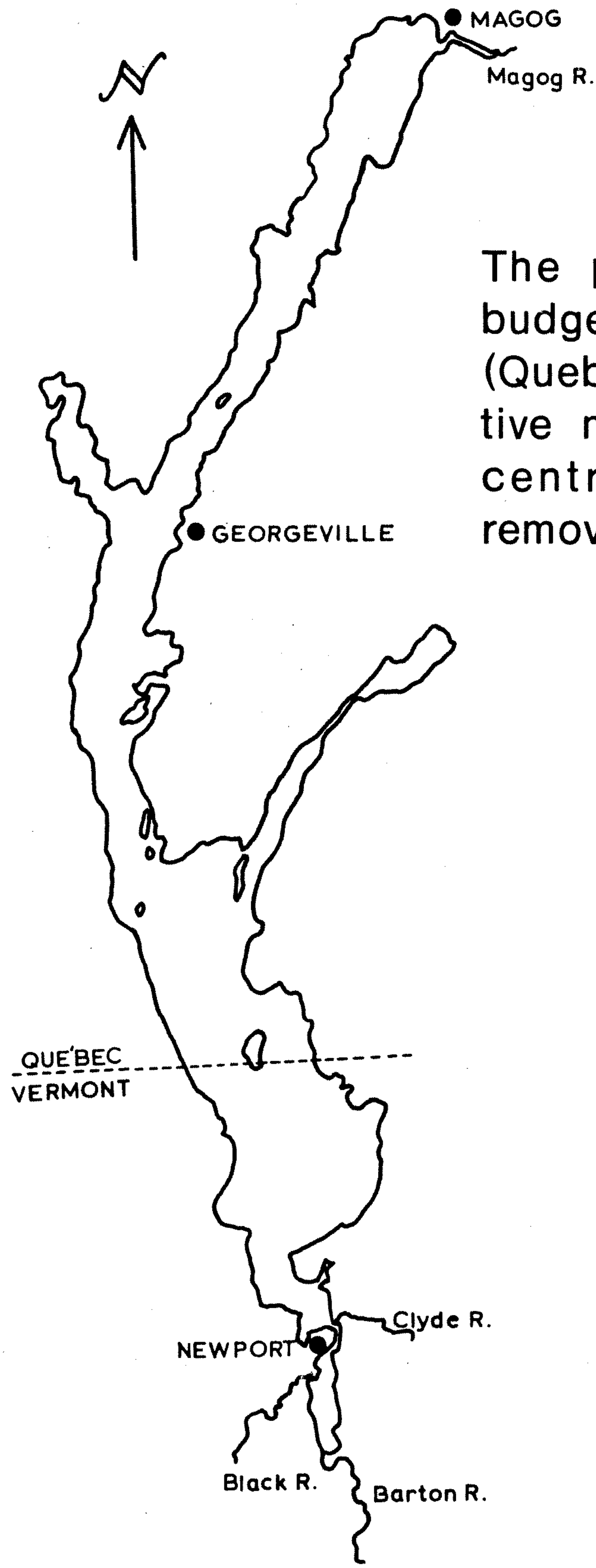

The phosphorus and nitrogen budgets of Lake Memphremagog (Quebec-Vermont); with a predictive model of its nutrient concentration following sewage removal.

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Lake Memphremagog Project
Limnology Research Group
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ABSTRACT

Lake Memphremagog is a long, narrow lake located on the Quebec-Vermont border. This study involved using a nutrient budget approach to elucidate the importance of external inputs of nutrients to the maintenance of a nutrient gradient within this lake. The results indicate that 63% of the water, 84% of the phosphorus, and 58% of the nitrogen entered the lake at its extreme southern end at Newport, Vermont. Approximately 37% of the phosphorus entering at Newport is contributed by the Newport sewage treatment plant.

The domination of this single southern inflow affects the nutrient concentrations throughout the lake. A decrease in nutrient concentration is observed with distance from Newport, but this is the effect of sedimentation of the nutrients rather than increased influence of other more dilute nutrient inputs.

The decrease, or gradient, is readily apparent in total and particulate phosphorus and for nitrogen. It is hypothesized that the lake is increasingly phosphorus limited with distance from Newport as evidenced by the increasing N/P and C/P ratios. The phosphorus gradient is present because 60% of the phosphorus is found in particulates, which are subject to sedimentation. There is evidence that the phosphorus is retained in particulate form in sedimenting matter and little is released for further recycling. As nitrogen dynamics are not tied to nitrogen availability, it is apparently loosely held by particualtes and

readily released on sedimentation.

The loading of phosphorus is seasonally constant, and fluctuations observed in nutrient concentrations within the lake are best explained by internal mechanisms such as fluctuation in sedimentation rates. The basins within the lake with well-defined thermoclines throughout the summer typically have high phosphorus concentrations in the winter and spring. These concentrations fall off as summer progresses. The shallower basins have summer increases in nutrients associated with the breakdown of the thermocline. This complete mixing of the water may either decrease the loss of nutrients by sedimentation or increase the rate of release of nutrients from the sediments.

A model was constructed for the prediction of mean annual nutrient concentration within the lake. The lake was considered to consist of four serially connected, completely mixed basins, with minimal turbulent mixing between the adjoining basins. The model was constructed in the matrix format suggested by Thomann (1972). The model gave accurate estimation of the present lake concentrations and predicted that the removal of the Newport STP would drop concentration even in the northern end of the lake by at least 12%. It is suggested that the model can be used as a basis for a more elaborate model for analyzing the factors involved in the seasonal nutrient dynamics within the lake.

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INTRODUCTION

Lake Memphremagog (lat. 45 06' N, long. 72 17' W) is a long (40 km) and narrow (mean width = 2.4 km) lake located on the Quebec-Vermont border. The lake is unusual not only because it is situated on an international boundary, but also because nearly 70% of its 1689 km^2 watershed is drained by three Vermont rivers which enter the lake at its extreme southern end (Figure 1). These rivers carry agricultural runoff, untreated sewage from several very small towns, as well as sewage effluent receiving only primary treatment from the town of Newport, Vt. situated at the entrance to the lake. The remaining portion of the watershed, 25% of which is in Canada, is little developed. Because of the hydrologic and nutrient dominance by the southern rivers, there exists within the lake a nutrient gradient from south to north which may be responsible for the gradients in primary and secondary productivity that have been found (Ross and Kalff, 1975, Nakashima and Leggett, 1975).

The problems associated with the process of eutrophication are already apparent, especially in the southern basin of the lake. Increased macrophyte growth, decreased transparency, and windows of algal scums are visible. These problems are a concern of area residents in both countries. There is also concern that the recreational potential of Lake Memphremagog will attract further development within its watershed, possibly exacerbating

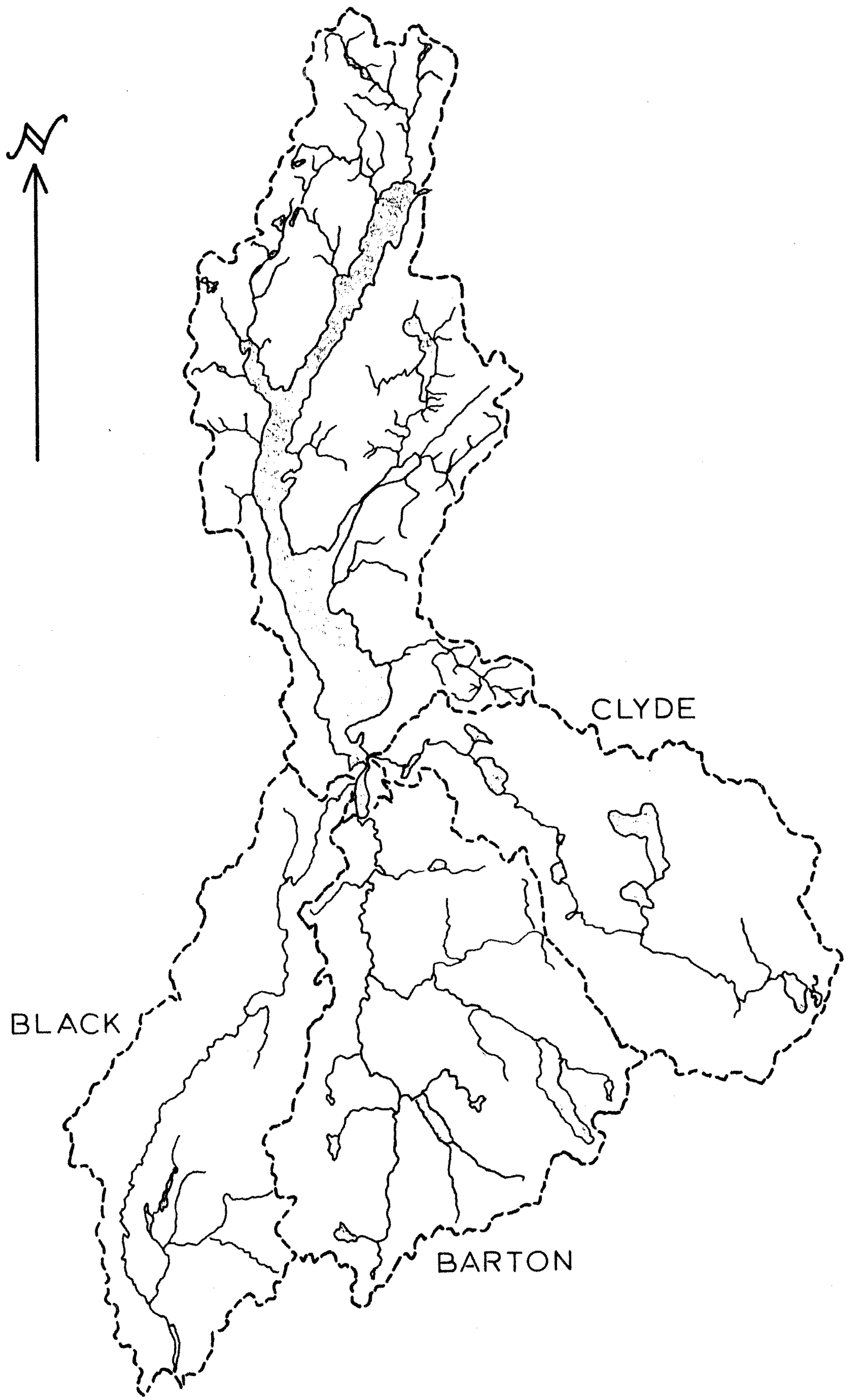

Figure 1. The watershed of Lake Memphremagog

an already environmentally dangerous situation.

The existence of a nutrient gradient offers a unique scientific opportunity to examine the process of eutrophication both in time and space. Too often the lakes that have been studied were completely mixed basins, and the events occurring within them are the average response of nutrient inputs mixing with the older waters of the lake. As such, any conclusions drawn about the dynamics of eutrophication are in actuality the lake's response integrated over the period of the hydrologic residence time. In Lake Memphremagog, where the flow is largely advective, there is decreased mixing of different aged waters, which potentially allows the in situ examination of the dynamic response of the biotic community to changes in ambient nutrient concentration.

The purpose of the present study was firstly to document the presence of this nutrient gradient and to record any seasonal fluctuations in the nutrient concentrations. Secondly, the study developed a nutrient budget for the lake in order to determine the amount of nutrient inflow and its impact throughout the lake. Thirdly, a predictive model was developed using the data from the nutrient budget which can be used to predict future nutrient concentrations throughout the lake.

METHODS

Sampling Locations

Of the estimated 50 permanent rivers and streams entering Lake Memphremagog, 19 were sampled intensively (Figure 2). The watersheds of these 19 rivers comprise 91% of the lake's watershed. Three rivers, the Clyde, Black, and Barton, alone drain 70% of the watershed and were accordingly sampled most intensively.

As embayments could affect incoming nutrient concentrations, the two river systems that pass through bays before entering the lake were sampled at more than 1 location. In the Fitch Bay system, the 4 streams entering Upper Fitch Bay were sampled as was the outlet from the bay (Narrows). In the South Bay system at the extreme southern end of the lake, two large rivers, the Black and Barton, enter a long, shallow bay containing extensive emergent and submergent aquatic macrophytes. The bay was sampled from a railroad bridge at its lower end.

Treated sewage from the town of Newport, Vermont enters the Clyde River near its entrance to the lake. Its effect on the chemistry of the Clyde River was estimated by sampling the river above and below the point of sewage input.

The lake itself was divided into 4 major basins, named from south to north, Newport Bay, South Basin, Central Basin, and North Basin (Figure 3). The morphometric characteristics of

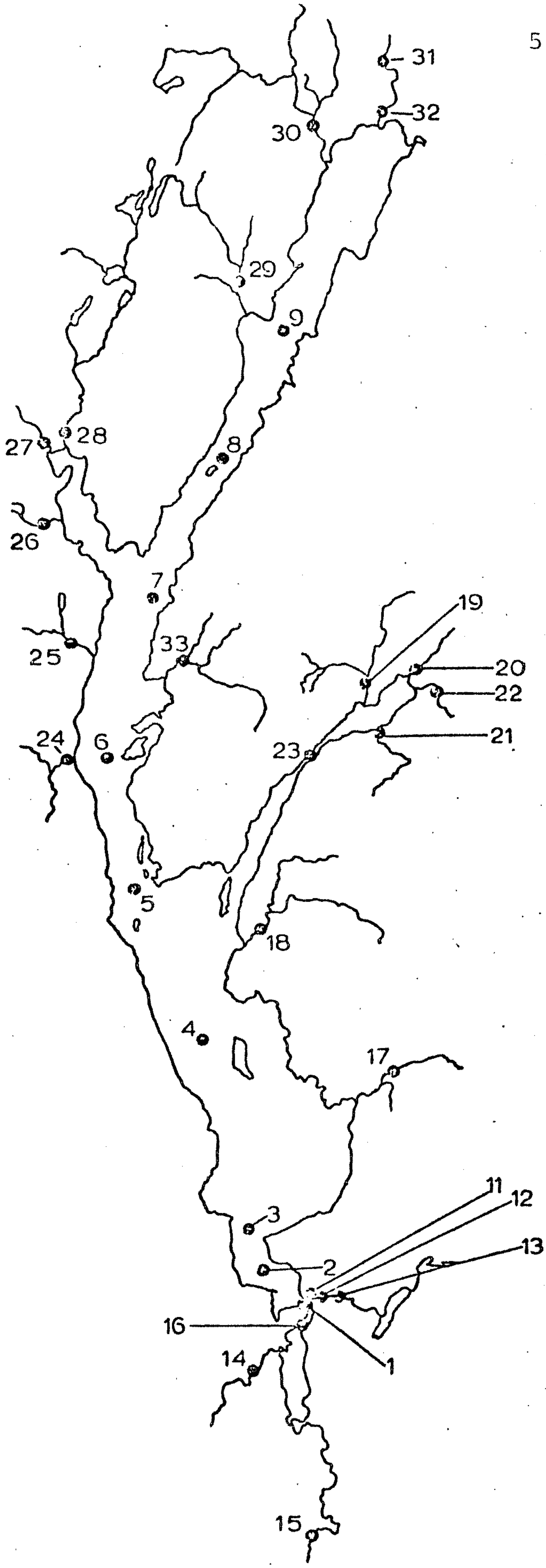

Figure 2. The sampling stations on and around Lake Memphremagog used in the 1974-75 study

Key to Sampling Location

1. Inflow
2. Pender Point
3. Indian Point
4. Border
5. Skinner Island
6. Molson Island
7. Central Basin
8. Lords Island
9. Spinney Point
11. Lower Clyde River
12. Newport Sewage Plant
13. Upper Clyde River
14. Black River
15. Barton River
16. South Bay at Railroad Bridge
17. Johns River
18. Tomkins Brook
19. Fitch Creek
20. Bunker Brook
21. Creek # 2
22. Creek # 3
23. Narrows
24. Vale Creek
25. Creek # 1
26. Glen Brook
27. West Brook
28. Powell Brook
29. Channel Brook
30. Castle Brook
31. Upper Cherry River
32. Lower Cherry River
33. Macphaerson Creek

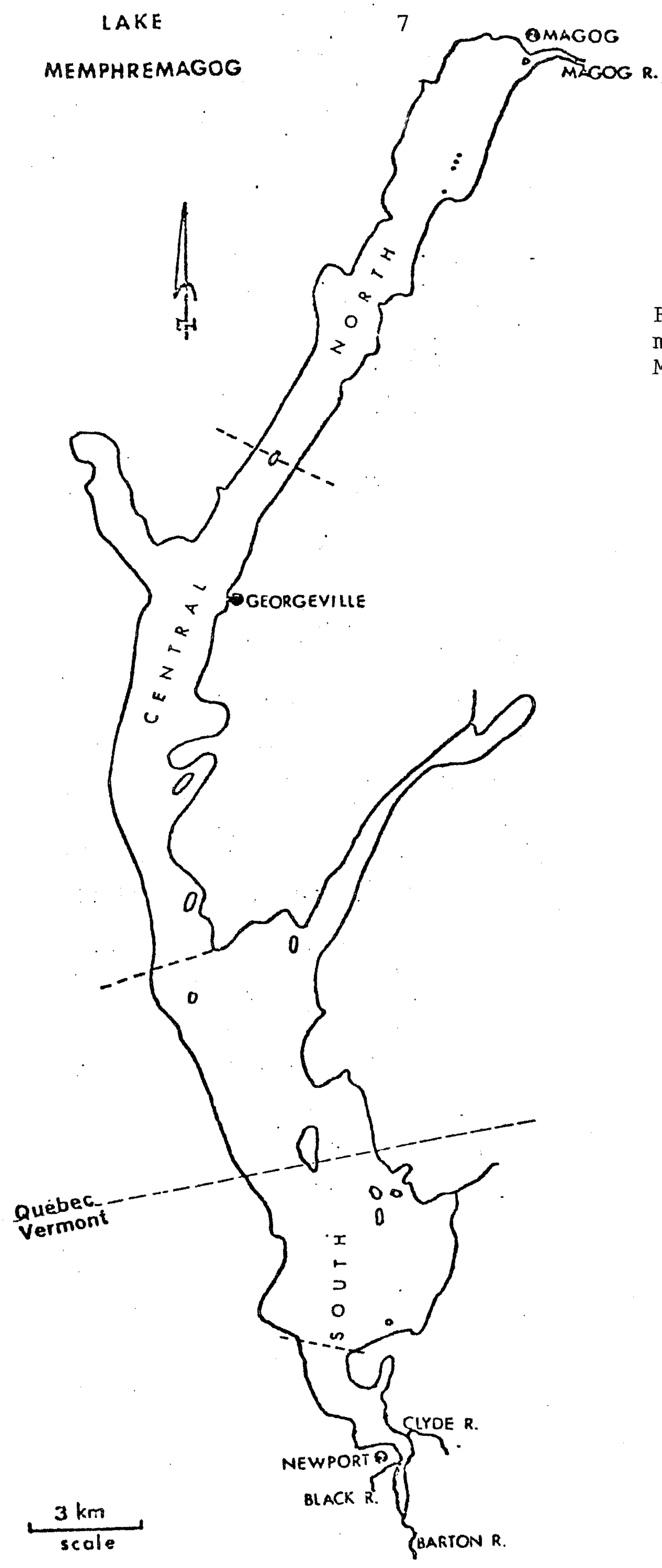

Figure 3. The four major basins in Lake Memphremagog

these basins are given in Table 1. Sampling stations were established at 9 points along the lake's longitudinal axis. The stations correspond to the entrance, center, and exit from each of the major basins. A sampling station at the outflow from the lake was abandoned when it became apparent that local contamination from the town of Magog, Que. was affecting the values obtained.

