RESPONSE OF EUTROPHIC SHAGAWA LAKE, MINNESOTA, USA, TO POINT-SOURCE, PHOSPHORUS REDUCTION

By

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Introduction

Evidence has been compiled over the past several years indicating the critical role the supply of phosphorus plays in controlling the productivity of aquatic systems. Vollenweider (1973) has shown that the trophic state of a great variety of lakes can be correlated with areal total phosphorus loading, mean depth, and hydraulic retention time. He has also shown that annual primary production of the Laurentian Great Lakes can be related to their phosphorus loading (Vollenweider, et al., 1974). Vollenweider (1969, 1973) and Dillon (1974) have derived mass balance equations to relate total phosphorus concentration to total phosphorus loading, mean depth, hydraulic flushing coefficient, and phosphorus deposition coefficient. Sakamoto (1966) and Dillon (1974) have demonstrated a good correlation between summer chlorophyll a concentrations and total phosphorus concentration at spring overturn. Further, Jones[1] has obtained a good relationship between potential phosphorus concentration and average summer chlorophyll a concentration for many lakes in Iowa as well as for a number of other lakes.

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[1] Personal communication from Mr. John R. Jones, Iowa State University.

Since the supply of phosphorus, to a large extent, controls the productivity of aquatic systems, its supply can often be curtailed to reduce the trophic state of adversely affected water bodies. A municipal tertiary wastewater treatment plant, which has been constructed at Ely, Minnesota, USA, reduced wastewater phosphorus concentration to less than 50 μg/l. The result has been a 70% reduction in the loading of phosphorus to nearby eutrophic Shagawa Lake during 1973-1974. This paper documents the phosphorus loading reduction and describes changes in the lake subsequent to that reduction.

Shagawa Lake

The Shagawa Lake basin was formed during the retreat of the Wisconsin glacier some 10,000 years ago. It is one of numerous lakes located in a sparsely populated region of northeastern Minnesota where iron mining and lumbering first attracted settlers. Now the area primarily attracts outdoor enthusiasts. The City of Ely began developing along the southern shore of Shagawa Lake around the turn of the century, attained a maximum population of about 6000 in the 1930's, and has since declined to a relatively stable population of about 5000 year-round residents. Wastewater from Ely initially flowed into the lake untreated, began receiving primary treatment in 1911, secondary treatment in 1952, and tertiary treatment to remove phosphorus in 1973.

Shagawa Lake is characterized by three basins of about 13 m maximum depth, a mean depth of 5.6 m, a mean volume of about 5.3×10^6 m^3, and a surface area of 925 ha (Figure 1). One major tributary, Burntside River, and several minor tributaries enter the lake; there is one outlet, Shagawa River. The hydraulic residence time is 8-9 months and the phosphorus residence time has been less than 6 months.

Surface water temperatures generally reach 22-24°C during summer months, while bottom temperatures sometimes reach nearly 20°C. Stratification exists below 5-6 m during summer months but is subject to break-down by passage of cold fronts and strong winds. The lake is ice-covered approximately five months a year. Specific conductance is about 60 μmho/cm, and alkalinity is 22 mg/l as $CaCO_3$. Anaerobic conditions have existed in the deep holes during summer stratification and during late winter under ice-cover.

Large blooms of diatoms and green algae develop during spring, and blue-green algal blooms dominate during the late summer. These blooms are in marked contrast to those of the generally oligotrophic, nearby lakes. Core analyses (Bradbury and Megard, 1972; Bradbury and Waddington, 1973) suggest that a marked increase in productivity occurred corresponding with the development of mining and lumbering in the area. The eutrophic state of Shagawa Lake was attributed to the supply of nutrients, particularly phosphorus, from the wastewater of Ely (Powers, et al., 1972; Smith, 1973; Malueg, et al., in press).

Materials and Methods

Tributary hydraulic flow has been monitored daily since 1966, utilizing gages installed and calibrated by the U.S. Geological Survey; wastewater flow has been monitored hourly. Details of tributary and wastewater flow, rainfall, evaporation, and ground-water are presented elsewhere (Malueg, et al., in press).

Weekly point samples were obtained from the tributaries for analysis of total phosphorus and orthophosphate phosphorus. Daily composite samples were obtained from wastewater during the interval 1972 to 1974. Prior to that time, grab samples were obtained at less frequent intervals. Phosphorus loadings were determined as described in Malueg, et al. (in press).

Total phosphorus (TP) and orthophosphate phosphorus (OP) were measured as described in Standard Methods (1968), and chlorophyll a (uncorrected for phaeo-pigments) was measured according to UNESCO (1966) methods.

Weekly samples for analysis of TP, OP, and chlorophyll a were obtained at the surface and at 1.5 m depth intervals to the bottom in each of the three basins.

