide similarities in phosphorus patterns indicated like processes or conditions in this respect in each of the various water bodies. Reference to Figures 3 and 4 will show that sometimes only 2 water bodies exhibited like patterns.

It may be noted in Figures 3 and 4 that there were often marked differences in the amount of SRP. Up and down oscillation was frequent at all stations in 1975, but those with larger percentages of sewage effluent, and higher P concentrations, showed considerably less amplitude most of the time (Figure 5). Amplitude increased as sewage (and P) load decreased. SRP declined with sewage load from Stations A through 8 but decreased with a slight increase in total P between Stations M and N.

Variation in per cent SRP during the growing season may possibly be attributed to varying utilization by autotrophs in the aeration and stabilization ponds and to assimilation by and release from autotrophic tissues in the more lightly loaded lakes. Neither of these would account for the similar patterns shown under ice cover when autotrophic activity was generally quite low or non-existent and metabolism slow, and this suggests that other explanations should probably be sought for growing season variation.

Comparison of 1975 weekly NH_3-, NO_2-, and NO_3-N concentrations at Stations A, B, and F (Figures 6, 7 and 8) shows that autotrophic activity was the prime remover of nitrogen from solution. The aeration pond (Station A)

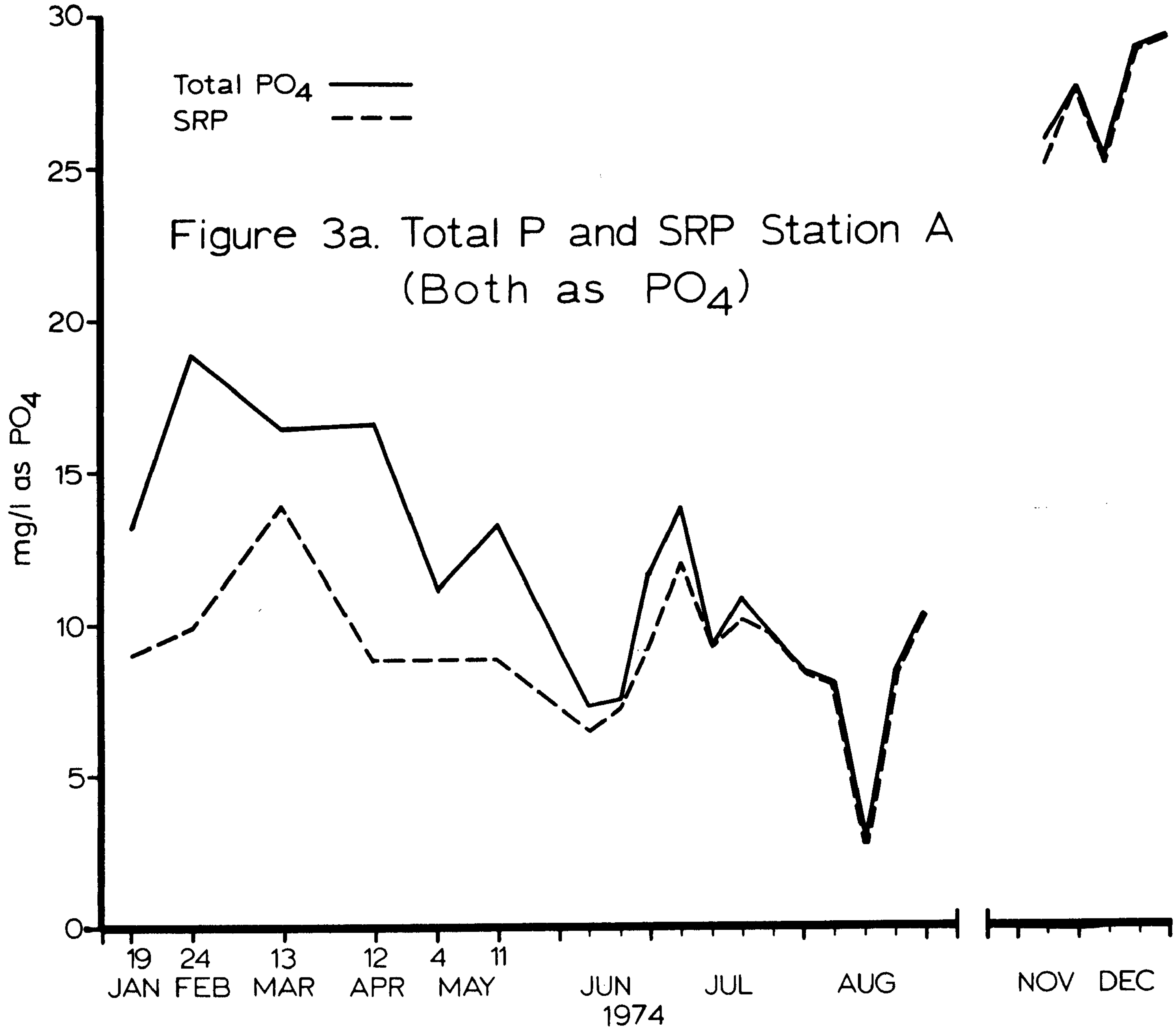


Figure 3a. Total P and SRP Station A (Both as PO_4)

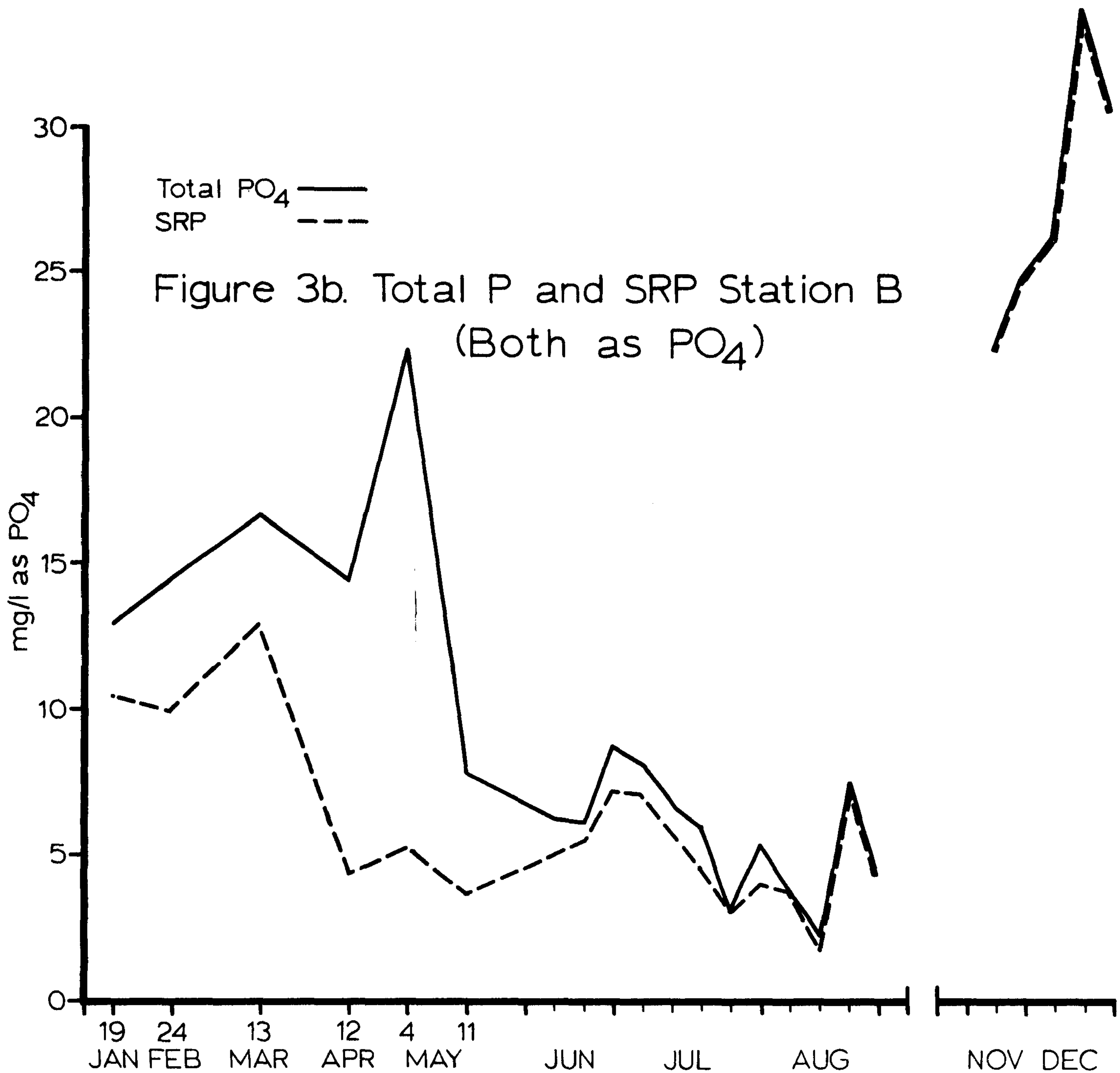


Figure 3b. Total P and SRP Station B (Both as PO_4)

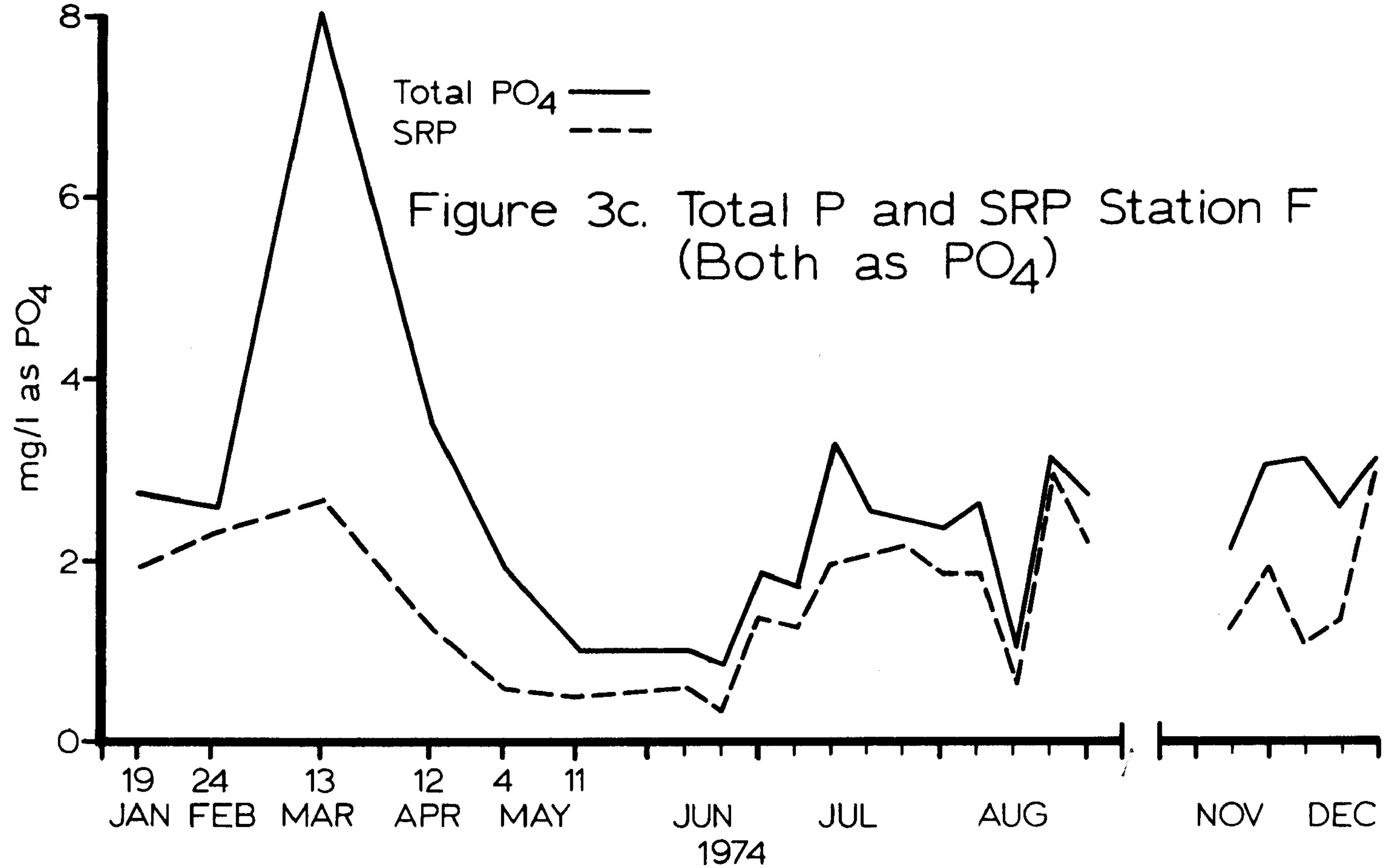


Figure 3c. Total P and SRP Station F (Both as PO_4)

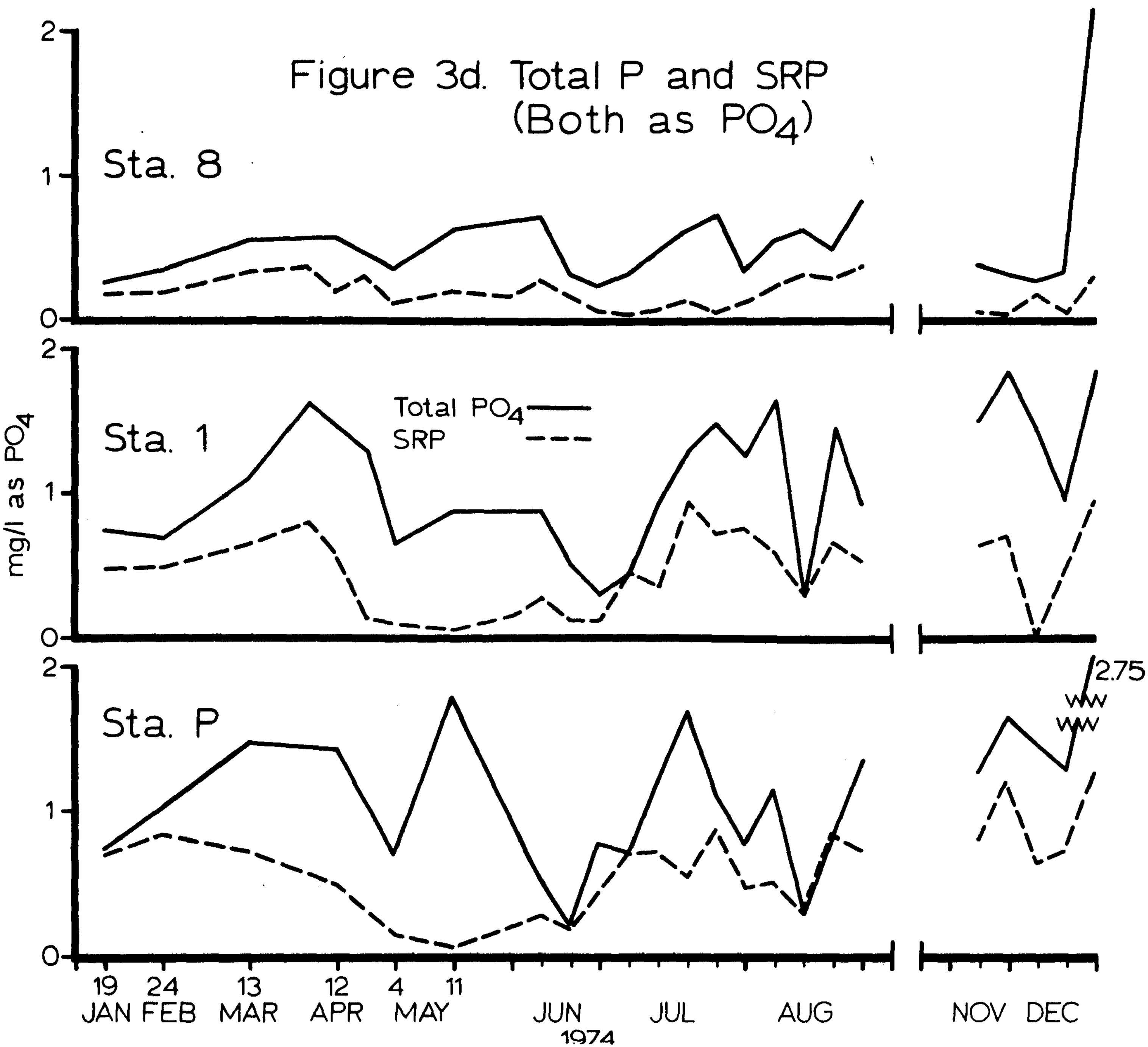


Figure 3d. Total P and SRP (Both as PO_4)

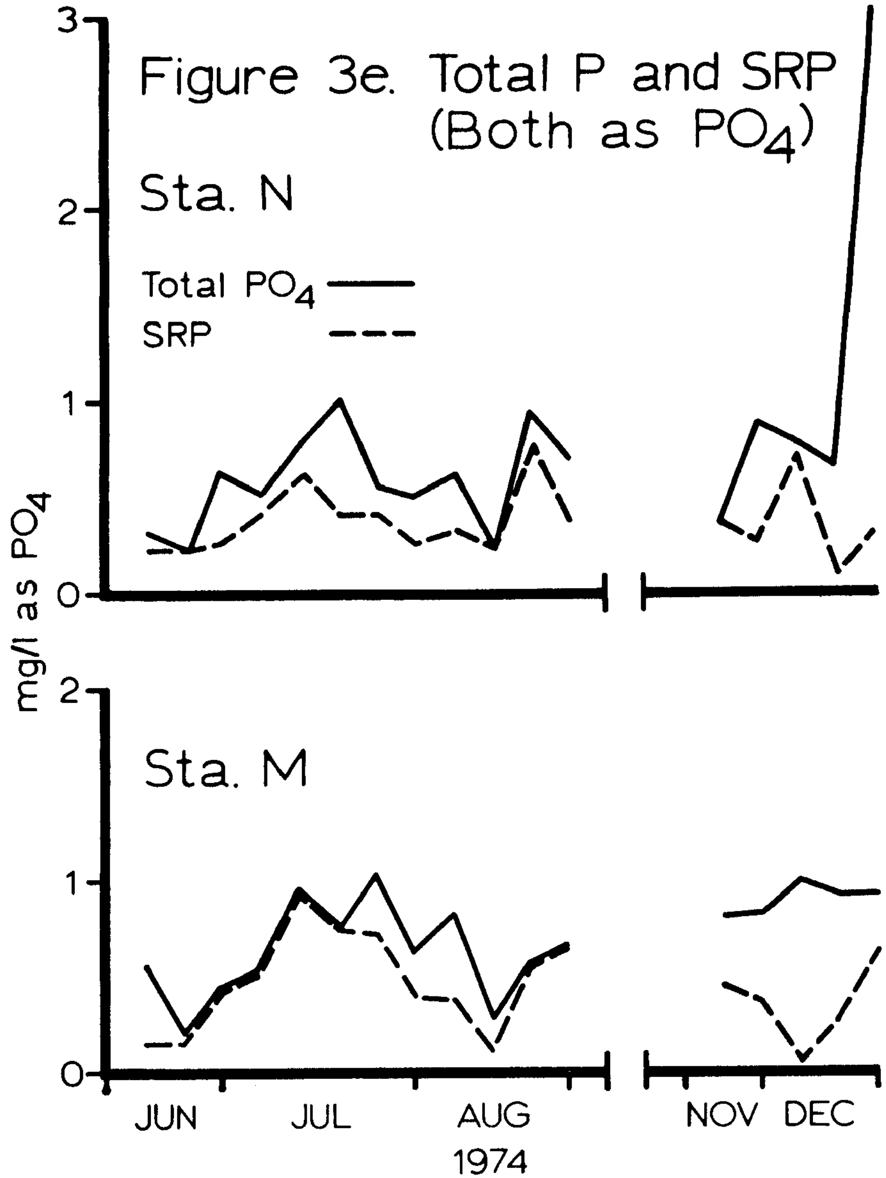


Figure 3e. Total P and SRP (Both as PO_4)

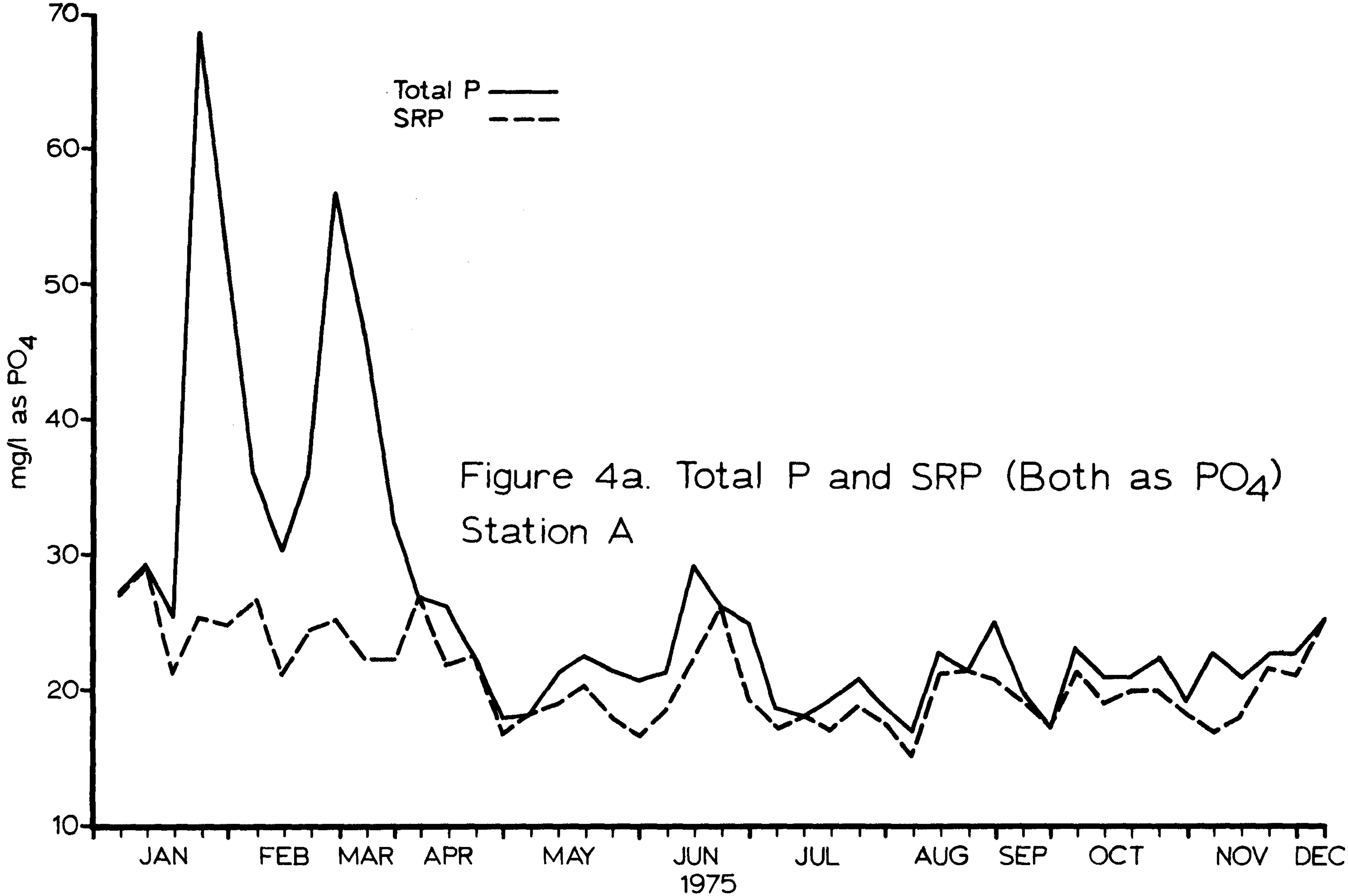


Figure 4a. Total P and SRP (Both as PO_4)
Station A

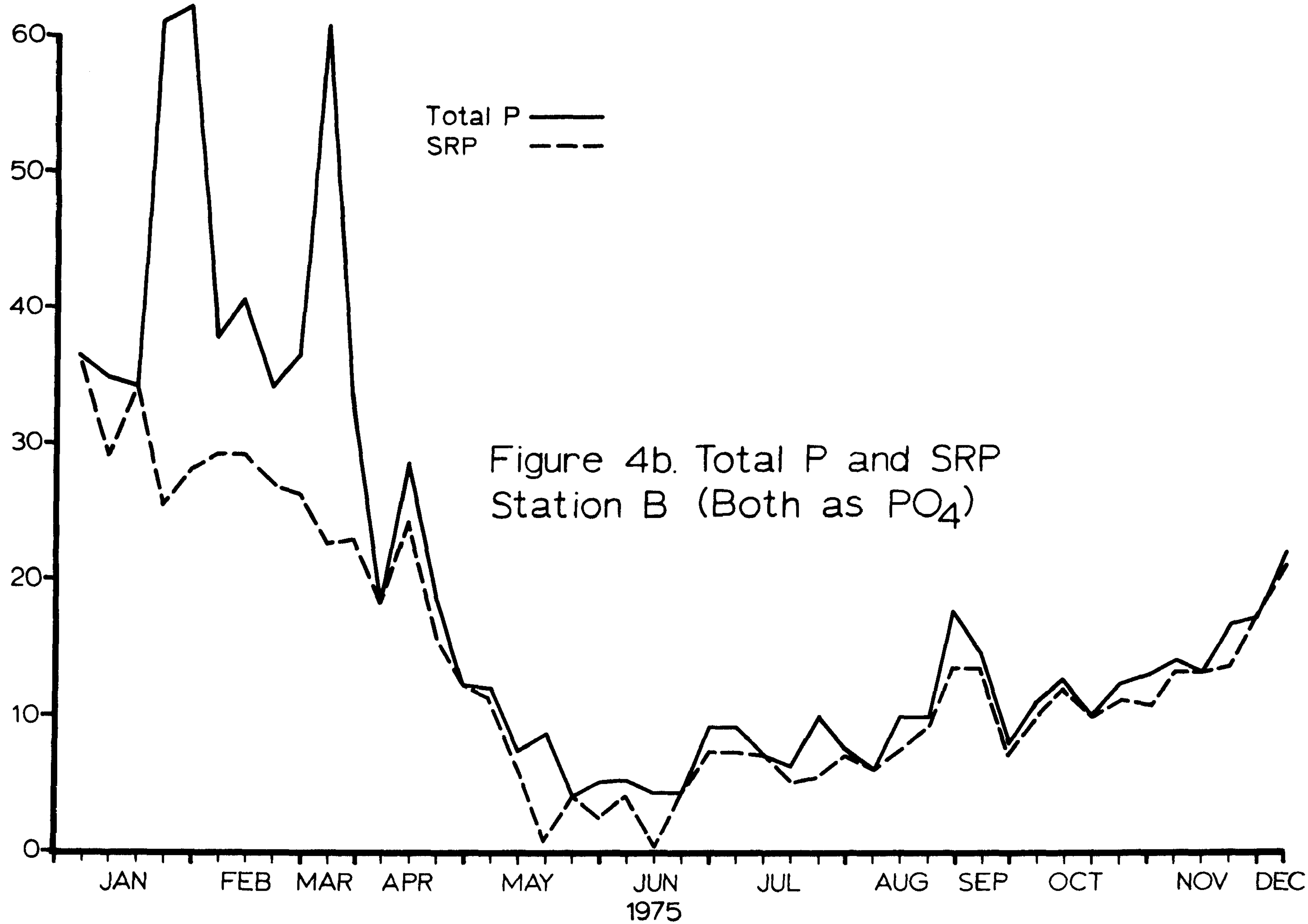


Figure 4b. Total P and SRP Station B (Both as PO_4)