The watershed of the lake was similarly divided into 4 portions corresponding to the 4 lake sections. The rivers entering each of the 4 lake sections are given in Table 2.

Sampling and Analytical Methods

Lake samples were taken with a Van Dorn water sampler and poured into polyethylene containers. Stream samples were taken at the surface with a plastic bucket, Van Dorn sampler or with the polyethylene container itself.

The samples were analyzed as follows:

Total Phosphorus: 50 ml aliquots were poured into 125 ml flasks as soon as possible after collection and stored until analysis. Samples were digested with 0.8 gm potassium persulfate for 45 minutes under heat and pressure, cooled and then analyzed using the modification of the ascorbic acid-molybdate method decribed by Johnson (1971). This method eliminates arsenic interference.

Total Particulate Phosphorus: known volumes were filtered through 0.45u membrane filters. The filters were dried and stored in petri dishes until analysis. The filters were placed

Table 1. The morphometric characteristics of the four major basins of Lake Memphremagog

Segment No.	Name	Volume (X 10^6 m^3)	Area (X 10^6 m^2)	Mean Depth (m)
1	Newport Bay	14.964	1.914	7.82
2	South Basin	287.327	40.01	7.18
3	Central Basin	1080.096	21.91	49.29
4	North Basin	256.72	19.08	13.46
	Total Lake	1639.107	82.914	19.769

Table 2. The watershed areas of the streams and stream systems entering each of the four major basins of Lake Memphremagog

		Watershed Area (m^2 X 10^6)
Segment 1		1202.11
South Bay System		
Barton	451	
Black	347	
Clyde River	368	
Unmonitored	36.11	
Segment 2		215.17
Johns River	29.3	
Tomkins River	19.1	
Fitch Bay System		
Fitch Creek	62.2	
Bunker Brook	14.0	
Unnamed #2	19.4	
Unnamed #3	12.2	
Unmonitored	5.5	
Upper Fitch Bay	1.97	
Unmonitored	51.5	
Segment 3		123.97
Vale Creek	12.7	
Unnamed #1	10.3	
Macphaerson Creek	14.6	
Powell Brook	30.7	
West Brook	14.2	
Glen Brook	7.9	
Unmonitored	33.57	
Segment 4		147.8
Channel Brook	13.8	
Castle Creek	36.9	
Cherry River	54.5	
Unmonitored	42.6	
Total Watershed Area		1689.05 km^2

in flasks, 50 ml of distilled water added, and digested in the same manner as for total phosphorus. The filters were subsequently removed from the flasks, as it was found that the filters absorbed the blue color formed upon the addition of reagents. The samples were filtered again through the original filter to remove particulate material. The samples were then analyzed as described for total phosphorus.

Samples for particulate and dissolved nitrogen, particulate carbon, and chloride were shipped for analysis to Canada Centre for Inland Waters, Burlington, Ontario.

Chlorophyll: known amounts of sample were filtered through a glass fiber filter and a small amount of $MgCO_3$ added. The filters were frozen until analyzed. The pigments were extracted by grinding the filters in a tissue grinder with cold 90% acetone. Samples taken before May 1975 were analyzed on a model III Turner fluorometer which had been calibrated against a trichromatic chlorophyll determination done on a B&L Spectronic 80. The correlation coefficient between the readings was 0.96. After May 1975 the trichromatic determinations alone were used.

Hydrologic Methods

Two rivers, the Black and the Clyde, were monitored continuously by the United States Geological Survey. The flow of thirteen other rivers was measured when water samples were taken using a dip-stick flow meter (Hydro-Bios Kiel). The instantaneous flow on these rivers was calculated by determining the total vertical velocity at measured intervals across the stream, averaging the velocity between these points, multiplying the resultant mean velocity by the area of each interval, and finally summing the flows of these intervals to obtain the total discharge (m^3/sec). These values were converted to cubic meters per day and divided by the watershed area (m^2) to produce a daily watershed flow coefficient (m/day). These individual coefficients were then regressed against the flow coefficients calculated for the Black and Clyde Rivers to obtain equations that could be used to estimate the daily flow from any of the watersheds, using the daily data obtained from the monitored rivers (Table 3).

Much better correlations were obtained when the Black River was used as the independent variable than when the Clyde River was used. In fact, low correlations were obtained when the values from these two monitored rivers were compared with each other ($r = 0.674$, $n = 457$). We believe that the lack of correlation between these two geographically-close rivers results from the presence of impoundments on the Clyde that are absent on the Black. These impoundments probably retard the flow of the Clyde. Evidence for this is the low correlation of either of these rivers with Fitch Creek which also contains a lake within its watershed.

The rivers on the eastern half of the lake had a different flow relationship to the Black River than did those on the west. The greater water discharge on the west may be the result of the greater mean slope of the watershed on that side.

For the purposes of estimating the inflow to the lake, all the rivers east of the Black and the outlet at Magog

Table 3. The regression equations used in the calculation of daily flow in the rivers entering Lake Memphremagog

East Rivers (all but the Black, Barton, Clyde and Johns)

$$F = A \times (.0002995 + 0.6413177 \times F_{BL}) \qquad r = .821$$

West Rivers

$$F = A \times (1.854703 \times F_{BL} - .000532815) \qquad r = .894$$

Johns

$$F = A \times (.0002104 + 0.6185 \times F_{BL}) \qquad r = .909$$

Barton and Black *

$$F = A \times F_{BL}$$

where:

F = Flow (m^3/day)

A = Watershed area (m^2)

F_{BL} = Watershed flow coefficient of Black River (m/day)

* The Black River is gaged at Coventry, Vermont, which incorporates only 91% of its total watershed. The watershed coefficient was calculated using this smaller watershed size, and total flow is estimated by multiplying the coefficient by the total watershed size.

(excluding the Clyde and the Johns) were considered to have the eastern flow relationship with the Black. All other rivers were considered to have the western relationship. Unmonitored rivers and areas having only direct runoff to the lake were considered to have the same relationship as did the rivers.

Precipitation data were obtained from daily measurements made by Quebec Provincial Weather Service and by NOAA weather stations located at Newport, Vt., Georgeville and Magog, Que. Precipitation falling on the lake surface (meters/month) was estimated using the average precipitation of all three stations. Precipitation in the form of snow was converted to its liquid equivalent by multiplying the value by 0.1.

External Nutrient Loading

Nutrient loading, expressed as milligrams per month or milligrams per year, was estimated by multiplying the estimated daily flow by the estimated daily nutrient concentration in each river. The method of obtaining daily flow was described earlier. Daily concentrations were estimated by interpolation between measured samples. For the western rivers, where samples were taken only in 1974, the mean concentration of the samples taken for a river was used instead. The loading from unmonitored streams and the parts of the watershed draining directly into the lake was estimated using the mean of the concentrations of the monitored streams on the same side of the lake (Table 4).

The loading from direct precipitation on the lake surface was estimated by multiplying the precipitation (m^3/month) by

Table 4. The values used in the nutrient budgets for streams, unmonitored areas, and precipitation.

Source	Total P	Total N	Chloride
Castle Brook	9.0	513	46375
Glen Brook	14.0	352	1580
Powell Brook	11.2	391	2110
Channel Brook	9.8	299	3062
Vale Brook	13.3	295	12625
Unnamed #1	15.5	441	1888
West Brook	13.2	396	1662
MacPhaerson	6.2	288	5100
Unmonitored (East)	12.2	416	4926
Unmonitored (West)	7.6	374	11040
Rain	31.3	1200	900
Snow	25.1	1200	900

the mean concentration of nitrogen or phosphorus. The concentrations used are given in Table 4. The rain and snow values are taken from Peters (1977). The nitrogen values are from rain sampled during this study. The amount of nitrogen in snow was assumed to be the same as in rain. The chloride values are from Shiomi and Kuntz (1973).

Hydrologic and Nutrient Budget

In Lake Memphremagog a single nutrient budget was considered inadequate to provide information concerning nutrient dynamics. Instead, separate budgets were constructed for each of the 4 basins with water being transported advectively between the basins (Figure 4). The budgets were constructed on a monthly basis beginning in August 1974 and ending in October 1975. As dissolved nitrogen values were not available until November 1974, the budget for this element commenced in December 1974. Budgets were constructed for water, total phosphorus, total nitrogen, and chloride. The chloride budget was to be used as a check of the other budgets, as chloride is conservative and therefore would not be lost by sedimentation.

The flow from segment to segment was considered to be purely advective, while the water within the basins was assumed to be completely mixed. The location of the basin limits (Indian Point, Skinners Island, and Lords Island) provide a certain amount of constriction between the basins and assure some reality to these assumptions. Estimates of turbulent mixing coefficients (Thomann, 1972) were attempted using the differences in chloride

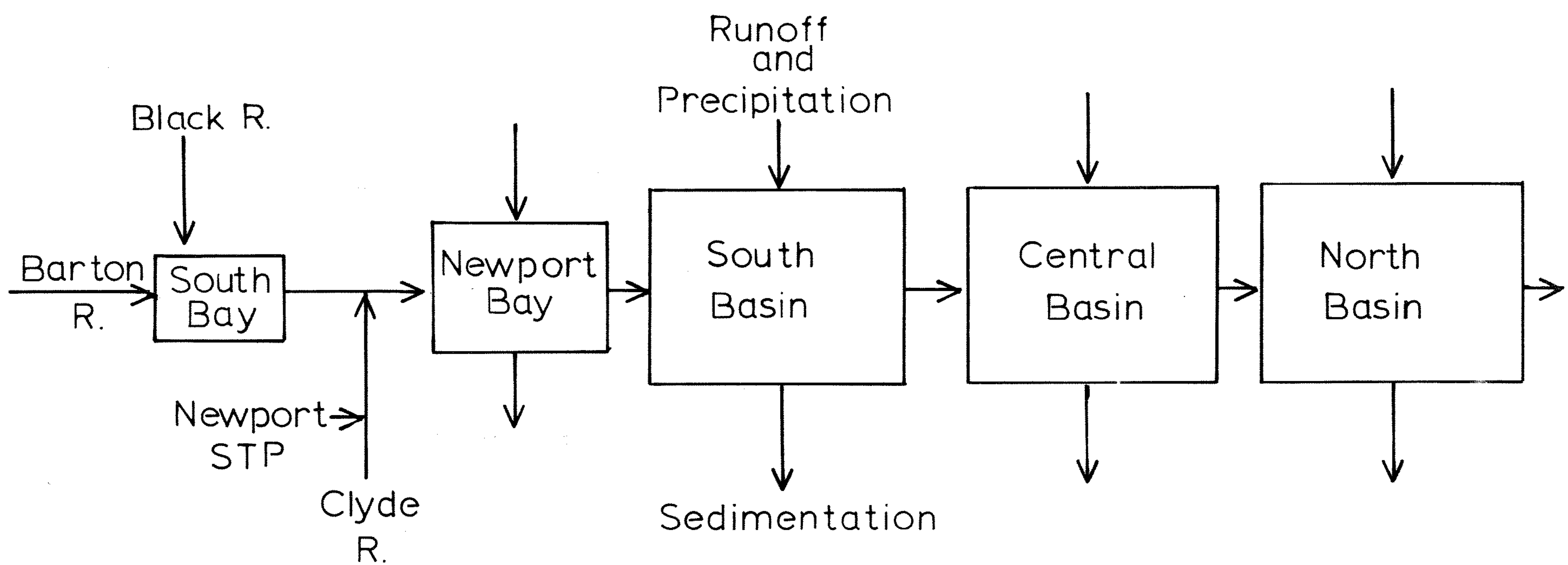

Figure 4. A conceptualization of the flow of water and nutrients through the major basins in Lake Memphremagog

concentration as estimates of turbulent transport. The differences in chloride concentrations were at some times so slight as to border on the limits of analytical precision and the coefficients obtained are suspect. The model using these coefficients will not be reported here.

The basic equation for the hydrologic budget is

$$\frac{\Delta S_i}{\Delta t} = \Sigma Q_{j,i} + Q_{i-1,i} - Q_{i,i+1} - E_i$$

where

$\frac{\Delta S_i}{\Delta t}$ = the change in volume in segment i

$\Sigma Q_{j,i}$ = the total water inputs from streams, direct runoff and precipitation to segment i

$Q_{i-1,i}$ = the inflow from the previous segment i-1

$Q_{i,i+1}$ = the loss to the next segment i+1

E_i = the evaporation from segment i

Contributions by groundwater were assumed to be negligible. Evaporation data was obtained from a reporting station in Lennoxville, Quebec and converted from pan to lake evaporation by multiplying by 0.7.

As the only terms that could not be measured were the flow between segments, the equation was rearranged to form

$$Q_{i,i+1} = \Sigma Q_{j,i} + Q_{i-1,i} - E_i - \Delta S_i / \Delta t$$

In the first segment (Newport Bay), $Q_{i-1,i}$ was zero and $Q_{i,i+1}$ could therefore be solved for this segment. With the assumption that changes in storage are instantaneously displaced down the entire lake, the inflows to the next 3 segments can then be solved sequentially.

The volumes of each of the basins were obtained by calculating the areas at each depth using a map prepared by the Canadian Hydrographic Service. Volumes between each depth were calculated using the formula for a truncated cone (Hutchinson, 1957), and these volumes were summed to produce the total segment volume. The volumes obtained are equivalent to the volume at a height of 208 m above Mean Sea Level. Changes in volume were calculated using the lake height data obtained from a U.S.G.S. recording gage situated in Newport, Vt. The volume of each segment for each month was calculated using the formula

$$V_{i,m} = (G_m - G_s)A_i + V_i$$

where

G_m = the gage height (m) on the first of the month

G_s = the standard mean gage height

A_i = the area of segment $\underline{i}$

V_i = the mean volume of segment $\underline{i}$

The term $\Delta S_i / \Delta t$ was the difference in volumes on a segment from the first of one month to the first of the next.

The nutrient budgets for chloride, total phosphorus, and total nitrogen were calculated on a monthly basis using the formula

$$V_i \frac{\Delta C}{\Delta t} = \Sigma W_{j,i} + C_{i-1}Q_{i-1,i} - C_iQ_{i,i+1} - K_iC_iV_i$$

where

V_i = volume of segment $\underline{i}$

$\Delta C / \Delta t$ = change in the mean concentration in segment $\underline{i}$

$\Sigma W_{j,i}$ = the external nutrient loading from the jth source to segment i

C_i = the mean monthly concentration of segment i

$C_{i-1}Q_{i-1,i}$ = the loading from the previous segment

$C_iQ_{i,i+1}$ = the loading to the next segment

K_iC_i = the net sedimentation loss

The only term that could not be measured was the net sedimentation coefficient, K_i. The equation was rearranged so that K_i could be estimated by difference.

$$K_i = (\Sigma W_{j,i} + C_{i-1}Q_{i-1,i} - C_iQ_{i,i+1}) / C_iV_i$$

The mean concentration (C_i) is a depth weighted value for the stations in the center of each segment (Stations 1, 3, 5, and 7). The storate term $\Delta C/ \Delta t$ was estimated by subtracting the amount present the previous month from the amount in the present month.

Nutrient Models

The model presented in this paper is designed to provide a basis for a predictive model for certain changes in nutrient loading. The model utilizes yearly rather than monthly values and therefore provides an estimate of the mean yearly concentration. The model is a steady-state mass-balance model using external nutrient loadings as the forcing functions. For each segment the equation used is

$$V_i \ \Delta C/ \Delta t = \Sigma W + C_{i-1}Q_{i-1,i} - C_iQ_{i,i+1} - K_iC_iV_i$$

At steady state, $V_i \ \Delta C/ \Delta t$ is zero and the equation becomes

$$C_i(Q_{i,i+1} + K_iV_i) - C_{i-1}(Q_{i-1,i}) = \Sigma W$$

In this arrangement the terms can be put in a matrix format of the form

$$(C)[A] = (W)$$

as described by Thomann (1972). The matrix [A] is a 4X4 square matrix which has as its terms

$$\begin{matrix} Q_{1,2} + V_1K_1 & 0 & 0 & 0 \\ -Q_{1,2} & Q_{2,3} + V_2K_2 & 0 & 0 \\ 0 & -Q_{2,3} & Q_{3,4} + V_3K_3 & 0 \\ 0 & 0 & -Q_{3,4} & Q_{4,0} + V_4K_4 \end{matrix}$$

The mean concentration (C) and the external loading (W) are 4X1 column matrices.

Lake concentrations can be predicted by rearranging the equation

$$(C) = [A]^{-1}(W)$$

using the inverse of matrix A.

With the assumption that the net sedimentation coefficients do not change over the years, future concentrations in the lake can be predicted using some estimate of hydrologic and nutrient loadings. In this study the model was used to estimate the new steady-state concentrations of nitrogen and phosphorus in the four basins if there were no sewage entering at Newport. This was done by using the total loadings estimated by the addition of the loading from the South Bay (Railroad Bridge) to the loading from the Upper Clyde River.

The model uses the total hydrologic and nutrient loading from November 1974 to October 1975. In the case of nitrogen, where no November data are available, mean loadings are calculated on an 11 month basis and then multiplied by 12. The net sedimentation rates were also obtained by multiplying the mean sedimentation coefficients obtained for each basin over the study period by 12.

RESULTS

Seasonal Changes in Temperature

Temperature was measured during the fall of 1974 and throughout the summer and fall of 1975 with a thermistor. The changes in temperature in the four basins during 1975 are illustrated in Figures 5 and 6.

In 1974 too few readings were taken to determine when fall overturn occurred. The Border station was isothermal on October 5 but Spinney and Central still were stratified. The surface temperatures on October 5 were 13 , the same found on October 5, 1975. By November 17, the surface temperatures had decreased to 6 and all stations were assumed to be isothermal. Ice formed in the South Basin by December 7. Ice was present in the North Basin by January 8. The Central Basin did not freeze over until late January.

The ice left the lake in late April and a stable thermocline had developed at all stations by June 2. The shallowest station Pender, located in Newport Bay, became isothermal by late July, the Border by early August. The northern, deeper stations retained theri stratification until late October.