Results

Loading reduction

The average annual load of wastewater and "natural" phosphorus for 1967-mid-1974 is summarized in Table 1. "Natural" phosphorus in the present context encompasses all phosphorus not measured as wastewater phosphorus and includes that contributed by tributaries, direct runoff (estimated), and rainfall. The wastewater supply accounted for about 81% of the total phosphorus load from 1967 to 1972 and was reduced to about 25% during 1973. The total phosphorus load to the lake was reduced to about 30% of its previous level. During 1973 and 1974, the lake had entered a phase of phosphorus washout, approximately 50% more phosphorus leaving the lake than entering. The supply of total phosphorus from all sources is summarized in Figure 2, delineating the difference between wastewater and "natural" loads. There was a significant decrease in the wastewater supply during the period January-March, 1973, when the treatment plant underwent testing prior to full-scale operation. A further decrease occurred in April, 1973, when the plant commenced full-scale operation. Occasional spikes from that time on indicate plant bypass due to temporary shutdown or excessively high flow.

Lake Changes

Total phosphorus (TP) concentration

The changes in concentration of TP in the upper 5.25 m (approximating the average mixed depth during stratification and representing about 80% of the lake volume) are summarized in Figure 3. Prior to ice-out (usually in late April), the mean concentration of TP increased during the interval from 1971 to 1973. When the lake was ice-free (May - early November), the differences were indistinguishable for 1971 and 1972, but a lower concentration occurred during the fall of 1973. During the ice-free season, the usual pattern was a decline in TP concentration to low values of 25-30 μg/l in June followed by a sharp increase in late summer to values near 90 μg/l. This increase was primarily a result of release of phosphorus by the sediments. During the ice-covered interval in 1974, the TP concentration was nearly constant at about 20 μg/l, less than half that of 1973 and slightly lower than that in 1971. An increase in concentration occurred during ice breakup, as had been observed in previous years. Subsequent to ice breakup, the concentrations were similar to those of previous years but slightly lower, particularly in July when the concentrations were nearly half those of the previous three years.

Displayed for comparison is the average concentration of TP in the upper 5.25 m of Burntside Lake during 1972. Burntside Lake is a lower mesotrophic to oligotrophic lake located upstream of Shagawa Lake and provides about 70% of the flow to Shagawa Lake. Burntside Lake serves as a useful control.

Orthophosphate phosphorus (OP) concentration

The average concentrations of OP in the mixed zone are summarized in Figure 4. High concentrations, ranging from 10-35 μg OP/l, existed during ice-cover each year. The trend during this interval was similar to that observed for TP, although during short intervals, the concentrations observed in 1971 and 1972 were nearly the same as those observed in 1973. The pattern observed each year after ice-out has been a decline of OP during the spring algal bloom to levels less than 2 μg/l for most of June. In early July, there has been an increase in OP originating from the sediments. The increase was particularly relevant in 1973 when the wastewater supply had been reduced, and the lake had entered a period of phosphorus washout. The concentrations of OP attained during July and August are not considered limiting to algal growth.

In early 1974, one year after initiation of treatment, OP concentrations were considerably lower than those observed in previous years during the winter months. However, the nearly constant concentration of 11 μg/l was sufficient to support a large, spring algal bloom. In contrast, OP concentrations in Burntside Lake were consistently low, generally less than 2 μg/l throughout the year.

Chlorophyll a concentration

The concentration of chlorophyll *a* has been used as an indicator of algal biomass throughout this study. A spring bloom at ice-out has occurred each year except 1973. In 1973, the ice-cover was more transparent than in other years and the maximum of the early algal bloom was reached before ice breakup. Fluctuations between 10 and 30 μg/l existed throughout most of June and July followed by a dramatic increase in early August. In 1972, this increase had occurred about one month earlier. These summer blooms are a response to the increased supply of nutrients from the sediments as indicated by the changes in TP and OP during this interval. This was especially evident in August, 1973, when essentially no phosphorus was supplied from wastewater. The blooms generally began to decline in September, responding to lower temperatures and decreased light levels.

In 1974, the spring bloom was of a magnitude similar to that in 1971 and 1972, but the June and July concentrations of chlorophyll a were lower than had been observed in previous years. The low constant pattern of chlorophyll a in Burntside Lake stands in marked contrast to that of productive Shagawa Lake.

Discussion

Sonzogni and Lee (1973), and Dillon (1974) have reviewed the response of lakes to which the supply of nutrients has been curtailed, and, in general, the response has been that which might be predicted by simple hydraulic or phosphorus washout models. Examples include Lake Washington, USA; Zellersee, Austria; and Little Otter Lake, Canada. A notable exception has been Lake Sammamish, USA, to which about 40% of the phosphorus supply had been curtailed. Lake Trummen, Sweden, also failed to respond significantly to diversion of large amounts of nutrients (Björk, 1972). The failure of predicted changes was attributed to high internal phosphorus loads in both lakes.