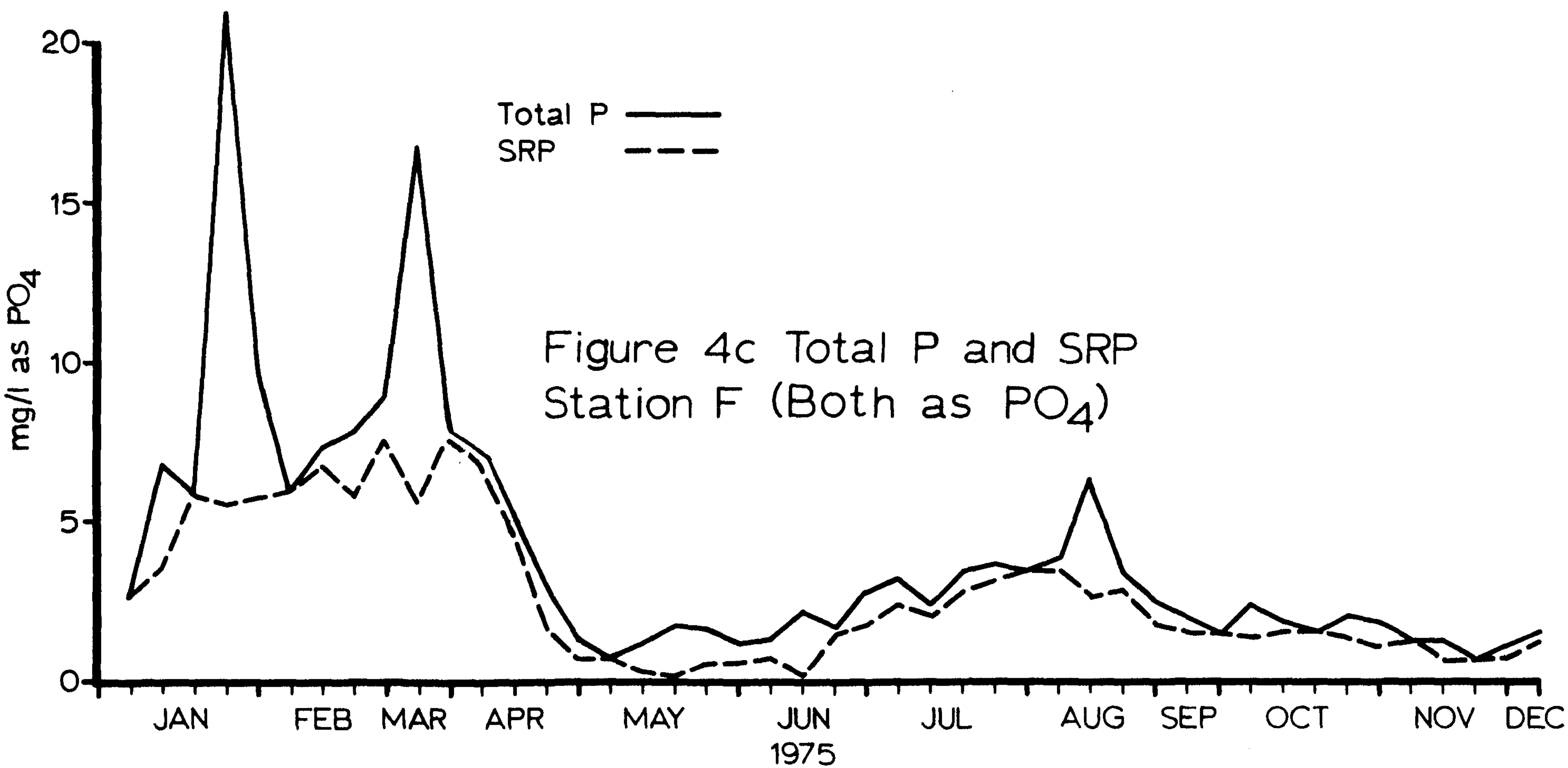
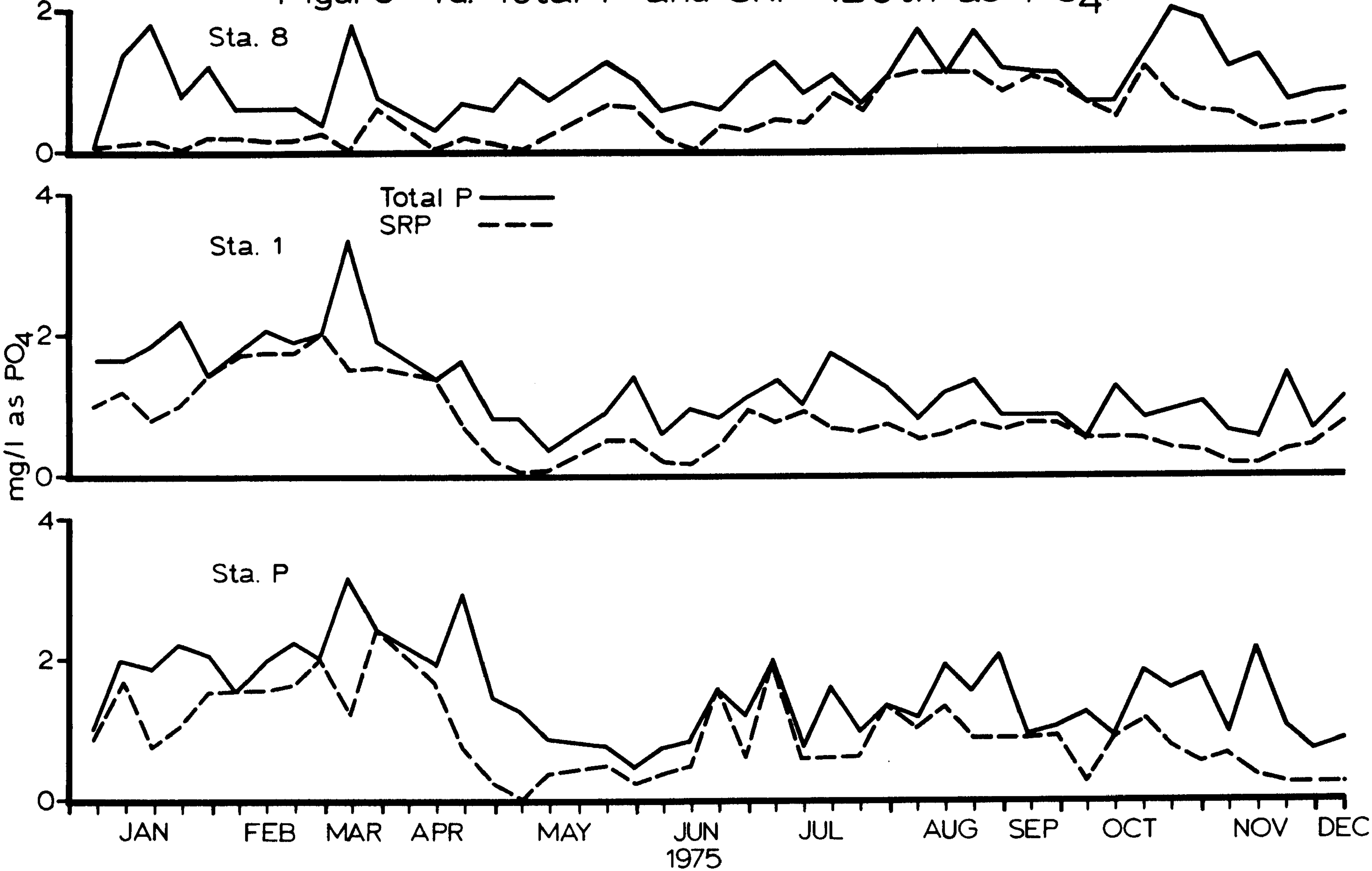


Figure 4c Total P and SRP Station F (Both as PO_4)

Figure 4d. Total P and SRP (Both as PO_4)



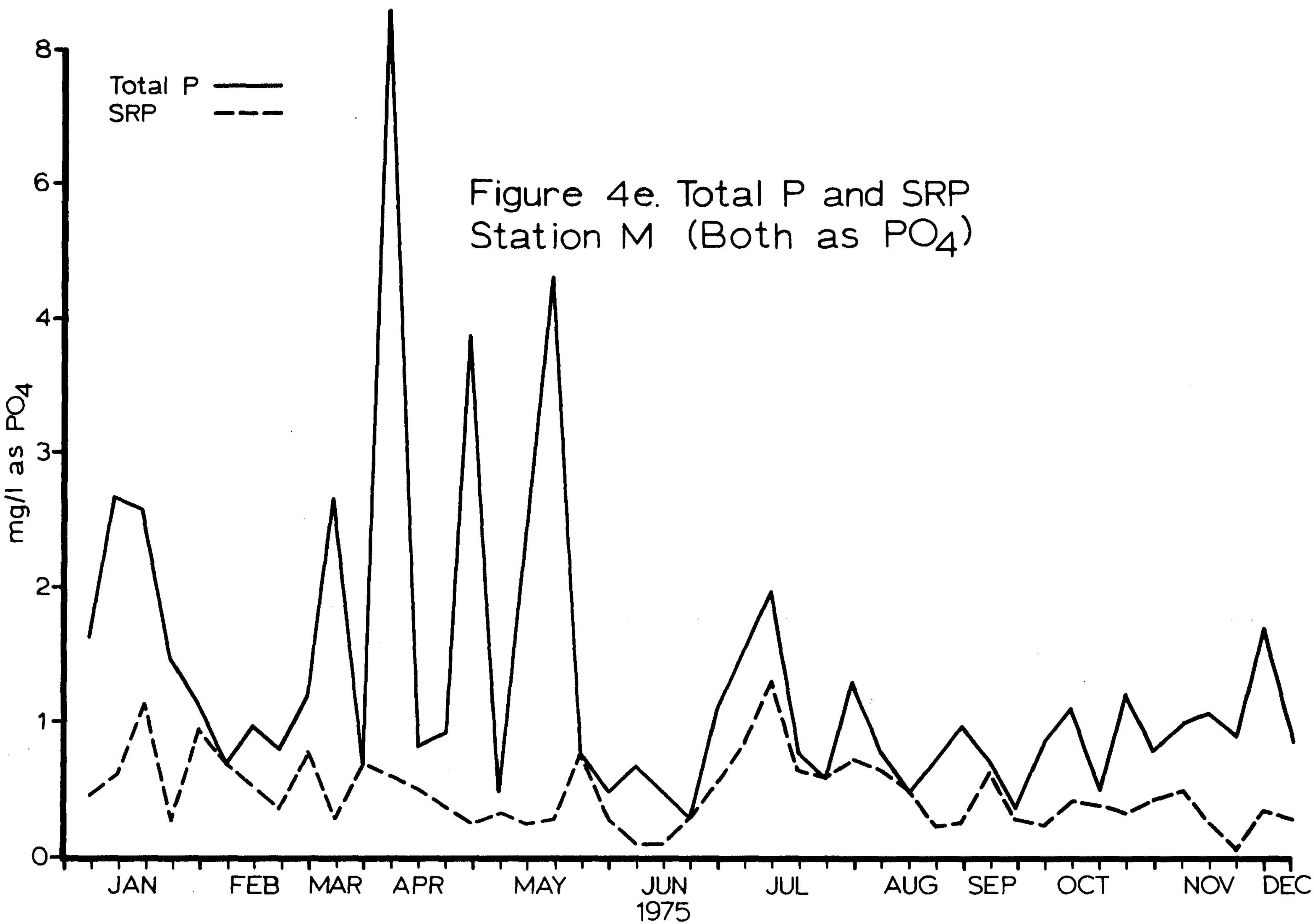


Figure 4e. Total P and SRP Station M (Both as PO_4)

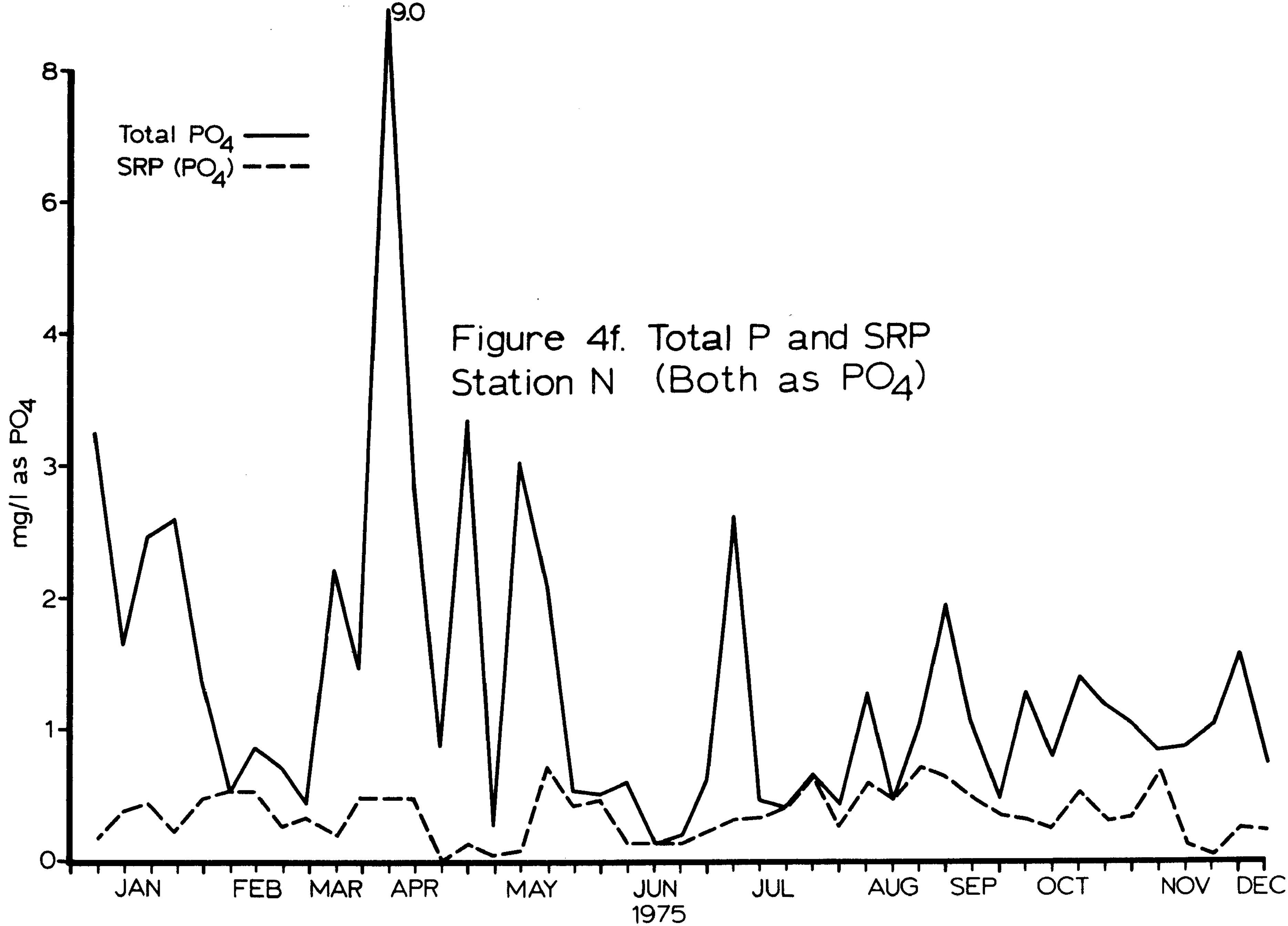


Figure 4f. Total P and SRP Station N (Both as PO_4)

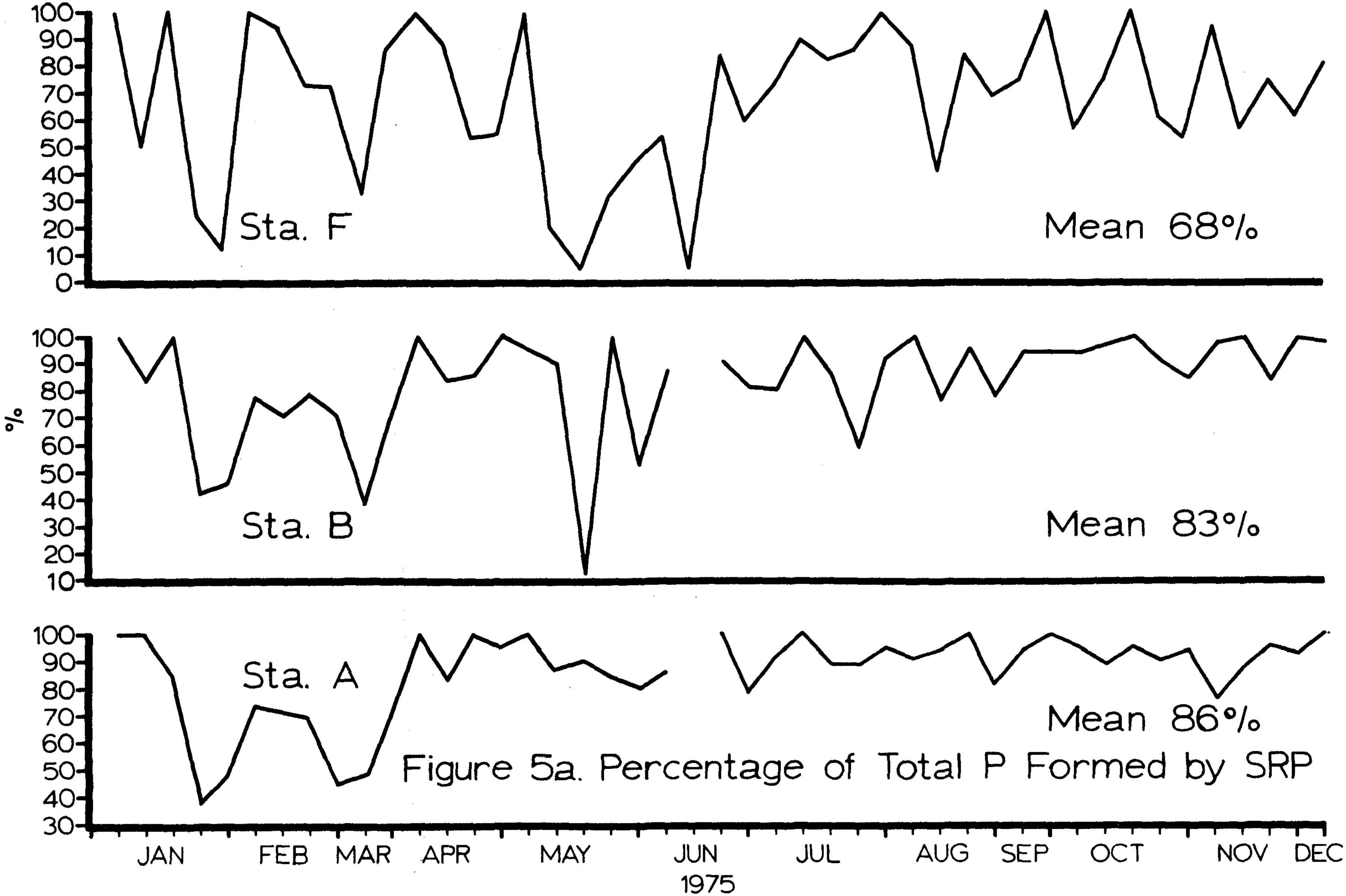


Figure 5a. Percentage of Total P Formed by SRP

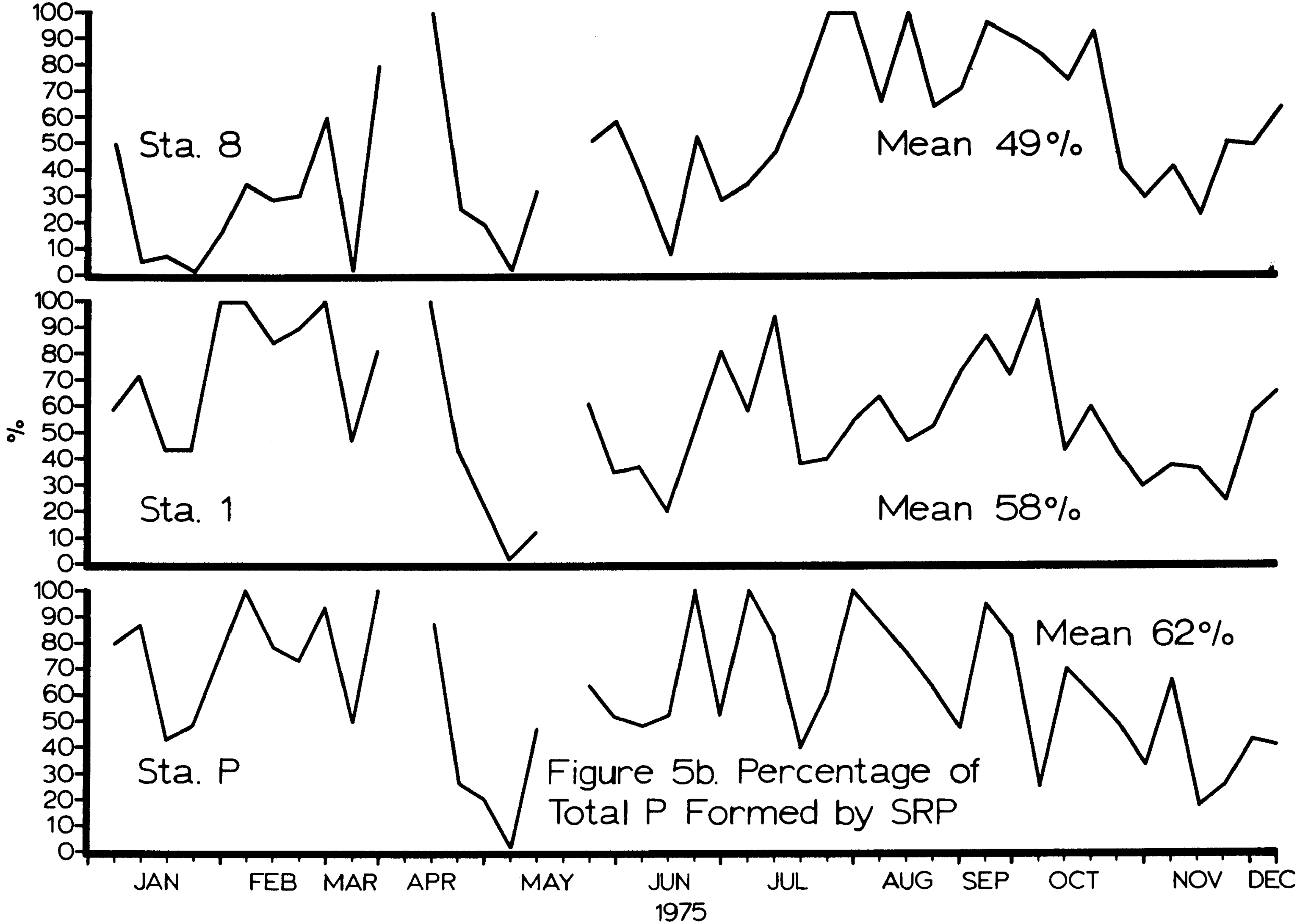


Figure 5b. Percentage of Total P Formed by SRP

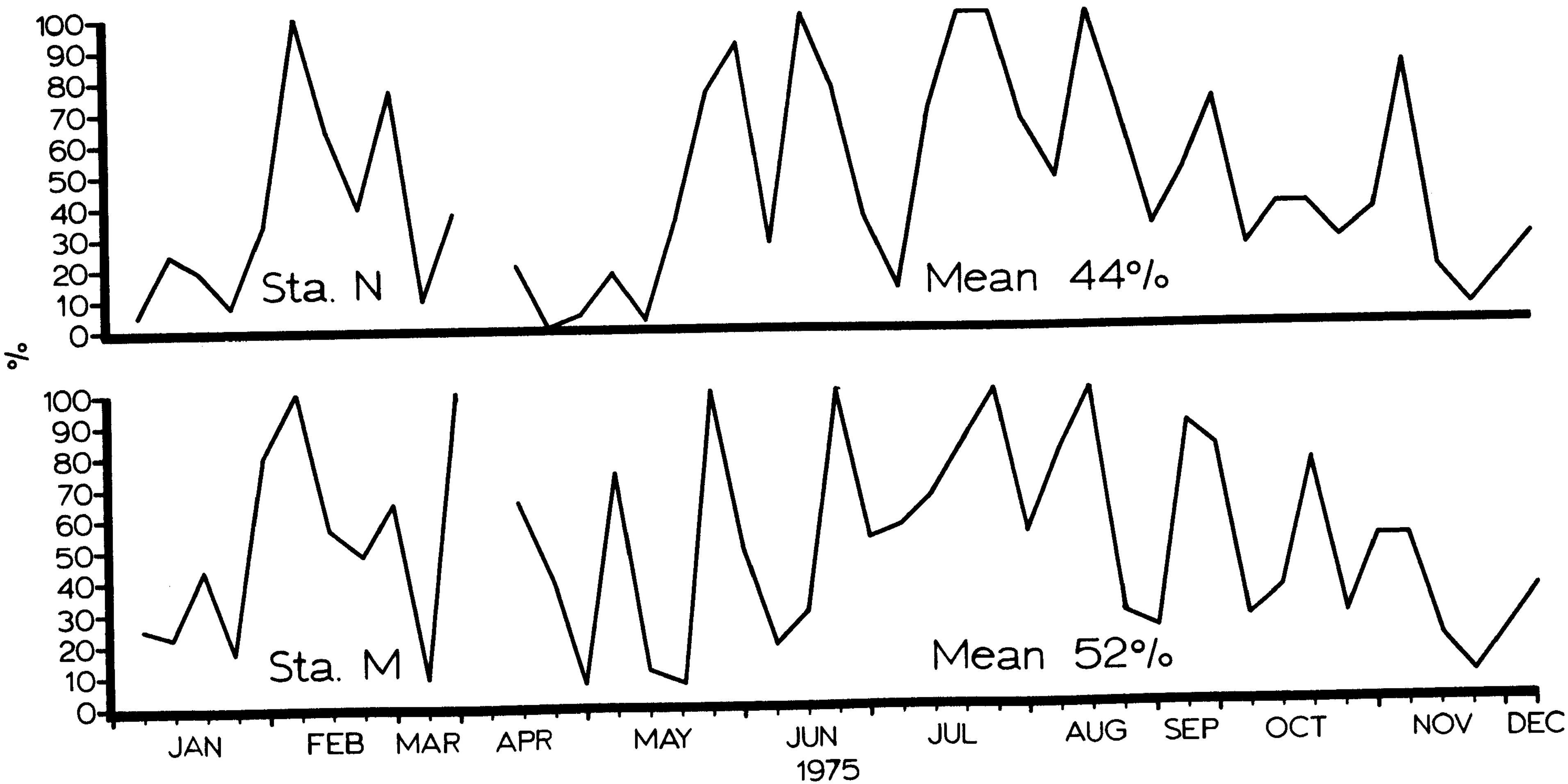
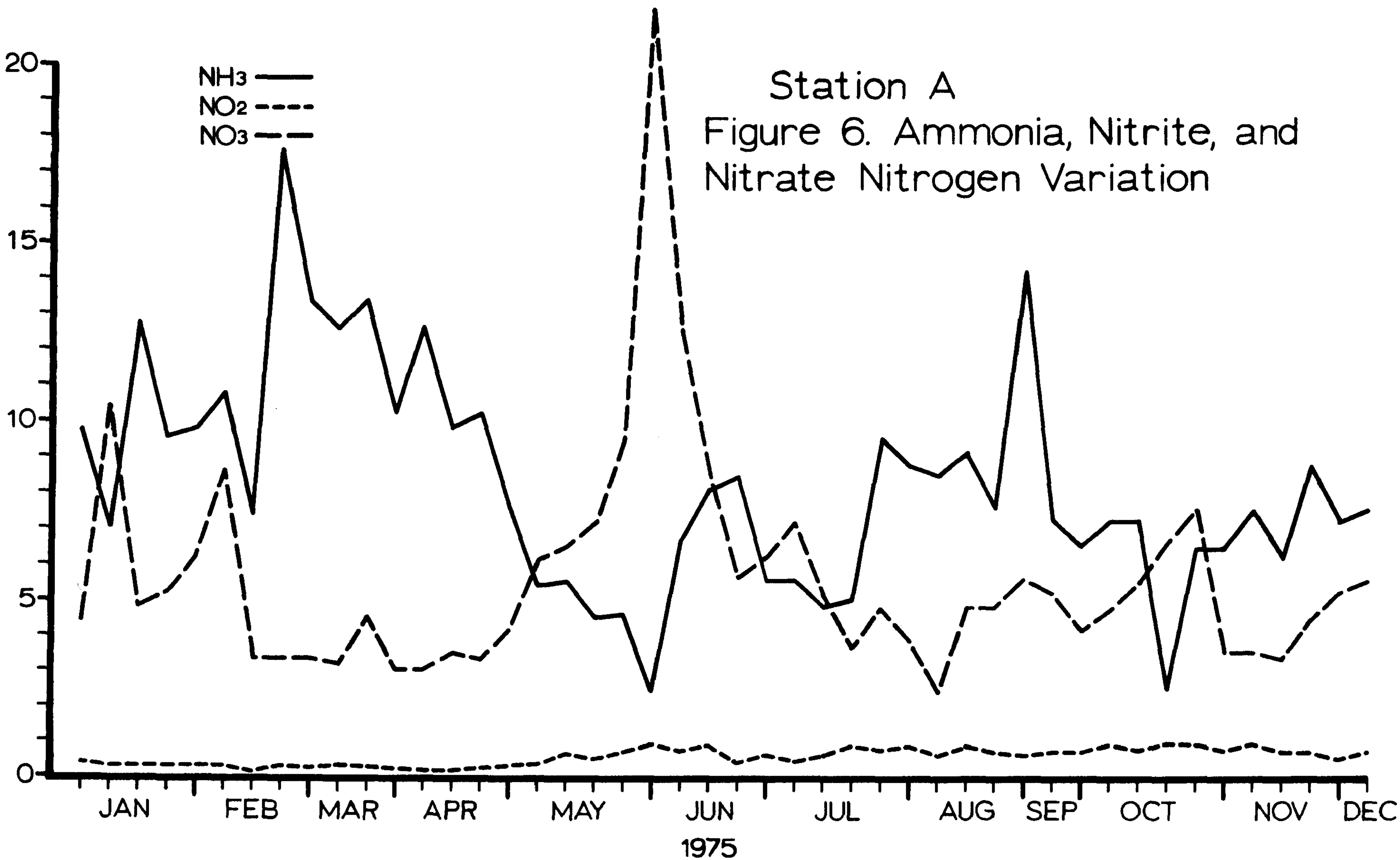