Nutrients

The existence of a nutrient gradient can be readily seen in Figures 7 and 8 and in Table 5. The gradient is most readily seen in the changes in total and particulate phosphorus. Total phosphorus enters the lake at a mean concentration of 49 mg/m^3;

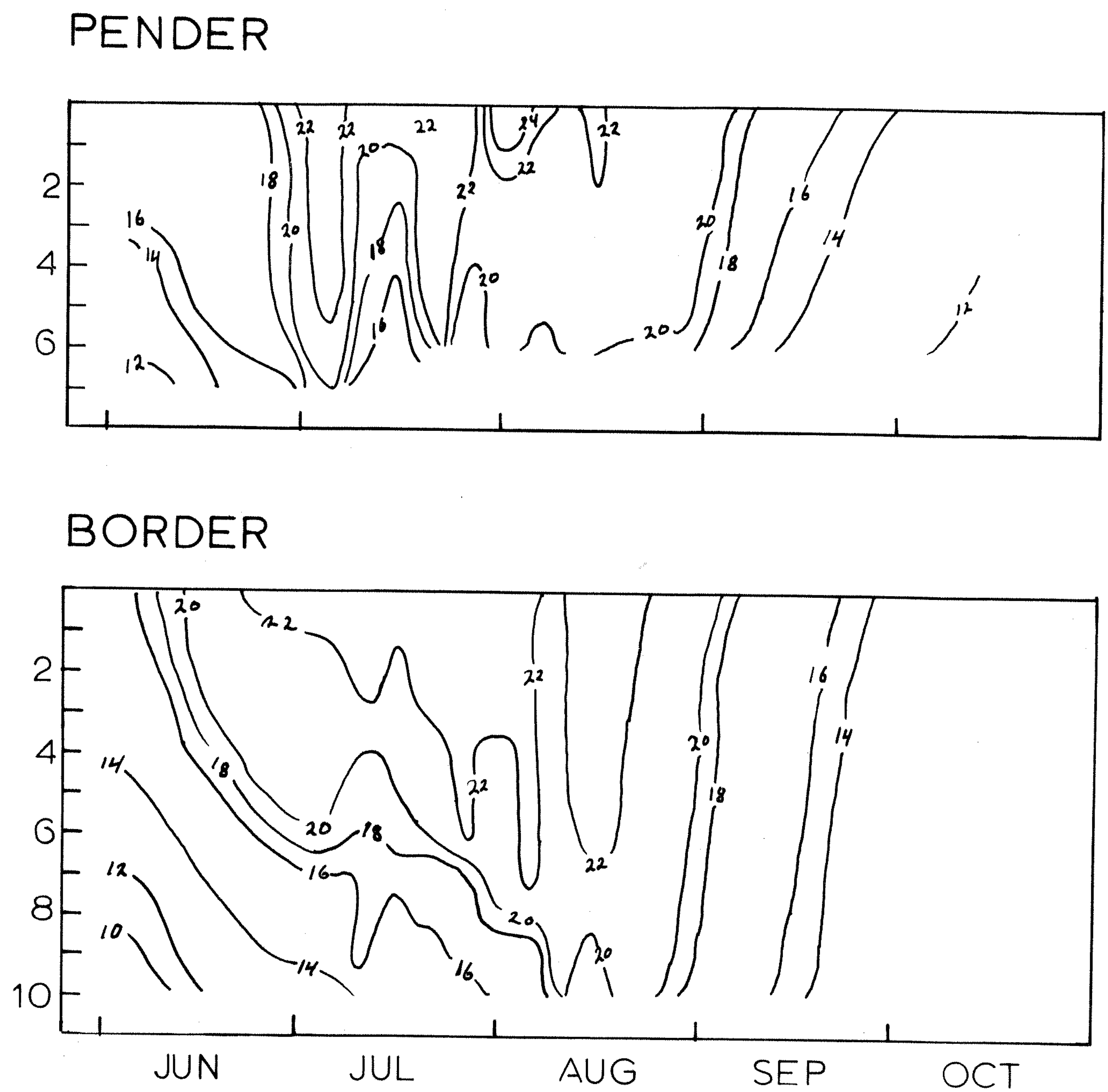

Figure 5. The changes in temperature during 1975 at the Pender Point and Border stations

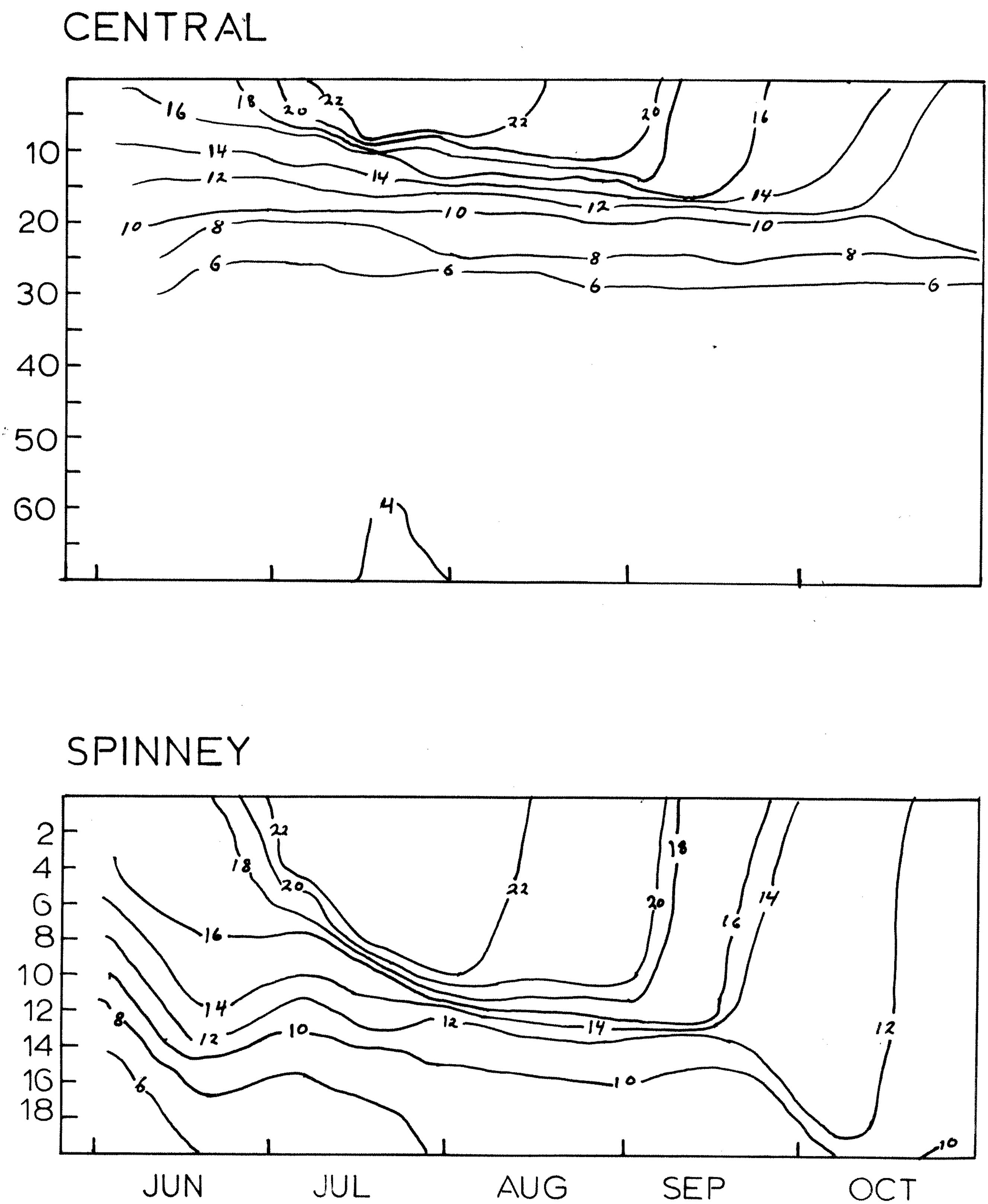

Figure 6. The changes in temperature during 1975 at the Central Basin and Spinney Point stations

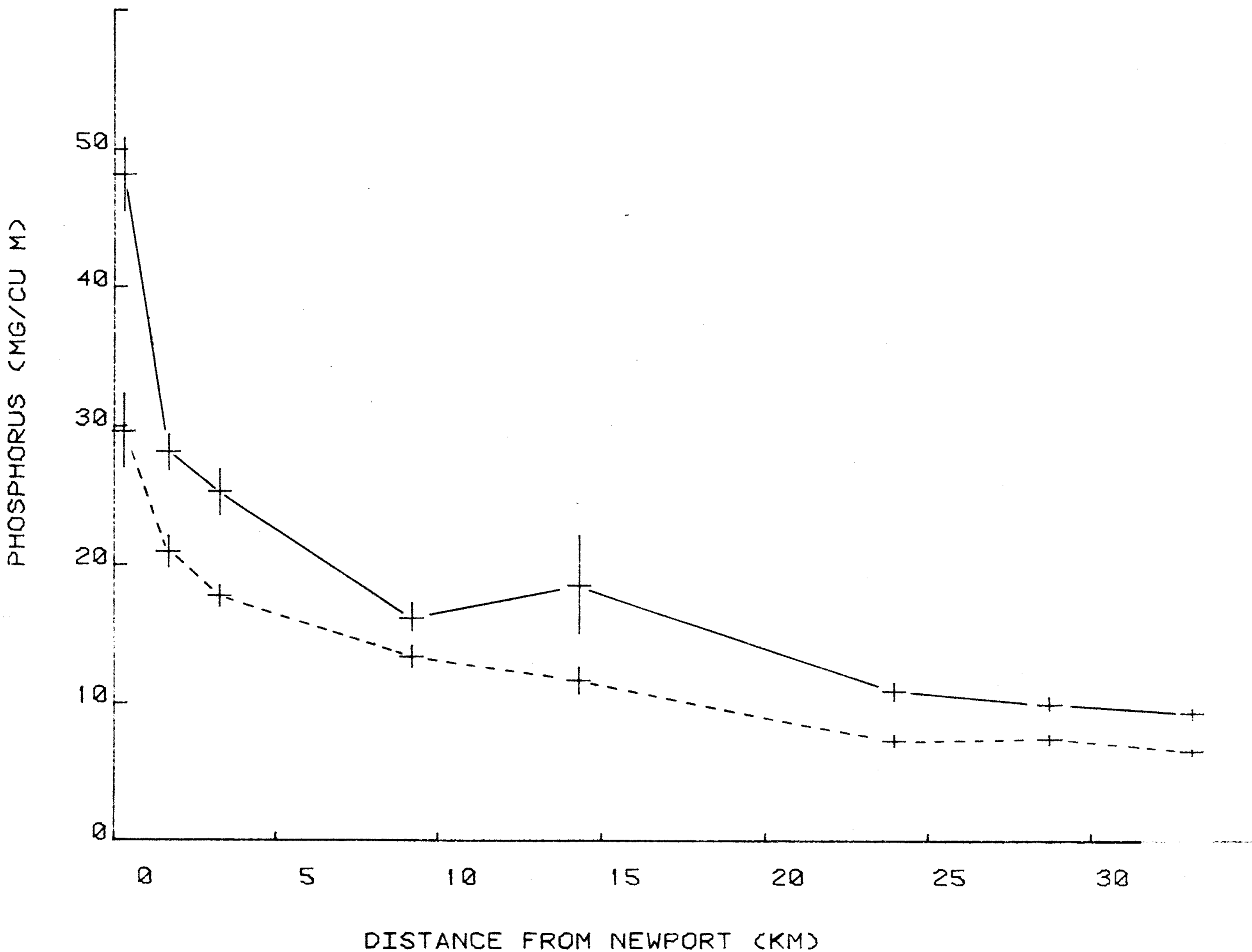

Figure 7. Changes in total and particulate phosphorus with distance from Newport, Vermont

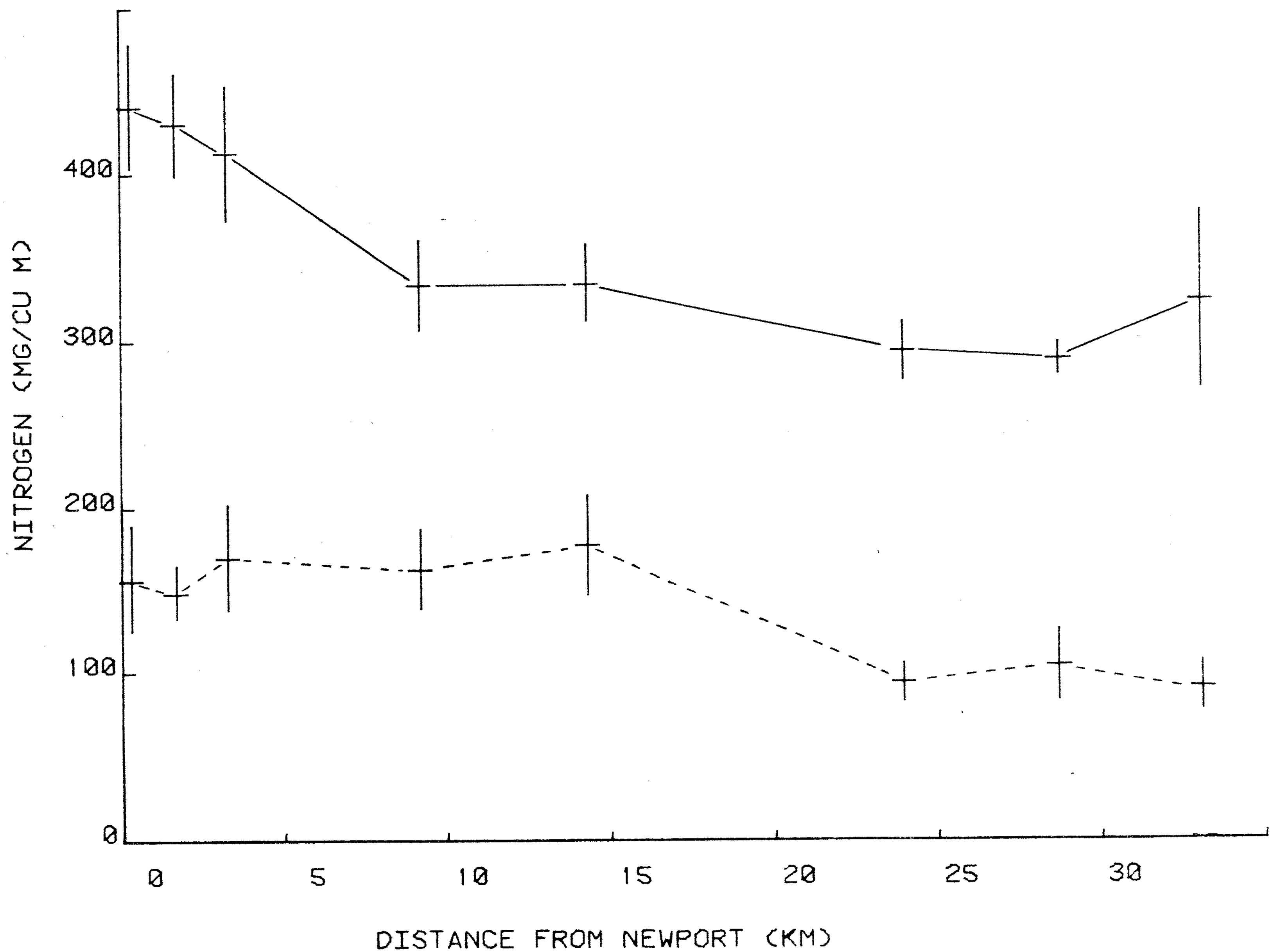

Figure 8. Changes in total and particulate nitrogen with distance from Newport, Vermont

Table 5. The arithmetic mean values of the measured variables of each of the stations along the longitudinal axis of Lake Memphremagog

STATION	TDN	PN	TN	CL	TP	PP	CAR	SD	CHA
INFLOW	305	157	462	7.3	48.1	29.7	898	1.8	7.13
PENDER	278	149	427	6.6	28.1	20.9	837	2.3	10.12
INDIAN	276	179	455	6.3	25.2	17.7	893	2.5	6.95
BORDER	203	163	366	5.7	16.1	13.3	862	3.1	7.91
SKINNER	192	177	369	5.7	18.5	11.6	959	3.2	8.90
CENTRAL	219	94	313	5.7	10.8	7.2	574	4.4	4.36
LORDS	184	104	288	5.7	9.9	7.3	570	4.3	4.85
SPINNEY	259	93	353	5.7	9.2	6.4	483	4.4	3.71

at the last station at Spinney Point, only 9 mg/m^3 remains. Particulate phosphorus remains at a fairly constant fraction (69%) of total phosphorus throughout the entire lake (Figure 9). Total nitrogen does not show any distinct gradient down the lake although particulate nitrogen does. Nitrogen apparently is neither fully utilized by the algae nor lost as the water flows down the lake.

The gradient in nutrients is reflected in corresponding changes in chlorophyll (Figure 10) and Secchi disk transparency (Figure 11). There is however some ambiguity as to the relationship of these two biological variables to the measured nutrients. Chlorophyll correlates best with particulate carbon (r = .54), then with particulate nitrogen (r = .31), and to almost the same degree with particulate phosphorus (r = .30). The inverse of transparency (1/SD) is only slightly correlated with chlorophyll (r = .28) and best correlated with total and particulate phosphorus (r = .75 and .78 respectively).

The ratios of the particulate forms of carbon, phosphorus and nitrogen also vary down the lake. The particulate carbon/nitrogen ratio remains constant (Figure 12), but both ratios involving phosphorus (C/P and N/P) increase until the Central Basin, after which they become relatively constant (Figures 13 and 14). The correlation between the mean N/P ratios and the C/P ratios is high (r = .98) indicating that the only variable changing in the ratios is phosphorus. These ratios indicate that the particulates in the water are becoming increasingly depleted of phosphorus relative to the amount of carbon and nitrogen. The approximately 30% of the total phosphorus remaining in the dissolved form appears

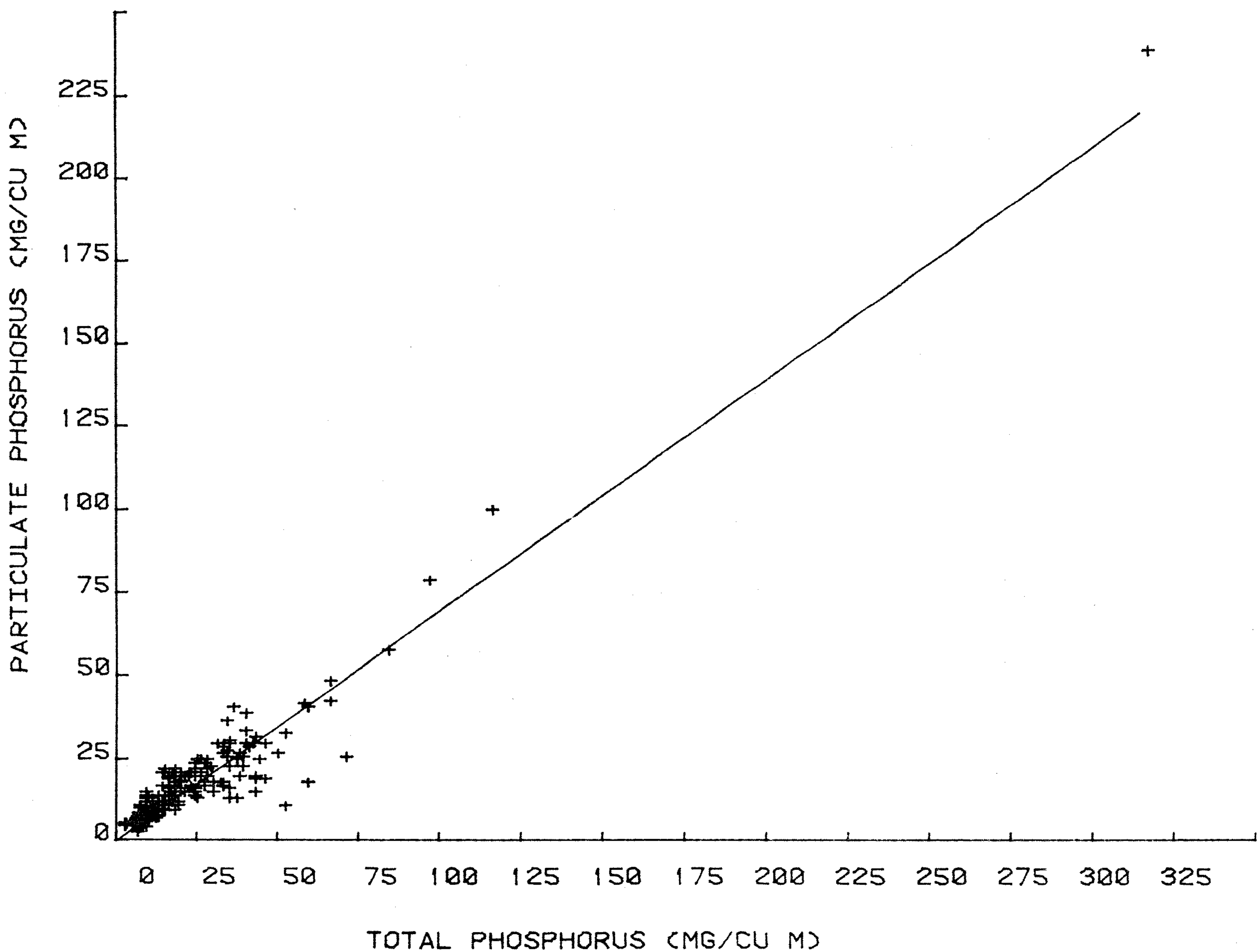

Figure 9. The relationship between total and particulate phosphorus in Lake Memphremagog