Shagawa Lake appears to have reached a state in which internal loading, especially during July and August, contributes a sufficient amount of phosphorus to produce large crops of algae. Mass balance estimates demonstrated that the internal load of phosphorus during July-August, 1971-1973, was sufficient to increase the average concentration in the lake 1-2 μg/l/day (Larsen, in prep.). Figures 3 and 4 display this increase, particularly in 1973, when during this interval, phosphorus leaving the lake exceeded that entering from external sources. Most of this internal load redeposited during fall circulation, and thus it had little influence on annual calculations of the phosphorus budget.

Although any attempt to predict the recovery of the lake will depend upon the ability to predict the course of internal loading, it is useful to compare the phosphorus mass in the lake with that predicted by a mass balance model of the type described by Vollenweider (1973) (Figure 6). This model assumes a well-mixed lake, no internal sources of loading, and a constant phosphorus deposition coefficient. For Shagawa Lake, a value for the phosphorus deposition coefficient was calculated as the difference between the phosphorus loss coefficient and the hydraulic loss coefficient. The phosphorus loss coefficient was calculated as the quotient of the average annual loading of total phosphorus to the lake and the average total phosphorus mass in the lake for the two years 1971 and 1972. To project TP concentrations in the lake, an average hydraulic and "natural" phosphorus loading year was calculated using weekly values from 1972 and 1973; residual wastewater phosphorus loadings were estimated from those obtained after April, 1973. Weekly model calculations were made to compare phosphorus and hydraulic washout models with observations in the lake.

In the absence of internal loading, both models suggest a rapid recovery reaching a steady state within two years. The hydraulic washout model better estimates the TP concentration during the 1973-1974 ice-covered interval. The ice-covered interval perhaps best represents average conditions in the lake in the absence of large influences of internal loading. Marked deviations from the models emphasize the importance of internal loading particularly during the summer period. During this period in 1973, the average concentration of TP in the lake increased from 30 μg/l to more than 80 μg/l, as a result of internal loading. A refined prediction of the recovery of the lake should include an estimate of the internal loading of phosphorus, a proposition of considerable difficulty.

Although not as rapid as could be expected in the absence of internal loading, there is certainly evidence suggesting a favorable response to reduced phosphorus loading to Shagawa Lake. Winter-time concentrations of TP and OP were lower in 1974 than they have been in previous years. The lake is in a phase of phosphorus washout, having lost about twice as much phosphorus as gained in 1973 and early 1974. The June-July concentrations of chlorophyll a in 1974 are at their lowest as compared with those of the previous three years.

Summary

The eutrophic state of Shagawa Lake has been attributed primarily to the supply of phosphorus from the wastewater of nearby Ely, Minnesota, USA. A recently constructed tertiary wastewater treatment plant has reduced the phosphorus load to the lake by about 70%. As a result, the lake has entered a phase of phosphorus washout. Average total and orthophosphate phosphorus concentrations in the lake are lower than in the past; chlorophyll a concentrations are only slightly lower. The significant amount of internal phosphorus loading during summer months suggests that the predicted achievement of a new equilibrium in about two years, based on a phosphorus washout model, will not be attained.

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List of Tables

Table 1. Annual total phosphorus supply to, and loss from, Shagawa Lake, 1967-1974

	Supply (kg)			Loss (kg)
Year	Wastewater	"Natural"	Wastewater % of Total	Shagawa River
1967	5245	797	87	2928
1968	5349	1530	78	6203
1969	5449	1328	80	5488
1970	5606	1766	76	6145
1971	5460	1379	80	4675
1972	5176	1064	83	3144
Average	5380	1310	81	4674
1973	543	1596	25	4308
1974 (Jan.-May)	70	628	10	1065