Figure 5c. Percentage of Total P Formed by SRP



Station A
Figure 6. Ammonia, Nitrite, and Nitrate Nitrogen Variation

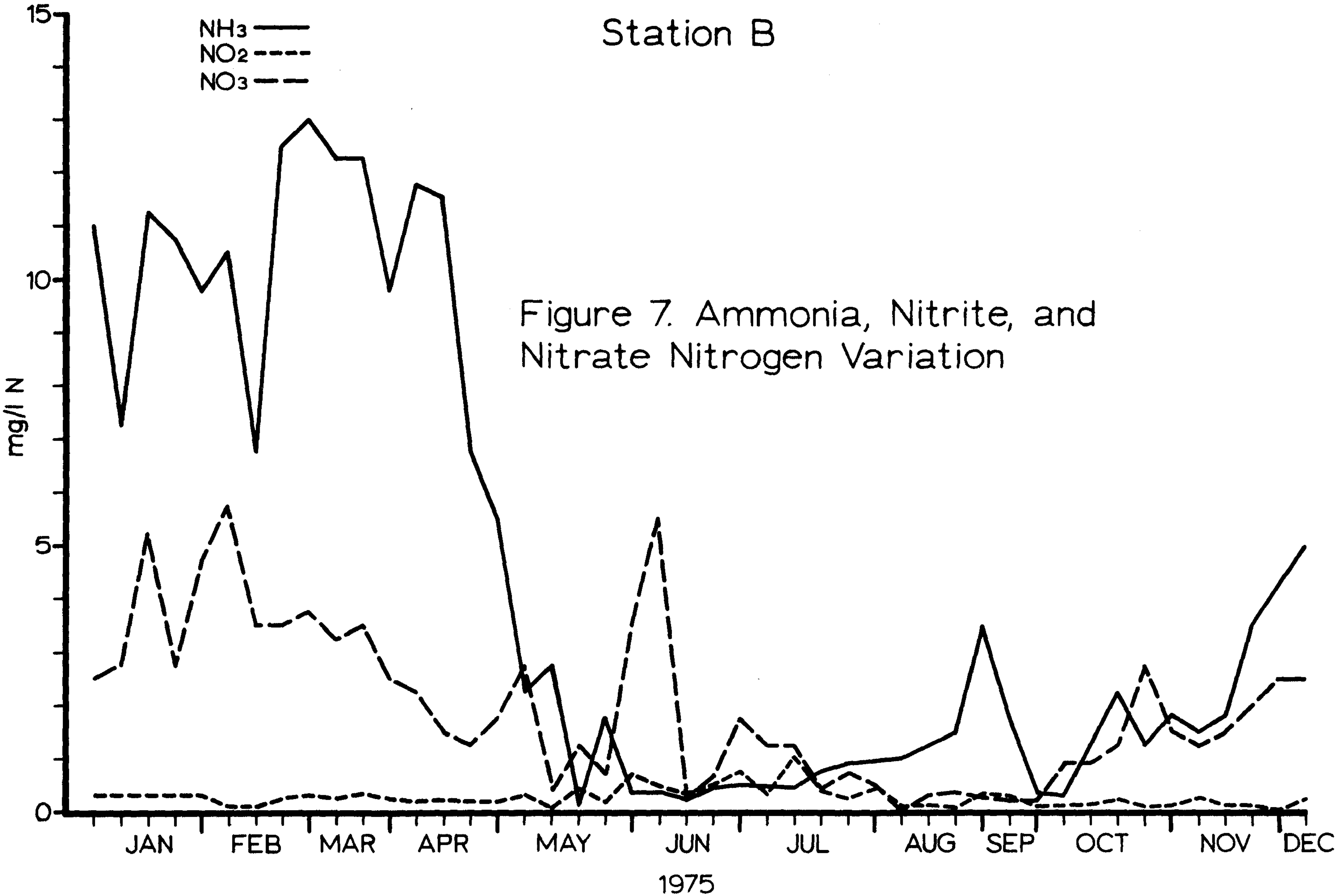


Figure 7. Ammonia, Nitrite, and Nitrate Nitrogen Variation

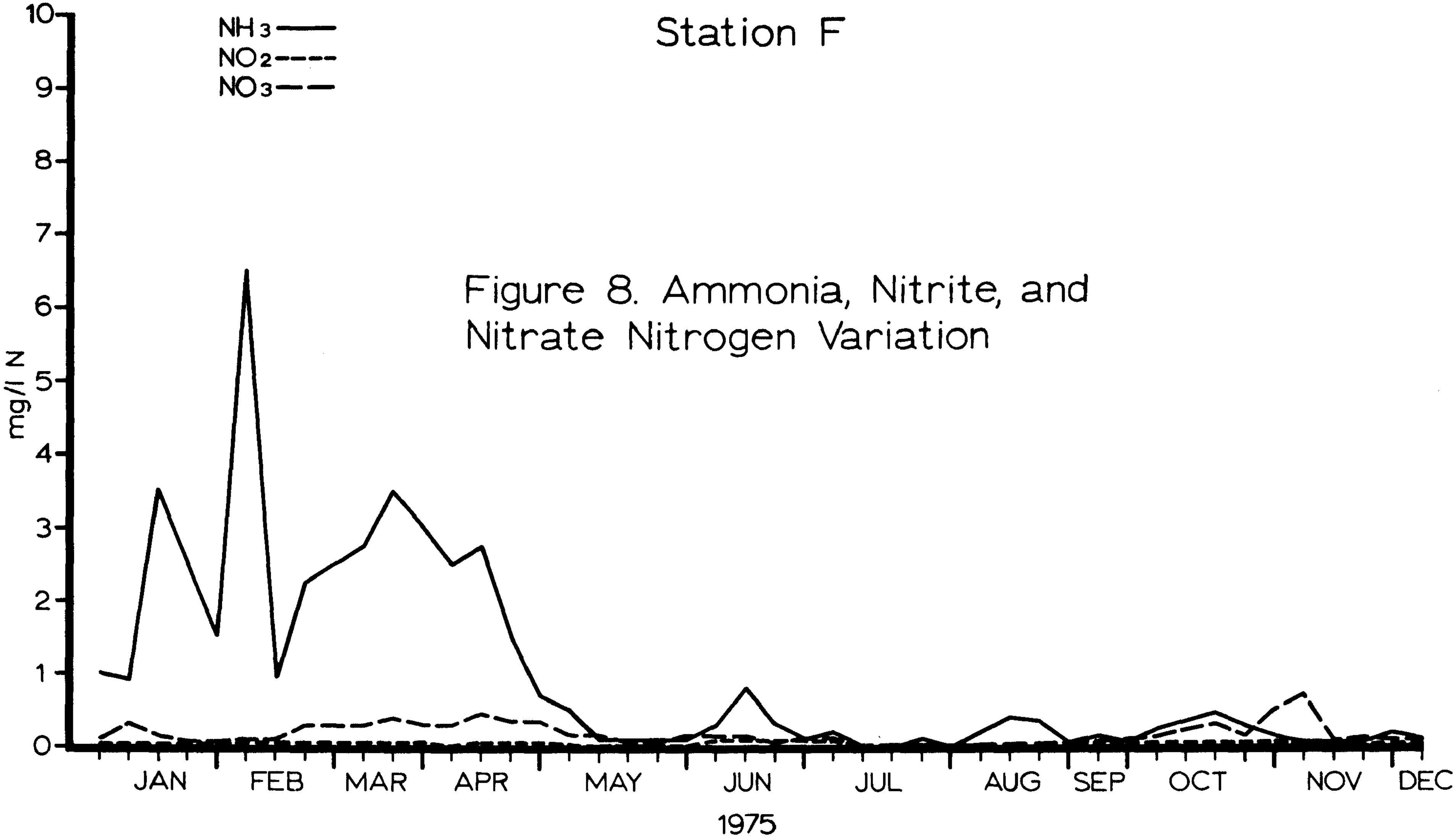


Figure 8. Ammonia, Nitrite, and Nitrate Nitrogen Variation

developed a plankton population in early May, 1975, and maintained it until early December when sampling stopped. The population density varied from 120 to 318,336 organisms per ml, but was usually above 10,000. Higher concentrations were in May, October, and November. The general nitrogen level (Figure 9) was lowered following development of phytoplankton; but a peak in June, due to NO_3-N increase, was above the winter level, and another in early September, reflecting NH_3-N rise (Figure 6), nearly equalled it. It is assumed that both high concentrations were present in wastewater entering the aeration pond. Autotrophic activity mainly, if not exclusively, affected NH_3-N in this period; nitrate varied over a wider range but not in manners that suggested a relationship with autotrophism.

Autotrophic nitrogen removal was more evident in the stabilization pond (Station B), but the June NO_3-N and September NH_3-N pulses carried over from Station A (Figures 6 and 7). Here NO_3-N decreased with NH_3-N. In Lake St. Clair (Station F) NH_3- and NO_3-N were reduced by photosynthesis (Figure 8), but concentration of NO_3-N was, relative to Stations A and B, quite low, and autotrophic influences were most noticeable on NH_3-N. A June peak in NH_3-N here corresponded to elevations of NO_3-N in Stations A and B.

Nitrogen variation in these 3 water bodies suggests that NH_3-N was selected first by active autotrophic organisms and that recourse was made to NO_3-N only after supplies of NH_3-N were inadequate to meet the population demands. In the aeration pond quantity of NH_3-N always appeared adequate, but in the stabilization pond and Lake St. Clair recourse was evidently made to NO_3-N after NH_3-N declined noticeably below 1.0 mg/l. At Station F summer production of NH_3-N did not attain 1.0 mg/l, and nitrate was suppressed until autumn. In the stabilization pond NO_3-N and NH_3-N were augmented at times by inflow from Station A, and relationships of these 2 forms of N were less clear-cut. Phytoplankton also developed in B and F in early May and endured until winter. Nitrogen fixation by blue-green algae occurred in Lake St. Clair each year.

Loads--In 1973 and 1974 the major part of the phosphorus load reaching the Lake Sallie inlet was discharged from Lake St. Clair, but in 1975 this wastewater affected load was exceeded by that contributed from non-point sources upstream from Detroit Lake (refer to Stations F and N in Table 9). This reversal was occasioned by higher concentrations in watershed drainage, not by greater amounts of runoff. Phosphorus was detained and lost to ground drainage in the stabilization pond (Station B) each year, but this was followed by a gain in Lake St. Clair (Station F), which apparently came to a large extent from this seepage. There was a phosphorus loss each year between the ditch-Pelican River junction and the Lake Sallie inlet (Station 1) that was occasioned by discharge loss (largest in 1973) and precipitation and loss to seepage in Muskrat Lake. Seepage into Lakes Sallie and St. Clair will be described later.

Considerable quantities of Pelican River-borne phosphorus remained in Lake Sallie each year, giving a 13.72 metric ton (15.11 ton) build-up over the 2-1/2 year period covered in Table 6. In 1973 and 1974 4.40 metric tons remained in the lake water mass, and during the first 6 months in 1975 this load built up to 11.22 metric tons. In early autumn 1974 bottom sediments

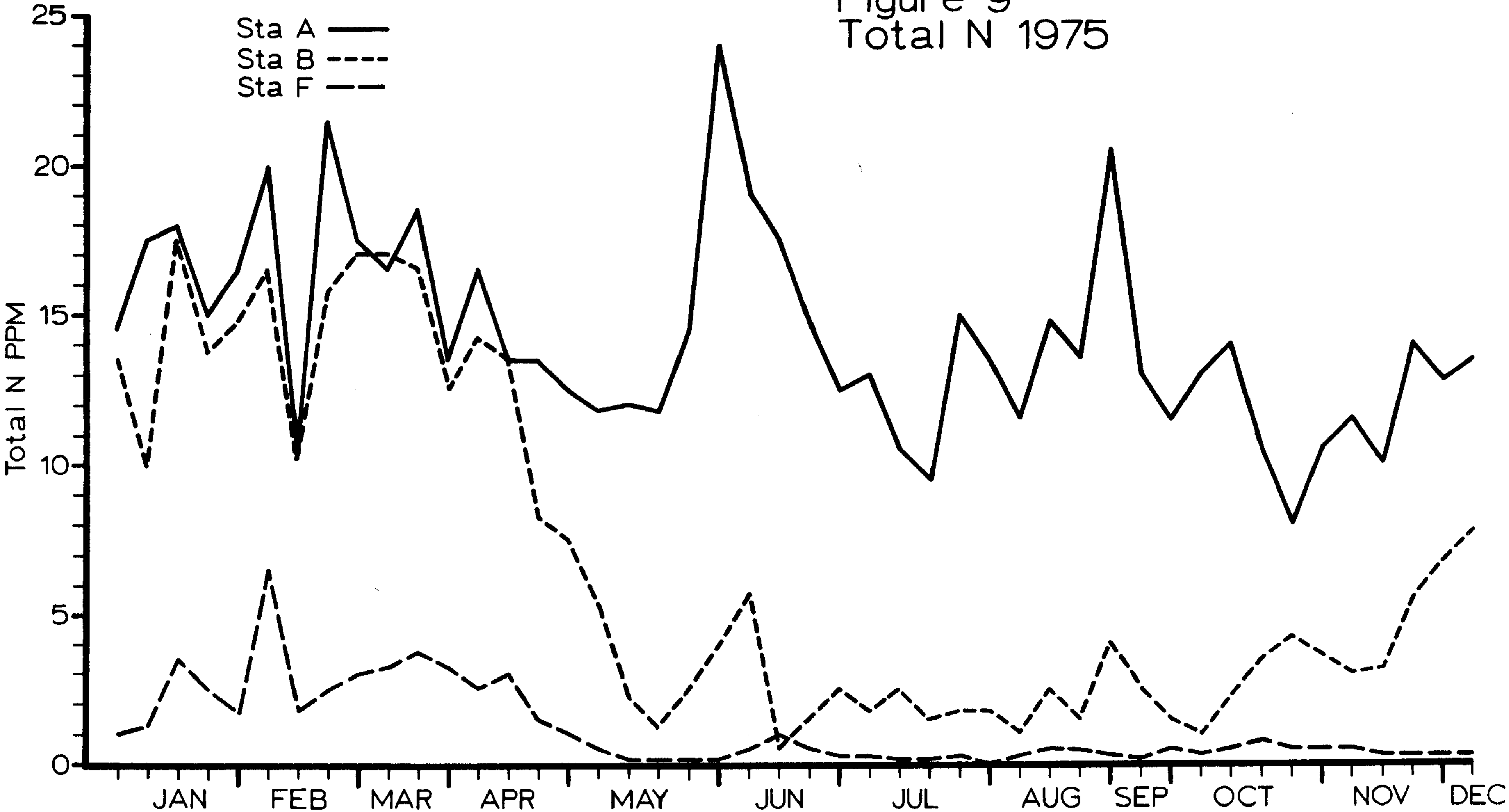


Figure 9
Total N 1975

(upper 15 centimeters) contained 45 metric tons of phosphorus, and it would appear that 2.50 metric tons, net, were added to bottom sediments from Pelican River inflow over this 2-1/2 year period (13.72 - 11.22).

TABLE 9. TOTAL PHOSPHORUS LOADS AT WATERSHED STATIONS (METRIC TONS)

	A	B	F	N	F + N	1	8
1973	12.02	6.34	10.46	6.40	16.86	12.70	6.10
1974	5.15	2.76	5.88	3.52	9.40	9.64	4.98
1975	6.18	4.12	5.96	9.98	15.94	9.52	7.06
TOTALS	23.35	13.22	22.30	19.90	42.20	31.86	18.14

1975: January-June records

Nitrogen loads were at times affected by nitrogen fixation from the atmosphere and groundwater seepage into lakes. Active nitrogen fixation occurred in Lake St. Clair (suggested by high pH and low oxygen levels over extended periods) but routine analytical methods did not denote N in the organic state and hence omitted quantities carried in bodies of organisms leaving the lake. It is assumed that loads leaving Lake St. Clair (Table 10) were in excess of those indicated by analyses for inorganic nitrogen compounds. Nitrogen loss at Station B seemingly reflects utilization by plants and loss to seepage. Nitrogen fixers rarely occurred there.

Organisms in Lake Sallie appeared to utilize more nitrogen than they fixed in 1974 and 1975, but the reverse seemed true in 1973. Nitrogen loads therefore have shortcomings for estimation of nutrient point source contributions, even at short distances from such sources, in this watershed.

Groundwater--

Locations of the 33 groundwater sampling wells are shown by X's in Figure 1, and a more detailed map of the well area is presented as Figure 10. Wells were grouped into sub-areas that represented distinctive surface regions as related to this project. These sub-areas are:

1. Airport and vicinity
2. Proposed irrigation area
3. N of stabilization pond
4. S of stabilization pond

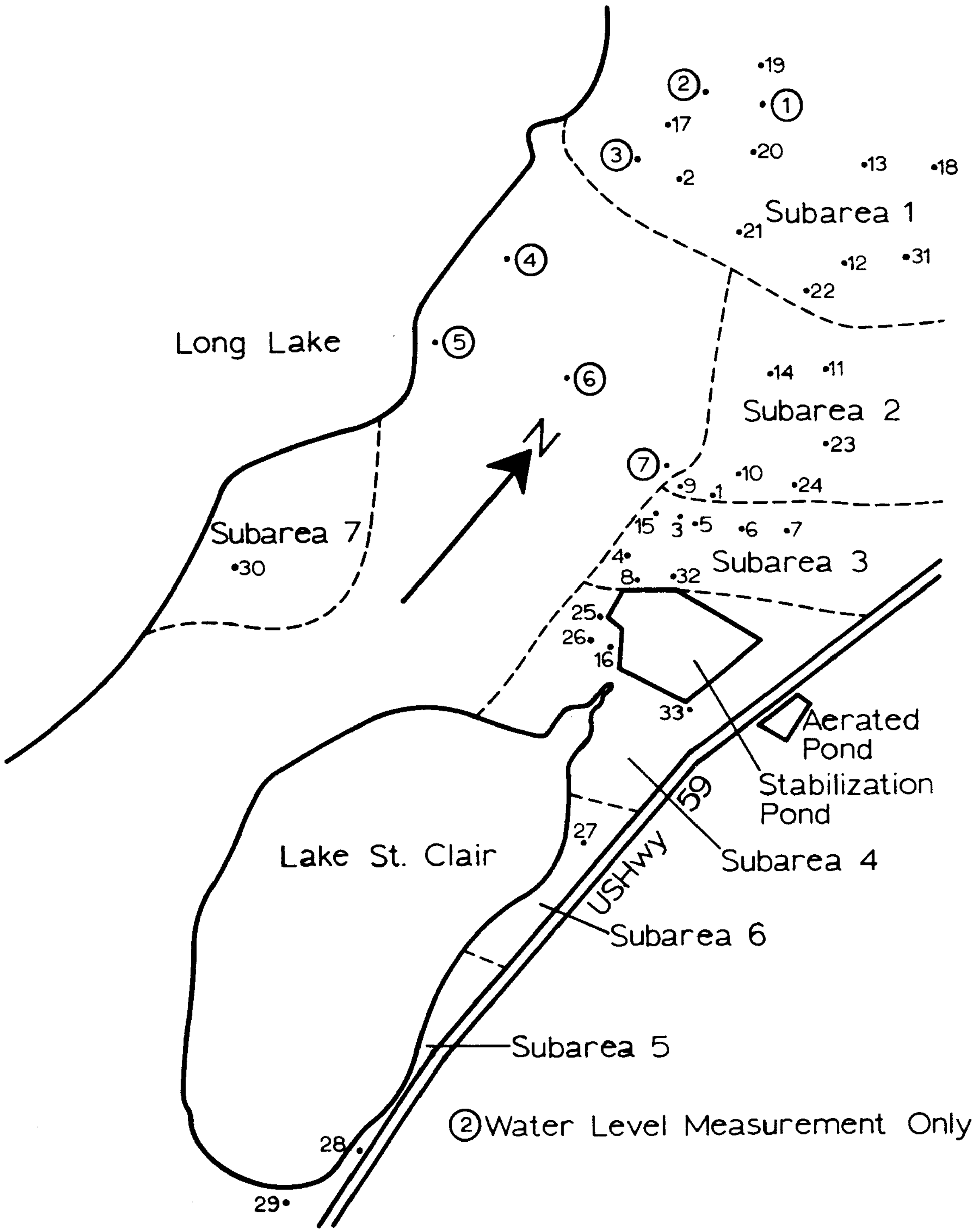


Figure 10. Locations of Ground Water Sampling Sites

5. S of Lake St. Clair

6. NE of Lake St. Clair

7. E of Long Lake

TABLE 10. TOTAL NITROGEN LOADS AT WATERSHED STATIONS (METRIC TONS)

	A	B	F	N	F + N	1	8
1973	19.60	7.40	6.24	2.96	9.20	7.74	9.04
1974	11.06	5.12	9.22	3.62	12.84	10.64	8.38
1975	9.80	4.04	6.30	3.84	10.14	10.80	5.74
TOTALS	40.46	16.56	21.76	10.42	32.18	29.18	23.16

1975: January-June records.

Well numbers in each sub-area and groundwater sampling periods appear in Table 11, and sub-areas are delineated in Figure 10. None of the above areas contains human habitations. Features of each well, bottom and water level elevations, earth strata penetrated, etc., are listed in Table 3.

General groundwater features—The considerable vertical extent of plastic screen provided by these wells seemingly permitted water to pass laterally through the pipes at or near the depth it occupied in the soil. Chemistry of water near the top of longer well water columns was usually noticeably, often markedly, different in 1 or more parameters from that near the bottom. This is quite evident in mean nutrient concentrations appearing in Table 12. It was also common for calcium and magnesium (Table 13), alkalinity (Table 14), oxygen and pH. Vertical temperature differences were often evident in the deeper wells, with surface temperature usually colder in winter and warmer in summer than that near the well bottoms.

Most wells maintained some oxygen in solution, top and bottom, over the 2 record periods. Nitrate nitrogen attained its greatest concentrations when oxygen was present and ammonia when it was absent, but ammonia at times occurred in the presence of oxygen and nitrate when oxygen was absent. Nitrogen values were often quite high, as evidenced by mean values in Table 12.

All parameters of water chemistry varied over the seasons in individual wells, which is assumed to indicate continuous lateral flow through each and not changes that would come about in a stagnant water column with passage of time. Random selection of any individual well records shows this, although it is more marked in some instances than others. PC-28T and B, for instance, over the 1973-74 record period, exhibited the following ranges:

	Top	Bottom
pH	7.15 - 7.80	6.95 - 7.70
Alkalinity	68 - 394 mg/1	164 - 398 mg/1
Hardness (T)	140 - 462 mg/1	375 - 710 mg/1
Calcium	90 - 315 mg/1	245 - 435 mg/1
Magnesium	50 - 147 mg/1	120 - 307 mg/1
Total PO_4	0.395-6.40 mg/1	0.26-4.50 mg/1
NH_3-N	0.46-2.40 mg/1	0.395-2.95 mg/1
NO_3-N	0.099-1.198 mg/1	0.003-1.00 mg/1
Oxygen	0.06-2.40 mg/1	0 - 0.4 mg/1

The above data are also illustrative of differences in upper and lower parts of the water columns in the deeper wells. In PC-28, which was selected at random, NH_3- exceeded NO_3-N, but this was by no means characteristic of all wells. NO_3-N/NH_3-N ratios for PC-28 were : top, 0.348, bottom, 0.19; whereas in PC-2, also picked at random, they were: top, 7.54, bottom, 9.78.

Nutrient concentration--Mean nitrogen and phosphorus concentration in groundwater at top and bottom of each well sampling site appears in Table 12 and the averages of top and bottom concentrations (top only for shallow wells) for groundwater sub-areas and wells contained in each are listed in Table 11. In the latter table it may be noted that, with the exception of sub-areas 4 and 7, phosphorus was markedly more concentrated in 1973-74 than in 1974-75. Sub-area 4 exhibited the highest P mean value each period, and its constancy over the 2 periods suggests a steady source of supply to that region, namely, the stabilization pond.

Nitrogen was also less concentrated in 1974-75, although to a less degree; but in this case it was sub-area 5 that showed the greatest constancy.

Concentrations of nutrients in groundwaters in this area is significant and critical for surface waters into which they discharge. The Detroit Lakes wastewater contributes these compounds to a relatively small part of the sampled groundwater area (sub-areas 4, 5, and 6); and surface land application in fertilizer, and perhaps in precipitation, seems the most likely source of nutrients, especially phosphorus, in the uninhabited region north of the stabilization pond. Time of P passage from soil surface to the saturated zone or water table is unknown.

Ground and surface water--Velocity of groundwater movement across the sampling area and time required for its emergence in surface water bodies were not directly measurable. Comparison of ground and surface water phosphorus concentrations over 1974 and 1975 suggests that about a year is required for the general appearance of unconfined groundwater in lakes and stream segments studied. Tables 6 and 11 show that high groundwater P levels in 1974 were followed by high surface water concentrations in 1975, which gave larger P loads from general drainage than from the sewage effluent. If this indicated ground-surface time relationship is valid, 1976 surface P levels should show a decline from the 1975 concentrations; and 20 records over the period from January 9 to July 24, 1976, indicate a general and, in most instances, a marked reduction at surface water stations representative of general watershed runoff. Mean P concentrations for 1974, 1975 and 1976 at these stations were:

	Long Lake	Campbell Creek	Floyd Lake	Little Floyd Lake	Station L	Station M	Detroit Lake
1974	0.19	0.20	0.20	0.20	0.31	0.23	0.22
1975	0.37	0.85	0.35	0.38	0.45	0.46	0.47
1976	0.22	0.28	0.25	0.32	0.29	0.25	0.30

With the exception of Little Floyd Lake, surface waters had significantly less P in 1976, many returning to near their 1974 mean concentration after record highs in 1975. Long Lake, situated near the groundwater sampling area, is considered particularly diagnostic in this respect.