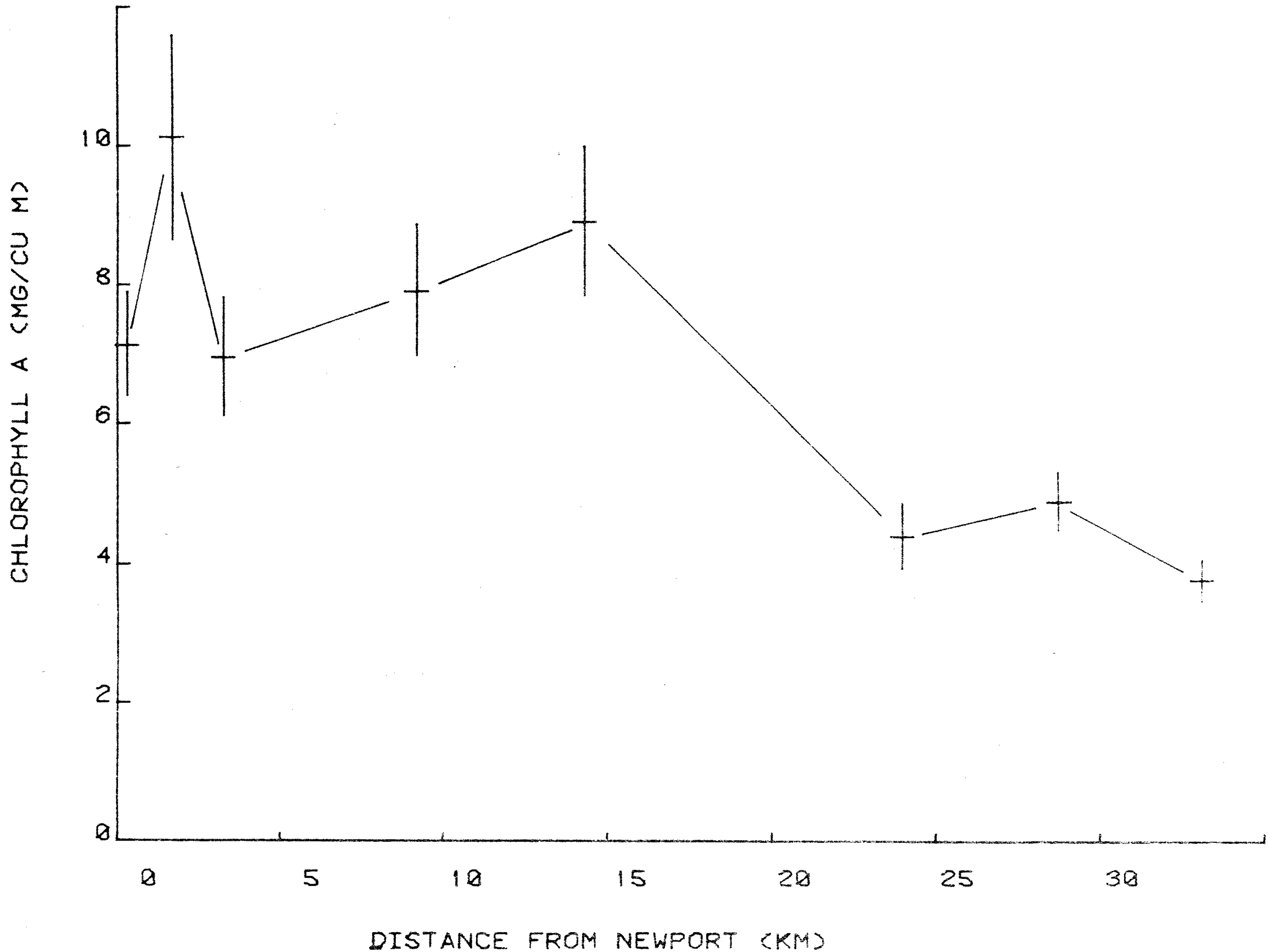

Figure 10. Changes in chlorophyll _a_ with distance from Newport, Vermont

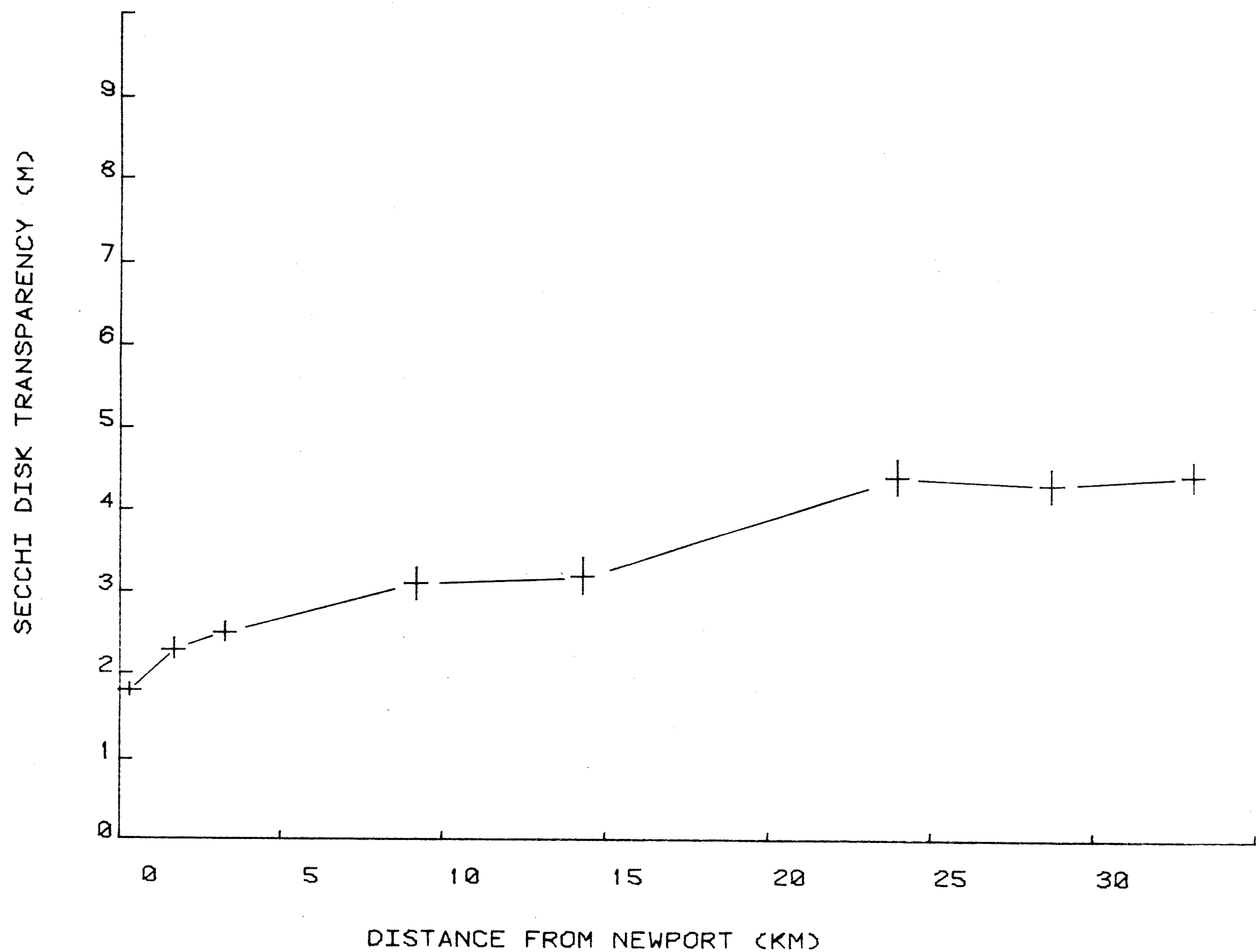

Figure 11. Changes in Secchi disk transparency with distance from Newport, Vermont

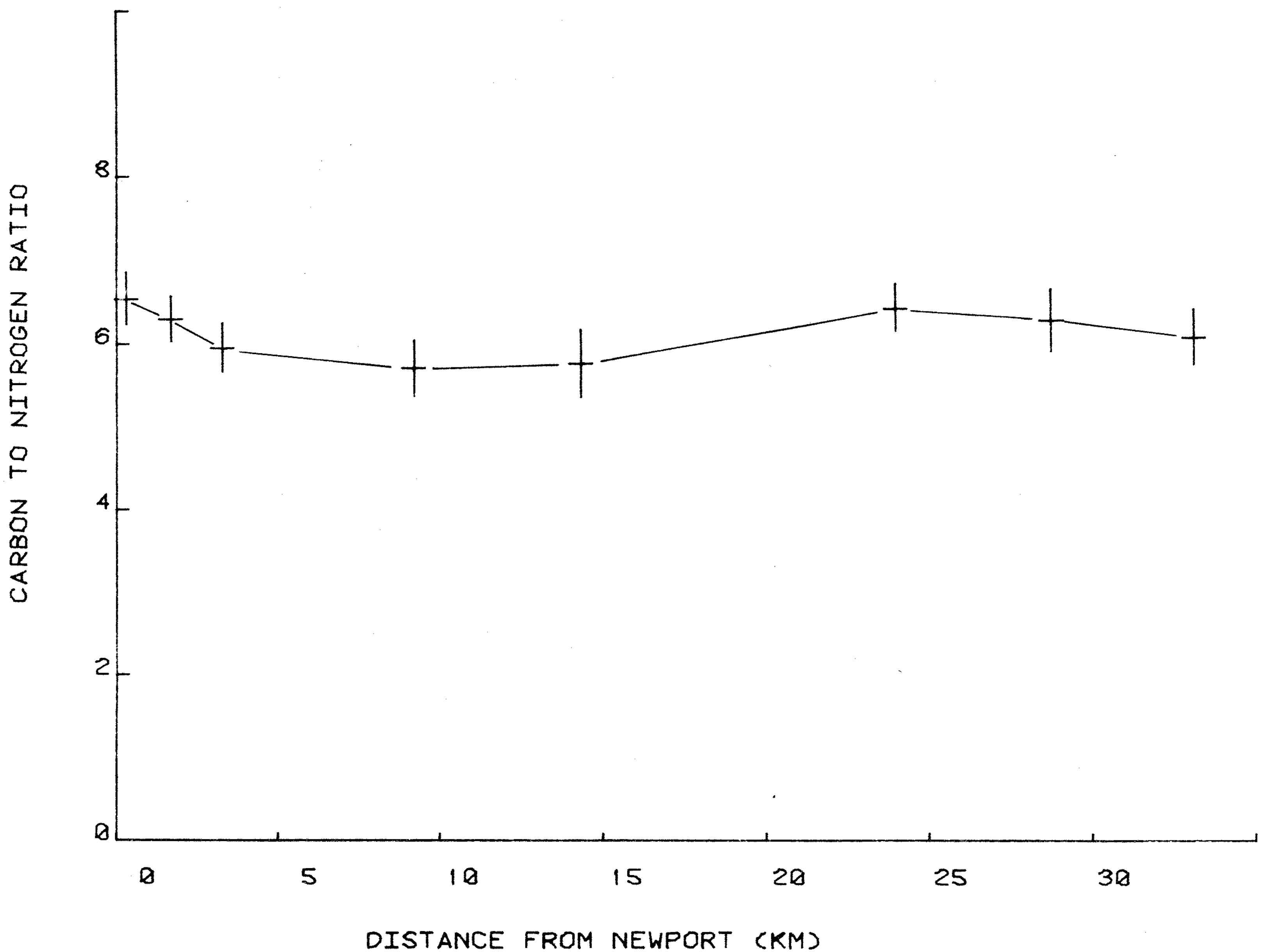

Figure 12. Changes in the carbon/nitrogen ratio with distance from Newport, Vermont

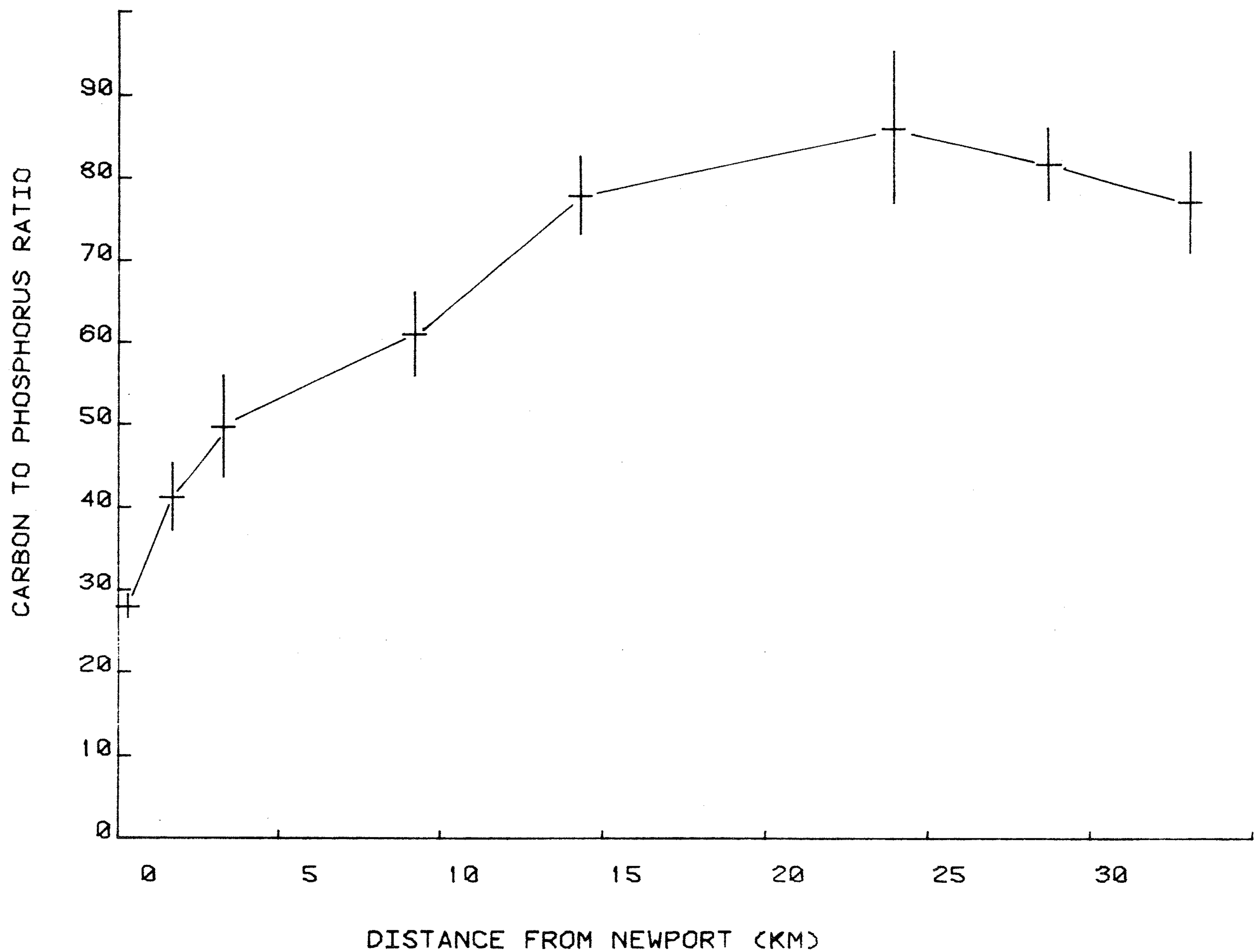

Figure 13. Changes in the carbon/phosphorus ratio with distance from Newport, Vermont

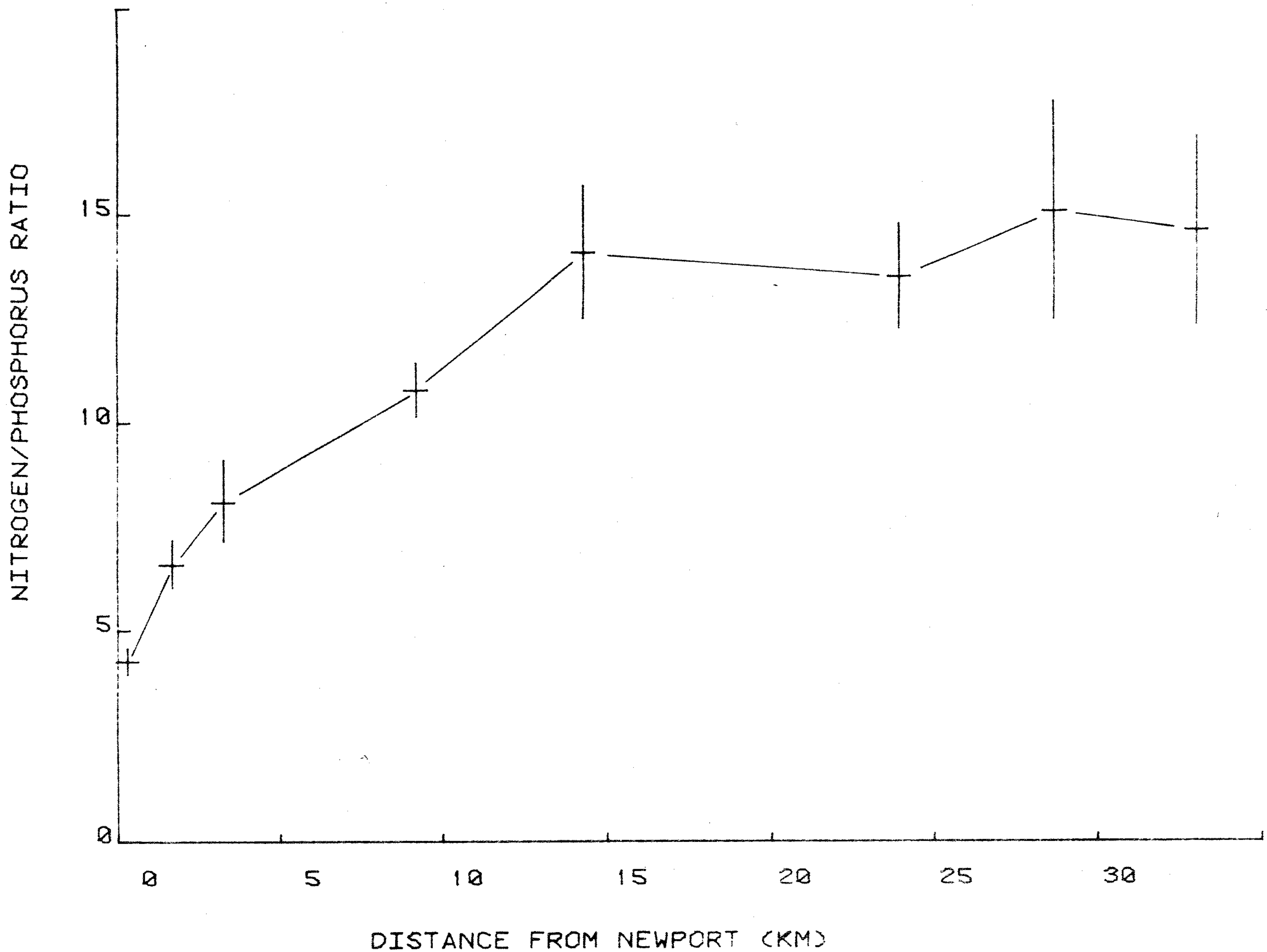

Figure 14. Changes in the nitrogen/phosphorus ratio with distance from Newport, Vermont

to be either unavailable or at steady state concentrations.