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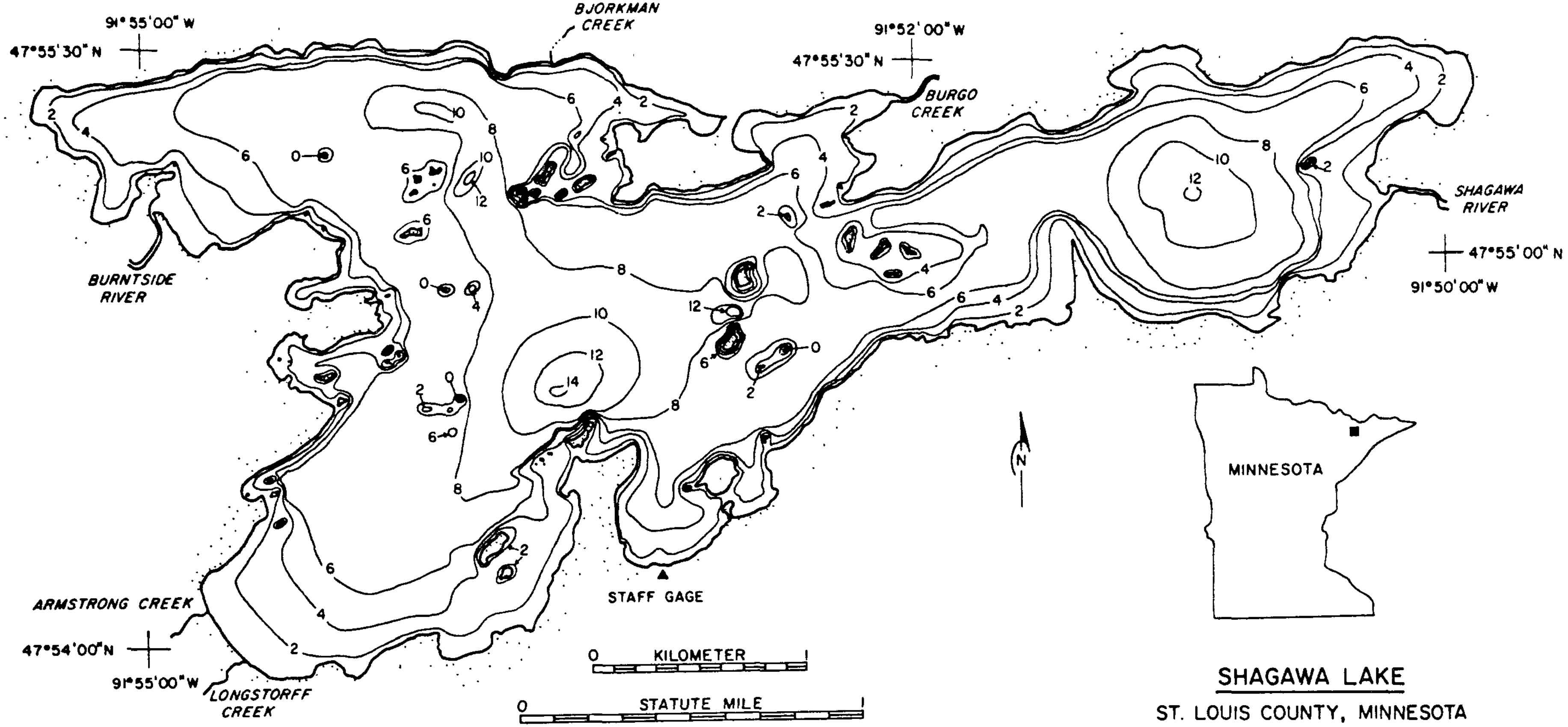