Groundwater movement--Mean groundwater elevation at each sampling site over 1974-75 and mean surface elevation of Long Lake appear in Figure 11, and contours and likely flow paths developed from these means in Figure 12. Water level elevation was lowest at Site 27 and highest near the airport at Site 13. The general flow trend was toward Lake St. Clair with divergences to east and west, as shown in Figure 12. The mean water level elevation in Long Lake was below that of the water table in ground areas to the east. but uncertainties regarding the course of the 1,349' water level contour do not permit a positive statement at this time. There seems little reason to doubt that Long Lake discharged to the ground in the vicinity of Well Site 30.

The lowest groundwater level was at Site 27, just east of Lake St. Clair (Figure 11). Water there was strikingly more highly mineralized, as indicated by hardness and alkalinity, than that at any other site (Tables 13 and 14). This could have resulted from a higher level of sulfate reduction during oxygenless periods promoted by dissolved organic matter from Lake St. Clair, with perhaps some contribution from shells and other materials in the saturated ground strata. Oxygen was absent for long periods in deeper water there in 1974.

Oxygen and hydrogen sulfide--Oxygen declined to 0.0 in only 13 of the 57 groundwater sampling sites (tops and bottoms of water columns are considered individual sites) but fell to this level in less than 50% of samples from any

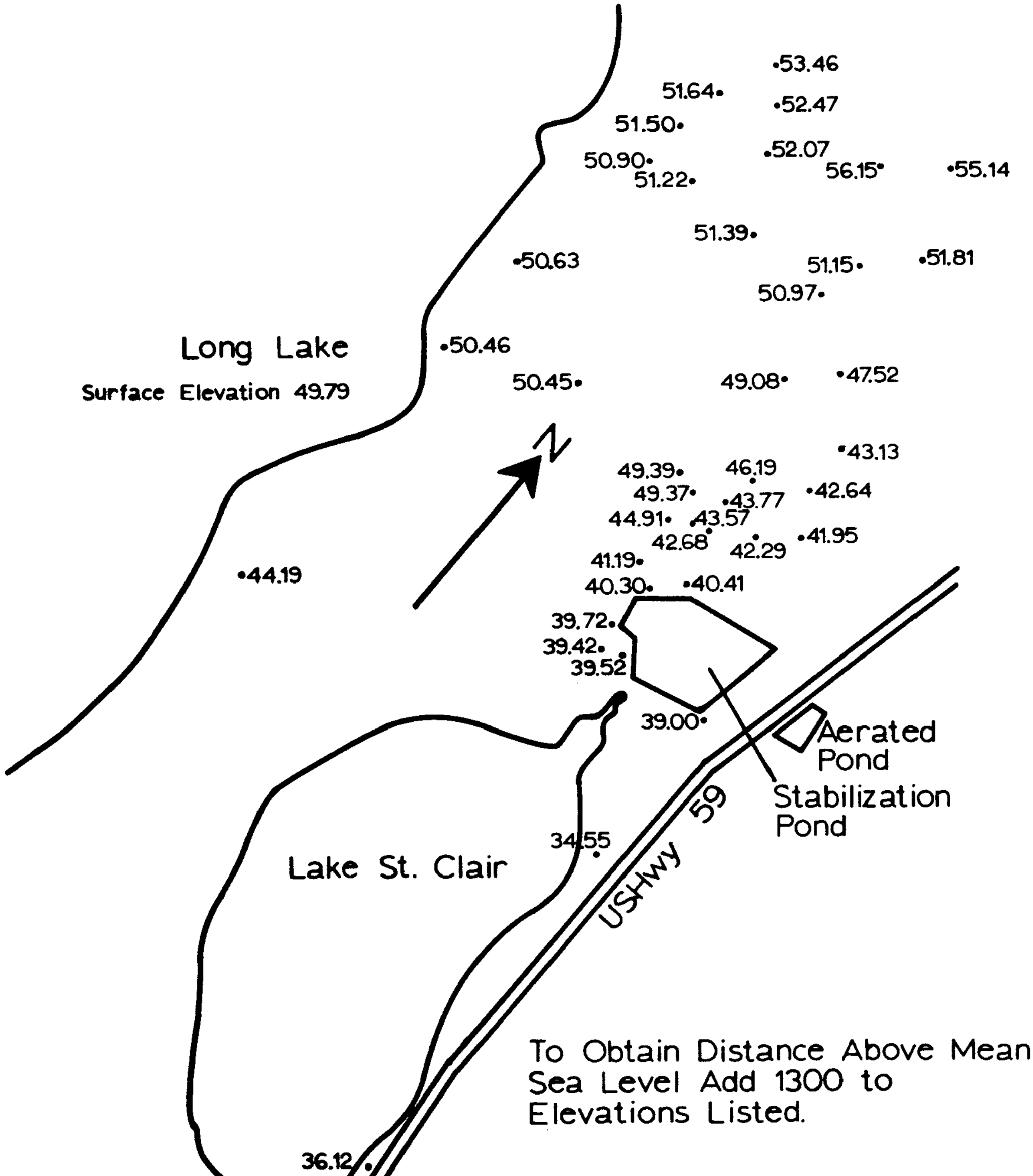


Figure 11. Mean Water Elevations in Individual Wells and Long Lake.

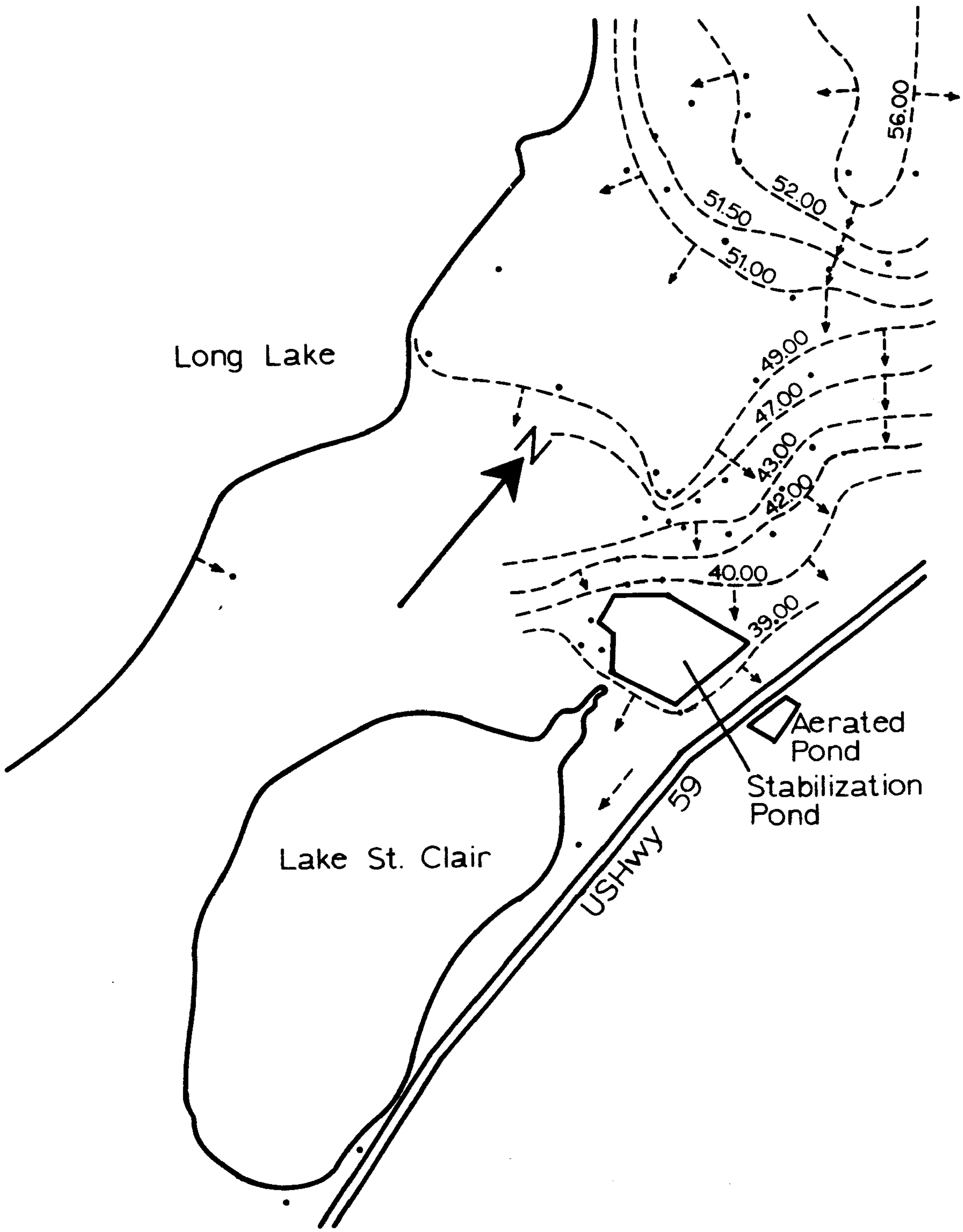


Figure 12. Groundwater Contours and Indicated Flow Paths.

site, and in only 2 places (Wells 9 and 27) was 0.0 O_2 found at the top of the water column. Site 27B was oxygenless over a long period, July-August, in 1974 (83% of samples that year) but lacked oxygen in only 24% of samples taken in 1975; however, oxygen was generally quite low there, attaining as much as 1.0 mg/l in only 13% of samples.

Groundwater was generally higher in oxygen in 1975; maxima for each site were usually attained that year. Oxygen ranges at individual sampling sites over the entire sampling period appear in Table 15.

Hydrogen sulfide odor of samples was rated subjectively according to its intensity (+ if weak, ++ moderate, and +++ if strong). + and ++ H_2S intensities were sometimes recorded when oxygen was in the 0.1 - 0.5 mg/l range, but +++ did not occur until O_2 was below 0.05 mg/l. Groundwater was frequently colored orange or gray (not in all wells or in any well at all times), the orange color when oxygen was substantially present and the gray when it was absent or nearly so. No iron analyses were conducted, but from the above it would appear that the orange color represented iron oxide(s) and the gray, iron sulfide.

Groundwater Seepage into Lakes

Nutrient Concentration--

Water entering seepage collectors in Lakes Sallie and St. Clair in areas shown in Figures 13 and 16 (1974 and 1975) invariably contained phosphorus and nitrogen. In St. Clair, total P concentration ranged from 0.27 to 2.10 mg/l (mean, 1.04 mg/l) and total inorganic nitrogen from 0.90 to 2.337 mg/l (mean, 1.59 mg/l); whereas, in Lake Sallie, total P range was 0.23 - 7.05 mg/l (mean, 1.63) and total nitrogen 1.07 - 8.1 mg/l (mean, 4.00). In seepage water entering both lakes, NH_3-N greatly exceeded the sum of NO_2- and NO_3-N.

Water and Nutrient Loads--

Rate of seepage inflow into either lake varied from day to day and between different collectors on the same day. Rates measured in 1974 are considered inaccurate. It was necessary to leave collectors for extended periods (19 - 24 hours), and bag capacity was usually exceeded. Collectors were not operated longer than 6.5 hours in 1975, and inflow rates so determined are deemed acceptable. Table 16 shows variation in seepage inflow volume and P and N loads so brought into each lake.

Nitrate values were omitted when sample volume was insufficient for all 3 N tests.

Measured seepage flow into Lake Sallie is excessive for the entire lake bottom except possibly on June 27 when the rate of 20 m^3/hectare/day would equal the indicated 1975 increment in the lake. With few exceptions, nitrogen load exceeded phosphorus load into Lake Sallie.

Since the seepage rate into the upper area of this lake is excessive for the entire bottom, it seems inadvisable to use these volume-area relationships to compute seepage loads for the whole lake. It is evident, however, that these lakes gain meaningful quantities of nutrients through their bottoms.

One hundred grams/hectare/day would result in 36.5 kg/hectare/year or 32.62 lbs./acre/year.

PRECIPITATION

Precipitation records represent the following periods and amounts of rainfall:

	Period	cm Rainfall	Inches Rainfall
1973	May 24 - September 1	31.01	12.21
1974	May 10 - August 15	13.59	5.35
1975	June 4 - August 1	17.30	6.81

Weekly visits to the study area during fall and winter seldom coincided with periods of precipitation. In summer it was often possible to collect several samples during the course of 1 rainstorm.

Nutrient Concentration

Phosphorus and nitrogen concentration varied from storm to storm and, over the courses of individual storms, seldom with any definite pattern. Storms of short duration tended to show a decline in both phosphorus and nitrogen as they continued, but this was not without exception, and the downward trend was often reversed in storms that endured for several hours. Phosphorus was almost always more concentrated in the unavailable than the available (SRP) form, and ammonia generally accounted for most of the nitrogen present, rarely being lower than nitrate (Table 17). Mean concentration of nitrogen was lower in 1975 than in either preceding year, but that of phosphorus higher.

Rain water has been acid to quite acid in reaction, with pH ranging from 5.40 to 3.20. Variation has been common, with values sometimes changing as much as 0.85 pH during a single storm. Alkalinity has not exceeded 7.5 mg/l, and hardness has been little higher (10 mg/l), with calcium exceeding magnesium. All tests for hardness were negative in 1975. Conductivity measurements made in 1975 ranged from 9.5 to 124 μmhos/cm, varying from 34 to 79 μmhos/cm in 1 storm.

Nutrient Loads

Table 18 gives load details by date for Lake Sallie, and Table 19 shows loads contributed to each lake in the upper watershed. The latter are based upon records acquired near Lake Sallie which are considered reasonably representative of the upper watershed.

Phosphorus contributions by precipitation to the total 2,423 hectares of watershed lake surface were:

1973	0.199 kilograms/hectare
1974	0.110 kilograms/hectare
1975	0.318 kilograms/hectare

These quantities are not very impressive when compared with seepage loads into Lakes Sallie and St. Clair. Precipitation contributed considerably more nitrogen, and kilograms N/hectare of watershed lake surface were:

1973	4.02
1974	2.07
1975	0.94

which are also rather modest figures with reference to the seepage mentioned above.

Variation noted in precipitation from storm to storm does not permit an accurate computation of annual precipitation loads based on mean concentrations of storms analyzed. These data are considered complete enough, however, to indicate the general magnitude of nutrient contribution from the atmosphere and permit comparison with other sources.

Nutrients supplied by summer precipitation to the 12,821 hectare watershed above Detroit Lake each year were:

	Phosphorus		Nitrogen	
	Metric Tons	Percent of Total in Discharge*	Metric Tons	Percent of Total in Discharge*
1973	2.78	43	53.82	1,987
1974	1.39	39	26.83	741
1975	2.88	29	15.30	398

*Detroit Lake outlet, Station N

Quantity of P dropped on the watershed in summer precipitation was a fraction of that discharged by Detroit Lake each year, but nitrogen falling in rain always markedly exceeded the load leaving this lake. The fate of atmospheric N and P on and in the soil of this watershed is unknown. Any that penetrates to the phreatic zone would be included to some extent in runoff.

LAKE CONDITIONS

Lake St. Clair

This small shallow lake (Figure 13) is entirely bordered by cattails which expand to form a marsh covering peat to the north. The stabilization pond discharge traverses this marsh enroute to Lake St. Clair. This lake is also fed by County Ditch #14, which enters from the north and exits to the east, and the surface outlet from Long Lake. The water level has generally remained very close to 406.7 m (1,334 feet) above mean sea level, and at this elevation, volume is 73.7 hm (598 af), surface area 57 ha (141 acres), mean depth 1.3 m (4.25 feet), and maximum depth 2.29 m (7.5 feet).

Bottom Materials--

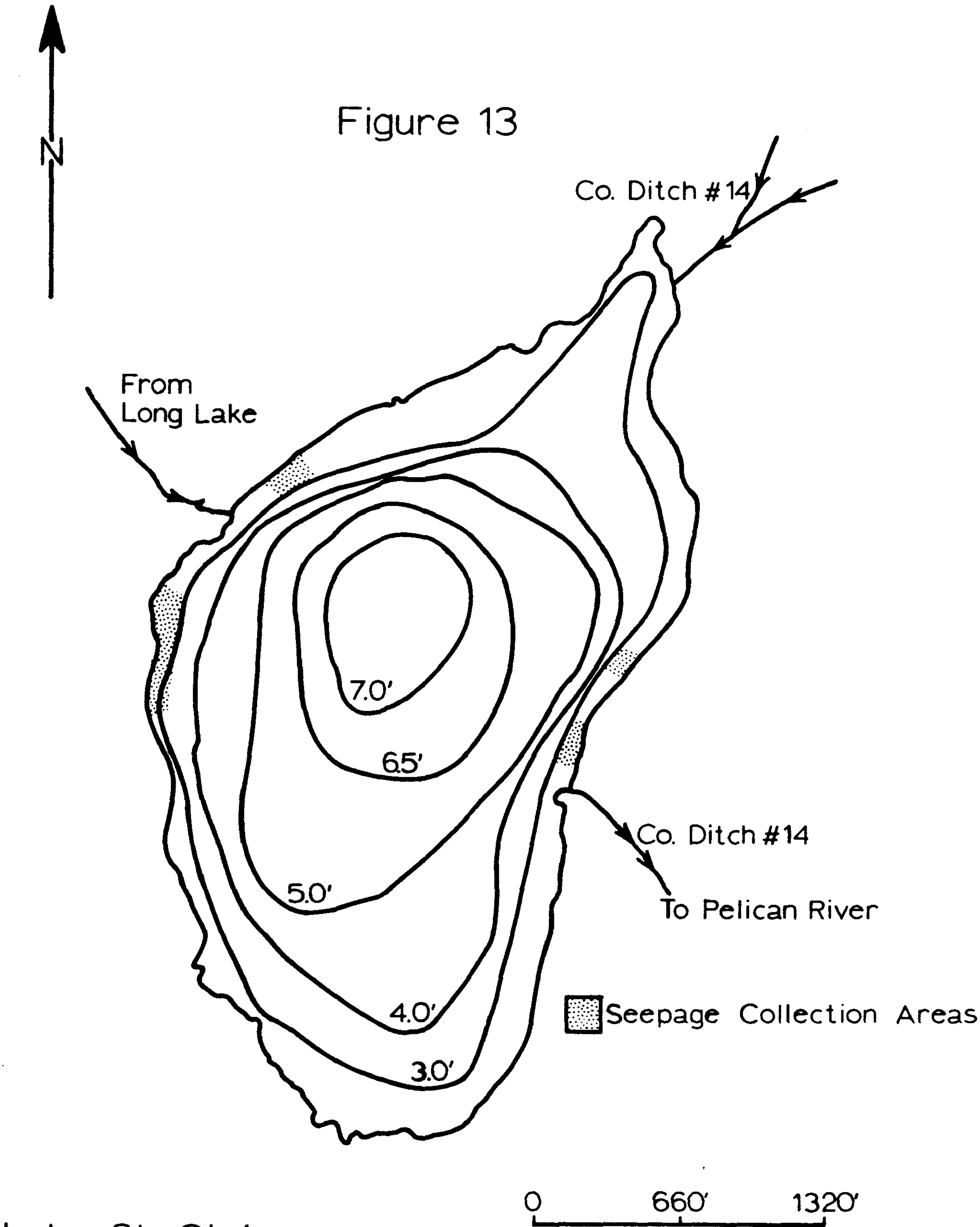
In situ, the bottom appeared to be covered with a homogeneous dark, oozy organic layer which proved to contain varying quantities of marl. Dried samples from near shore were dark and crumbly with finely divided plant remnants, snail shells, and sand; but those from near center had the appearance of gray cement, and their reduction to particle size required grinding in a mortar. Marl lost to acidification formed 80 - 85% of central lake bottom deposits but never more than 30% of those near shore.

Nutrient content--Samples (1974) collected near shore contained no detectable inorganic phosphorus, but those from near lake center had 0.0038 - 0.0225% phosphorus in this form. Total phosphorus, largely organic, comprised 0.185% of littoral sediments and 0.065 - 0.225% of those under deeper water. Percentage nitrogen was 0.137 - 0.265 for littoral regions and 0.418 - 1.139 for the more highly calcified sediments from the central region. Total phosphorus sediment load was 9.80 and total nitrogen was 35.6 metric tons for the 57 ha (141 acres) lake, but only 189 kg of inorganic P (SRP) was present in bottom materials.

Water Chemistry--

Routine analyses of Lake St. Clair water were from its outlet and are discussed in other report sections (Station F). Mention shall be made here of oxygen and pH relationships that appear to accompany algal nitrogen fixation. Figure 14 shows pH and oxygen levels at Station F over much of 1975 and oxygen near the lake center from June to August. In March, under ice cover, both pH and O_2 were low, reflecting effects of respiration-decomposition in the absence of photosynthesis. With the disappearance of ice cover in April, O_2 rose to 180% saturation and pH to 8.9, indicating intensive photosynthesis which produced O_2 and increased pH by converting HCO_3 to CO_3. In late May and June, another pH rise was not accompanied by an equivalent one in O_2 at Station F, although O_2 increase seemed more in line with pH rise at the lake center. In late June and early July, O_2 decline to winter saturation levels at Station F did not pull pH down to 8.0, and concentration at lake center was above 100% saturation. From late July to mid-August, pH level was consistent with that of O_2 near the lake center, but O_2 at the lake outlet was noticeably below what would be expected from the indicated photosynthetic effect on pH. In late August, O_2 rose to nearer 100% saturation as pH declined and, thereafter, with 1 exception, followed pH trends. On July 16 and 24, O_2 at the lake center ran contrary to pH.

Figure 13



Lake St. Clair
8/24/66
Minnesota
Department of Conservation

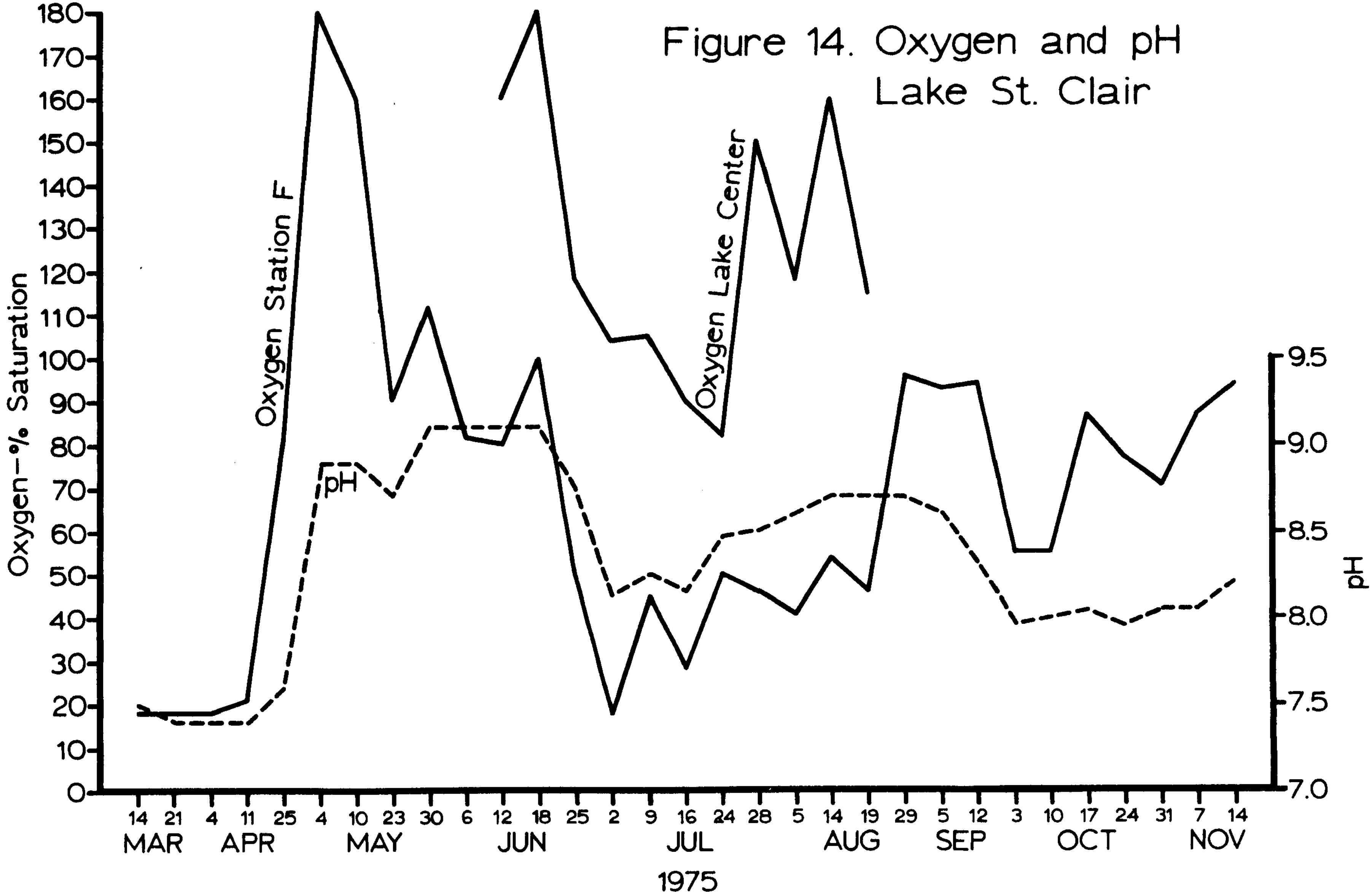


Figure 14. Oxygen and pH Lake St. Clair

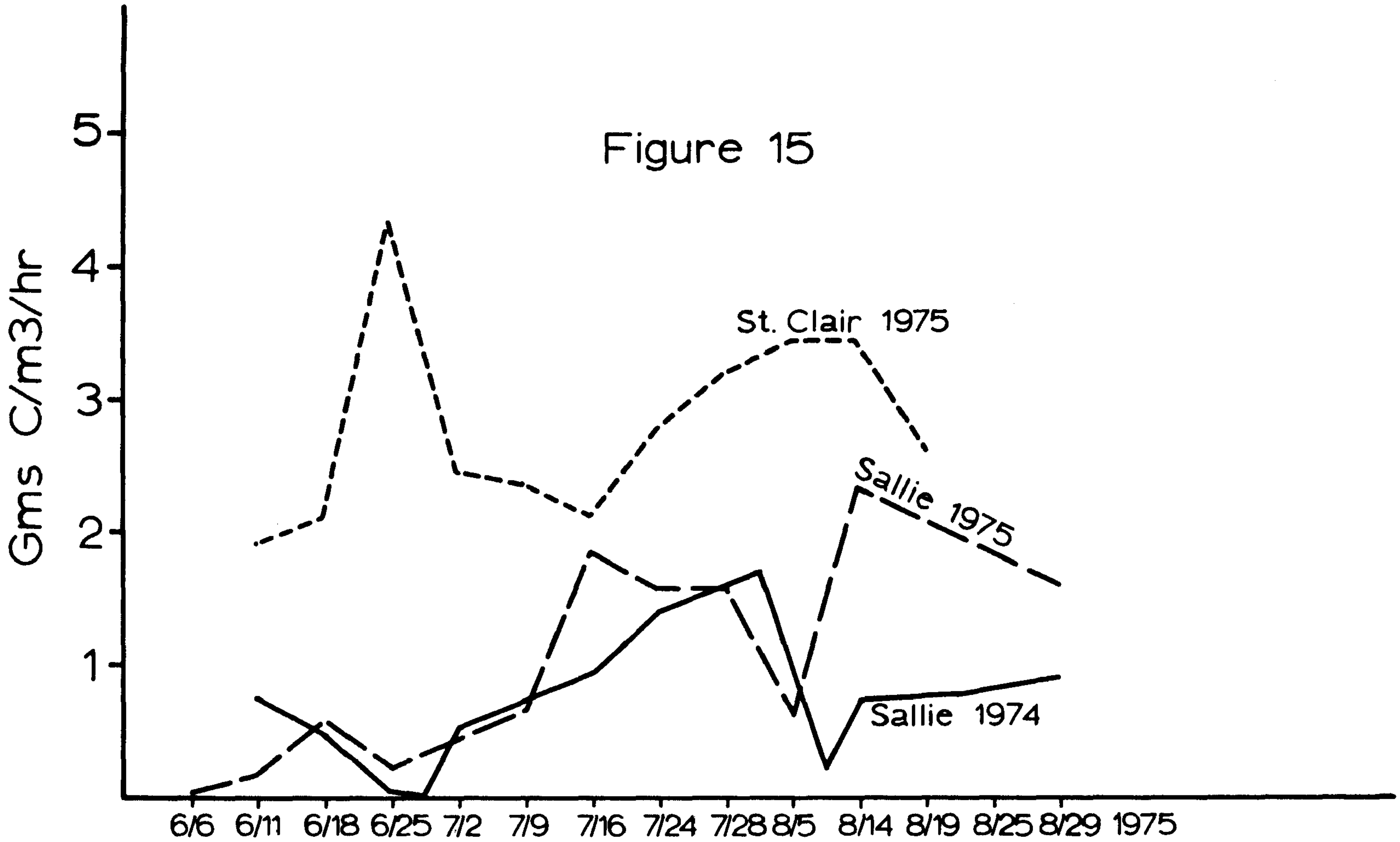


Figure 15

Mean C Fixed Per Hour - 8:30AM - 2:30PM CDT
Phytoplankton

Since pH normally reflects the relative intensity of photosynthesis and respiration-decomposition, rising with O_2 as the former gains ascendancy and falling with O_2 as dominance swings toward the latter, decline in O_2 that is unaccompanied by an equivalent one in pH indicates oxygen consumption without or with much reduced CO_2 production. Since this anomalous pH-O_2 relationship has been observed over a number of years only when the autotrophic population has been dominated or nearly dominated by blue-green algae (usually heterocystous forms), it has been assumed that O_2 loss without equivalent pH suppression reflects O_2 consumption in nitrogen fixation. Plankton samples collected at weekly intervals at Station F over the period May 30 - November 14, 1975, showed dominance by heterocystous blue-green algae (Aphanizomenon and Anabaena, individually or together) from May 30 through August 14; a slight dominance by green algae (Closterium and Chlorococcum) August 19, with Aphanizomenon still abundant; regained dominance by blue-greens from August 29 - September 12; and dominance by greens and diatoms thereafter except for Aphanizomenon on October 17. These plankton studies will be dealt with in detail in a forthcoming M.S. thesis and are mentioned here only to verify involvement of blue-green algae in aberrant pH-O_2 relationships. If this type of relationship truly reflects O_2 loss to nitrogen fixation (and there seems no other process to account for it), Lake St. Clair was subject to considerable nitrogen fixation, which over the years may play a large role in nitrogen accumulation in bottom sediments. Since routine analyses did not include procedures for organic nitrogen in water samples, St. Clair N contributions to County Ditch #14 cannot be estimated.