Distinct seasonal changes were found in the amount and form of nitrogen and phosphorus in the four basins. In all basins the particulate forms of carbon, nitrogen and phosphorus showed distinct increases in the summer which are reflected in increases in chlorophyll concentrations. As might be expected, the lowest particulate concentrations are found during the winter.

At Newport, Vt. the inflow concentrations of total and particulate phosphorus were variable with little indication of seasonal trends (Figure 15). This lack of seasonality may be the result of the dilution of the sewage-influenced Clyde River by the larger flow of the Black and Barton river system. As the final concentration would depend on the relative daily flows of the two sources, the result might be the highly fluctuating yet seasonally constant inflow of nutrient concentrations observed.

The lake stations in Newport Bay and the South Basin tended to have distinct increases in total phosphorus beginning in July and lasting until October. Although this trend is seen also in particulate nitrogen, there is no evidence of it in total nitrogen. This trend is most striking at the Border Station where there is a two-fold increase during August (Figure 16). These increases are associated with increases in chlorophyll concentration at the Border, shown in Figure 17. In the Central and North Basin, there are also seasonal peaks in total phosphorus but these occur in the winter and early summer (Figure 18) and are not associated with increases in particulate phosphorus or chlorophyll.

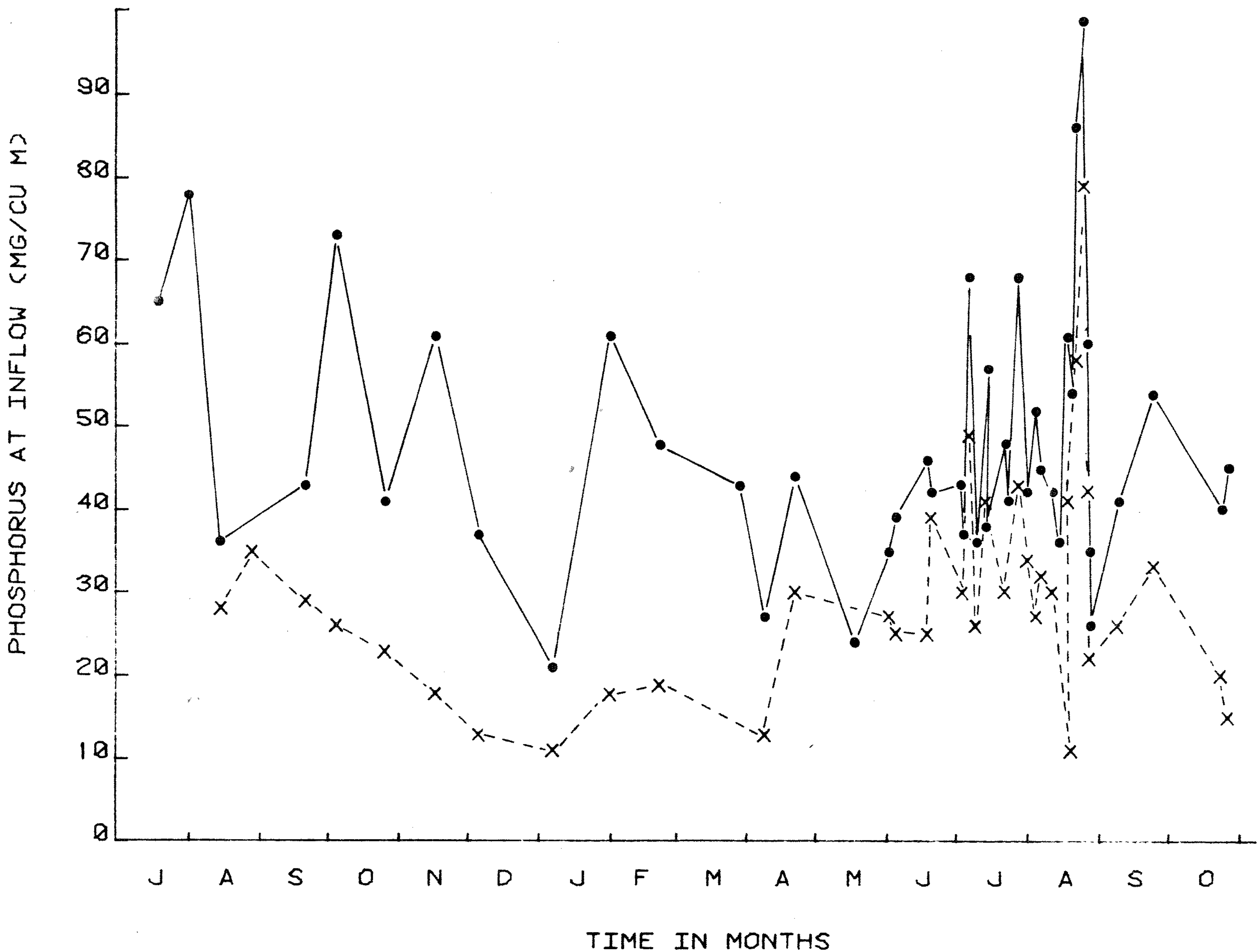

Figure 15. Seasonal changes in total and particulate phosphorus at the inflow at Newport, Vermont

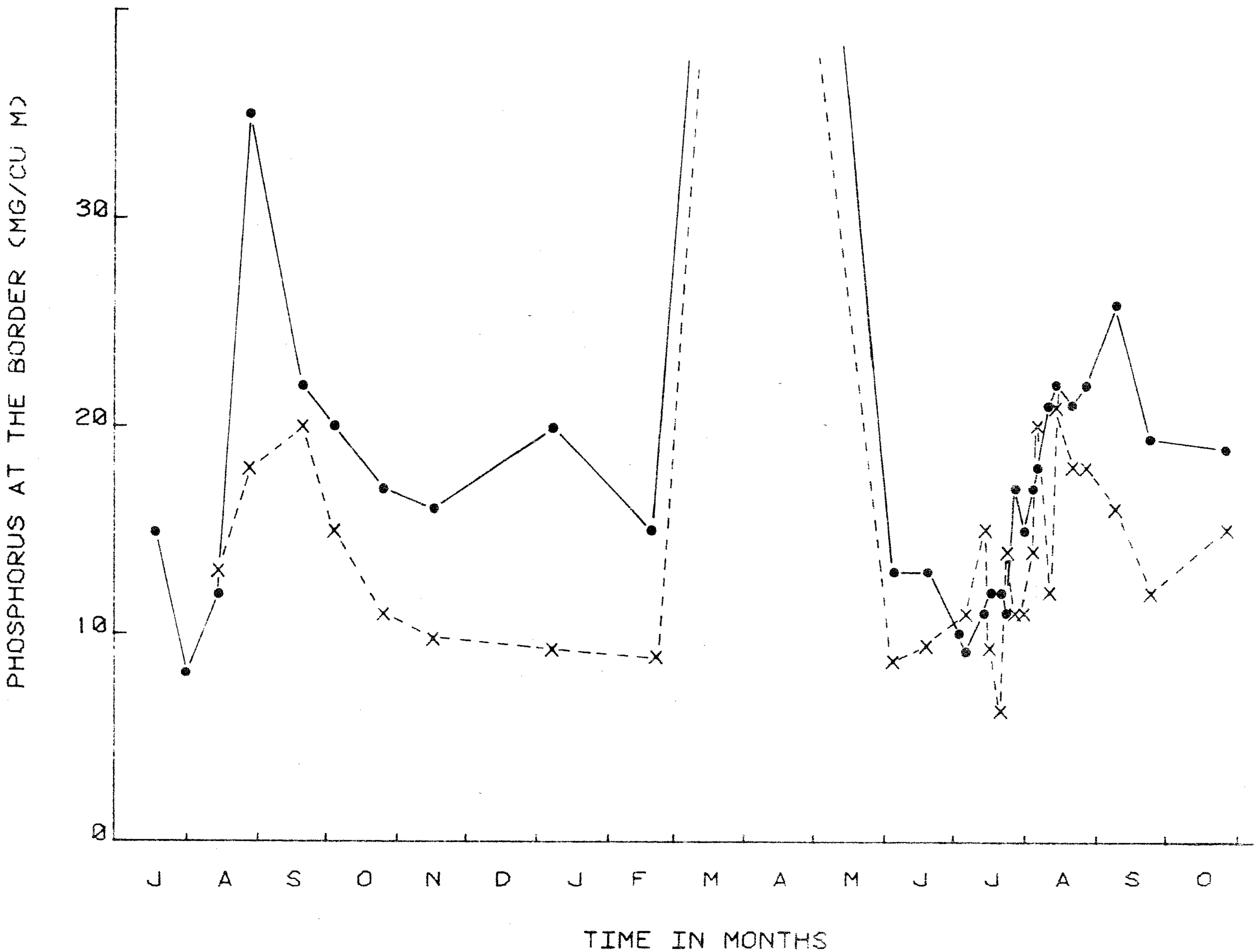

Figure 16. Seasonal changes in total and particulate phosphorus at the Border

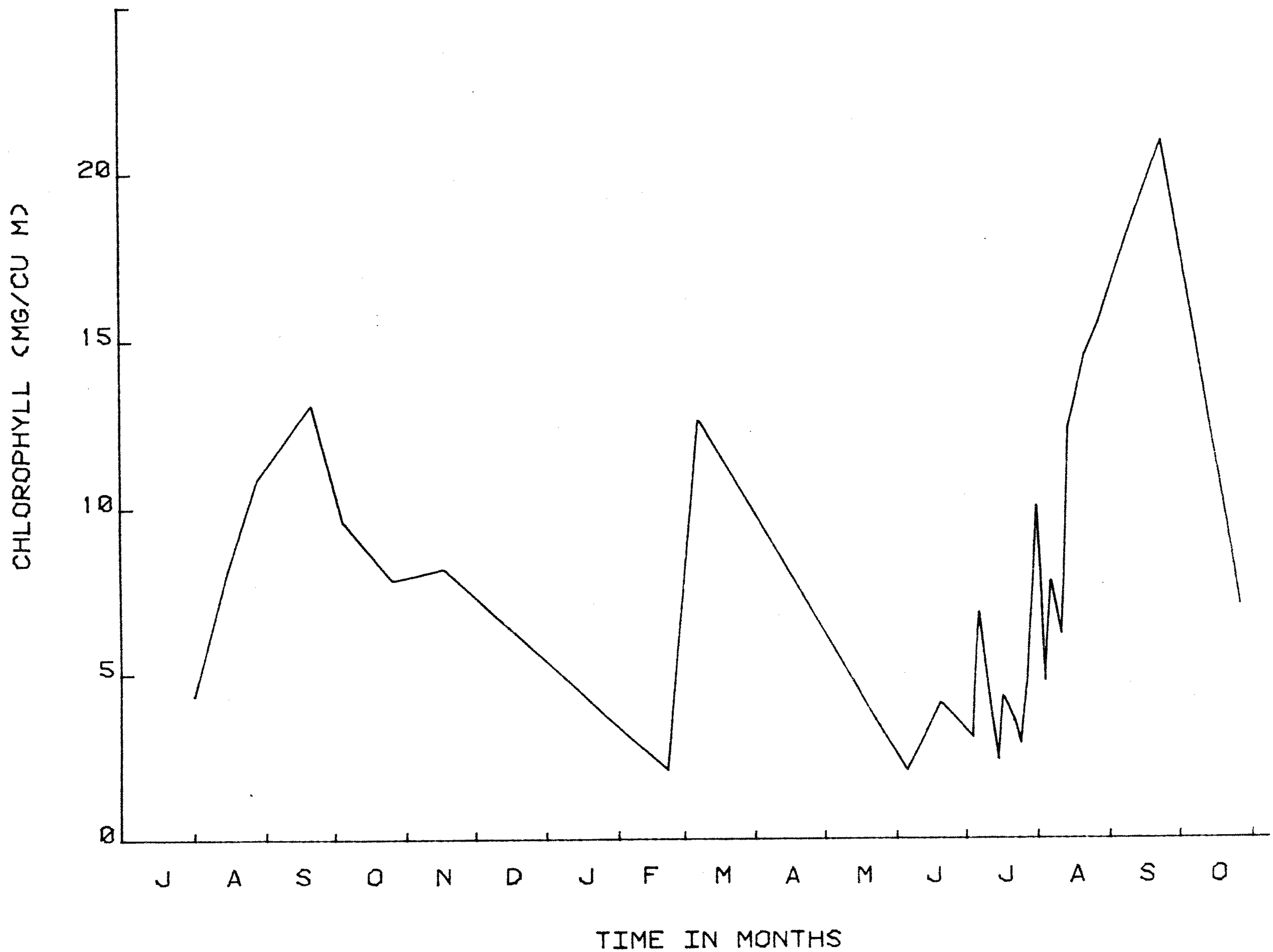

Figure 17. Seasonal changes in chlorophyll _a_ at the Border

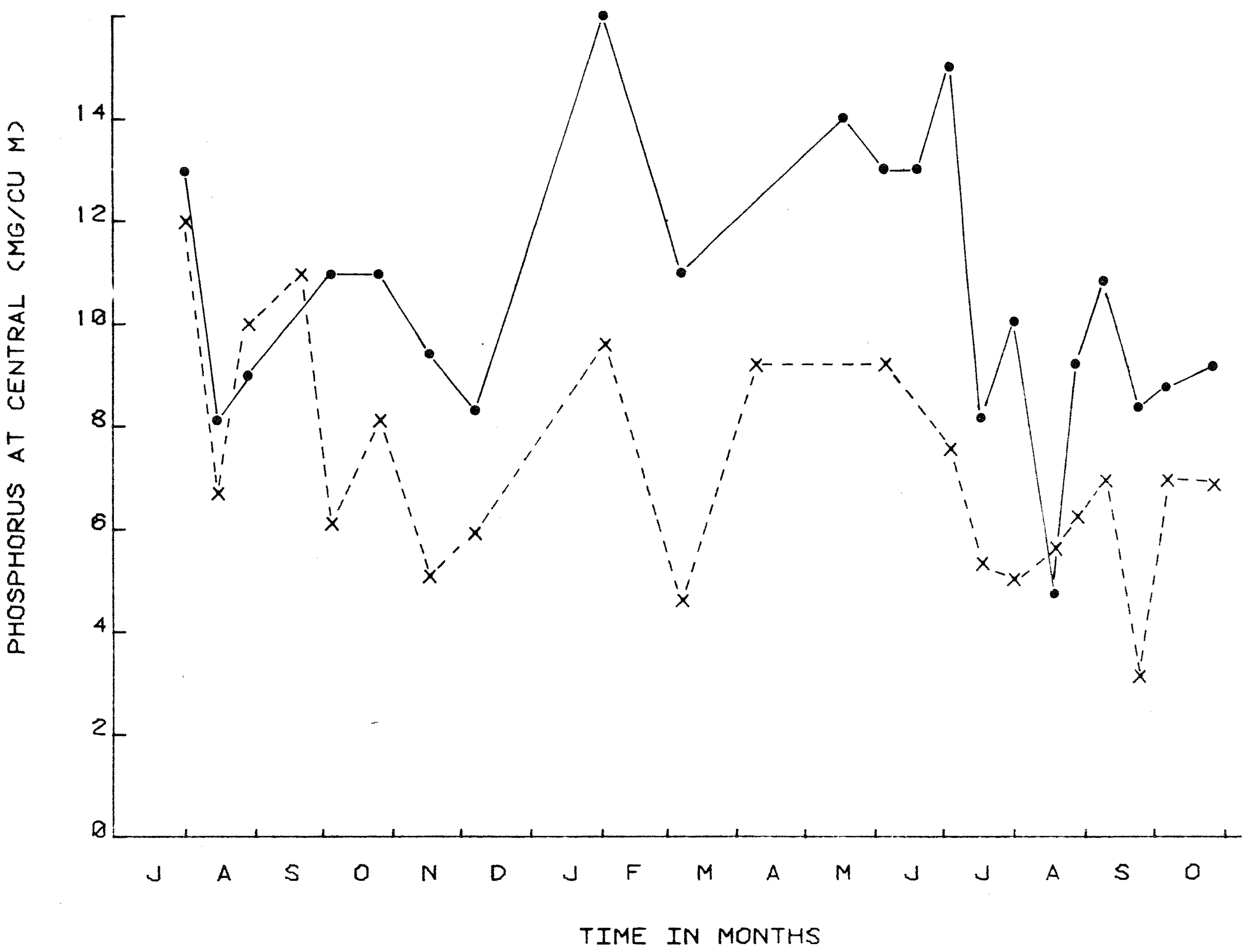

Figure 18. Seasonal changes in total and particulate phosphorus in the Central Basin

The elemental ratios at the different stations also show seasonal trends. The C/N ratio (Figure 19) shows some increase in late summer. The C/P and N/P ratios show distinct increases in the summer time (Figures 20 and 21).

A large amount of nutrients was found under the ice at the Border Station during March 1974. Total phosphorus concentration reached 320 mg/m^3 just under the ice on March 8, and 74% of this was in a particulate form. Normal phosphorus values were found at 3, 6, and 9 meters. This high phosphorus concentration was associated with a bloom of the dinoflagellate *Glenodinium*. The bloom was declining by March 13.

The Hydrologic Budget

The hydrologic loading to each segment is detailed in Tables 6 and 7. Runoff from the watershed accounted for 90% of the water input to the lake. Of this, 70% (63% of the total input) entered at Newport, Vermont. The South Basin's watershed accounted for 10% of the runoff. This clearly establishes the hydrologic dominance of the southern rivers. In each segment, excluding Newport Bay, approximately 80-90% of the segment's water enters from the previous segment.

Precipitation accounts for the remaining 10% of the hydrologic input and evaporation removes 5% of the total input. The remaining 95% of the input can be accounted for in changes in lake volume over the 15 months of the study or in outflow at Magog.