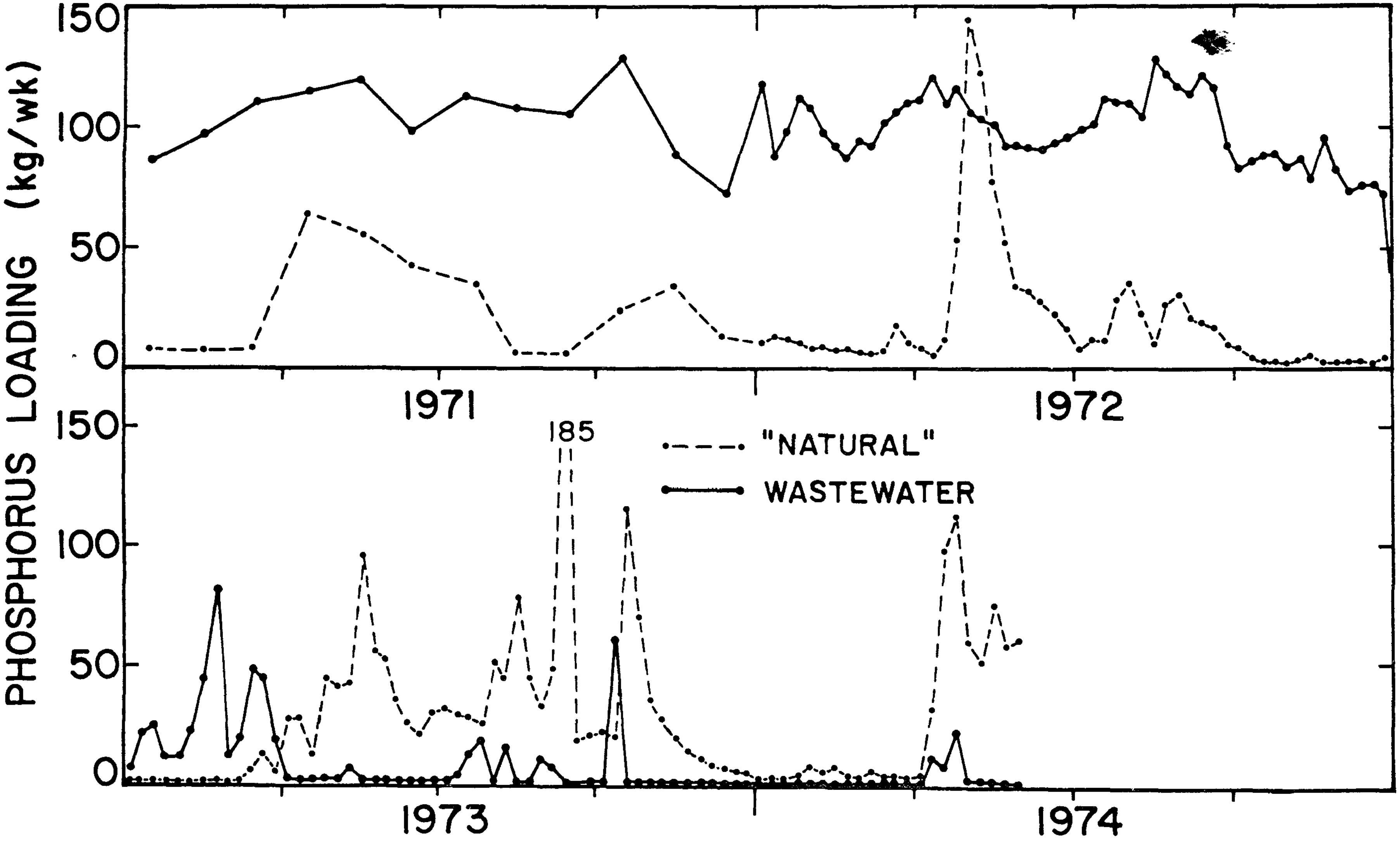
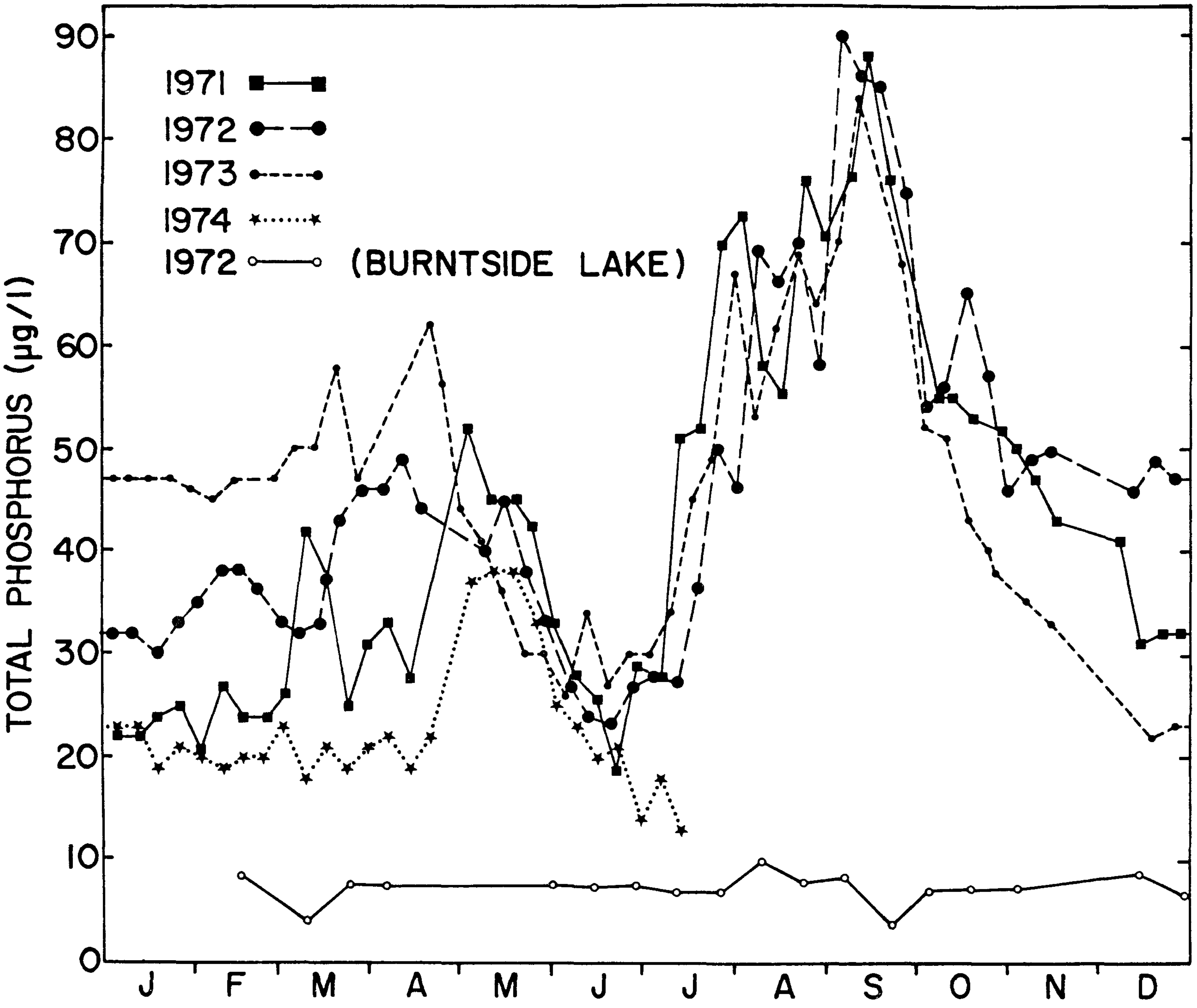