Primary Production--

This measurement, conducted only for phytoplankton in 1975, indicated a quite productive situation (Figure 15). Light and dark bottles were suspended within the 7.0' contour (Figure 13) where O_2 levels, at least at 2-hour intervals, were generally more in accord with pH than at Station F. Nitrogen fixation may have exaggerated O_2 loss to respiration and obscured its gain in net computations. These 2 sources of error may be compensating, but that appears speculative at this time.

Macrophytes and their attached algae have produced the largest quantities of photosynthate in this lake, but their primary production has not been measured. Navigation through the dense weed growth has been possible only with a light canoe.

Lake Sallie

Morphometric data for this lake appearing in the 1973 report (1) contained erroneous measurements that apparently stemmed from planimetering an off-scale photocopy. Corrected measurements, which also appear in the watershed descriptive section of this report, are as follows:

Area	503 hectares (1,242 acres)
Volume	2,552 hectare meters (20,689 acre feet)
Maximum depth	17 meters (55 feet)
Mean depth	5 meters (17 feet)

A contour map of Lake Sallie is presented here as Figure 16. For other

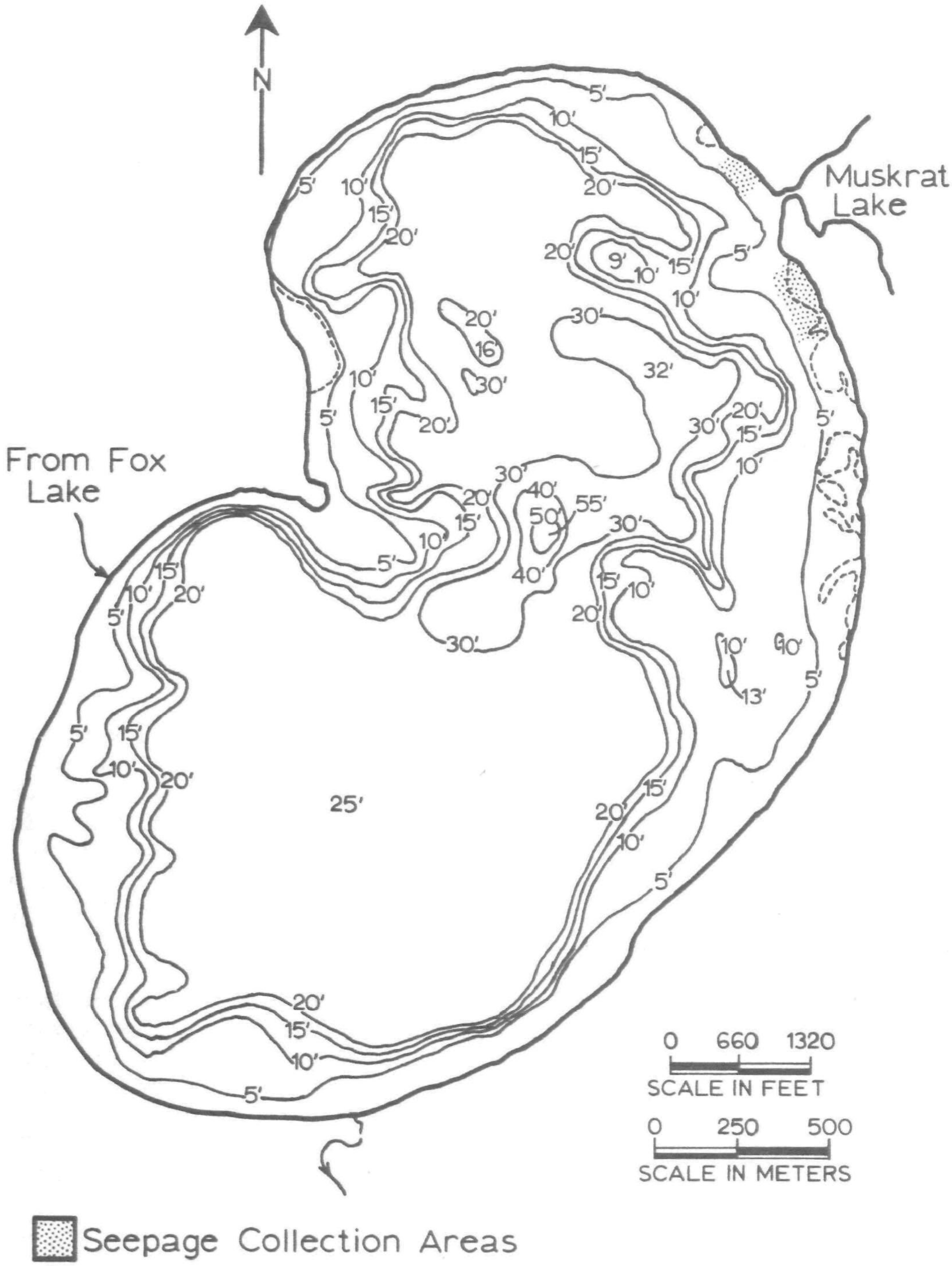


Figure 16. Hydrographic Map of Lake Sallie, Minnesota

morphometric and geological details, the reader is referred to the 1973 report (1).

Thermal Stratification--

Volumes corresponding to plotted contour intervals, and rounded off to the nearest volume unit, were as follows:

Depth Interval		Volume	
Meters	Feet	Hectare Meters	Acre Feet
0.00 - 1.52	0 - 5	701	5,683
1.52 - 3.04	5 - 10	563	4,564
3.04 - 4.56	10 - 15	461	3,739
4.56 - 6.08	15 - 20	409	3,317
6.08 - 9.12	20 - 30	371	3,010
9.12 - 12.16	30 - 40	41	331
12.16 - 15.20	40 - 50	5	41
15.20+	50+	1	8

Thermocline development was usually intermittent. It persisted for longer periods in 1973, beginning in June, than in 1974 or 1975, but even then was removed by wind action 3 times before disappearing for good in September. In 1974 a thermocline was present 14 days and in 1975 8 days, beginning in early July each year. It was usually characteristic for thermoclines to form at or above mid-depth and then move deeper prior to disappearing. This may be illustrated by changing volume of hypolimnion shown in Table 20. In 1973, August and September thermoclines were each of very few days' duration.

Hypolimnions seldom amounted to noteworthy percentages of lake volume. Reference to the depth-volume table above will indicate approximate depth of the hypolimnion on each listed date. In early June, 1973, its upper surface fell from 5 to 11 meters and from late June to mid-July from 4 to 7 meters.

Winter stagnation occurred each year in the usual fashion. Full circulation usually began with the end of ice cover in April and endured until June or July.

Bottom Materials--

The bottom of Lake Sallie is composed of sand overlaid with varying quantities of organic materials and marl. In deeper areas (Figure 17) sand comprises 25% or less of superficial sediments (upper 15 cm) whereas along the lake margins it makes up 75%.

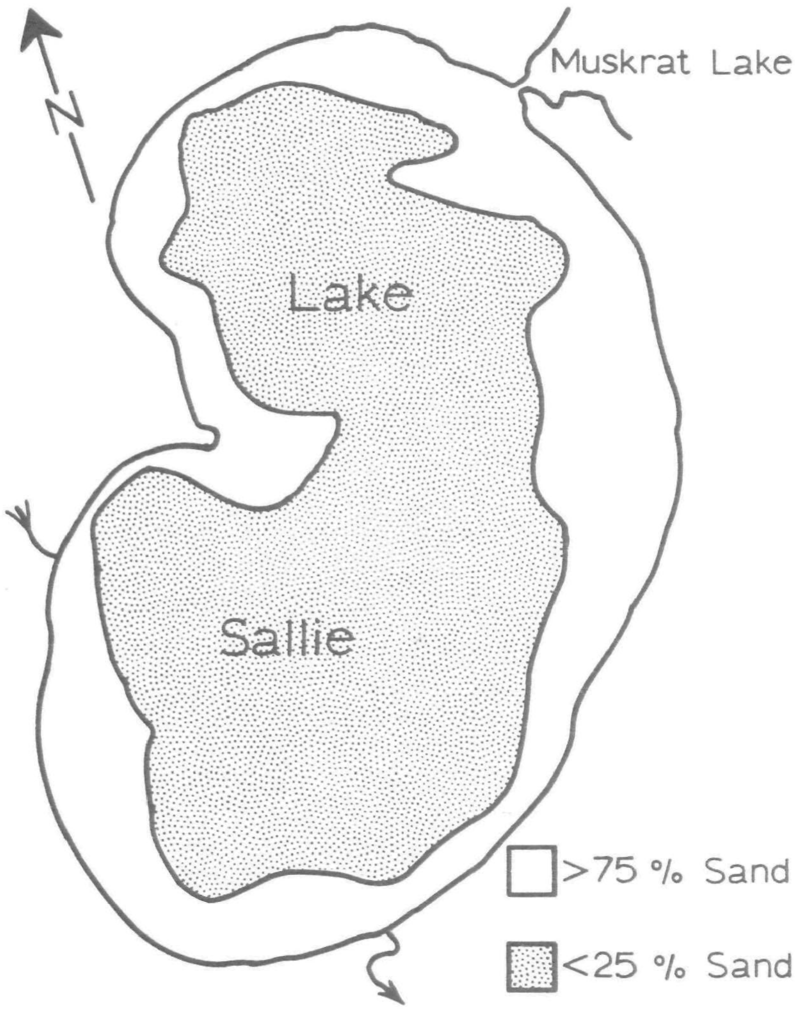


Figure 17. Bottom Sediments in Lake Sallie

Nutrient Loads--In 1974 sediment samples represented the upper 15 cm (6") and 4 depth zones. Details and nutrient loads were:

Depth Zone					Metric Tons		
m	Feet	ha	Acres	Mean Weight per $0.093\ m^2$ ($1\ ft^2$)	N	Total P	SRP
0-3.04	0-10	181	447	2.49 kg	111	30	6
3.04-6.1	10-20	68	169	1.39 kg	69	6	1
6.1-9.14	20-30	225	556	0.94 kg	77	14	3
9.14-12.2	30-40	26	63	-	-	-	-
12.2-15.2	40-50	2	5	-	-	-	-
15.2+	50+	1	2	0.69 kg	0.02	0.037	0.007
Totals		503	1,242	-	257	50	10

In terms of quantity per hectare, Lake Sallie had 82% of the N and 58% of the total P sediment loads of Lake St. Clair; however, its inorganic P (SRP) was 6 times as great.

Specific gravity of bottom sediments declined with depth as organic matter and marl became more prominent constituents. Concentration of soluble reactive phosphorus (SRP) was greatest where sediment density was lowest and organic debris highest and lowest in areas of intermediate density where marl was most common. Total P was most concentrated in regions with largest marl deposits and less abundant near shore and in deepest lake regions. This makes it appear that calcium, or processes related to its deposit, reduce phosphorus availability and that CO_2 production enhances it. Percent total N, total P, and SRP in sediments of each of the 4 lake regions was:

Depth Zone	Percent Total N	Percent Total P	Percent SRP	Predominant Bottom Constituent
0.00-3.04 m	0.23	0.026	0.015	Sand
3.04-6.10 m	0.068	0.08	0.012	Marl
6.10-9.14 m	1.15	0.08	0.011	Marl
15.20+ m	0.904	0.033	0.053	Organic debris

Nitrogen appeared to accumulate more in deeper lake sediments and did not seem influenced by marl.

Weed growth--Weed growth declined in 1971 following initial harvest in 1970 (1) and again in 1972 following 1971 harvest. In 1973 and 1974, the weed harvester recovered such small quantities that it was operated only for a few days each year, but in 1975 higher water level permitted it to operate in lake areas it had previously been unable to enter, and a sizable quantity of weeds was removed. During all 4 years attempts were made to relate weeds removed to the areas shown in Figure 18. This was successfully done for the first 3 harvest years; but in 1975, Areas 2 and 3, 5 and 6, and 7, 8 and 9 were harvested together. This was dictated largely by economic factors, and the groupings used confined operations to a definite lake region in each case. Quantities removed from each area each year in kilograms were:

Area	1970	1971	1972	1975
1	97,853	6,578	2,645	2,080
2	138,119	1,928	1,418	15,837
3	105,351	31,477	24,523	
4	5,770	1,850	0	2,702
5	19,856	54,711	12,191	19,700
6	47,430	14,520	18,711	
7	673	0	0	420
8	3,336	0	0	
9	9,616	0	0	
Total	428,004	111,064	59,488	40,739

Since a large part of the area harvested in 1975 was too shallow to be reached by the harvester in preceding years, the full effects of suppression by previous harvests are masked.

The most productive area (Area 2) in 1970 exhibited a sharp decline in 1971 and 1972 and probably fared no better in 1975. The more productive areas of 1971 and 1972 retained this status in 1975, and Areas 4, 7, 8, and 9 produced weeds in 1975 after being barren for 1 or 2 of the previous harvest years. Kilograms of phosphorus removed in weeds showed a steady decline over the 6-year period, despite the fact that new areas were included in the 1975 harvest. Mean total phosphorus concentration varied from 0.25 - 0.39% of dry weed weight and mean total N concentration from 0.27 - 0.29%. Values for N appearing in the 1973 report (1) have not been repeated; and, in view of the reproducibility of later analyses, now appear too high. Kilograms of P and N

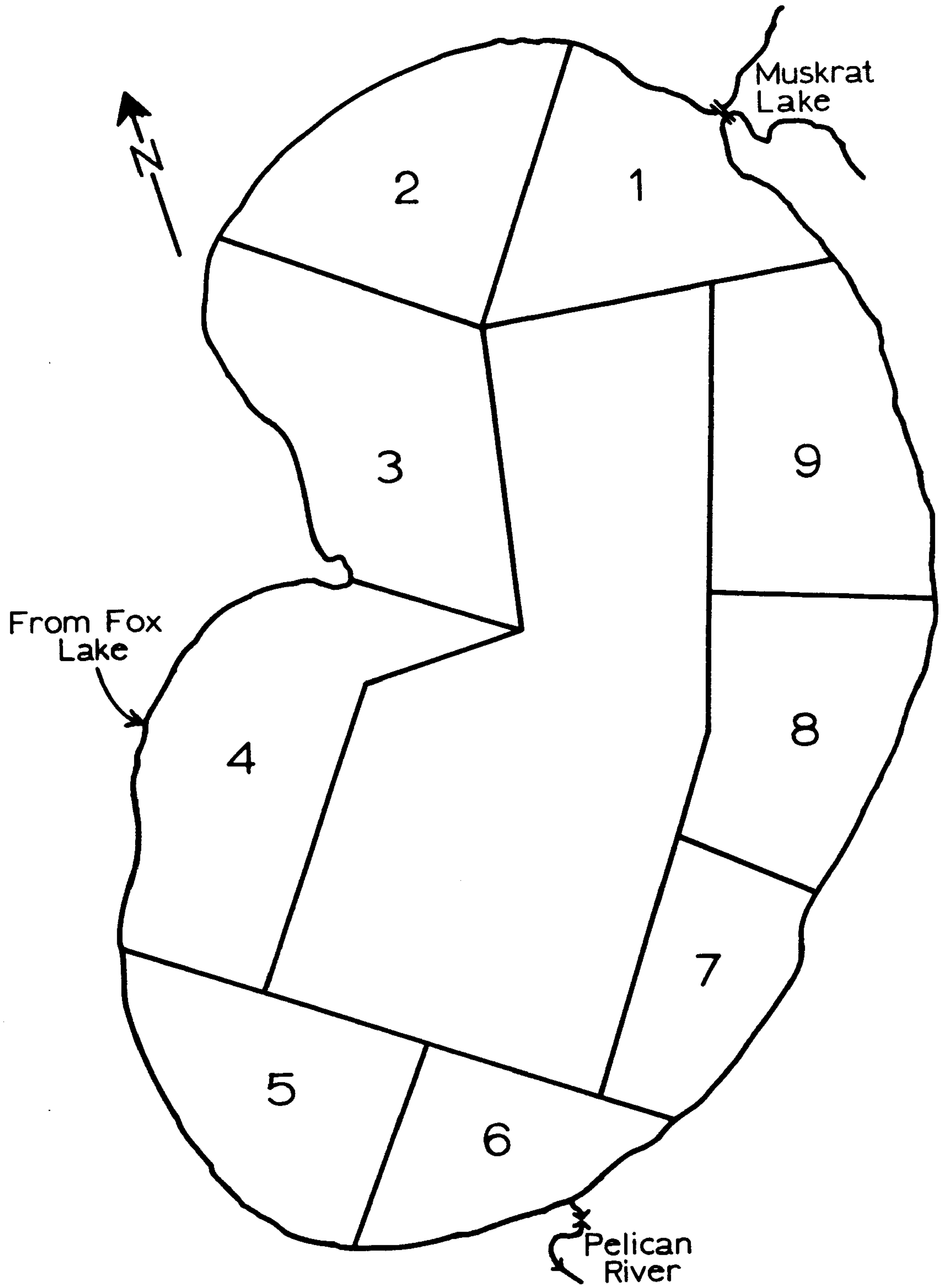


Figure 18. Weed Harvest Areas in Lake Sallie

removed with each year's harvest were:

	P	N
1970	100	-
1971	26	-
1972	17	11.56
1975	10	8.50

As previously indicated (1), weed harvest offers no promise as a nutrient reducer, but it does appear to exercise long-term control over weed growth.

Continued weed removal was associated with some qualitative changes in the macrophyte population. Potamogeton crispus L., which occurred only as isolated individuals in 1969-71, grew densely in pure stands over large bottom areas in 1972 and later. Vallisneria and Ruppia were conspicuous during early harvest years, but the former became quite rare in 1972 and the latter in 1975. In 1972 and 1975, harvester hauls were dominated by Ceratophyllum, Myriophyllum, and Potamogeton pectinatus, and relative abundance of these 3 varied in different areas.

Water Chemistry--

pH--As mentioned previously (1), surface water in the limnetic zone has been characterized by a high pH over most of the year. This has been largely attributed to a high summer photosynthetic level and the low volume of decomposition zones in Lake Sallie, but photosynthesis under ice has also been noted. In February, 1973, pH and oxygen both indicated the occurrence of photosynthesis in the upper limnetic zone (Figure 19). This was not suggested by data for the next 2 winters when pH was noticeably lower (Figures 20 and 21). Weekly records may often fail to show peak conditions, and it appears that in the past photosynthesis was not awarded due credit for higher pH levels under ice.

Oxygen--Very low or 0.0 oxygen values have been noted only in deep waters of the limnetic zone during summer and winter stagnation periods. In 1973, 0.0 concentration occurred in the hypolimnion in July and August, but the winter minimum observed was 0.25 mg/l in early March. In 1974, 0.0 was noted in July and 0.25 mg/l in late March, but in 1975 there were no 0.0 values recorded, and the winter minimum was 1.21 mg/l.

Association of generally high pH with some low oxygen records in summer of 1974 and 1975 indicate the occurrence of algal nitrogen fixation in the limnetic zone and lake outlet (Figures 20 and 21), with the discrepancy more marked in 1975. It is believed that sampling at hourly intervals would be much more diagnostic of this phenomenon.

Intra-lake nitrogen, phosphorus, hardness, and alkalinity relationships were similar to those given in 1973 (1) and will not be detailed here.