Over the period of study, the lake height varied over 0.6 m, having maxima in the spring and in late fall, with a minimum during

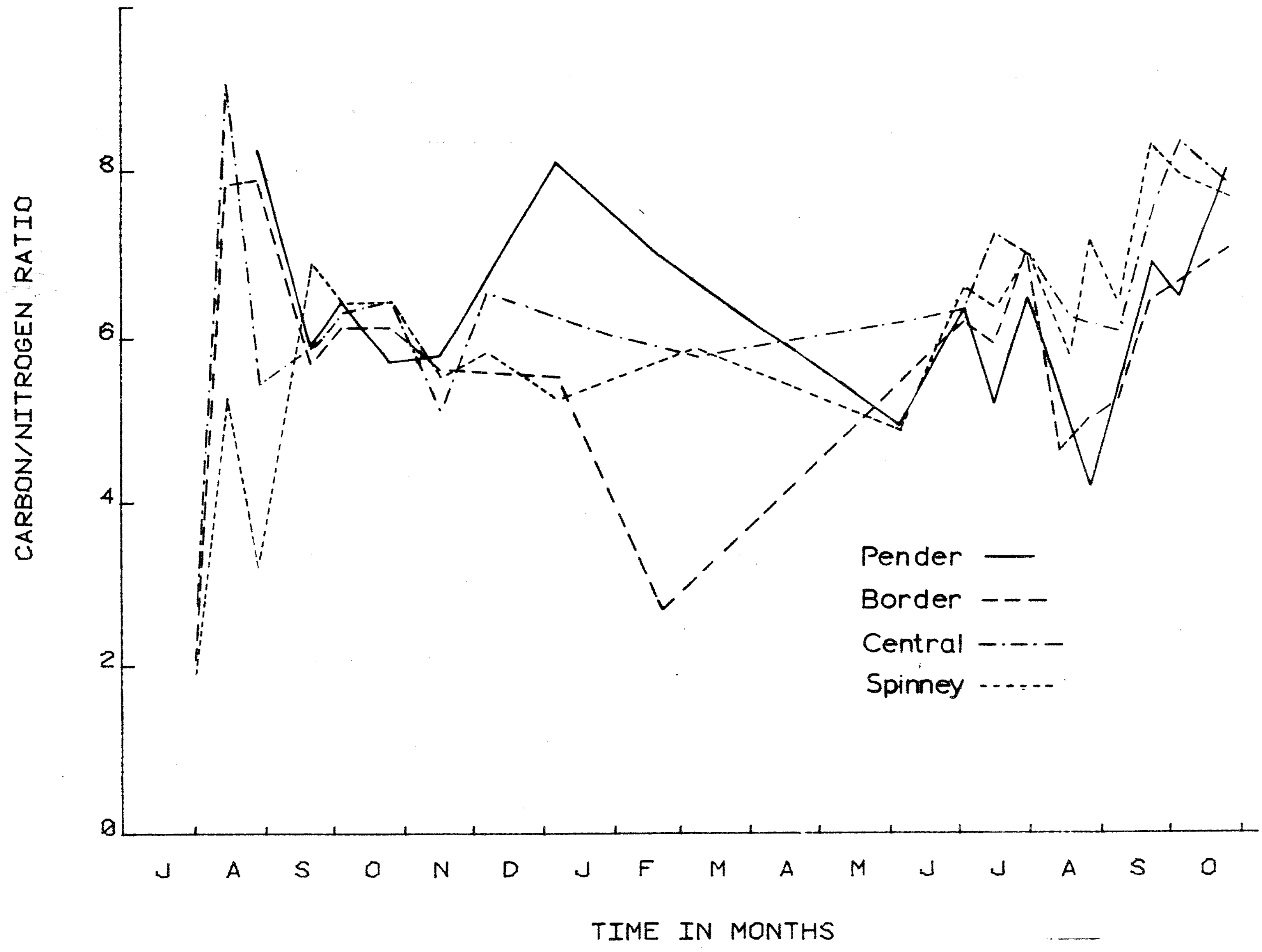

Figure 19. Seasonal changes in the C/N ratio in the four basins

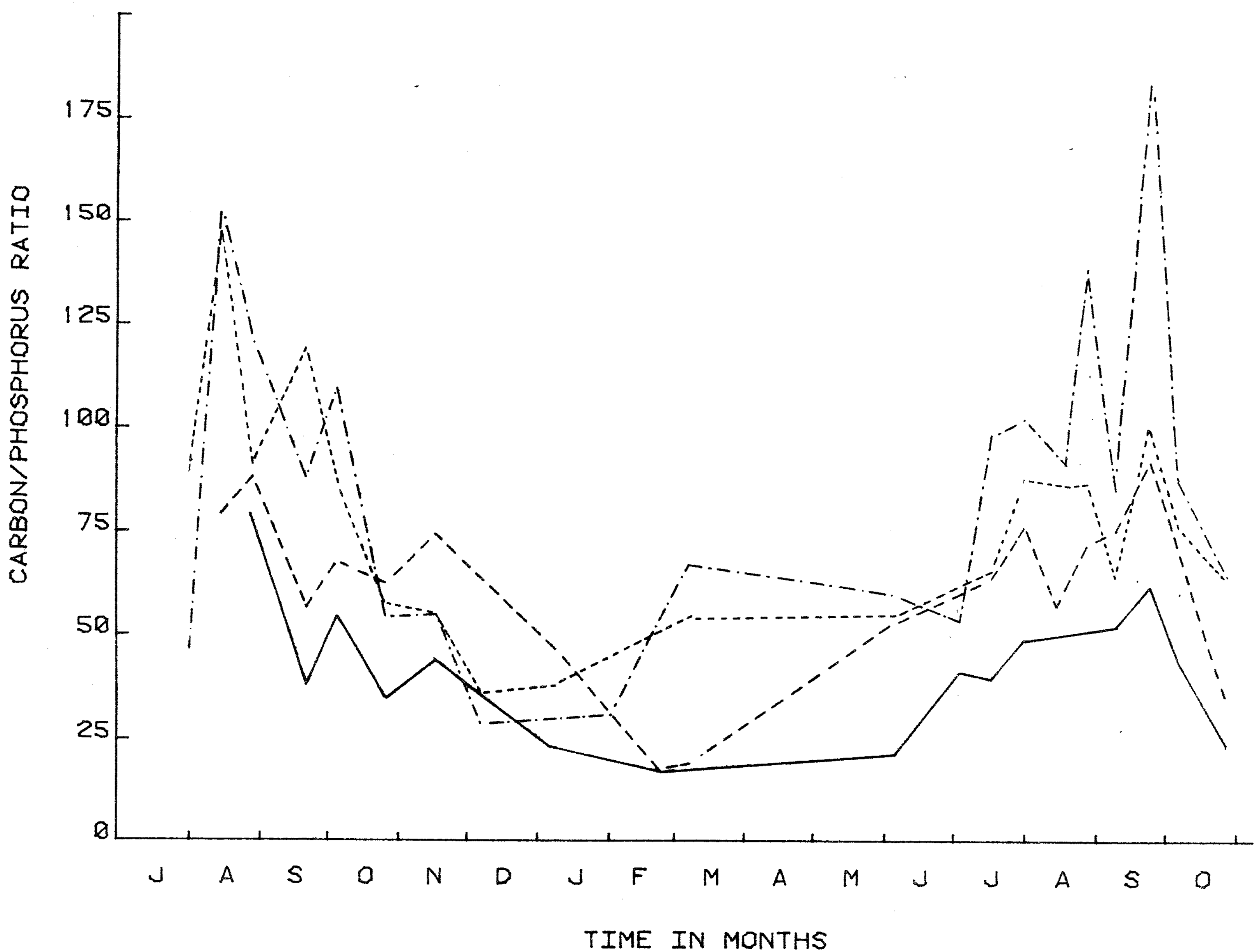

Figure 20. Seasonal changes in the C/P ratio in the four basins

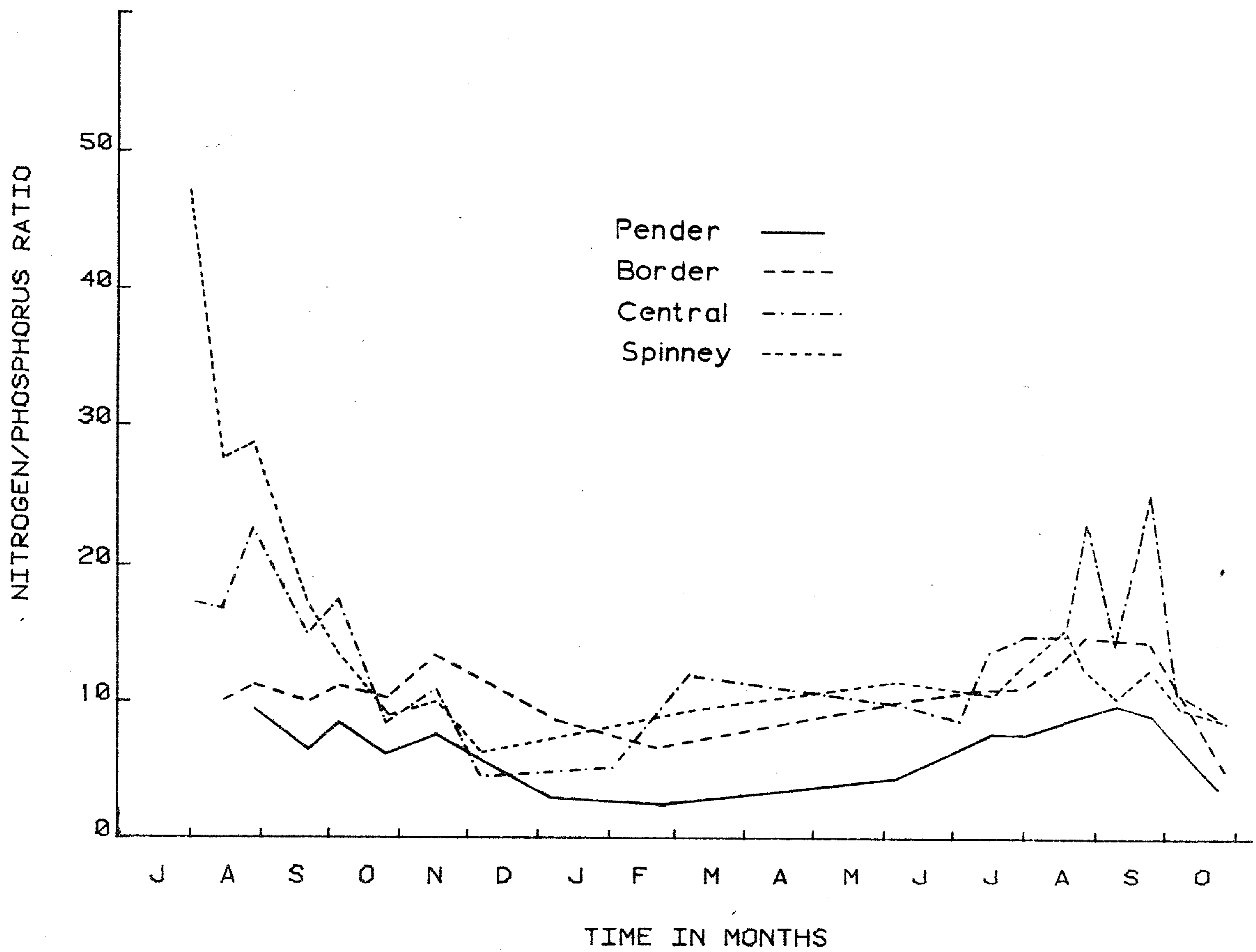

Figure 21. Seasonal changes in the N/P ratio in the four basins

Table 6. The sources of water to the major basins of Lake Memphremagog from August 1974 to October 1975

NEWPORT BAY

MØ	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
A	28.580e 06	28.435e 06	99	14.435e 04	1	.000e 00	0
S	23.237e 06	23.009e 06	99	22.844e 04	1	.000e 00	0
O	25.522e 06	25.425e 06	100	97.208e 03	0	.000e 00	0
N	50.889e 06	50.659e 06	100	22.990e 04	0	.000e 00	0
D	54.361e 06	54.252e 06	100	10.887e 04	0	.000e 00	0
J	38.536e 06	38.369e 06	100	16.671e 04	0	.000e 00	0
F	24.897e 06	24.782e 06	100	11.471e 04	0	.000e 00	0
M	72.636e 06	72.452e 06	100	18.470e 04	0	.000e 00	0
A	13.583e 07	13.572e 07	100	10.742e 04	0	.000e 00	0
M	81.073e 06	80.934e 06	100	13.852e 04	0	.000e 00	0
J	33.293e 06	33.193e 06	100	10.012e 04	0	.000e 00	0
J	18.419e 06	18.143e 06	99	27.607e 04	1	.000e 00	0
A	17.297e 06	16.993e 06	98	30.426e 04	2	.000e 00	0
S	47.986e 06	47.727e 06	99	25.857e 04	1	.000e 00	0
O	68.819e 06	68.644e 06	100	17.498e 04	0	.000e 00	0
MEAN	48.091e 06	47.916e 06	100	17.566e 04	0	.000e 00	0

SOUTH BASIN

MØ	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
A	35.696e 06	36.635e 05	10	30.180e 05	8	29.014e 06	81
S	31.710e 06	34.727e 05	11	47.760e 05	15	23.461e 06	74
O	31.450e 06	37.259e 05	12	20.324e 05	6	25.691e 06	82
N	62.675e 06	74.934e 05	12	48.065e 05	8	50.375e 06	80
D	64.144e 06	75.420e 05	12	22.762e 05	4	54.326e 06	85
J	47.767e 06	51.862e 05	11	34.855e 05	7	39.096e 06	82
F	30.641e 06	34.050e 05	11	23.982e 05	8	24.838e 06	81
M	87.234e 06	10.765e 06	12	38.615e 05	4	72.607e 06	83
A	15.747e 07	20.243e 06	13	22.458e 05	1	13.498e 07	86
M	92.507e 06	87.762e 05	9	28.961e 05	3	80.835e 06	87
J	38.925e 06	35.082e 05	9	20.933e 05	5	33.324e 06	86
J	26.704e 06	26.149e 05	10	57.719e 05	22	18.317e 06	69
A	26.536e 06	29.882e 05	11	63.613e 05	24	17.187e 06	65
S	60.246e 06	71.955e 05	12	54.061e 05	9	47.644e 06	79
O	80.753e 06	84.850e 05	11	36.582e 05	5	68.610e 06	85
MEAN	58.297e 06	66.043e 05	11	36.725e 05	6	48.020e 06	82

Table 6. continued

CENTRAL BASIN

MØ	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
A	49.ØØ2e Ø6	25.68Øe Ø5	5	16.59Øe Ø5	3	44.775e Ø6	91
S	41.244e Ø6	22.163e Ø5	5	26.253e Ø5	6	36.4Ø2e Ø6	88
O	38.584e Ø6	24.812e Ø5	6	11.172e Ø5	3	34.986e Ø6	91
N	61.481e Ø6	68.94Øe Ø5	11	26.421e Ø5	4	51.945e Ø6	84
D	71.7Ø5e Ø6	7Ø.413e Ø5	1Ø	12.512e Ø5	2	63.412e Ø6	88
J	65.535e Ø6	41.459e Ø5	6	19.159e Ø5	3	59.474e Ø6	91
F	32.996e Ø6	22.553e Ø5	7	13.182e Ø5	4	29.422e Ø6	89
M	99.559e Ø6	1Ø.812e Ø6	11	21.226e Ø5	2	86.624e Ø6	87
A	16.335e Ø7	22.329e Ø6	14	12.345e Ø5	1	13.979e Ø7	86
M	97.839e Ø6	87.2Ø7e Ø5	9	15.919e Ø5	2	87.527e Ø6	89
J	43.258e Ø6	25.412e Ø5	6	11.5Ø7e Ø5	3	39.566e Ø6	91
J	28.972e Ø6	12.195e Ø5	4	31.727e Ø5	11	24.58Øe Ø6	85
A	29.296e Ø6	15.71Øe Ø5	5	34.967e Ø5	12	24.229e Ø6	83
S	62.7ØØe Ø6	66.2Ø5e Ø5	11	29.716e Ø5	5	53.1Ø8e Ø6	85
O	86.738e Ø6	83.567e Ø5	1Ø	2Ø.1Ø9e Ø5	2	76.37Øe Ø6	88
MEAN	64.817e Ø6	59.848e Ø5	9	2Ø.187e Ø5	3	56.814e Ø6	88

NORTH BASIN

MØ	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
A	58.561e Ø6	31.552e Ø5	5	14.393e Ø5	2	53.967e Ø6	92
S	48.792e Ø6	27.Ø53e Ø5	6	22.776e Ø5	5	43.8Ø9e Ø6	9Ø
O	44.533e Ø6	3Ø.428e Ø5	7	96.919e Ø4	2	4Ø.521e Ø6	91
N	66.656e Ø6	87.6Ø5e Ø5	13	22.921e Ø5	3	55.6Ø3e Ø6	83
D	81.335e Ø6	89.458e Ø5	11	1Ø.855e Ø5	1	71.3Ø4e Ø6	88
J	78.8Ø7e Ø6	51.977e Ø5	7	16.622e Ø5	2	71.947e Ø6	91
F	36.238e Ø6	27.668e Ø5	8	11.436e Ø5	3	32.328e Ø6	89
M	11.489e Ø7	13.826e Ø6	12	18.415e Ø5	2	99.225e Ø6	86
A	18.348e Ø7	28.74Øe Ø6	16	1Ø.71Øe Ø5	1	15.367e Ø7	84
M	1Ø.76Øe Ø7	11.12Øe Ø6	1Ø	13.811e Ø5	1	95.1Ø4e Ø6	88
J	47.724e Ø6	31.26Øe Ø5	7	99.827e Ø4	2	43.6ØØe Ø6	91
J	31.961e Ø6	14.Ø96e Ø5	4	27.525e Ø5	9	27.799e Ø6	87
A	32.923e Ø6	18.645e Ø5	6	3Ø.336e Ø5	9	28.Ø25e Ø6	85
S	69.771e Ø6	84.Ø64e Ø5	12	25.781e Ø5	4	58.787e Ø6	84
O	96.743e Ø6	1Ø.665e Ø6	11	17.445e Ø5	2	84.334e Ø6	87
MEAN	73.335e Ø6	75.821e Ø5	1Ø	17.513e Ø5	2	64.Ø31e Ø6	87

Table 7. The hydrologic budget for Lake Memphremagog from August 1974 to October 1975

NEWPORT BAY

MO	INFLOW	STORAGE	EVAP	OUTFLOW
A	28.580e 06	-6.124e 05	17.815e 04	29.014e 06
S	23.237e 06	-3.383e 05	11.386e 04	23.461e 06
O	25.522e 06	-1.691e 05	.000e 00	25.691e 05
N	50.889e 06	51.326e 04	.000e 00	50.375e 06
D	54.361e 06	34.995e 03	.000e 00	54.326e 06
J	38.536e 06	-5.599e 05	.000e 00	39.096e 05
F	24.897e 06	58.325e 03	.000e 00	24.838e 06
M	72.636e 06	29.162e 03	.000e 00	72.607e 06
A	13.583e 07	84.571e 04	.000e 00	13.498e 07
M	81.073e 06	46.660e 03	19.155e 04	80.835e 06
J	33.293e 06	-2.450e 05	21.432e 04	33.324e 06
J	18.419e 06	-1.341e 05	23.575e 04	18.317e 06
A	17.297e 06	-7.582e 04	18.619e 04	17.187e 06
S	47.986e 06	24.497e 04	96.443e 03	47.644e 06
O	68.819e 06	13.998e 04	69.653e 03	68.610e 06
MEAN	48.091e 06	-1.478e 04	85.727e 03	48.020e 06

SOUTH BASIN

MO	INFLOW	STORAGE	EVAP	OUTFLOW
A	35.696e 06	-1.280e 07	37.247e 05	44.775e 06
S	31.710e 06	-7.073e 06	23.804e 05	36.402e 06
O	31.450e 06	-3.536e 06	.000e 00	34.986e 06
N	62.675e 06	10.731e 06	.000e 00	51.945e 06
D	64.144e 06	73.164e 04	.000e 00	63.412e 06
J	47.767e 06	-1.171e 07	.000e 00	59.474e 06
F	30.641e 06	12.194e 05	.000e 00	29.422e 06
M	87.234e 06	60.970e 04	.000e 00	86.624e 06
A	15.747e 07	17.681e 06	.000e 00	13.979e 07
M	92.507e 06	97.552e 04	40.047e 05	87.527e 06
J	38.925e 06	-5.121e 06	44.808e 05	39.566e 06
J	26.704e 06	-2.805e 06	49.289e 05	24.580e 06
A	26.536e 06	-1.585e 06	38.927e 05	24.229e 06
S	60.246e 06	51.215e 05	20.164e 05	53.108e 06
O	80.753e 06	29.266e 05	14.563e 05	76.370e 06
MEAN	58.297e 06	-3.089e 05	17.923e 05	56.814e 06

Table 7. continued

CENTRAL BASIN

MO	INFLOW	STORAGE	EVAP	OUTFLOW
A	49.002e 06	-7.013e 06	20.474e 05	53.967e 06
S	41.244e 06	-3.874e 06	13.085e 05	43.809e 06
O	38.584e 06	-1.937e 06	.000e 00	40.521e 06
N	61.481e 06	58.773e 05	.000e 00	55.603e 06
D	71.705e 06	40.072e 04	.000e 00	71.304e 06
J	65.535e 06	-6.412e 06	.000e 00	71.947e 06
F	32.996e 06	66.787e 04	.000e 00	32.328e 06
M	99.559e 06	33.394e 04	.000e 00	99.225e 06
A	16.335e 07	96.841e 05	.000e 00	15.367e 07
M	97.839e 06	53.429e 04	22.013e 05	95.104e 06
J	43.258e 06	-2.805e 06	24.630e 05	43.600e 06
J	28.972e 06	-1.536e 06	27.093e 05	27.799e 06
A	29.296e 06	-8.682e 05	21.397e 05	28.025e 06
S	62.700e 06	28.051e 05	11.084e 05	58.787e 06
O	86.738e 06	16.029e 05	80.048e 04	84.334e 06
MEAN	64.817e 06	-1.692e 05	98.520e 04	64.001e 06

NORTH BASIN

MO	INFLOW	STORAGE	EVAP	OUTFLOW
A	58.561e 06	-6.106e 06	17.762e 05	62.891e 06
S	48.792e 06	-3.373e 06	11.352e 05	51.030e 06
O	44.533e 06	-1.686e 06	.000e 00	46.219e 06
N	66.656e 06	51.173e 05	.000e 00	61.539e 06
D	81.335e 06	34.891e 04	.000e 00	80.986e 06
J	78.807e 06	-5.583e 06	.000e 00	84.389e 06
F	36.238e 06	58.152e 04	.000e 00	35.657e 06
M	11.489e 07	29.076e 04	.000e 00	11.460e 07
A	18.348e 07	84.320e 05	.000e 00	17.505e 07
M	10.760e 07	46.521e 04	19.098e 05	10.523e 07
J	47.724e 06	-2.442e 06	21.368e 05	48.030e 06
J	31.961e 06	-1.337e 06	23.505e 05	30.948e 06
A	32.923e 06	-7.560e 05	18.563e 05	31.823e 06
S	69.771e 06	24.424e 05	96.156e 04	66.367e 06
O	96.743e 06	13.956e 05	69.446e 04	94.653e 06
MEAN	73.335e 06	-1.473e 05	85.472e 04	72.627e 06

the winter months. The change in water height is not the result of evaporation, but of manipulation of the outflow at the Dominion Textile Company at Magog. The outflow volumes are gaged at Magog and these values were used to estimate the validity of our budget. The results, shown in Figure 22, indicate that the relationship is quite good (r = .981) although the budget tends to underestimate the outflow at low flows.