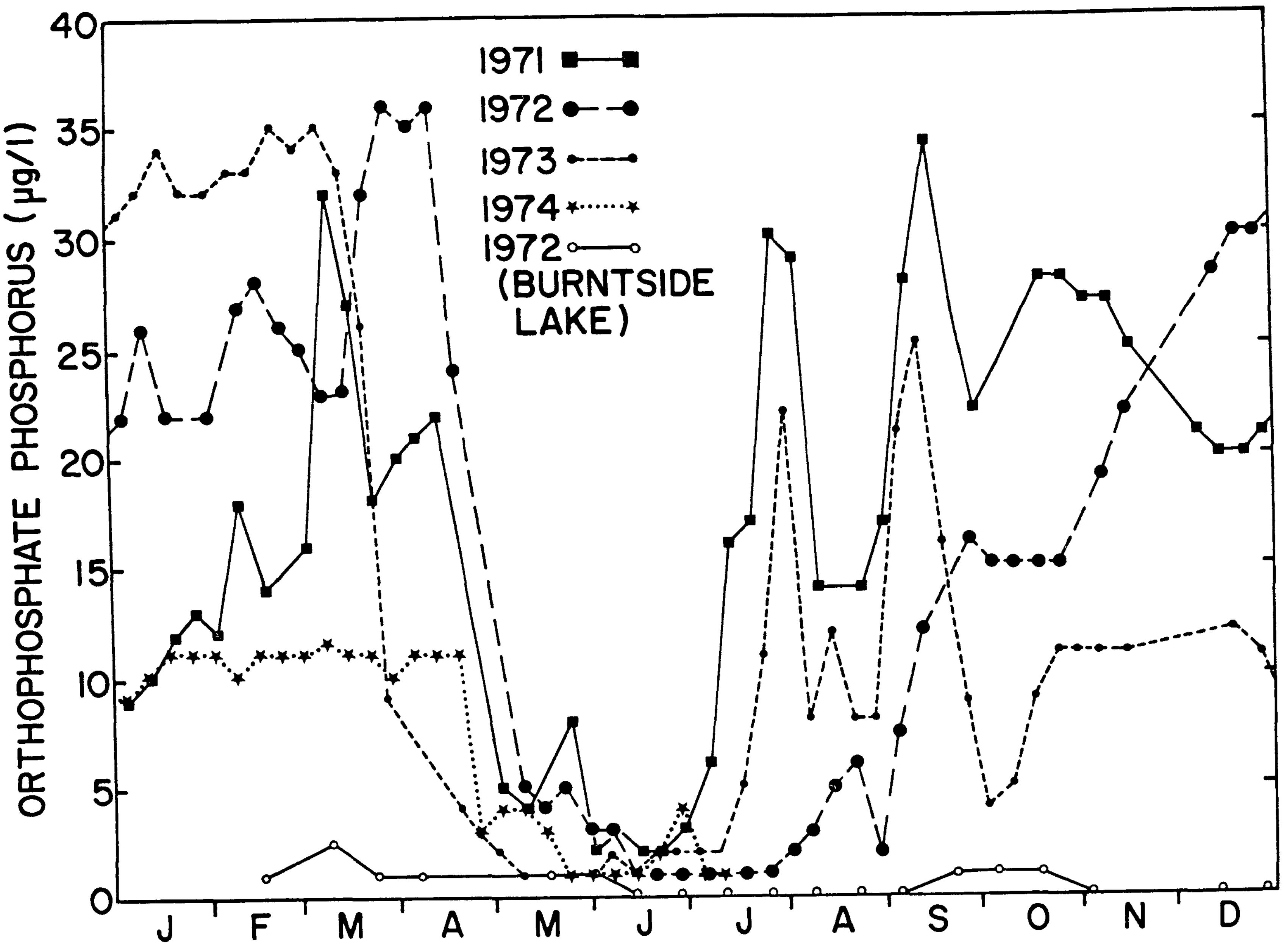
SHAGAWA LAKE

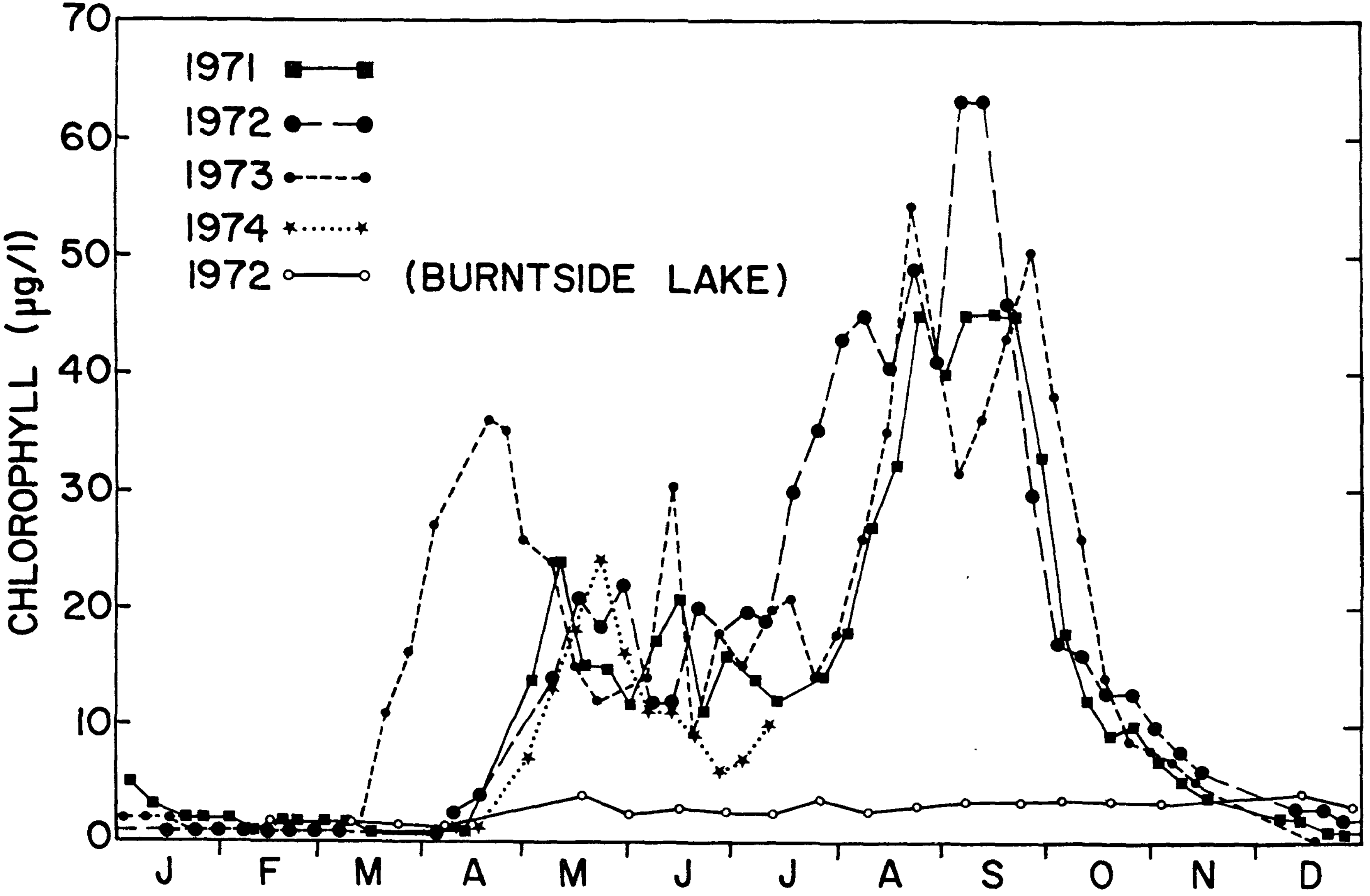
ST. LOUIS COUNTY, MINNESOTA

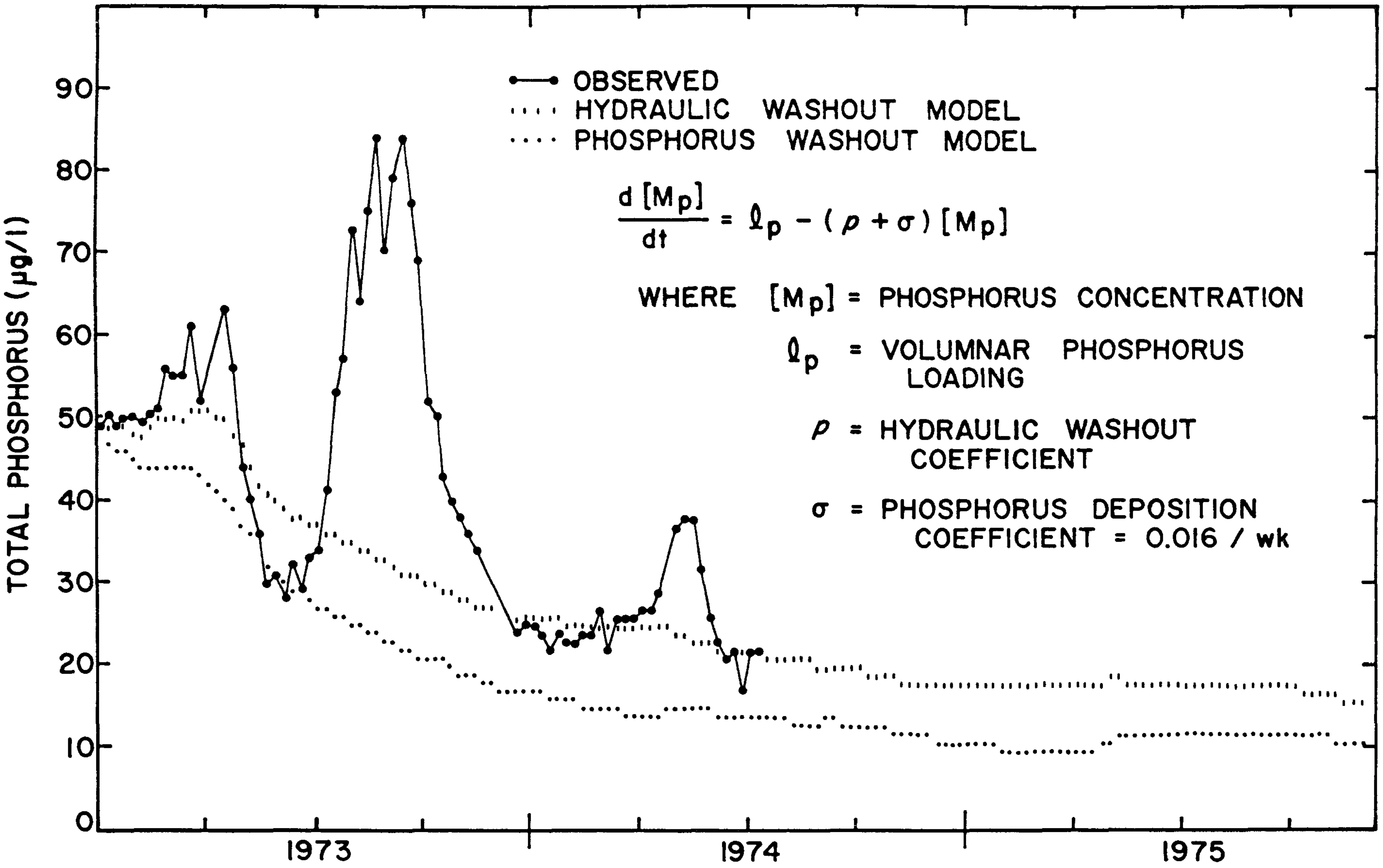
CONTOUR INTERVAL . 2 METERS
DATE OF SURVEY . AUGUST 18-21, 1972
GAGE DATUM : 407.8 METERS ABOVE MEAN SEA LEVEL


PHOSPHORUS LOADING (kg/wk)
150
100
50
0
1971
1972
150
100
50
0
185
"NATURAL"