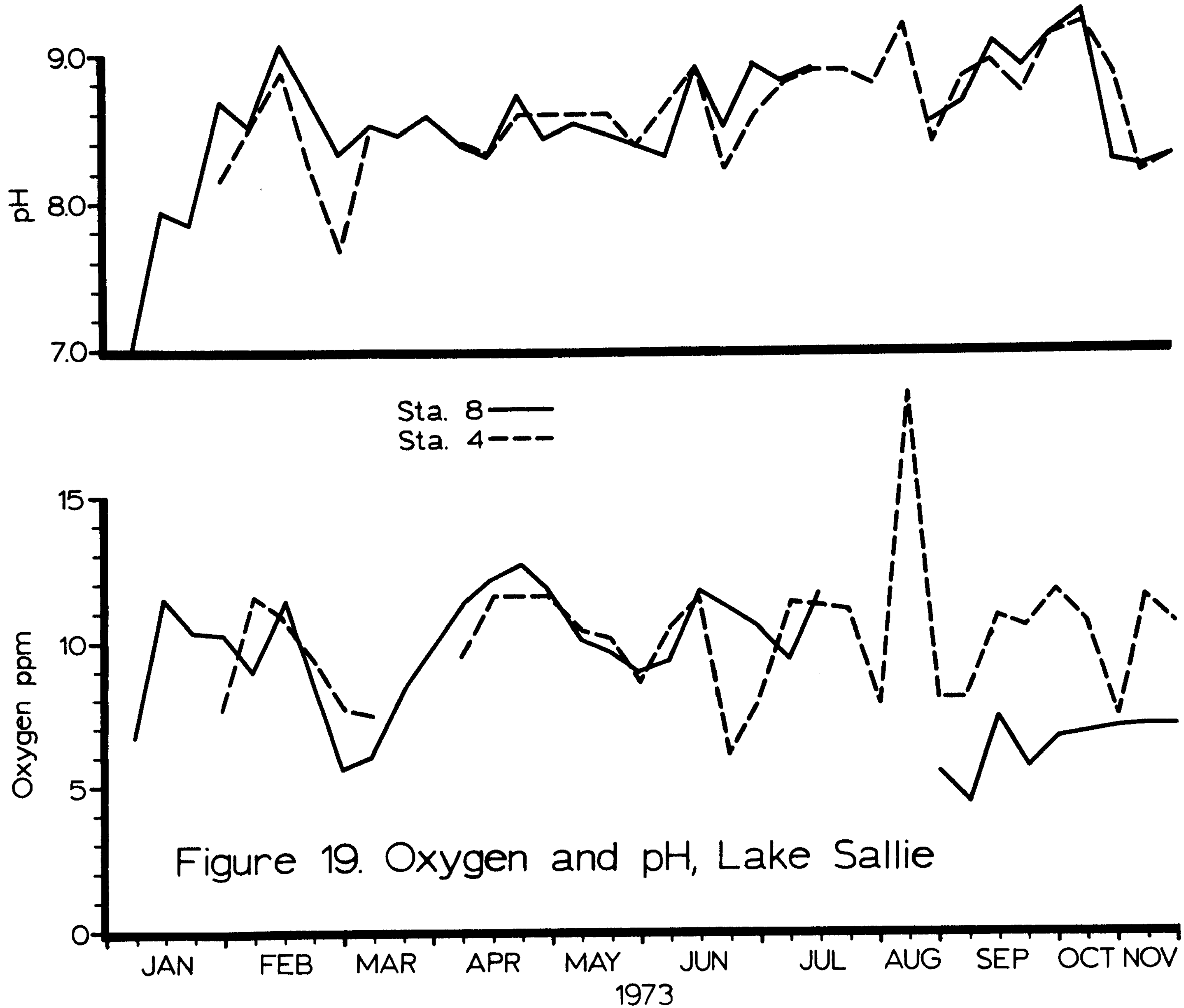


Figure 19. Oxygen and pH, Lake Sallie

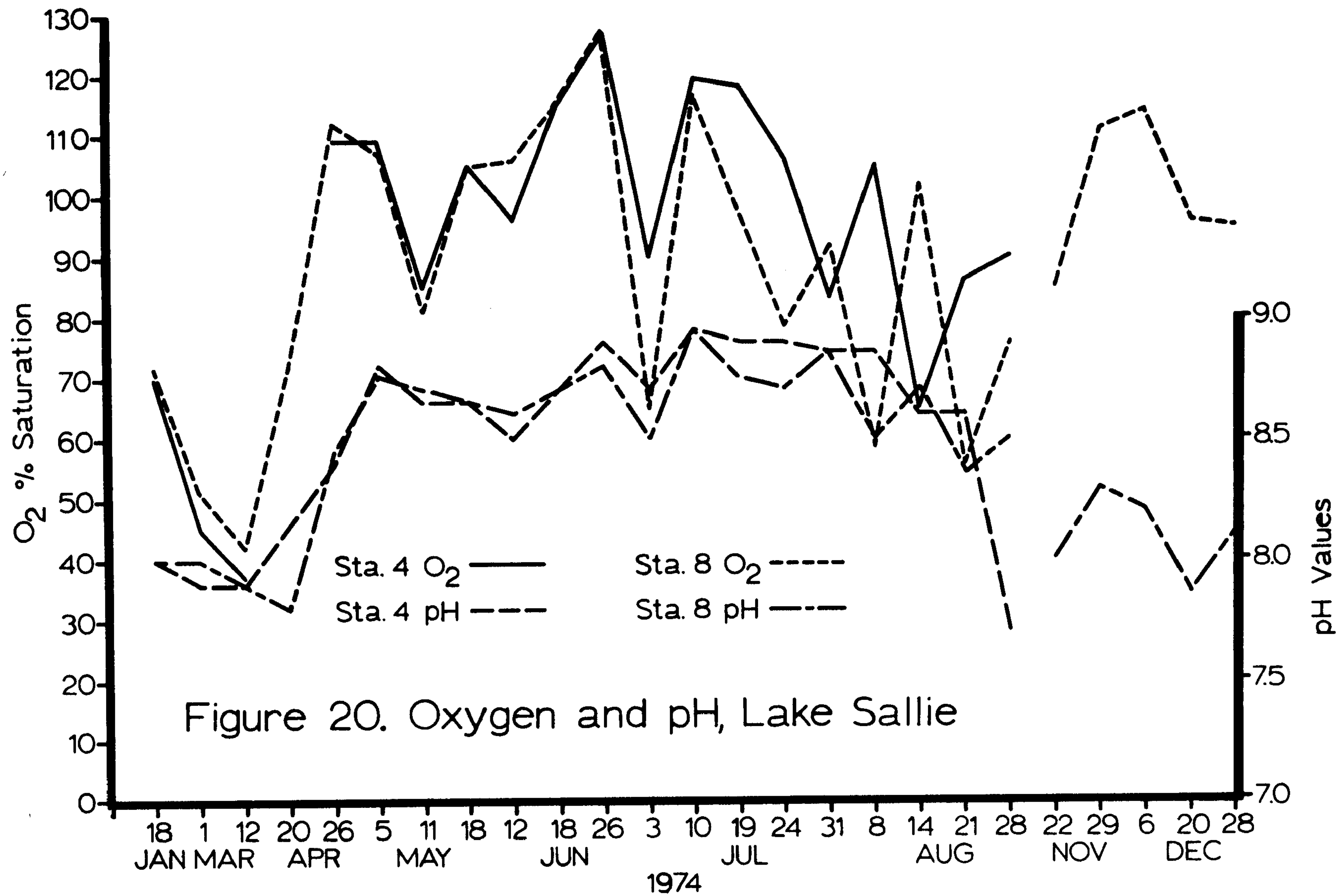


Figure 20. Oxygen and pH, Lake Sallie

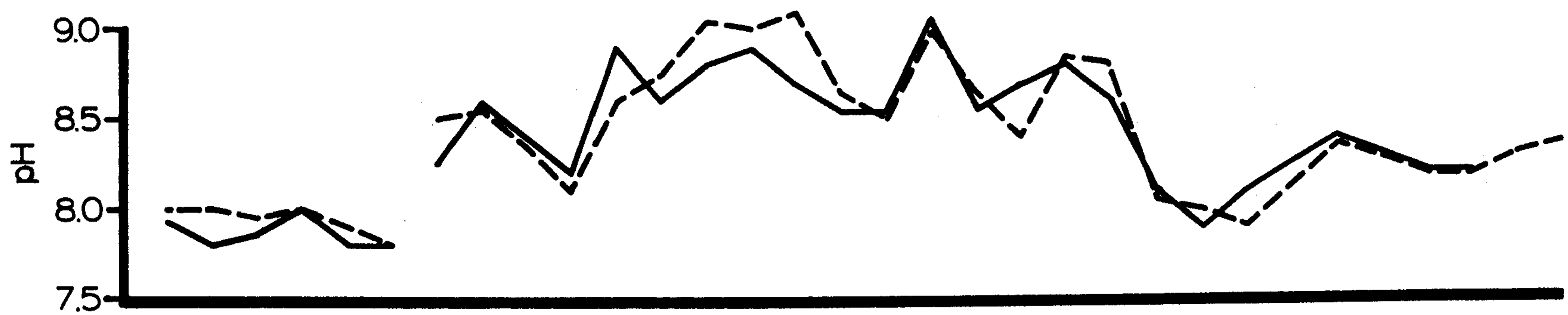
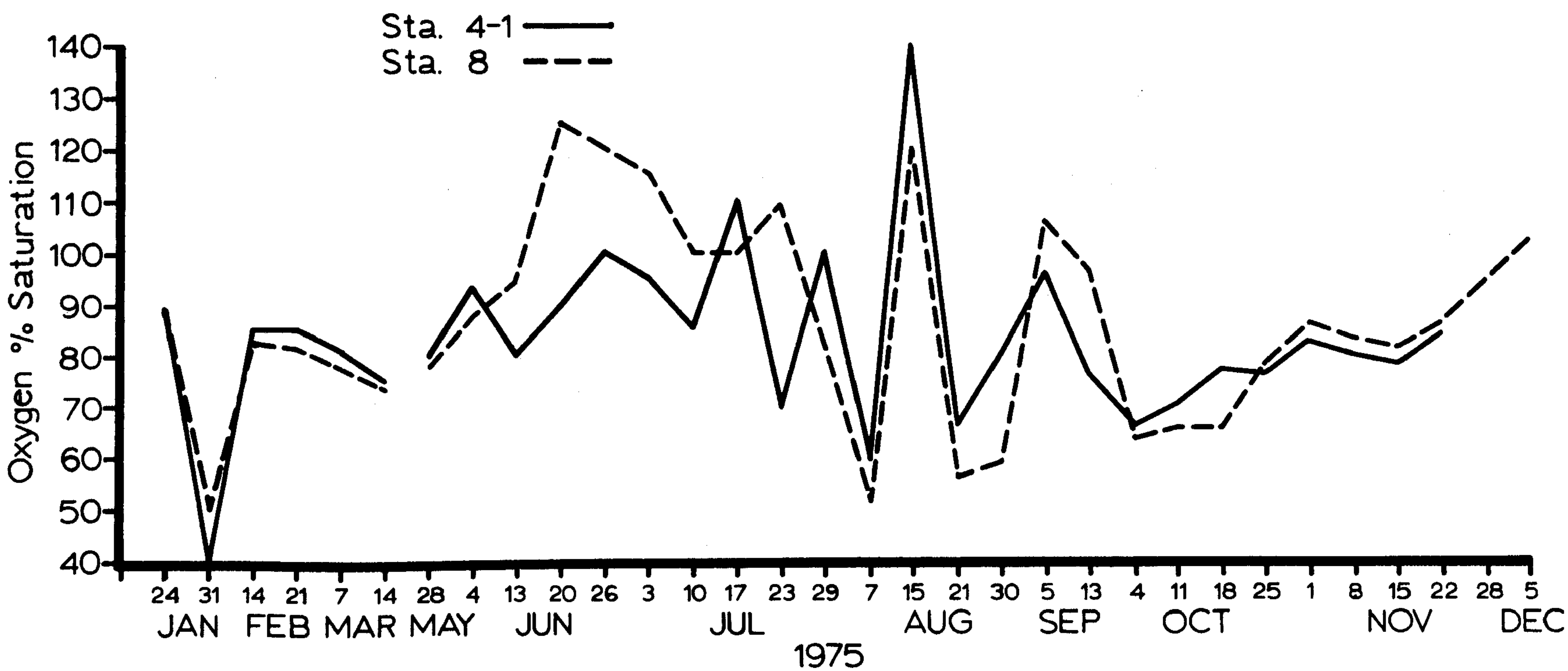


Figure 21. Oxygen and pH, Lake Sallie



Primary Production--

Lake Sallie had a lower rate of carbon fixation by phytoplankton than Lake St. Clair and generally had a higher rate in 1975 than in 1974 (Figure 15). Greater carbon fixation in July and August of 1975 may have resulted from lowered competition provided by removal of weeds and attached algae in June and July. Measured rates indicate a quite productive phytoplankton situation each year.

WATERSHED PHYTOPLANKTON

Quantitative aspects of individual phytoplankton analyses covering the period May 30 - November 21, 1975, appear in Table 21. Station 4-1 is surface water near the center of Lake Sallie.

In order of declining production the stations may be ranked A, F, 4-1, 8, B, P, N, and M. Productivity of the aeration pond (A) was as would be expected from its nutrient content, and its greater average depth; but phytoplankton in the stabilization pond (B) failed to closely approach its nutrient potential until November when high concentrations coincided with high density in A. Study of Table 21 will suggest that B's long period of low productivity did not result from growth in A, and this appears true since plankton in B was suppressed by an extensive and luxuriant growth of duckweed (Lemna minor and L. trisulca) which was invaded in some areas by an alga (Rhizoclonium sp.) in late August. Density of this surface cover was great enough to form a firm walking surface for shore birds and smaller waterfowl. About 85% of the total surface area was occupied, and interference with light penetration was very great.

Lake St. Clair (F) did not live up to the phytoplankton potential inherent in its nutrient loading, but there plankton had to compete with a very dense weed growth. Very dense and extensive growths of weeds, Chara, and other attached algae present in Detroit Lake were considered to be its primary autotrophic populations.

Phytoplankton productivity in Muskrat Lake, measured at Station 1, also seemed to be overshadowed by dense growths of rooted and attached vegetation, and its plankton increase above that of inflowing water (at P) speaks for its basic high productivity. Phytoplankton in Lake Sallie, although at times achieving rather respectable numbers as compared to the aeration pond (A), had to contend with light occlusion by dense surface drifts of blue-green algae that persisted for weeks. Competition from attached vegetation was reduced by weed harvest over the period June 28 - July 29, 1975, which included areas previously too shallow for operation of the harvester. The wind-accumulated blue-green algae produced nuisance conditions, but they also lowered photosynthate production.

Phytoplankton has varied qualitatively with location and season, In 1975 dominance in the aerated pond alternated between green and non-heterocystous blue-green algae (Chroococcus) over the year; the stabilization pond plankton was dominated by green algae and diatoms except on 2 dates when blue-greens were predominant; Lake St. Clair, with 1 exception, had heterocystous blue-green algae greatly outnumbering all other groups; the Pelican River above Detroit Lake (Station M) had diatoms predominant in all samples; in Detroit Lake dominance varied among diatoms, green algae, and Chrysophyceae, except on 3 dates when Chroococcus gained slight numerical superiority; in Muskrat Lake diatoms and greens were most numerous until June when heterocystous blue-greens assumed and retained dominance until October 4, except for a brief period in August when they were briefly replaced by diatoms, and diatoms and greens came to the fore again from October - December; and Lake Sallie was dominated by heterocystous blue-greens from early July until December, with greens and diatoms predominant from January - June. The 2 Floyd Lakes were dominated by heterocystous blue-green phytoplankton in 8 weeks spread over July, August and October.

TROPHIC STATE INDEX

A criterion that will reliably indicate lake productivity level or trophic state is being sought. Articles on the subject tend to either offer a number of choices (12) or to be limited to the activity of a single biotic segment (13). Productivity is regulated by nutrient supply, but conditions in a water body may forestall attainment of productivity inherent in available nutrients. A workable trophic state index (TSI) would need to reflect total autotrophic activity realized over a given time period, which would entail encompassing the activities of all 3 autotrophic populations, plankton, macrophytes, and periphyton, or as many as are present.

Development

For more than 20 years this author has noted a reversal of normal background Mg/Ca quotients in highly productive standing water bodies. This was especially noticeable in raw sewage lagoons or stabilization ponds where a sewage Mg/Ca quotient of 0.40 → 0.50 would change to 2.00 or more in the very actively photosynthesizing pond liquor. The increased ratio in the ponds came about through reduction of calcium, which precipitated as $CaCO_3$ when much or all bicarbonate was converted to normal carbonate by phytoplankton. Magnesium carbonate, being much more soluble, left solution to a much lesser extent; magnesium concentration of sewage generally showed little change in ponds. Calcium and magnesium (hardness) were considered not particularly relevant to objectives of stabilization pond experiments and were measured only occasionally, despite their relationship to photosynthetic accomplishment. The Mg/Ca quotient was kept in mind, however, and later used as an indication of productivity level in comparison of 2 or more lakes.

Work on the Detroit Lakes area eutrophication project, after expansion from Lake Sallie, has shown that the Mg/Ca ratio may be used to develop a TSI that so far has reflected productivity conditions in the lakes and ponds involved. This index was developed as follows.

The stabilization pond, Lake St. Clair, Lake Sallie, and Detroit Lake all had higher mean Mg/Ca quotients in their outflows than in their major inflows, regardless of events in the preceding water body(ies). Figures 22, 23, 24 and 25 show that higher Mg/Ca values characterized outflows from these water bodies at all times in the case of Detroit Lake and practically all the time in the other 3. The stabilization pond, Lake St. Clair, and Lake Sallie all received inflow from situations that frequently or generally supported intense photosynthesis, yet they continued to reduce calcium and increase the Mg/Ca quotient.

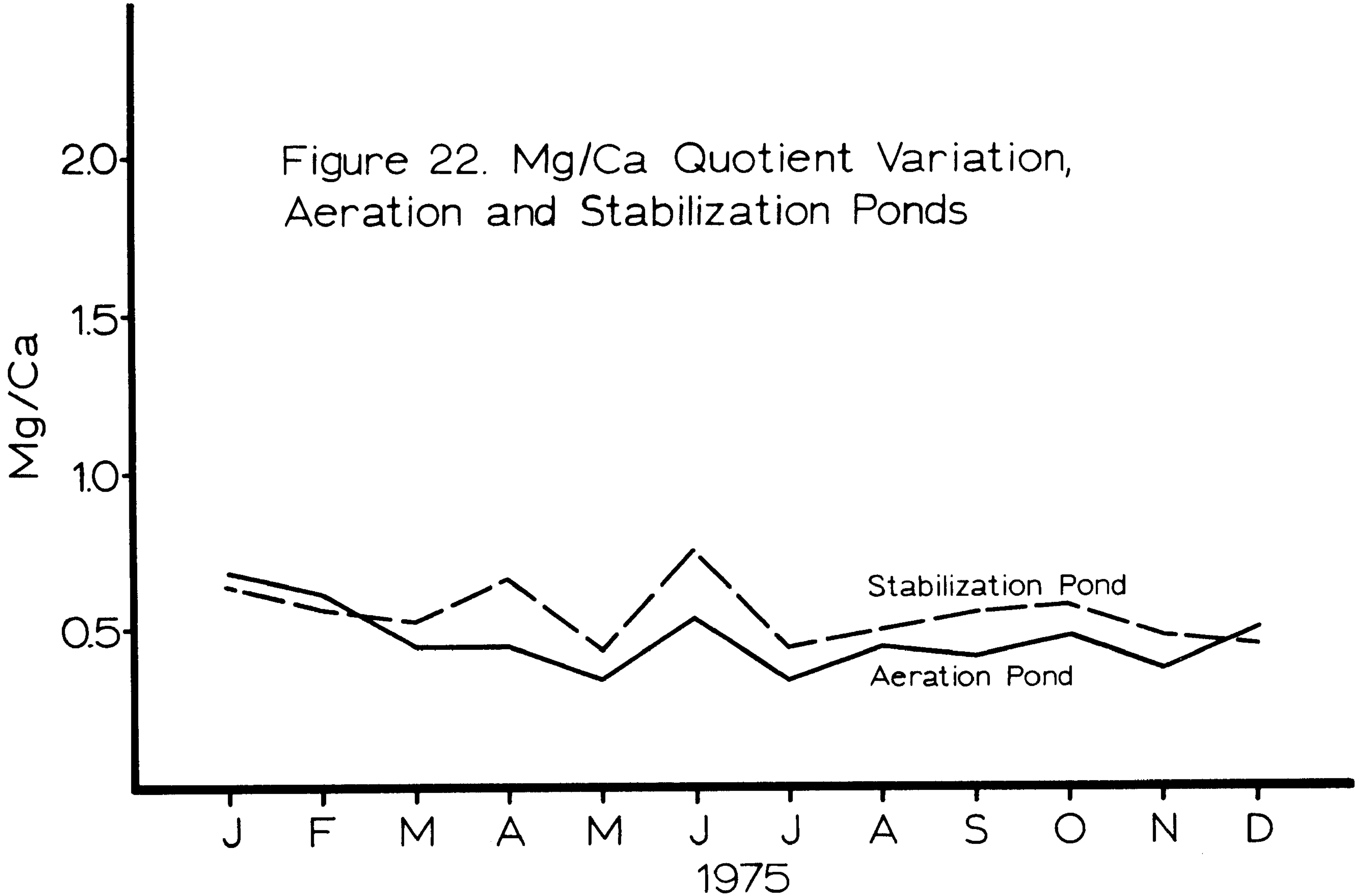


Figure 22. Mg/Ca Quotient Variation, Aeration and Stabilization Ponds

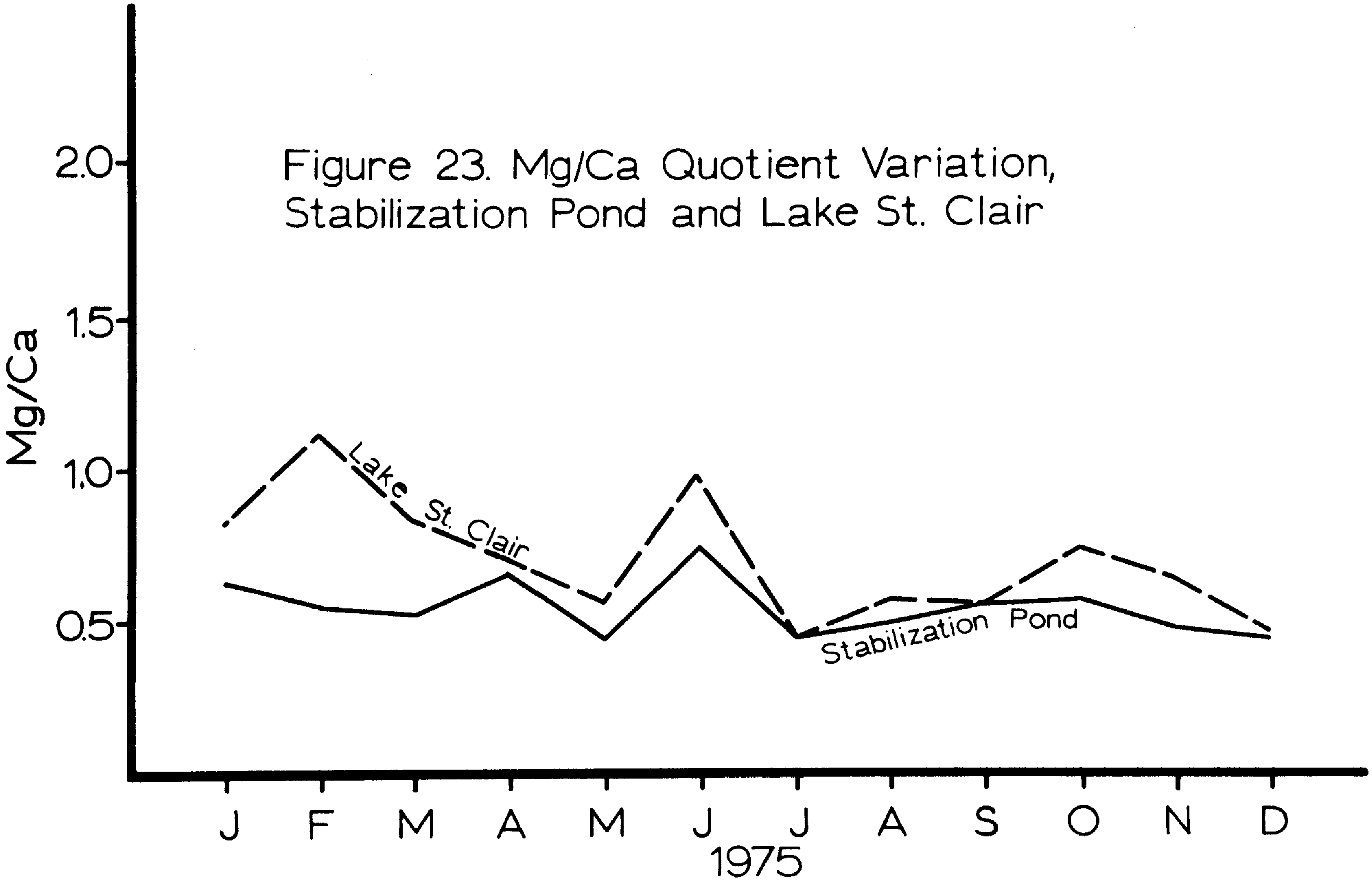


Figure 23. Mg/Ca Quotient Variation, Stabilization Pond and Lake St. Clair

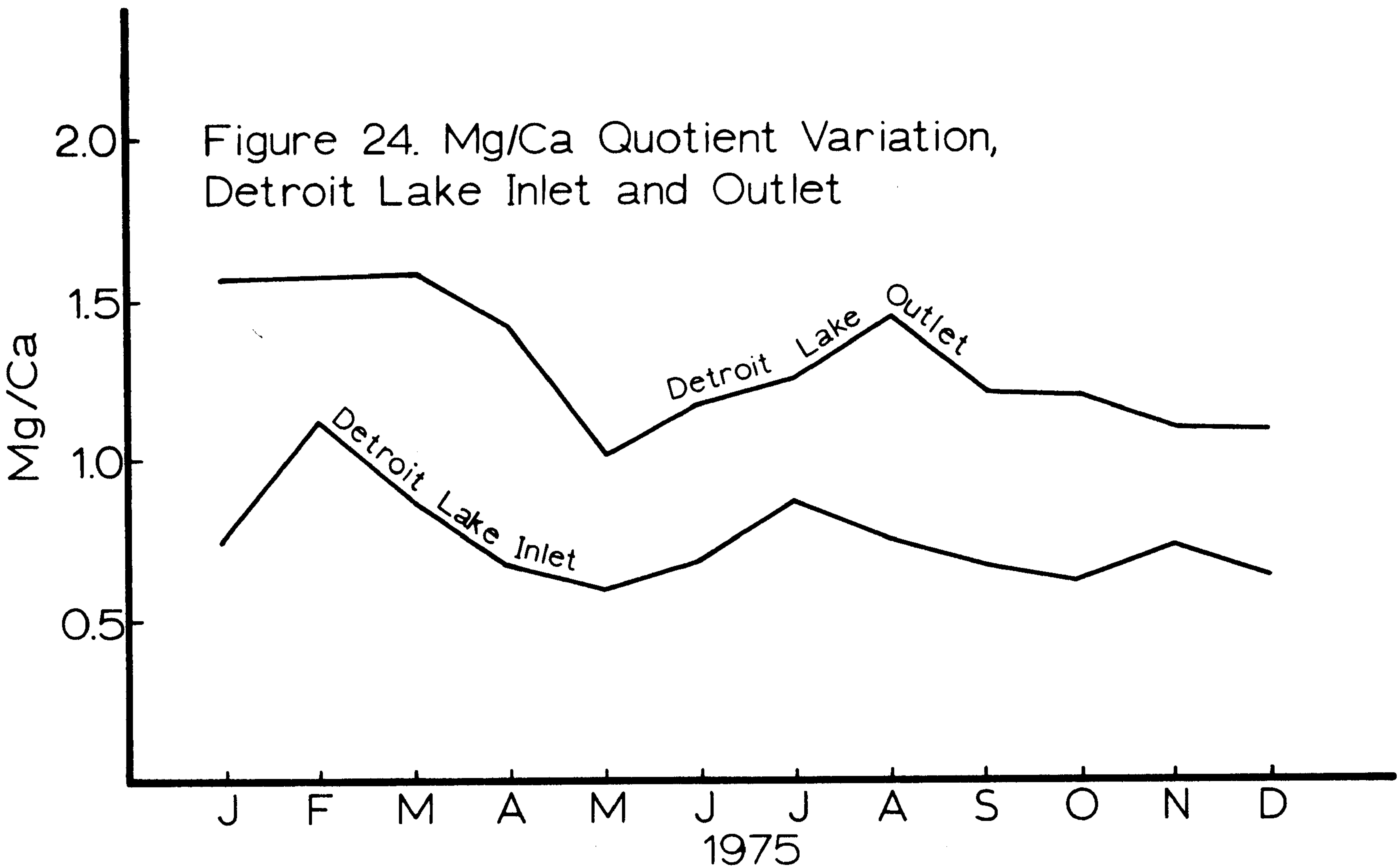


Figure 24. Mg/Ca Quotient Variation, Detroit Lake Inlet and Outlet

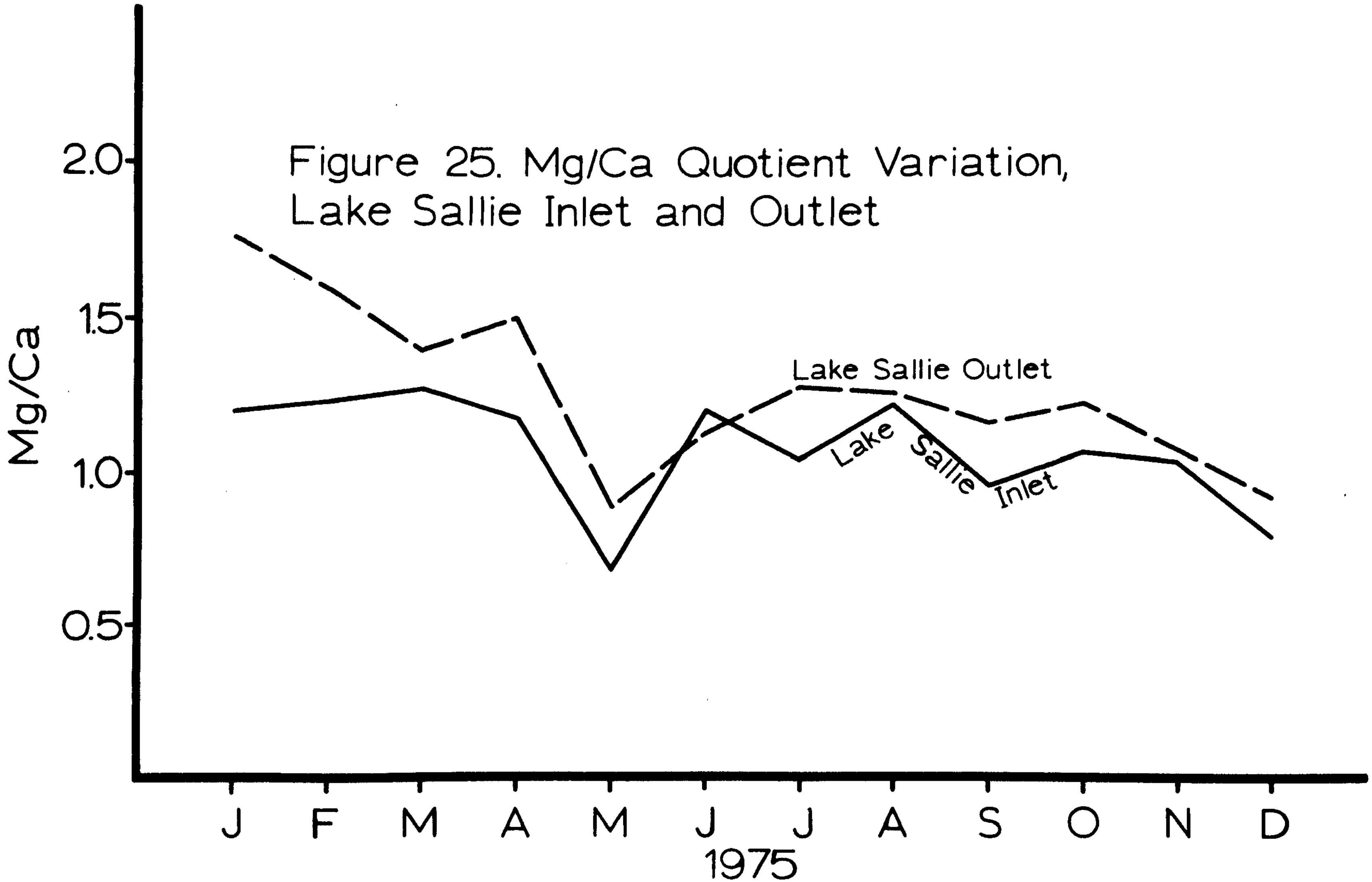


Figure 25. Mg/Ca Quotient Variation, Lake Sallie Inlet and Outlet

Increase of the Mg/Ca quotient thus appeared to reflect level of photosynthate formation during residence and this led to application of the following formula:

$$\frac{O - I}{R} = TSI$$

In which: O = Mean Mg/Ca quotient in outflow
I = Mean Mg/Ca quotient in inflow
R = Residence or detention time in years

Experience with these lakes suggests that means desirably should be based on 12 consecutive months' data, to include all annual events such as stratification, full circulation, ice cover, etc. Our data show variation from week to week to be the general pattern, and it appears that sampling every 2 weeks would be near the minimum frequency for best results. Delay in annual funding caused a gap of 2 months in 1974 data (September - October), but records acquired that year indicated similar Mg/Ca relationships to those acquired at weekly intervals in 1975. Routine collection of Ca and Mg data began in June, 1974, and continued through August, 1976; but since discharge data are available only through June, 1975, the period June, 1974 - June, 1975, is alone considered in computation of TSI's. Detention time in each lake is based upon volume of outflow.