The mean residence time in the lake is estimated by dividing the lake's volume by the total yearly outflow. The total estimated residence time is 1.88 years which is similar to the 2.3 years estimated by Morse and Flanders (1971) using only estimates of the 3 Vermont rivers, and the 1.7 years estimated by the U.S. Environmental Protection Agency (1974). The mean residence times for the 4 segments from north to south are, respectively, 0.026 months, 3.62 months, 15.03 months, and 2.82 months.

The Nutrient Budgets

The chloride budget was constructed chiefly as a check on the accuracy of the other budgets. A detailed listing of the budget is given in Tables 8 and 9. As chloride is considered a conservative element, there should be no sedimentation of the material within the basin and the budget equation should be

$$J = \Delta S + 0$$

Any amount of chloride not accounted for by this equation can be considered as an error in the budget. The sources of this error are several. It could be that the source is confined to the chloride budget alone. Errors in the analysis of chloride are

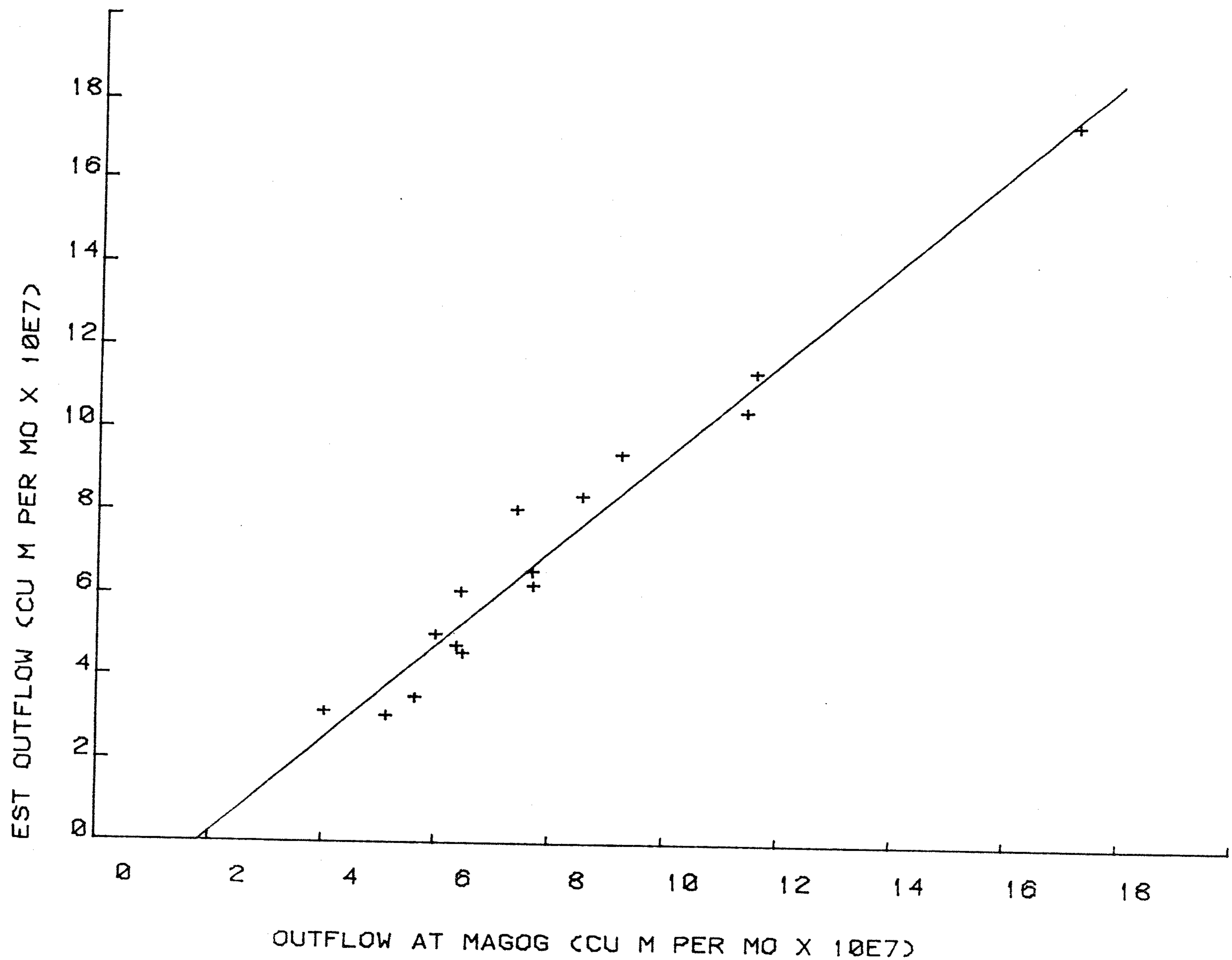

Figure 22. The relationship between the actual and estimated outflow of water from Lake Memphremagog as measured at the Dominion Textile dam in Magog, Que.

Table 8. The sources of chloride to the major basins of Lake Memphremagog from August 1974 to October 1975

NEWPORT BAY

MØ	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
A	20.027e 10	20.014e 10	100	12.992e 07	0	.000e 00	0
S	17.244e 10	17.224e 10	100	20.560e 07	0	.000e 00	0
O	19.310e 10	19.301e 10	100	87.488e 06	0	.000e 00	0
N	46.504e 10	46.484e 10	100	20.691e 07	0	.000e 00	0
D	41.811e 10	41.801e 10	100	97.936e 06	0	.000e 00	0
J	29.003e 10	28.988e 10	100	15.004e 07	0	.000e 00	0
F	22.096e 10	22.085e 10	100	10.324e 07	0	.000e 00	0
M	61.842e 10	61.825e 10	100	16.623e 07	0	.000e 00	0
A	10.187e 11	10.186e 11	100	96.674e 06	0	.000e 00	0
M	53.167e 10	53.154e 10	100	12.467e 07	0	.000e 00	0
J	17.090e 10	17.081e 10	100	90.112e 06	0	.000e 00	0
J	14.220e 10	14.195e 10	100	24.847e 07	0	.000e 00	0
A	13.682e 10	13.654e 10	100	27.384e 07	0	.000e 00	0
S	41.958e 10	41.935e 10	100	23.272e 07	0	.000e 00	0
O	45.382e 10	45.366e 10	100	15.748e 07	0	.000e 00	0
MEAN	36.347e 10	36.331e 10	100	15.809e 07	0	.000e 00	0

SOUTH BASIN

MØ	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
A	23.163e 10	28.423e 09	12	27.162e 08	1	20.049e 10	87
S	16.795e 10	20.256e 09	12	42.984e 08	3	14.340e 10	85
O	19.620e 10	23.101e 09	12	18.291e 08	1	17.127e 10	87
N	44.114e 10	47.477e 09	11	43.259e 08	1	38.933e 10	88
D	46.769e 10	47.228e 09	10	20.486e 08	0	41.841e 10	89
J	34.671e 10	32.519e 09	9	31.369e 08	1	31.106e 10	90
F	25.987e 10	21.830e 09	8	21.584e 08	1	23.588e 10	91
M	71.837e 10	67.917e 09	9	34.753e 08	0	64.698e 10	90
A	11.164e 11	11.551e 10	10	20.212e 08	0	99.891e 10	89
M	52.771e 10	48.965e 09	9	26.065e 08	0	47.614e 10	90
J	19.553e 10	24.570e 09	13	18.840e 08	1	16.907e 10	86
J	13.530e 10	19.498e 09	14	51.947e 08	4	11.060e 10	82
A	12.859e 10	16.986e 09	13	57.252e 08	4	10.588e 10	82
S	40.662e 10	44.622e 09	11	48.655e 08	1	35.714e 10	88
O	47.567e 10	52.147e 09	11	32.924e 08	1	42.023e 10	88
MEAN	38.770e 10	40.737e 09	11	33.052e 08	1	34.365e 10	89

Table 8. continued

CENTRAL BASIN

MO	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
A	25.585e 10	12.734e 09	5	14.931e 08	1	24.162e 10	94
S	20.919e 10	10.991e 09	5	23.628e 08	1	19.584e 10	94
O	20.658e 10	12.304e 09	6	10.054e 08	0	19.327e 10	94
N	34.413e 10	34.160e 09	10	23.779e 08	1	30.759e 10	89
D	41.131e 10	34.890e 09	8	11.261e 08	0	37.529e 10	91
J	37.138e 10	20.549e 09	6	17.243e 08	0	34.911e 10	94
F	18.985e 10	11.184e 09	6	11.864e 08	1	17.743e 10	93
M	58.277e 10	53.565e 09	9	19.103e 08	0	52.730e 10	90
A	90.418e 10	11.061e 10	12	11.110e 08	0	79.246e 10	88
M	50.221e 10	43.208e 09	9	14.328e 08	0	45.757e 10	91
J	21.361e 10	12.601e 09	6	10.356e 08	0	19.997e 10	94
J	14.757e 10	60.547e 08	4	28.554e 08	2	13.866e 10	94
A	14.482e 10	77.956e 08	5	31.470e 08	2	13.338e 10	92
S	34.482e 10	32.805e 09	10	26.745e 08	1	30.934e 10	90
O	52.716e 10	41.404e 09	8	18.098e 08	0	48.395e 10	92
MEAN	35.703e 10	29.657e 09	8	18.168e 08	1	32.556e 10	91

NORTH BASIN

MO	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
A	36.472e 10	63.484e 09	17	12.953e 08	0	29.994e 10	82
S	29.273e 10	51.828e 09	18	20.498e 08	1	23.885e 10	82
O	28.711e 10	65.266e 09	23	87.227e 07	0	22.097e 10	77
N	49.241e 10	16.489e 10	33	20.629e 08	0	32.546e 10	66
D	57.761e 10	17.601e 10	30	97.695e 07	0	40.062e 10	69
J	54.835e 10	15.859e 10	29	14.960e 08	0	38.827e 10	71
F	29.117e 10	11.956e 10	41	10.293e 08	0	17.058e 10	59
M	96.871e 10	44.538e 10	46	16.573e 08	0	52.167e 10	54
A	13.565e 11	55.572e 10	41	96.386e 07	0	79.983e 10	59
M	69.731e 10	20.618e 10	30	12.430e 08	0	48.989e 10	70
J	31.862e 10	65.690e 09	21	89.844e 07	0	25.203e 10	79
J	18.804e 10	31.520e 09	17	24.773e 08	1	15.404e 10	82
A	19.465e 10	38.025e 09	20	27.302e 08	1	15.389e 10	79
S	53.751e 10	18.105e 10	34	23.203e 08	0	35.414e 10	66
O	72.313e 10	21.400e 10	30	15.701e 08	0	50.755e 10	70
MEAN	52.257e 10	16.915e 10	32	15.762e 08	0	35.185e 10	67

Table 9. The chloride budget for Lake Memphremagog from August 1974 to October 1975

NEWPORT BAY

MO	INFLOW	STORAGE	NET SED	OUTFLOW
A	20.027e 10	-1.599e 10	15.770e 09	20.049e 10
S	17.244e 10	59.152e 08	23.130e 09	14.340e 10
O	19.310e 10	13.986e 09	78.397e 08	17.127e 10
N	46.504e 10	35.731e 08	72.138e 09	38.933e 10
D	41.811e 10	40.278e 08	-4.334e 09	41.841e 10
J	29.003e 10	17.445e 09	-3.847e 10	31.106e 10
F	22.096e 10	-7.810e 09	-7.110e 09	23.588e 10
M	61.842e 10	-2.134e 10	-7.219e 09	64.693e 10
A	10.187e 11	-1.662e 10	36.404e 09	99.891e 10
M	53.167e 10	-1.214e 10	67.664e 09	47.614e 10
J	17.090e 10	13.181e 09	-1.136e 10	16.907e 10
J	14.220e 10	10.004e 08	30.592e 09	11.060e 10
A	13.682e 10	19.222e 09	11.717e 09	10.588e 10
S	41.958e 10	-1.871e 10	81.152e 09	35.714e 10
O	45.382e 10	85.738e 07	32.728e 09	42.023e 10
MEAN	36.347e 10	-8.939e 08	20.710e 09	34.365e 10

SOUTH BASIN

MO	INFLOW	STORAGE	NET SED	OUTFLOW
A	23.163e 10	-7.377e 10	63.778e 09	24.162e 10
S	16.795e 10	17.286e 08	-2.961e 10	19.584e 10
O	19.620e 10	88.492e 09	-8.556e 10	19.327e 10
N	44.114e 10	62.632e 09	70.916e 09	30.759e 10
D	46.769e 10	-9.357e 09	10.176e 10	37.529e 10
J	34.671e 10	-2.461e 10	22.214e 09	34.911e 10
F	25.987e 10	22.340e 09	60.044e 09	17.748e 10
M	71.837e 10	-1.107e 11	30.174e 10	52.730e 10
A	11.164e 11	-2.826e 10	35.225e 10	79.246e 10
M	52.771e 10	-4.567e 10	11.581e 10	45.757e 10
J	19.553e 10	14.269e 10	-1.471e 11	19.997e 10
J	13.530e 10	-4.868e 10	45.314e 09	13.866e 10
A	12.859e 10	75.785e 09	-8.108e 10	13.338e 10
S	40.662e 10	17.723e 10	-7.995e 10	30.934e 10
O	47.567e 10	18.545e 09	-2.682e 10	48.395e 10
MEAN	38.770e 10	16.561e 09	45.579e 09	32.556e 10

Table 9. continued

CENTRAL BASIN

MO	INFLOW	STORAGE	NET SED	OUTFLOW
A	25.585e 10	-1.529e 11	10.877e 10	29.994e 10
S	20.919e 10	-1.999e 10	-9.670e 09	23.885e 10
O	20.658e 10	41.812e 10	-4.325e 11	22.097e 10
N	34.413e 10	-2.185e 11	23.718e 10	32.546e 10
D	41.131e 10	-2.370e 11	24.767e 10	40.062e 10
J	37.138e 10	-1.631e 11	14.625e 10	38.827e 10
F	18.985e 10	-1.700e 10	36.267e 09	17.058e 10
M	58.277e 10	-5.453e 10	11.563e 10	52.167e 10
A	90.418e 10	-7.971e 09	11.231e 10	79.983e 10
M	50.221e 10	68.436e 10	-6.720e 11	48.989e 10
J	21.361e 10	-2.746e 11	23.620e 10	25.203e 10
J	14.757e 10	-6.239e 10	55.923e 09	15.404e 10
A	14.482e 10	56.941e 10	-5.785e 11	15.389e 10
S	34.482e 10	10.627e 09	-1.995e 10	35.414e 10
O	52.716e 10	96.468e 08	99.595e 08	50.755e 10
MEAN	35.703e 10	32.277e 09	-2.710e 10	35.185e 10

NORTH BASIN

MO	INFLOW	STORAGE	NET SED	OUTFLOW
A	36.472e 10	-4.489e 10	68.041e 09	34.156e 10
S	29.273e 10	83.043e 08	96.347e 08	27.479e 10
O	28.711e 10	61.340e 09	-2.799e 10	25.376e 10
N	49.241e 10	-6.576e 09	14.369e 10	35.529e 10
D	57.761e 10	-1.963e 10	14.116e 10	45.608e 10
J	54.835e 10	-7.291e 10	15.317e 10	46.809e 10
F	29.117e 10	-7.561e 09	10.695e 10	19.178e 10
M	96.871e 10	64.258e 09	29.297e 10	61.149e 10
A	13.565e 11	11.530e 10	26.334e 10	97.787e 10
M	69.731e 10	23.323e 09	58.375e 09	61.561e 10
J	31.862e 10	-2.214e 10	55.959e 09	28.480e 10
J	18.804e 10	-3.772e 10	43.176e 09	18.259e 10
A	19.465e 10	13.017e 10	-1.196e 11	18.403e 10
S	53.751e 10	65.508e 09	53.121e 09	41.888e 10
O	72.313e 10	90.808e 08	98.181e 09	61.587e 10
MEAN	52.257e 10	17.723e 09	89.348e 09	41.550e 10

possible, as the magnification of small differences in concentrations when multiplied by lake volume or incoming water. For example, a change in concentration from 5.0 to 5.1 mg/l would result in a change in the total amount in Central Basin of 1.50 X 10^9 mg. As the limits of analytical accuracy was 0.1 mg/l, some of the variation in the budget may be accounted for by variation in the collection and analysis of chloride

A second source of variation is in the construction of the budget itself. A monthly budget was chosen to provide sensitivity to seasonal changes. It however also amplifies the degree of variation that can be associated with a single number because of the large number of possibilities for rounding errors or the number of estimations that must be made. For example, changes in storage were estimated using the mean monthly concentration and the segment volumes on the first day of each month. Changing to using the mean monthly volume or using the concentration on the first day of the month may have produced somewhat different results. The estimation of storage is only one of many simplifications made during the construction of a nutrient budget and their cumulative error may be considerable.

A third source of error is associated with the assumption related to water mixing and flow. It was assumed that each basin was completely mixed and that flow between segments was advective. If there was turbulent mixing between segments, the estimated outflow and loading could be considerably different.