WASTEWATER
1973
1974


1971
1972
1973
1974
1972
(BURNTSIDE LAKE)
TOTAL PHOSPHORUS (μg/l)
0
10
20
30
40
50
60
70
80
90
J
F
M
A
M
J
J
A
S
O
N
D


1971
1972
1973
1974
1972 (BURNTSIDE LAKE)
ORTHOPHOSPHATE PHOSPHORUS (µg/l)
0
5
10
15
20
25
30
35
40
J
F
M
A
M
J
J
A
S
O
N
D


1971
1972
1973
1974
1972
(BURNTSIDE LAKE)
CHLOROPHYLL (µg/l)
70
60
50
40
30
20
10
0
J
F
M
A
M
J
J
A
S
O
N
D


OBSERVED
HYDRAULIC WASHOUT MODEL
PHOSPHORUS WASHOUT MODEL
$\frac{d[M_p]}{dt} = \ell_p - (\rho + \sigma)[M_p]$
WHERE $[M_p]$ = PHOSPHORUS CONCENTRATION
ℓ_p = VOLUMNAR PHOSPHORUS LOADING
ρ = HYDRAULIC WASHOUT COEFFICIENT
σ = PHOSPHORUS DEPOSITION COEFFICIENT = 0.016 / wk
TOTAL PHOSPHORUS (μg/l)
90
80
70
60
50
40
30
20
10
0
1973
1974
1975