Values for the stabilization pond (Station B) were:

O	0.54
I	0.48
R	0.09 years

Thus: $$\frac{0.54 - 0.48}{0.09} = 0.67$$

TSI's for the 4 bodies were:

Stabilization pond	0.67
Lake St. Clair	2.90
Detroit Lake	0.27
Lake Sallie	0.27

When TSI's were computed from the means of chemical records for the 18 month period, June, 1974 - December, 1975, and average water residence times over the period January, 1973 - June, 1975, the following values were obtained:

Stabilization pond	2.67
Lake St. Clair	2.80

Detroit Lake	0.35
Lake Sallie	0.27

Relationship to Nutrient Loading and Local Conditions

TSI values appearing above were not consistent with nutrient loading as shown below, but they were indicative of relative amounts of photosynthate produced in each lake. From its nutrient loading, the stabilization pond would be expected to be much more productive than Lake St. Clair, but during most of the growing seasons of 1974 and 1975 up to 85% of its surface was densely covered with duckweed which restricted light supply to underlying water and largely limited photosynthate production to neuston over most of the growing season. Plant growth was also deterred by frequent water level changes in 1975. Duckweed in Lake St. Clair was minimal along margins and had no noticeable effect on macrophyte and plankton growth.

Nutrient Loading, kg/ha/day

	Stabilization Pond		Lake St. Clair		Detroit Lake		Lake Sallie	
	P	N	P	N	P	N	P	N
1973	3.54	5.77	0.50	0.36	0.016	0.008	0.069	0.042
1974	1.81	3.90	0.34	0.54	0.012	0.012	0.062	0.069
1975	6.74	5.81	0.58	0.56	0.045	0.026	0.104	0.117

Detroit Lake, with lower nutrient loadings, had a higher TSI than Lake Sallie, but during 1974 and 1975 Lake Sallie exhibited dense accumulations of drifted blue-green algae that blocked light penetration through extensive areas of water surface and was also subjected to weed harvest that removed considerable quantities of attached vegetation by the middle of the 1975 growing season. So far, Detroit Lake has not produced blue-green phytoplankton in any noticeable quantity but, as previously mentioned, has produced dense growths of rooted and attached plants.

The earth fill dam which forms the 26-hectare (65-acre) impoundment known as Muskrat Lake is penetrated by seepage that was measured in upper Lake Sallie and which has often produced wet surface soil on land areas below the dam. Measurement of Ca and Mg was rather spotty at the Muskrat Lake inlet (Station P) in 1974 but was routine with other stations in 1975. Nutrient loadings (kg/ha/day) were:

	P	N
1973	1.49	1.24
1974	1.21	1.32
1975	1.01	0.91

Mean detention time was 0.016 years, and the Muskrat Lake TSI for 1975 based on this figure was 1.875. Most growth was by macrophytes and attached vegetation. Mean phytoplankton density was about 33% of that in Lake Sallie.

Since this method of indicating productivity level embraces all autotrophic elements, plankton, periphyton, and macrophytes, it is hardly justifiable to check its validity against the development and/or activity of a single autotrophic population, e.g., phytoplankton. However, in the 2 lakes subjected to detailed study (Sallie and St. Clair) primary production by phytoplankton was considerably more intense with the higher TSI (Figure 15).

Relation to Varying Hardness

May the Mg/Ca quotient system be applied to lakes with greater Mg and Ca with like results? In the Pelican River watershed annual mean hardness has ranged from 204 to 302 mg/l. In 1972 mean annual hardness in Main Bay of the recently rewatered Devils Lake chain in North Dakota was 1,045 mg/l. With a calculated water residence time of 6.3 years its TSI was 0.55, which appears reasonable when its TSI and biota are weighed against those in the Pelican River lakes. Its phytoplankton was quite dense (mean concentration 30,000 cells/ml) and its weed growth was comparable to 1974-75 populations in Detroit Lake, in which mean phytoplankton density in 1975 was 395 cells/ml. Over the years Main Bay has produced great quantities of fish food (15).

Another question is: Does the Mg/Ca based TSI hold true when noncarbonate compounds of Mg and Ca (noncarbonate hardness) greatly exceed Ca and Mg carbonates? The answer appears to be yes. In Lake Sallie in 1975 noncarbonate hardness exceeded carbonate hardness by only 16 mg/l, but in Main Bay of Devils Lake in 1972 noncarbonate was 557 mg/l greater than carbonate hardness. Within these ranges, at least, use of the Mg/Ca ratio seems to discount such differences.

General Considerations

It has been pointed out elsewhere in this report that about a year is required for groundwater to appear in surface streams and lakes in this study area. In 1973-74 mean Mg concentration in PC well sites, omitting No. 27, was 114 mg/l, and in 1975 its mean concentration in the Lake Sallie outlet was 115 mg/l; whereas mean calcium was 214 mg/l in 1974 for the wells and 91 mg/l in the Lake Sallie outlet. This illustrates removal of Ca and lack of change in Mg. Since evaporation exceeds precipitation by about 25 cm (10 in.) per year, it is assumed that groundwater values represent general inflow into lakes.

The stabilization pond, Lake St. Clair, and Muskrat Lake are 3 highly trophic situations with nutrient loadings that are probably rarely if ever duplicated in larger water bodies. Their very high TSI's are considered beyond the range of natural or the great majority of culturally enriched lakes; and, while TSI's in their range would indubitably indicate water bodies with severe eutrophication, problem lakes are produced with TSI's of a much lower level. Data recorded here suggest that troublesome or potentially troublesome quantities of photosynthate are being produced when the TSI approaches 0.25, but the limited number of lakes represented dictates that caution be exercised at this time in assigning critical thresholds. TSI's based on Mg/Ca quotients show a broad positive relationship to nutrient loading in these water bodies, e.g., those with a P loading of 0.47 - 4.03 kg/ha/day have considerably higher TSI's than those within the 0.024 - 0.078 kg/ha/day range. However, there was variation within each of these ranges that suggests influences of conditions in individual water bodies.

Data on these waters indicate that lake conditions are overshadowed by loading differences approaching an order of magnitude, but Working Paper No. 474, compiled by the U.S. Environmental Protection Agency, November, 1975 (16), suggests that loading is much less influential. P loadings reported for 168 lakes and reservoirs placed in 4 trophic level categories were as follows:

Category	No. Lakes	Loading Range gms $P/m^2/yr$
Hypereutrophic	8	0.19 - 261.49
Eutrophic	128	0.06 - 817.68
Mesotrophic	21	0.04 - 1.34
Oligotrophic	11	0.03 - 0.51

Several lakes included in the EPA report lacked loading data. Minimum P loading noted for the Pelican River lakes, 0.024 kg/ha/day, is equivalent to 0.876 $gms/m^2/yr$. Since the 4 trophic categories used by the EPA tend to reflect opinion more than a calculable relationship, loading may be more influential than their data indicate.

An impression gained from the Pelican River data is that other elements may become more limiting than N and P to photosynthesis. When wastewater effluent is involved, these elements are usually more abundant with N and P, and their influences may erroneously suggest positive effects of N and P with increases above their influential range. Muskrat Lake's having a higher P loading and a lower TSI than Lake St. Clair lends support to this impression, as inflow into Muskrat Lake has a much lower percentage of the wastewater effluent, despite its higher P loading, much of which has come from Detroit Lake.

No attempt is being made at this time to assign TSI values or ranges to denote historical trophic state designations, e.g., eutrophic, mesotrophic, etc. This may not be desirable, since, if the TSI considered here proves generally applicable, a single number will suffice to show productivity level. Regardless of its general applicability, this TSI is expected to be very valuable in assessing productivity changes in these lakes, and it should find similar uses elsewhere. It may not be generally useful to indicate specific state of degradation since this frequently depends upon type as much as quantity of plant life; however, it appears applicable to ascertainment of potential.

Procedural modifications may be required for (1) lakes with large and persistent hypolimnia in which full circulation could restore much photosynthetically precipitated calcium, (2) reservoirs with extended hypolimnion discharges, and (3) lakes lacking surface outlets. In the first instance an acceptable evaluation may possibly be gained by considering only the time interval from the beginning of spring circulation to just before the disappearance of the hypolimnion in autumn. For the second and third situations if residence time can be rather accurately estimated, near surface sampling within the water body may permit detection of changes helpful in determining realistic productivity estimates. Groundwater near Long Lake (Figure 1) at times demonstrated Mg/Ca change indicative of exposure to a photosynthetic environment, but, although this occurrence could show lake discharge to the ground, it is questionable that it could be used as a dependable indication of lake discharge quality. This TSI procedure may also encounter problems in application to soft water lakes.

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APPENDIX

University of North Dakota
MS Thesis

Pattern of Watershed Enrichment and Its Effects on Nutrient Budgets and Weed Growth in a Culturally Eutrophied Lake

Stanley J. Miekicki

Abstract

This study localized major nutrient sources along the Pelican River and evaluated their effect on nutrient budgets in Lake Sallie, Minnesota. Consequences of weed harvest on nutrient removal were also studied. Data included chemistry of water, sediments, and aquatic macrophytes.

Weekly analyses from June 1972 - May, 1973, showed nutrients to be most concentrated at stations below entry of sewage effluent from the city of Detroit Lakes, Minnesota. Nitrogen concentrations were lowest during the growing season with highest levels occuring from December to March. Levels fell in March and April when warm weather returned. Phosphorus levels were also lowest in summer. A steady increase in both ortho- and total phosphorus occurred from December to March. This buildup was also depleted when warm weather and photosynthesis increased.

Sediment samples taken from June - August, 1972, in Lake Sallie showed phosphorus and nitrogen to be most concentrated under deep water.

Over the period July 11 - September 18, 1972, 15 kg of phosphorus and 12 kg of nitrogen were removed in 59,487 kg of weeds harvested in Lake Sallie, quantities far below those removed in 1970 and 1971. Cost per kilogram of nutrients removed was greater than in 1971, and weeds contained less nitrogen than in 1970 or 1971.

Macrophyte growth in harvest areas declined over 1970, 1971, and 1972, and abundance of some individual species changed. Lesser amounts of nitrogen entered the lake in July, 1972, which could have slowed weed growth.

Removal of weeds and fish appears inadequate to reduce nutrients to any meaningful extent in a lake unless more nutrients than enter the lake are so removed. This has not been possible in Lake Sallie, and the major hope for recovery of this lake is curtailment of nutrients it receives via the Pelican River.

University of North Dakota
MS Thesis

Weed Harvest Effects on Algal Nutrients and Primary Production in a Culturally Enriched Lake

David F. Brakke

Abstract

This study evaluated lake chemical and physical conditions and primary production by phytoplankton during and following large-scale aquatic plant removal. Data cover the final year of weed harvest (1972) and the first year following (1973).

Summer stagnation developed, disappeared and reformed each year. The photosynthetically important limit of light penetration moved upward from June to August, 1972, when it was at 2 meters or less. Red light reached greater depths than green in early summer and less thereafter. Incident radiation varied between 20 and 484 langleys/day. Phosphorus levels were higher in 1973; total phosphorus maximum at 9 meters was 2.30 mg/l. Ammonia was depleted in surface water each summer; maximum concentration (3.10 mg/l) was reached at 9 meters under ice. Anoxic conditions developed under stable thermoclines and in deeper water in winter.

Phytoplankton photosynthesis and respiration increased from 1972 to 1973. Both were greatest in August. Maximum gross primary production was 780 mg $C/m^3/hr$. Considerable daily and seasonal variation was found at all depths. Production increase in 1973 was greatest at 0.5 meters. Photosynthetic decline at mid-day was common on clear days; increases were frequent with overcast. Greatest photosynthetic efficiency, $\frac{mgC/m^3/hr}{langleys/hr}$, was in August (maximum, 34.98) when bloom conditions developed and incident radiation declined.

University of North Dakota
MS Thesis

Phytoplankton Variation Over the Upper Pelican River Watershed, Becker County, Minnesota

John W. Stambaugh, Jr.

Abstract

Those parts of the upper Pelican River watershed, Minnesota, that have been affected by wastewater elements have experienced nuisance growths of blue-green algae from time to time. This study considers growth of phytoplankters in lakes and stream reaches of the upper watershed in 1975 and relates their composition and abundance to nitrogen and phosphorus concentrations. Phytoplankton biomass expressed as numbers generally agreed with its volume but did not in computing percent composition of the major algal groups. Diversity, as number of genera, could not be correlated with nutrients of wastewater origin, because it was influenced by many variables.

Nitrogen/phosphorus ratios, calculated for all sample sites, were usually very low, around 1. Correlations claimed for low N/P ratios and growth of heterocystous blue-green algae by Schindler were not substantiated by this study.

University of North Dakota
MS Thesis

Chlorophyll Densities and Plankton Counts As Measurements of Phytoplankton Biomass

William M. West

Abstract

Water bodies in the Pelican River watershed, Minnesota, showed seasonal trends in phytoplankton populations over 1975-76. Lake Sallie was dominated by green algae in late spring, diatoms in early summer, blue-greens from July through early winter, and a mixed diatom and green algae population from late winter through early spring. Blue-greens were poorly represented in samples from sewage aeration and stabilization ponds. Errors associated with plankton counting were found to be about 10%. The pigment extraction method does not permit computation of a percentage error. Comparison of plankton counts and chlorophyll densities indicates that the latter may not be depended upon for accurate biomass estimates on any given date. There are a number of problems in chlorophyll procedures that need be remedied.

TABLE 1. MAGNITUDE FEATURES OF LAKES AND PONDS

	Surface Area		Volume		Maximum Depth		Mean Depth	
	Hectares	Acres	Hectare Meters	Acre Feet	Meters	Feet	Meters	Feet
Floyd Lake	397	980	1,554	12,604	11	36	4	13
Little Floyd Lake	83	206	434	3,520	11	35	5	17
Detroit Lake	1,185	2,928	5,648	45,800	24	80	5	16
Lake St. Clair	57	140	74	598	2	7	1	4
Long Lake	172	426	897	7,277	15	50	5	17
Muskrat Lake	26	65	42	341	5	15	2	5
Lake Sallie	503	1,242	2,552	20,689	17	55	5	17
Aerated pond	1	3	2	20	--	--	2	7
Stabilization pond	10	25	3-8	23-69	--	--	<1	1-3

Values are to nearest whole units.
One hectare meter equals 10,000 m^3 or 1 hectare x 1 m (8.10835 acre feet).

TABLE 2. DISCHARGES AT SELECTED POINTS IN THE UPPER PELICAN RIVER WATERSHED

		A	B	F	N	F + N	1	8
1973	hm	143	100	622	2,514	3,136	2,650	3,155
	af	1,156	810	5,044	20,383	25,427	21,491	25,580
1974	hm	127	89	752	2,544	3,296	3,240	3,446
	af	1,030	723	6,095	20,629	26,724	26,275	27,942
1975	hm	63	44	457	1,450	1,907	2,365	2,552
	af	508	357	3,703	11,755	15,458	19,179	20,691
Totals	hm	333	233	1,831	6,508	8,339	8,255	9,153
	af	2,694	1,890	14,842	52,767	67,609	66,945	74,213

hm = hectare meters
af = acre feet
1975 records January - June only

TABLE 3. INDIVIDUAL WELL FEATURES

Well PC	Bottom Elev.	Mean Water Level Elev.	Mean Depth Water Column: Feet	Mean Depth Water Column: Meters	Length Screen Above Bottom: Feet	Length Screen Above Bottom: Meters	Water Column In:
1	38.74	43.77	5.03	1.53	10	3.04	Brown over gray till
2	24.33	51.22	26.89	8.20	30	9.15	Sand and gravel over sand over sand and gravel
3	34.09	43.57	9.48	2.89	20	6.10	Sand over gravel over brown and gray till
4	37.59	41.19	3.60	1.10	10	3.04	Brown and gray clayey till
5	25.48	42.68	17.20	5.24	20.5	6.25	Gravel over sand and gravel over gray till
6	25.66	42.29	16.63	5.07	20	6.10	Sand and gravel, lower 0.76 m gray till
7	16.69	41.95	25.26	7.70	5	1.52	Sand and gravel, lower 0.3 m gray till
8	38.72	40.30	1.58	0.48	10	3.04	Tan and gray till
9	45.29	49.37	4.08	1.24	10	3.04	Tan and gray till, gray clayey
10	44.11	46.19	2.08	0.63	10	3.04	Sand and gravel over gray till
11	34.34	47.52	13.18	4.02	17.5	5.33	Sand and gravel over gray till
12	47.34	51.15	3.81	1.16	6	1.83	Sand and gravel over silt and brown and gray till
13	51.59	56.15	4.56	1.39	6	1.83	Brown silt over gray till
14	46.21	49.08	2.87	0.88	10	3.04	Sandy silt over brown and gray till
15	38.49	44.91	6.42	1.96	12	3.66	Sand and gravel over gray till
16	31.89	39.52	7.63	2.33	10	3.04	Sand and gravel over gray till
17	29.46	51.50	22.04	6.72	28	8.54	Sand over fine sand over gray till

(continued)

TABLE 3. (continued)

Well PC	Bottom Elev.	Mean Water Level Elev.	Mean Depth Water Column Feet	Mean Depth Water Column Meters	Length Screen Above Bottom Feet	Length Screen Above Bottom Meters	Water Column In:
18	45.47	55.14	9.67	2.95	10	3.04	Sand and gravel over brown silt over gray till
19	50.74	53.46	2.72	0.83	10	3.04	Gray till
20	25.56	52.07	26.51	8.08	30	9.15	Silt over sand and gravel over sand over gravel over gray till
21	19.37	51.39	32.02	9.76	34	10.36	Silt over gravel over sand over sandy gray till
22	32.42	50.97	18.55	5.66	25	7.62	Sandy gravel and silt over gray fine sand over gray till
23	26.59	43.13	16.64	5.04	26	7.93	Sand and gravel over gray till
24	25.68	42.64	16.96	5.17	20	6.10	Dirty sand and gravel over gray till
25	21.70	39.72	18.02	5.49	22	6.70	Dirty sand over sand and gravel over brown and gray till
26	26.39	39.42	13.03	3.97	18	5.49	Sand and gravel over clay with snail shells
27	19.09	34.55	15.46	4.71	20	6.10	Clay mixed with sand, pebbles and snail shells
28	16.67	36.12	19.45	5.93	20	6.10	Sand and gravel over gray clay
29	10.90	36.48	25.58	7.80	27	8.23	Gravel over sand and gravel over clay and silt over gray till
30	28.84	44.19	15.35	4.68	20	6.10	Gravel over cobble and gravel over sand over gray till

(continued)

TABLE 3. (continued)

Well PC	Bottom Elev.	Mean Water Level Elev.	Mean Depth Water Column		Length Screen Above Bottom		Water Column In:
			Feet	Meters	Feet	Meters	
31	41.83	51.81	9.98	3.04	20	6.10	Brown clay over gray till
32	34.94	40.41	5.47	1.67	15	4.57	Sand and gravel over gray till
33	6.66	39.00	32.34	9.86	15	4.57	Clay and shells over gravel over clay and shells over gravel with limestone cobbles over gravel over gray till

TABLE 4. TEMPERATURE AND PRECIPITATION RECORDS, DETROIT LAKES, MINNESOTA, 1973-75

	Mean Air Temperatures						Precipitation					
	1973		1974		1975		1973		1974		1975	
	°C	°F	°C	°F	°C	°F	cm	inches	cm	inches	cm	inches
Jan	-12.25	9.9	-16.60	2.1	-12.90	8.7	0.41	0.16	1.95	0.77	6.55	2.58
Feb	- 9.88	14.2	-11.60	11.1	-12.90	8.7	0.20	0.08	1.07	0.42	3.89	1.53
Mar	1.83	35.3	- 6.10	21.0	- 9.16	15.5	1.70	0.67	3.00	1.18	1.80	0.71
Apr	5.22	41.4	4.90	40.8	0.72	33.3	2.87	1.13	3.17	1.25	4.98	1.96
May	12.04	53.7	10.32	50.6	12.65	54.8	4.95	1.95	11.68	4.60	5.46	2.15
June	18.10	64.6	17.10	62.8	16.76	62.2	12.62	4.97	4.39	1.73	22.61	8.90
July	19.80	67.7	22.14	71.9	21.36	70.5	19.15	7.54	13.56	5.34	6.53	2.57
Aug	22.00	71.7	17.54	63.6	17.76	64.0	9.78	3.85	9.55	3.76	10.97	4.32
Sept	14.26	57.7	11.87	53.4	10.71	51.3	15.79	6.22	1.07	0.42	5.64	2.22
Oct	10.37	50.7	8.30	47.0	8.44	47.2	9.98	3.93	5.03	1.98	3.45	1.36
Nov	- 2.94	26.7	- 1.39	29.5	- 1.22	29.8	3.28	1.29	3.55	1.40	1.63	0.64
Dec	-11.32	11.6	- 7.10	19.2	-10.21	13.6	2.92	1.15	1.24	0.49	0.33	0.13
Year	5.60	42.1	4.10	39.4	3.50	38.3	83.65	32.94	59.28	23.34	73.83	29.07
DN*	+ 1.60	+ 2.9	+ 0.10	+ 0.4	- 0.50	- 0.7	+23.79	+ 9.37	- 1.52	- 0.60	+13.03	+ 5.13

*Departure from normal.

TABLE 5. PELICAN RIVER DISCHARGE NEAR FERGUS FALLS, MINNESOTA, WATER YEARS 1973-75

	1973		1974		1975	
	Hectare Meters	Acre Feet	Hectare Meters	Acre Feet	Hectare Meters	Acre Feet
October	413	3,350	654	5,300	329	2,670
November	359	2,910	741	6,010	350	2,840
December	324	2,630	694	5,630	232	1,880
January	348	2,820	705	5,720	229	1,860
February	344	2,790	665	5,390	286	2,320
March	826	6,700	730	5,920	469	3,800
April	877	7,110	1,220	9,890	1,512	12,260
May	664	5,380	1,880	15,240	2,046	16,590
June	339	2,750	2,051	16,630	1,709	13,860
July	200	1,620	916	7,430	1,813	14,700
August	179	1,450	652	5,290	1,251	10,140
September	388	3,150	408	3,310	1,017	8,250
Total	5,261	42,730	11,316	91,750	11,243	91,170

TABLE 6. MEAN ANNUAL NUTRIENT CONCENTRATIONS, mg/l, WATERSHED STATIONS

	Aer. Pond	Stab. Pond	Long Lake	Lake St. Clair	Sta. G	Sta. H	Campbell Creek	Floyd Lake	Little Floyd Lake	Sta. L	Sta. M	Detroit Lake	Muskrat Lake Inlet	Lake Sallie Inlet	Lake Sallie Outlet
								TOTAL P							
1973	7.53	6.30	0.19	1.78	1.79	1.82	0.30	0.19	0.18	0.28	0.26	0.24	0.59	0.54	0.17
1974	5.12	4.30	0.19	0.98	1.02	0.99	0.20	0.20	0.20	0.31	0.23	0.22	0.38	0.36	0.17
1975	8.62	6.40	0.37	1.30	1.35	1.37	0.85	0.35	0.38	0.45	0.46	0.47	0.66	0.41	0.32
								TOTAL N							
1973	13.87	7.49	0.21	1.29	1.79	1.24	1.00	0.15	0.15	0.26	0.36	0.17	0.61	0.45	0.28
1974	9.89	7.20	0.22	1.68	1.16	1.25	0.27	0.26	0.28	0.24	0.40	0.21	0.68	0.39	0.32
1975	14.27	6.86	0.23	1.15	1.18	1.27	0.81	0.37	0.24	0.31	0.40	0.18	0.47	0.37	0.19

TABLE 7. MEAN MONTHLY CONCENTRATIONS TOTAL P, mg/l

	A	B	E	F	G	H	I	J	K	L	M	N	P	1	8
								1973							
J	7.92	8.58	0.10	1.94	1.86	1.86	0.18	0.09	0.06	0.06	0.11	0.09	0.53	0.54	0.02
F	7.26	9.24	0.07	2.48	2.43	2.29	0.24	0.06	0.11	0.07	0.07	0.12	0.66	0.59	0.04
M	7.92	6.27	0.10	1.98	2.00	1.90	0.37	0.11	0.08	0.13	0.17	0.12	0.70	0.68	0.09
A	8.25	5.00	0.12	0.94	0.97	0.90	0.11	0.13	0.12	0.09	0.12	0.11	0.25	0.29	0.17
M	6.00	2.31	0.22	0.53	0.62	0.65	0.11	0.16	0.10	0.22	0.09	0.13	0.19	0.28	0.09
J	10.23	8.25	0.25	1.71	1.78	1.85	0.33	0.17	0.18	0.21	0.39	0.26	0.96	0.66	0.17
J	*12.00	* 5.28	*0.43	*1.39	*1.45	*1.68	*0.36	*0.29	*0.33	*0.90	*0.50	*0.41	*0.53	0.63	0.17
A	*10.90	* 8.58	*0.20	*2.94	*3.07	*4.09	*0.22	*0.18	*0.18	----	*0.22	*0.29	*0.86	*0.92	*0.25
S	*11.22	* 8.58	*0.28	*3.33	*3.07	*2.54	*0.33	*0.17	*0.17	*0.37	*0.43	*0.34	*0.60	0.75	0.23
O	4.62	4.29	0.16	1.00	1.14	1.02	0.26	0.22	0.20	0.20	*0.32	*0.23	*0.69	*0.39	*0.23
N	* 9.57	* 5.00	*0.16	*2.38	*2.27	*2.16	*0.76	*0.48	*0.46	*0.53	*0.42	*0.56	*0.43	0.43	0.42
D	* 4.62	* 4.29	----	*0.77	*0.84	*0.92	----	----	----	----	----	----	*0.66	*0.27	----
								1974							
J	* 4.36	* 4.29	----	*0.91	----	----	----	----	----	----	----	----	*0.25	*0.25	*0.07
F	* 6.33	* 4.78	----	*0.84	----	----	----	----	----	----	----	----	*0.34	*0.23	*0.10
M	* 5.44	* 5.51	----	*2.64	*2.39	*2.40	----	----	----	----	----	*0.10	*0.37	0.46	0.16
A	* 5.53	* 3.13	----	*1.17	*1.19	*1.22	----	----	----	----	----	*0.16	*0.43	0.43	0.19
M	2.85	1.70	----	0.40	0.40	0.39	----	----	----	----	----	0.15	0.35	0.23	0.16
J	2.96	2.34	0.15	0.40	0.37	0.35	0.16	0.12	0.13	0.14	0.12	0.12	0.18	0.18	0.13
J	3.43	1.94	0.20	0.80	0.91	0.91	0.32	0.21	0.22	0.36	0.27	0.22	0.37	0.36	0.16
A	2.50	1.48	0.15	0.78	0.74	0.74	0.21	0.18	0.16	0.22	0.19	0.20	0.41	0.36	0.20
N	8.78	7.84	0.18	0.84	0.95	0.84	0.11	0.20	0.22	0.20	0.28	0.21	0.49	0.56	0.11
D	9.13	10.07	0.28	0.97	1.26	1.03	0.18	0.42	0.28	0.63	0.32	0.50	0.61	0.48	0.32

(continued)

TABLE 7. (continued)

	A	B	E	F	G	H	I	J	K	L	M	N	P	1	8
								1975							
J	13.46	15.22	0.52	3.03	3.16	3.18	0.48	0.64	0.54	0.53	0.63	0.75	0.62	0.58	0.35
F	13.07	12.39	0.19	2.45	2.54	2.67	0.28	0.17	0.24	0.34	0.31	0.22	0.65	0.63	0.18
M	12.98	15.86	0.32	4.18	3.54	4.65	*3.10	0.75	0.71	0.57	0.56	0.61	0.93	0.86	0.42
A	7.72	6.52	0.44	1.00	0.98	1.61	3.35	0.38	0.83	1.15	1.18	1.33	2.13	0.43	0.16
M	6.86	3.08	0.56	0.43	0.47	0.49	0.34	0.53	0.37	0.44	0.51	0.43	0.29	0.29	0.34
J	8.31	1.99	0.22	0.64	0.73	0.68	0.23	0.21	0.15	0.19	0.22	0.14	0.38	0.28	0.23
J	6.27	2.74	0.33	1.02	1.03	1.15	0.43	0.19	0.20	0.40	0.41	0.31	0.47	0.45	0.32
A	7.10	3.68	0.45	1.30	1.17	0.87	0.39	0.23	0.36	0.40	0.25	0.41	0.57	0.34	0.48
S	6.15	3.80	0.21	0.59	----	----	----	----	----	----	0.18	0.26	0.35	0.28	0.36
O	6.98	4.04	0.31	0.62	0.57	0.52	0.32	0.31	0.33	0.37	0.30	0.39	0.51	0.29	0.43
N	7.25	5.19	0.46	0.34	0.33	0.30	0.22	0.24	0.27	0.23	0.39	0.37	0.43	0.26	0.33
D	* 8.13	* 7.34	*0.42	*0.49	*0.31	*0.31	*0.25	*0.21	*0.19	*0.27	*0.28	*0.25	*0.29	*0.36	*0.27

*One sample only.

TABLE 8. MEAN MONTHLY CONCENTRATIONS TOTAL N, mg/l

	A	B	E	F	G	H	I	J	K	L	M	N	P	1	8
								1973							
J	20.16	21.64	0.28	3.99	4.30	3.44	2.07	0.26	0.22	0.50	0.56	0.30	1.42	1.26	0.65
F	18.34	19.28	0.27	4.51	4.75	4.20	3.97	0.30	0.27	0.52	0.62	0.35	2.04	1.90	0.30
M	15.39	11.18	0.34	3.30	3.45	3.54	2.79	0.28	0.28	0.55	0.85	0.35	1.77	1.48	0.30
A	14.28	5.81	0.22	0.22	0.22	0.26	0.47	0.12	0.13	0.17	0.19	0.08	0.11	0.13	0.14
M	10.94	1.96	0.14	0.18	0.09	0.15	0.29	0.07	0.10	0.14	0.16	0.12	0.12	0.09	0.12
J	11.20	6.04	0.10	1.08	0.70	0.84	0.31	0.06	0.09	0.17	0.55	0.11	0.52	0.17	0.09
J	*13.55	* 1.75	*0.09	*0.07	*0.09	*0.12	*0.26	*0.10	*0.12	*0.21	*0.36	*0.14	*0.14	0.10	0.16
A	*13.01	* 2.40	*0.09	*0.78	*0.81	*1.14	*0.14	*0.09	*0.10	----	*0.14	*0.11	*0.49	*0.01	0.08
S	*14.31	* 5.45	*0.21	*0.76	*0.78	*0.85	*0.31	*0.21	*0.175	*0.06	*0.17	*0.10	*0.38	0.10	0.33
O	11.29	3.59	0.18	0.48	0.14	0.17	0.24	0.07	0.08	0.13	0.17	*0.11	*0.13	*0.04	0.19
N	*10.22	* 3.00	*0.45	*0.10	*0.11	*0.16	*0.20	*0.12	*0.13	*0.12	*0.22	*0.06	*0.11	0.09	0.75
D	*13.85	* 7.85	----	*0.02	*0.015	*0.05	----	----	----	----	----	----	*0.12	*0.03	----
								1974							
J	14.07	14.00	----	2.75	----	----	----	----	----	----	----	----	*3.16	*0.37	*0.54
F	14.85	16.50	----	5.30	----	----	----	----	----	----	----	----	*0.51	*0.81	*0.51
M	15.07	14.50	----	4.44	*4.53	*4.74	----	----	----	----	----	0.17	*0.97	0.84	0.47
A	11.35	6.40	----	2.67	*2.76	*2.87	----	----	----	----	----	0.33	*1.16	0.78	0.37
M	9.63	2.64	----	0.10	0.11	0.11	----	----	----	----	----	0.11	0.11	0.14	0.13
J	3.03	1.90	0.13	0.20	0.34	0.43	0.08	0.09	0.12	0.02	0.04	0.10	0.12	0.15	0.12
J	7.65	1.09	0.10	0.28	0.36	0.56	0.19	0.19	0.18	0.13	0.17	0.13	0.28	0.10	0.08
A	10.58	1.78	0.06	0.06	0.04	0.06	0.14	0.11	0.15	0.13	0.50	0.13	0.07	0.06	0.13
N	8.49	5.70	0.54	0.62	0.70	0.71	0.64	0.67	0.63	0.58	0.80	0.44	0.24	0.33	0.57
D	9.26	7.51	0.29	0.44	0.44	0.51	0.31	0.25	0.31	0.35	0.49	0.25	0.21	0.30	0.29

(continued)

TABLE 8. (continued)

	A	B	E	F	G	H	I	J	K	L	M	N	P	1	8
							1975								
J	16.24	14.06	0.36	2.04	1.81	2.00	1.64	1.33	0.43	0.65	0.76	0.60	0.58	0.47	0.38
F	17.27	14.95	0.61	3.41	3.49	3.68	1.85	0.45	0.35	0.79	0.58	0.28	1.13	1.04	0.35
M	16.04	14.96	0.22	3.50	3.39	3.46	2.00	0.44	0.34	0.46	1.55	0.31	1.11	1.29	0.23
A	13.84	10.85	0.52	1.87	1.94	2.11	2.46	0.55	0.50	0.52	0.53	0.38	0.93	0.89	0.43
M	15.35	3.28	0.22	0.19	0.16	0.18	0.28	0.48	0.24	0.16	0.16	0.13	0.12	0.11	0.15
J	16.09	2.43	0.06	0.42	0.46	0.59	0.17	0.08	0.09	0.10	0.13	0.06	0.24	0.17	0.06
J	12.33	1.91	0.05	0.12	0.18	0.36	0.09	0.13	0.06	0.07	0.10	0.08	0.13	0.08	0.11
A	15.06	2.35	0.05	0.22	0.46	0.65	0.10	0.18	0.07	0.08	0.12	0.07	0.24	0.05	0.25
S	12.19	2.07	0.06	0.87	----	----	----	----	----	----	0.08	0.04	0.32	0.05	0.06
O	11.09	3.04	0.14	0.63	0.59	0.56	0.08	0.21	0.25	0.24	0.18	0.10	0.29	0.16	0.07
N	12.17	4.65	0.15	0.37	0.24	0.23	0.10	0.13	0.15	0.20	0.26	0.07	0.20	0.09	0.12
D	*13.58	* 7.85	*0.13	*0.26	*0.27	*0.21	*0.21	*0.14	*0.16	*0.19	*0.33	*0.07	*0.36	*0.06	*0.12

*One sample only.

TABLE 11. MEAN NUTRIENT CONCENTRATIONS IN INDIVIDUAL WELLS (TOP AND BOTTOM) AND IN GROUNDWATER SUB-AREAS

		July, 1973-August, 1974		November, 1974-August, 1975	
Sub-area	Well No.	Total P	Total N	Total P	Total N
1	2	0.70	5.38	0.32	2.87
	12	0.91	6.15	0.33	10.27
	13	1.25	9.28	0.33	9.72
	17	0.71	6.32	0.26	8.83
	18	0.68	3.86	0.28	1.71
	19	1.17	6.17	0.33	6.29
	20	0.78	5.25	0.34	2.10
	21	1.03	4.71	0.25	1.15
	22	0.95	3.17	0.31	0.21
	31	1.04	5.97	0.34	8.98
	SA1	0.92	5.63	0.31	5.21
2	1	0.82	3.21	0.30	1.37
	9	0.51	3.00	0.55	0.62
	10	0.54	2.72	0.53	3.48
	11	0.64	3.96	0.51	3.55
	14	0.68	3.44	0.66	1.89
	23	0.65	5.22	0.29	6.10
	24	0.61	5.16	0.34	2.98
	SA2	0.64	3.82	0.45	2.86
3	3	0.57	7.31	0.38	4.04
	4	0.62	6.26	0.35	3.47
	5	0.69	6.95	0.29	9.38
	6	0.81	6.19	0.40	4.63
	7	0.66	4.10	0.38	3.44
	8	0.68	1.34	0.28	0.95
	15	0.59	8.87	0.35	9.71
	32	0.89	1.61	0.31	1.64
	SA3	0.69	5.33	0.34	4.66
4	16	1.28	3.31	1.56	3.04
	25	0.64	2.83	0.31	0.81
	26	0.85	2.21	0.45	0.80
	33	1.58	2.74	1.90	3.19
	SA4	1.09	2.77	1.06	1.96
5	28	0.65	1.75	0.35	0.76
	29	0.57	1.78	0.30	2.64
	SA5	0.62	1.77	0.33	1.70
6	27	1.00	1.62	0.41	0.55
7	30	0.57	1.20	0.58	0.69

TABLE 12. MEAN NUTRIENT CONCENTRATIONS AT TOP AND BOTTOM OF GROUNDWATER IN INDIVIDUAL WELLS

	1973-74		1974-75	
Well	Total P	Total N	Total P	Total N
1T	0.82	3.21	0.30	1.37
2T	0.68	5.37	0.33	0.37
2B	0.71	5.88	0.30	5.37
3T	0.53	7.25	0.40	3.10
3B	0.80	7.37	0.36	4.98
4T	0.62	6.26	0.35	3.47
5T	0.67	6.03	0.26	4.17
5B	0.70	7.87	0.32	5.21
6T	0.84	6.29	0.39	4.61
6B	0.77	6.09	0.40	4.65
7T	0.68	2.96	0.36	3.52
7B	0.64	5.23	0.39	3.36
8T	0.68	1.34	0.28	0.95
9T	0.73	2.19	0.55	0.62
9B*	0.39	3.81		
10T	0.54	2.72	0.53	3.48
11T	0.76	5.02	0.56	3.10
11B	0.51	2.90	0.46	3.99
12T	0.91	6.15	0.33	10.27
13T	1.25	9.28	0.33	9.72
14T	0.68	3.44	0.66	1.89
15T	0.55	9.49	0.35	9.41
15B	0.63	8.25	0.35	10.00
16T	1.14	3.19	0.99	2.67
16B	1.41	3.42	2.13	3.40
17T	0.66	6.94	0.25	8.57
17B	0.76	5.70	0.27	9.08
18T	0.58	5.19	0.24	0.81

* 3 records only

(continued)

TABLE 12. (continued)

	1973-74		1974-75	
Well	Total P	Total N	Total P	Total N
18B	0.77	2.53	0.31	2.60
19T	1.17	6.17	0.33	6.29
20T	0.61	7.34	0.33	3.30
20B	0.95	3.16	0.34	0.89
21T	0.89	4.65	0.22	1.14
21B	1.24	4.76	0.27	1.16
22T	0.97	2.22	0.29	0.25
22B	0.92	4.11	0.32	0.16
23T	0.65	5.66	0.29	6.52
23B	0.64	4.77	0.28	5.65
24T	0.64	5.32	0.34	1.69
24B	0.57	5.00	0.34	4.26
25T	0.49	2.52	0.33	0.78
25B	0.79	3.14	0.29	0.84
26T	0.90	1.27	0.48	0.59
26B	0.84	5.36	0.42	1.00
27T	0.96	1.54	0.37	0.49
27B	1.05	1.70	0.44	0.60
28T	0.69	1.51	0.30	0.59
28B	0.60	1.99	0.39	0.88
29T	0.63	1.87	0.31	2.50
29B	0.50	1.69	0.29	2.77
30T	0.62	0.99	0.45	0.51
30B	0.52	1.41	0.70	0.86
31T	1.19	7.08	0.35	9.43
31B	0.88	4.85	0.33	8.52
32T	0.72	1.68	0.32	1.35
32B	1.05	1.53	0.30	1.92

(continued)

TABLE 12. (continued)

	1973-74		1974-75	
Well	Total P	Total N	Total P	Total N
33T	1.62	2.79	1.82	3.07
33B	1.53	2.69	1.97	3.32
Mean	0.80	4.31	0.46	3.44

TABLE 13. MEAN CALCIUM AND MAGNESIUM CONCENTRATIONS, GROUNDWATER, mg/l AS $CaCO_3$

PC Well No.	July, 1973-August, 1974				November, 1974-August, 1975			
	Top		Bottom		Top		Bottom	
	Ca	Mg	Ca	Mg	Ca	Mg	Ca	Mg
1	158	89	---	---	167	70	---	---
2	225	77	227	83	176	66	202	82
3	174	98	184	100	147	75	181	79
4	217	84	---	---	201	73	---	---
5	162	94	177	105	162	81	176	86
6	170	90	168	96	168	86	167	84
7	146	78	151	81	156	74	156	83
8	193	106	---	---	203	108	---	---
9	259	101	---	---	175	67	---	---
10	164	88	---	---	169	84	---	---
11	175	106	307	168	178	93	236	109
12	238	119	---	---	179	89	---	---
13	223	135	---	---	181	94	---	---
14	138	106	---	---	126	64	---	---
15	220	121	226	118	218	85	216	91
16	214	119	237	114	215	102	221	105
17	236	113	242	122	221	103	226	109
18	242	112	355	157	166	79	295	105
19	269	135	---	---	262	113	---	---
20	168	97	257	117	201	95	207	106
21	103	79	166	120	89	67	116	72
22	250	120	254	159	243	112	245	114
23	228	106	235	121	244	97	253	109
24	158	94	164	95	166	67	205	89
25	187	77	218	101	199	68	203	67
26	214	104	382	159	245	111	278	117
27	688	566	716	632	773	743	814	740
28	224	107	362	201	205	107	387	225
29	166	116	160	150	171	114	188	110
30	183	134	190	197	171	163	174	178
31	213	100	449	193	164	72	189	78
32	238	87	249	99	200	75	197	82
33	223	126	228	118	237	106	235	119
M	214	118	263	150	205	109	240	131

TABLE 14. MEAN ALKALINITIES, GROUNDWATER, mg/l AS $CaCO_3$

PC Well No.	1973-74		1974-75	
	Top	Bottom	Top	Bottom
1	213	---	208	---
2	240	262	207	237
3	230	230	185	221
4	254	---	224	---
5	199	236	195	222
6	218	221	212	213
7	194	206	202	205
8	282	---	281	---
9	277	---	214	---
10	227	---	224	---
11	237	426	212	294
12	321	---	194	---
13	262	---	208	---
14	188	---	160	---
15	275	275	231	236
16	414	447	350	381
17	286	315	270	268
18	293	440	210	303
19	358	---	309	---
20	224	305	241	248
21	139	235	124	171
22	297	331	293	299
23	278	311	284	315
24	225	226	201	262
25	261	292	246	256
26	306	523	305	361
27	819	848	653	669
28	235	285	161	266
29	263	274	229	248
30	321	372	327	342
31	254	566	169	218
32	317	338	238	255
33	412	434	413	416
M	282	350	248	274

TABLE 15. OXYGEN RANGES AT GROUNDWATER SAMPLING SITES, APRIL, 1974 - AUGUST, 1975 (mg/l)

Site	O_2 Range	Site	O_2 Range
1T	2.6 - 9.3	20T	2.6 - 9.8
2T	5.7 - 11.8	20B	0.0 - 5.45
2B	4.7 - 9.5	21T	0.7 - 7.57
3T	2.8 - 12.1	21B	0.0 - 1.5
3B	5.84-11.3	22T	0.2 - 1.4
4T	5.0 - 10.4	22B	0.0 - 1.36
5T	6.25-10.4	23T	1.4 - 10.2
5B	6.1 - 9.3	23B	0.81 - 9.5
6T	5.1 - 8.6	24T	0.99 - 8.8
6B	5.2 - 8.7	24B	1.2 - 7.6
7T	7.7 - 9.2	25T	4.6 - 8.2
7B	6.4 - 8.5	25B	3.8 - 7.82
8T	0.6 - 9.8	26T	0.3 - 6.96
9T	0.0 - 7.2	26B	0.1 - 6.86
10T	5.8 - 10.3	27T	0.0 - 1.0
11T	1.0 - 11.8	27B	0.0 - 1.0
11B	0.0 - 6.7	28T	0.1 - 3.27
12T	2.5 - 10.1	28B	0.0 - 1.0
13T	8.5 - 11.8	29T	0.3 - 10.6
14T	4.9 - 10.1	29B	0.2 - 8.0
15T	2.9 - 10.2	30T	0.1 - 4.2
15B	7.2 - 10.2	30B	0.0 - 4.1
16T	0.1 - 4.2	31T	4.0 - 10.1
16B	0.0 - 0.8	31B	0.0 - 8.5
17T	6.0 - 9.7	32T	0.6 - 10.78
17B	1.3 - 9.0	32B	0.3 - 7.45
18T	0.96-12.6	33T	0.0 - 6.8
18B	0.25 - 9.7	33B	0.0 - 0.78
19T	7.2 - 9.0		

TABLE 16. VARIATION IN SEEPAGE VOLUME AND P AND N LOADS (Quantities/Hectare/Day)

1975	m^3 H_2O	Grams P	Grams N
	Lake St. Clair		
6/11	162	54	41
6/18	11	36	--
7/16	24	160	--
7/24	11	40	--
8/5	104	90	94
8/19	19	60	--
	Lake Sallie		
6/9	32	110	3
6/17	31	27	--
6/27	20	100	0.4
7/1	37	200	570
7/11	27	103	590
7/15	35	220	520
7/29	65	230	385
8/6	128	290	730
8/15	102	450	1,030
8/26	252	500	4,140

TABLE 17. NUTRIENT CONCENTRATION IN RAIN, DAILY MEANS, mg/l

Date	Total P	Available P	NH_3-N	NO_2-N	NO_3-N	Total N
			1973			
5/24	0.08	0.08	0.20	0.006	0.15	0.36
6/16	0.15	0.09	0.40	0.004	0.28	0.68
6/17	0.25	0.20	1.60	0.010	0.59	2.20
6/25	0.14	0.08	1.00	0.006	0.75	1.75
7/1	0.05	0.04	2.60	0.010	2.05	4.66
7/9	0.03	0.03	1.50	0.004	0.37	1.87
7/22	0.10	0.06	0.53	0.005	0.19	0.73
7/23	0.04	0.03	0.53	0.003	0.18	0.71
7/24	0.03	0.03	0.51	0.003	0.26	0.77
7/29	0.06	0.04	0.90	0.006	0.23	1.14
7/30	0.04	0.04	0.92	0.005	0.17	1.10
8/5	0.05	0.03	1.02	0.004	0.32	1.34
8/7	0.07	0.06	2.05	0.004	0.41	2.46
8/31	0.07	0.06	0.59	0.004	0.17	0.76
9/1	0.05	0.04	1.19	0.006	0.53	1.73
Mean	0.07	0.06	1.04	0.005	0.44	1.48
			1974			
5/10	0.03	0.02	0.69	0.002	1.43	2.12
7/16	0.22	0.06	1.23	0.004	1.004	2.24
7/21	0.06	0.03	0.65	0.002	0.40	1.05
8/2	0.08	0.01	0.41	0.006	0.30	0.72
8/12	0.02	0.00	0.57	0.003	0.26	0.83
8/15	0.06	0.00	1.04	0.005	1.22	2.26
Mean	0.08	0.02	0.77	0.004	0.77	1.54
			1975			
6/4	0.08	0.03	0.83	0.00	0.75	1.58
6/11	0.05	0.007	0.46	0.002	0.15	0.61
6/17	0.11	0.01	0.43	0.003	0.11	0.54
6/19	0.14	0.02	0.28	0.002	0.11	0.38
6/30	0.27	0.04	0.43	0.003	0.18	0.61
7/9	0.14	0.03	--	--	--	--
8/1	0.11	0.02	0.34	0.001	0.09	0.43
Mean	0.13	0.02	0.46	0.002	0.23	0.69

TABLE 18. PRECIPITATION AND NUTRIENTS FALLING ON LAKE SALLIE

Date	Total P *mg/l	Total N *mg/l	M^3 Rain	Acre Feet Rain	Kg P	Kg N	Lbs. P	Lbs. N
				1973				
5/24	0.03	0.36	1,233	1	0.036	0.45	0.08	1
6/16	0.15	0.68	93,708	76	14	64	31	141
6/17	0.25	2.20	70,281	57	18	155	39	341
6/25	0.14	1.75	60,417	49	9	106	19	233
7/1	0.05	4.66	44,388	36	2	207	5	456
7/9	0.03	1.87	165,222	134	5	309	11	682
7/22	0.04	0.725	85,077	69	4	62	8	136
7/23	0.04	0.71	59,184	48	2	42	5	93
7/24	0.03	0.77	390,861	317	12	301	26	664
7/29	0.06	1.14	108,504	88	6	124	14	273
7/30	0.04	1.10	14,796	12	0.45	16	1	36
8/5	0.05	1.34	133,164	108	7	179	15	394
8/7	0.07	2.46	59,184	48	4	146	9	321
8/31	0.07	0.76	170,154	138	12	129	26	285
9/1	0.05	1.73	104,805	85	5	181	12	400
Totals			1,560,978	1,266	100	2,021	221	4,456
				1974				
5/10	0.03	1.43	157,824	128	5	335	10	738
7/16	0.22	2.24	146,727	119	32	329	71	725
7/21	0.06	1.05	260,163	211	15	274	34	603
8/2	0.08	0.72	24,660	20	2	18	4	39
8/12	0.02	0.83	83,844	68	2	70	4	154
8/15	0.06	2.26	7,398	6	0.45	17	1	37
Totals			680,616	552	56	1,043	124	2,296
				1975				
6/4	0.08	1.58	46,854	38	4	74	8	163
6/11	0.05	0.61	23,427	19	1	15	3	32
6/17	0.11	0.54	44,388	36	5	24	11	53
6/19	0.14	0.38	295,920	240	41	112	91	248
6/30	0.27	0.61	351,405	285	95	215	209	473
7/9	0.14	---	30,825	25	5	---	10	---
8/1	0.11	0.43	76,446	62	9	33	19	73
Totals			869,265	705	160	473	351	1,042

*Daily means.

TABLE 19. NUTRIENTS CONTRIBUTED BY RAIN TO LAKE SURFACES (KILOGRAMS)

	St. Clair	Long	Big Floyd	Little Floyd	Detroit	Muskrat	Sallie	Total All Lakes
				1973				
P	11	34	79	17	236	5	100	482
N	228	687	1,597	335	4,770	101	2,021	9,739
				1974				
P	6	19	44	9	132	3	56	269
N	118	355	824	173	2,461	52	1,043	5,026
				1975				
P	18	54	126	27	378	8	160	771
N	53	161	374	79	1,116	24	473	2,280

TABLE 20. DATES AND VOLUMES OF HYPOLIMNIA APPEARING IN LAKE SALLIE

Date	Hypolimnion Volume	Per Cent of Total Volume
June 6, 1973	418 hm	16.37
11	276 hm	10.80
13*	47 hm	1.84
27	461 hm	18.06
July 3	409 hm	16.02
10	360 hm	14.10
14*	276 hm	10.80
August 7*	169 hm	6.60
September 26*	26 hm	1.01
July 10, 1974	418 hm	16.37
19	233 hm	9.13
24*	47 hm	1.84
July 3, 1975	47 hm	1.84
11*	45 hm	1.76

*Last date thermocline observed

TABLE 21. PHYTOPLANKTON CONCENTRATION AT WATERSHED STATIONS, MAY - NOVEMBER, 1975 (NOS. PER ML)

	A	B	F	M	N	P	1	4-1	8
5/30	318,336	450	13,961	142	189	907	1,357	486	869
6/6	186,558	109	12,928	39	75	1,573	14,694	165	318
6/11	332	62	18,533	40	124	3,393	2,664	64	178
6/17	120	27	17,848	62	189	2,181	2,592	163	247
6/24	1,355	130	8,639	76	317	1,232	1,257	178	167
7/1	14,699	113	11,580	58	454	2,277	1,506	189	756
7/8	49,332	243	19,868	45	429	2,065	1,792	1,830	5,868
7/15	58,424	298	12,441	105	392	2,789	1,399	12,220	1,728
7/23	30,098	371	34,470	116	652	1,915	3,645	8,079	8,346
7/27	23,330	589	37,606	88	648	2,532	4,135	8,612	4,628
8/5	124	424	27,171	67	599	3,907	49	1,260	1,071
8/14	309	529	10,519	163	313	1,640	4,556	6,657	4,769
8/19	1,891	755	720	108	306	800	3,844	3,618	8,975
8/29	3,139	194	1,935	72	363	485	3,560	9,535	4,889
9/5	5,399	631	1,461	141	749	827	4,066	11,126	18,098
9/12	6,500	370	359	74	642	328	3,550	4,295	9,739
10/3	6,556	205	221	86	227	262	624	9,443	11,098
10/10	31,798	134	101	96	435	334	359	11,338	9,658
10/17	203,677	157	237	108	500	172	336	10,962	8,900
10/24	48,760	254	184	328	403	334	613	14,864	14,256
10/31	164,161	322	254	209	301	185	1,026	9,755	10,369
11/7	129,767	17,976	12	227	259	320	1,034	7,721	6,063
11/14	143,625	14,567	105	194	416	260	529	33,671	3,735
11/21	43,445	46,517	170	258	501	275	245	1,524	1,372

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/3-79-046	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE WATERSHED AND POINT SOURCE ENRICHMENT AND LAKE TROPHIC STATE INDEX		5. REPORT DATE April 1979 issuing date 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Joe K. Neel		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Biology The University of North Dakota Grand Forks, North Dakota 58202		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. R800490
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Research Laboratory--Corvallis Office of Research and Development Environmental Protection Agency Corvallis, Oregon 97330		13. TYPE OF REPORT AND PERIOD COVERED final 1/1973--12/1975 14. SPONSORING AGENCY CODE EPA/600/02

15. SUPPLEMENTARY NOTES

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16. ABSTRACT

Water in the permeable soils of the upper Pelican River watershed, Minnesota, requires slightly more than a year to move generally out of the phreatic zone into surface channels and basins. Its nutrient content seems mainly responsible for the load borne in surface waters above entrance of a wastewater effluent, and groundwater changes have been followed a year later by similar ones in surface water. In 1975 P load from nonpoint sources markedly exceeded that from the wastewater effluent. Nutrients in groundwater are assumed to result from soil surface application, but only quantities supplied by precipitation have been measured. The most noxious conditions in surface waters have been occasioned by heterocystous blue-green phytoplankters, but the greatest plant mass has been produced by rooted and attached vegetation. Blue-green algae have not been predominant in some water bodies and only intermittently in most others. Their occurrence appeared controlled by environmental conditions other than nutrient loading in the ranges encountered here. Groundwater seepage into these lakes contributed more nutrients than precipitation, but the latter supplied what may be significant amounts to watershed soils. A trophic state index based on change in Mg/Ca quotient relative to water residence time has reliably depicted relative total productivity levels in 6 lakes or ponds, and its general applicability, at least to natural lakes, now appears likely.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77)

☆ U.S. Government Printing Office: 1979—698-322/141