All these errors of course can affect all of the nutrient budgets. The high degree of correlation between the estimated and actual outflow from the lake give a degree of confidence in the external loadings. The mean residual chloride (termed net sedimentation) was relatively low, being 5.7%, 11.7%, 7.6%, and 17% of the total loading in segments 1 to 4 respectively. Monthly differences were considerably larger (Table 10). Many of these differences appear to be associated with changes in the storage term, and perhaps if this is calculated in some other manner, some of these differences will disappear.

The budgets for phosphorus and nitrogen are presented below with the cautionary note that because of the differences found in the chloride budget, the absolute amounts may not be accurate. For this reason the discussion of the budgets will largely be limited to relative rather than absolute changes.

The phosphorus budget is detailed in Tables 11 and 12. A total of 36,283 kilograms of phosphorus is estimated to have entered Lake Memphremagog during the time of the study.* This is equivalent to a specific loading rate of 0.322 $gm/m^2/yr$, a value approximately 40% lower than that observed in the EPA study (1974). Of the total phosphorus input, 92.1% of this entered from the watershed. The rivers at Newport contributed 84% of the total loading and the watershed of South Basin another 4.8%. These comparisons are shown in Table 13.

As also shown in Table 13, the mean phosphorus concentration of the external inputs decreases as the water flows north. It is doubtful that this decrease in incoming concentration is the cause of the phosphorus gradient as 80-90% of the loading to

* 15 months

Table 10. The percent of the monthly incoming chloride not accounted for in changes in storage or in outflow

MO	SEG 1	SEG 2	SEG 3	SEG 4
AUG	7.874	27.534	42.513	18.656
SEP	13.413	-17.632	-4.622	3.291
OCT	4.060	-43.603	-209.365	-9.751
NOV	15.512	16.076	68.921	29.182
DEC	-1.037	21.757	60.215	24.439
JAN	-13.264	6.407	39.380	27.933
FEB	-3.218	23.106	19.103	36.732
MAR	-1.167	42.004	19.842	30.243
APR	3.574	31.551	12.422	19.413
MAY	12.727	21.945	-133.813	8.371
JUN	-6.646	-75.249	110.579	17.563
JUL	21.514	33.492	37.896	22.961
AUG	8.564	-63.051	-399.441	-61.418
SEP	19.341	-19.661	-5.785	9.883
OCT	7.212	-5.638	1.889	13.577

Table 11. The sources of phosphorus to the major basins of Lake Memphremagog from August 1974 to October 1975

NEWPORT BAY

MO	INFLOW	STORAGE	NET SED	OUTFLOW
A	13.732e 08	10.700e 07	53.943e 07	72.676e 07
S	10.508e 08	-2.315e 07	29.147e 07	78.244e 07
O	14.135e 08	-4.998e 07	62.788e 07	83.563e 07
N	26.386e 08	92.941e 06	10.646e 08	14.810e 08
D	17.773e 08	81.681e 05	-1.884e 08	18.840e 08
J	13.534e 08	28.350e 05	-2.437e 08	15.688e 08
F	12.785e 08	-7.500e 07	26.804e 07	10.854e 08
M	31.354e 08	-1.323e 08	48.921e 07	27.785e 08
A	52.373e 08	-8.351e 07	14.145e 08	39.063e 08
M	25.012e 08	70.832e 06	66.714e 07	17.632e 08
J	13.599e 08	-6.136e 07	54.133e 07	87.997e 07
J	14.962e 08	11.583e 07	96.396e 07	41.645e 07
A	83.435e 07	78.045e 06	22.767e 07	52.863e 07
S	21.716e 08	-1.074e 08	55.375e 07	17.252e 08
O	29.257e 08	39.829e 05	96.952e 07	19.522e 08
MEAN	20.365e 08	30.640e 05	54.576e 07	14.876e 08

SOUTH BASIN

MO	INFLOW	STORAGE	NET SED	OUTFLOW
A	88.530e 07	16.005e 08	-1.584e 09	86.921e 07
S	99.587e 07	-2.233e 09	22.835e 08	94.488e 07
O	96.466e 07	-8.386e 08	11.553e 08	64.792e 07
N	16.964e 08	-6.137e 07	94.349e 07	81.432e 07
D	19.879e 08	-2.268e 08	12.722e 08	94.259e 07
J	16.496e 08	32.372e 07	49.170e 07	83.417e 07
F	11.584e 08	13.996e 09	-1.330e 10	46.550e 07
M	30.572e 08	74.415e 07	-3.493e 09	58.063e 08
A	42.641e 08	-1.235e 10	68.840e 08	97.292e 08
M	20.110e 08	-2.881e 09	28.818e 08	20.106e 08
J	10.317e 08	-1.782e 08	69.419e 07	51.568e 07
J	66.022e 07	17.784e 08	-1.429e 09	31.082e 07
A	81.045e 07	94.820e 07	-5.987e 08	46.097e 07
S	20.582e 08	-7.187e 08	15.827e 08	11.942e 08
O	21.857e 08	57.329e 06	63.230e 07	14.960e 08
MEAN	16.944e 08	-2.578e 06	-1.058e 08	18.028e 08

Table 11. continued

CENTRAL BASIN

MO	INFLOW	STORAGE	NET SED	OUTFLOW
A	95.039e 07	-3.440e 08	76.989e 07	52.452e 07
S	10.522e 08	87.892e 07	-2.413e 08	41.458e 07
O	71.113e 07	-9.446e 08	12.377e 08	41.802e 07
N	94.514e 07	-1.292e 09	17.110e 08	52.564e 07
D	10.324e 08	53.879e 07	-9.135e 07	58.492e 07
J	89.479e 07	18.921e 08	-1.623e 09	62.594e 07
F	50.272e 07	38.375e 08	-3.675e 09	34.002e 07
M	59.755e 08	23.354e 08	22.420e 08	13.981e 08
A	10.004e 09	-2.411e 09	99.153e 08	24.991e 08
M	21.612e 08	-4.869e 09	57.092e 08	13.210e 08
J	58.066e 07	-1.172e 09	13.434e 08	40.926e 07
J	42.370e 07	-1.286e 09	14.783e 08	23.145e 07
A	58.808e 07	98.677e 07	-5.939e 08	20.024e 07
S	13.636e 08	33.645e 07	55.298e 07	47.421e 07
O	16.556e 08	13.396e 06	93.742e 07	70.479e 07
MEAN	19.227e 08	-9.990e 07	13.112e 08	71.146e 07

NORTH BASIN

MO	INFLOW	STORAGE	NET SED	OUTFLOW
A	61.952e 07	13.959e 07	-4.532e 06	48.446e 07
S	52.738e 07	41.752e 07	-3.207e 08	43.052e 07
O	49.433e 07	36.920e 06	-1.462e 07	47.203e 07
N	68.057e 07	-6.193e 08	65.800e 07	64.185e 07
D	69.558e 07	-9.840e 07	16.333e 07	63.065e 07
J	70.661e 07	22.824e 07	-1.453e 08	62.367e 07
F	38.708e 07	28.610e 07	-2.011e 08	30.206e 07
M	16.220e 08	29.294e 07	22.921e 07	10.998e 08
A	28.784e 08	36.382e 07	63.164e 07	18.829e 08
M	15.081e 08	-2.232e 08	48.824e 07	12.431e 08
J	48.948e 07	-5.211e 08	48.563e 07	52.496e 07
J	33.956e 07	-5.934e 08	65.431e 07	27.863e 07
A	33.791e 07	76.460e 07	-6.407e 08	21.403e 07
S	69.193e 07	-6.337e 07	10.821e 07	64.708e 07
O	91.683e 07	13.134e 06	12.944e 06	89.076e 07
MEAN	85.968e 07	28.274e 06	14.031e 07	69.110e 07

Table 12. The phosphorus budget for Lake Memphremagog from August 1974 to October 1975

NEWPORT BAY

MØ	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
A	13.732e Ø8	13.687e Ø8	1ØØ	45.183e Ø5	Ø	.ØØØe ØØ	Ø
S	1Ø.5Ø3e Ø8	1Ø.436e Ø8	99	71.5Ø2e Ø5	1	.ØØØe ØØ	Ø
O	14.135e Ø8	14.1Ø5e Ø8	1ØØ	3Ø.426e Ø5	Ø	.ØØØe ØØ	Ø
N	26.386e Ø8	26.343e Ø8	1ØØ	42.651e Ø5	Ø	.ØØØe ØØ	Ø
D	17.773e Ø8	17.768e Ø8	1ØØ	55.Ø69e Ø4	Ø	.ØØØe ØØ	Ø
J	13.534e Ø8	13.526e Ø8	1ØØ	84.416e Ø4	Ø	.ØØØe ØØ	Ø
F	12.785e Ø8	12.776e Ø8	1ØØ	82.16Øe Ø4	Ø	.ØØØe ØØ	Ø
M	31.354e Ø8	31.317e Ø8	1ØØ	36.897e Ø5	Ø	.ØØØe ØØ	Ø
A	52.373e Ø8	52.361e Ø8	1ØØ	12.119e Ø5	Ø	.ØØØe ØØ	Ø
M	25.Ø12e Ø8	24.969e Ø8	1ØØ	43.357e Ø5	Ø	.ØØØe ØØ	Ø
J	13.599e Ø8	13.568e Ø8	1ØØ	31.339e Ø5	Ø	.ØØØe ØØ	Ø
J	14.962e Ø8	14.876e Ø8	99	86.41Øe Ø5	1	.ØØØe ØØ	Ø
A	83.435e Ø7	82.482e Ø7	99	95.234e Ø5	1	.ØØØe ØØ	Ø
S	21.716e Ø8	21.635e Ø8	1ØØ	8Ø.934e Ø5	Ø	.ØØØe ØØ	Ø
O	29.257e Ø8	29.2Ø2e Ø8	1ØØ	54.767e Ø5	Ø	.ØØØe ØØ	Ø
MEAN	2Ø.365e Ø8	2Ø.321e Ø8	1ØØ	43.532e Ø5	Ø	.ØØØe ØØ	Ø

SOUTH BASIN

MØ	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
A	88.53Øe Ø7	64.Ø75e Ø6	7	94.465e Ø6	11	72.676e Ø7	82
S	99.587e Ø7	63.935e Ø6	6	14.949e Ø7	15	78.244e Ø7	79
O	95.466e Ø7	65.414e Ø6	7	63.613e Ø6	7	83.563e Ø7	87
N	16.964e Ø8	12.422e Ø7	7	91.194e Ø6	5	14.81Øe Ø8	87
D	19.879e Ø8	9Ø.38Øe Ø6	5	13.485e Ø6	1	18.84Øe Ø8	95
J	16.496e Ø8	6Ø.167e Ø6	4	2Ø.667e Ø6	1	15.688e Ø8	95
F	11.534e Ø8	53.895e Ø6	5	19.Ø88e Ø6	2	1Ø.854e Ø8	94
M	3Ø.572e Ø8	2Ø.ØØ9e Ø7	7	78.585e Ø6	3	27.785e Ø8	91
A	42.641e Ø8	33.Ø98e Ø7	8	26.822e Ø6	1	39.Ø63e Ø8	92
M	2Ø.11Øe Ø8	15.711e Ø7	8	9Ø.648e Ø6	5	17.632e Ø8	88
J	1Ø.317e Ø8	86.194e Ø6	8	65.521e Ø6	6	87.997e Ø7	85
J	66.Ø22e Ø7	63.1Ø4e Ø6	1Ø	18.Ø66e Ø7	27	41.645e Ø7	63
A	81.Ø45e Ø7	82.714e Ø6	1Ø	19.911e Ø7	25	52.863e Ø7	65
S	2Ø.582e Ø8	16.38Øe Ø7	8	16.921e Ø7	8	17.252e Ø8	84
O	21.857e Ø8	11.898e Ø7	5	11.45Øe Ø7	5	19.522e Ø8	89
MEAN	16.944e Ø8	11.5ØØe Ø7	7	91.8Ø4e Ø6	5	14.876e Ø8	88

Table 12. continued

CENTRAL BASIN

MØ	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
A	95.Ø39e Ø7	29.258e Ø6	3	51.926e Ø6	5	86.921e Ø7	91
S	1Ø.522e Ø8	25.187e Ø6	2	82.172e Ø6	8	94.488e Ø7	9Ø
O	71.113e Ø7	28.248e Ø6	4	34.967e Ø6	5	64.792e Ø7	91
N	94.514e Ø7	79.585e Ø6	8	51.239e Ø6	5	81.432e Ø7	86
D	1Ø.324e Ø8	81.28Øe Ø6	8	84.959e Ø5	1	94.259e Ø7	91
J	89.479e Ø7	47.6Ø7e Ø6	5	13.Ø19e Ø6	1	83.417e Ø7	93
F	5Ø.272e Ø7	25.68Øe Ø6	5	11.542e Ø6	2	46.55Øe Ø7	93
M	59.755e Ø8	12.513e Ø7	2	43.99Øe Ø6	1	58.Ø63e Ø8	97
A	1Ø.ØØ4e Ø9	25.9Ø8e Ø7	3	15.559e Ø6	Ø	97.292e Ø8	97
M	21.612e Ø8	1Ø.Ø81e Ø7	5	49.828e Ø6	2	2Ø.1Ø6e Ø8	93
J	58.Ø66e Ø7	28.966e Ø6	5	36.Ø16e Ø6	6	51.568e Ø7	89
J	42.37Øe Ø7	13.575e Ø6	3	99.3Ø6e Ø6	23	31.Ø82e Ø7	73
A	58.8Ø8e Ø7	17.663e Ø6	3	1Ø.945e Ø7	19	46.Ø97e Ø7	78
S	13.636e Ø8	76.4Ø5e Ø6	6	93.Ø12e Ø6	7	11.942e Ø8	88
O	16.556e Ø8	96.635e Ø6	6	62.94Øe Ø6	4	14.96Øe Ø8	9Ø
MEAN	19.227e Ø8	69.ØØ7e Ø6	4	5Ø.897e Ø6	3	18.Ø28e Ø8	94

NORTH BASIN

MØ	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
A	61.952e Ø7	49.95Øe Ø6	8	45.Ø49e Ø6	7	52.452e Ø7	85
S	52.738e Ø7	41.512e Ø6	8	71.289e Ø6	14	41.458e Ø7	79
O	49.433e Ø7	45.974e Ø6	9	3Ø.336e Ø6	6	41.8Ø2e Ø7	85
N	68.Ø57e Ø7	1Ø.952e Ø7	16	45.417e Ø6	7	52.564e Ø7	77
D	69.558e Ø7	1Ø.234e Ø7	15	83.1Ø8e Ø5	1	58.492e Ø7	84
J	7Ø.661e Ø7	67.941e Ø6	1Ø	12.734e Ø6	2	62.594e Ø7	89
F	38.7Ø8e Ø7	36.134e Ø6	9	1Ø.925e Ø6	3	34.ØØ2e Ø7	88
M	16.22Øe Ø8	18.499e Ø7	11	38.852e Ø6	2	13.981e Ø8	86
A	28.784e Ø8	36.5Ø3e Ø7	13	14.2Ø6e Ø6	Ø	24.991e Ø8	87
M	15.Ø81e Ø8	14.384e Ø7	1Ø	43.228e Ø6	3	13.21Øe Ø8	88
J	48.948e Ø7	48.98Øe Ø6	1Ø	31.246e Ø6	6	4Ø.926e Ø7	84
J	33.956e Ø7	21.954e Ø6	6	86.154e Ø6	25	23.145e Ø7	68
A	33.791e Ø7	42.713e Ø6	13	94.951e Ø6	28	2Ø.Ø24e Ø7	59
S	69.193e Ø7	13.7Ø2e Ø7	2Ø	8Ø.693e Ø6	12	47.421e Ø7	69
O	91.683e Ø7	15.744e Ø7	17	54.6Ø4e Ø6	6	7Ø.479e Ø7	77
MEAN	85.968e Ø7	1Ø.369e Ø7	12	44.533e Ø6	5	71.146e Ø7	83

Table 13. A summary of the mean monthly inputs of phosphorus to Lake Memphremagog, 1974, 1975 in kilograms/month

Segment	Runoff	Precipitation	Total Loading	Incoming Concentration
1	2032.0	4.4	2036	42
2	115.0	91.8	207	20
3	69.0	50.9	120	15
4	10.4	44.5	55	6
Total	2227	191.6	2418	

each segment is from the previous segment rather than from sources external to the lake. The northern segment's watershed contributes little to the loading of the water within the segment. The data suggest that sedimentation is the major factor involved in the decrease in nutrient concentration. A mean of 27%, 6.2%, 68% and 16% of the phosphorus loading is sedimented in the four basins respectively. Table 14 lists the monthly sedimentation rates as a fraction of the mean segment concentration. In both Tables 12 and 14, it can be seen that there are seasonal trends in these net sedimentation rates. In Newport Bay, the highest sedimentation rates are in the fall and spring. There is a period of net release from the sediments in December and January. In the South Basin, again there are peaks of sedimentation in spring and fall, but there is now a period of net release in July and August and in February. The summer phosphorus release corresponds to the period when the phosphorus increase is seen in the water and strongly suggests that this increase is not the result of increases in external loading. The high release rates seen in South Basin during February, coincide with the _Glenodinium_ bloom under the ice.

In the Central and North Basins, the mean sedimentation coefficients are lower than in the southern basins. There are considerably more months having net release rather than sedimentation. Some of these periods occur during the winter when nutrient concentrations were highest in these basins. However, because of the high degree of variability of the chloride residuals in these two basins, some caution should be used in the interpretation of

Table 14. The monthly sedimentation coefficients of phosphorus in the four basins of Lake Memphremagog

MO	SEG 1	SEG 2	SEG 3	SEG 4
AUG	1.403	-.276	.073	-.002
SEP	.593	.311	-.024	-.149
OCT	1.341	.226	.112	-.006
NOV	2.545	.221	.169	.253
DEC	-.368	.303	-.010	.082
JAN	-.411	.124	-.173	-.077
FEB	.431	-3.094	-.326	-.095
MAR	.895	-.191	.148	.096
APR	3.417	.362	.568	.235
MAY	2.019	.431	.380	.160
JUN	1.349	.182	.132	.172
JUL	2.836	-.394	.164	.283
AUG	.500	-.111	-.078	-.373
SEP	1.037	.249	.064	.044
OCT	2.273	.112	.104	.005

seasonal trends in these two basins. Often the monthly variations are bordering on the limits of analytical precision.

The total nitrogen budget is given in Tables 15 and 16. A total of 697,000 kilograms of nitrogen entered the lake during the 15 months of the study, this is equivalent to 557,000 kg/yr or a specific loading of 6.72 $gm/m^2/yr$. Eighty percent of this loading enters from the watershed, 20% from precipitation. The rivers flowing in at Newport contributed 324,000 kg/yr or approximately 58% of the total loading. The marked drop in the percent contribution from the Newport rivers over what was seen for phosphorus is the result of the minimal effect of the Newport sewage treatment plant effluent on the nitrogen contributions of the Clyde River. The concentrations of nitrogen in the Clyde River below the treatment plant are often only slightly higher or even less than above the plant. This results in estimated negative loadings from the plant. In Table 17 the percent contribution of the treatment plant to the Clyde River loading is estimated by dividing the loadings of phosphorus, nitrogen and chloride at the station below the plant by the loadings of the station above the plant. It can be seen that in several months, the nitrogen values drop below 100%. These values are the result of the low discharge volume of the effluent. It is estimated that the average flow from the plant is 1/1000th of the flow of the Clyde. In order to bring about a significant change in river concentration, the effluent concentrations have to be very high relative to the concentrations in the river. The relative differences in effluent

Table 15. The sources of nitrogen to the major basins of Lake Memphremagog from December 1974 to October 1975

NEWPORT BAY

MO	INFLOW	STORAGE	NET SED	OUTFLOW
D	17.620e 09	36.449e 07	-1.139e 10	28.649e 09
J	20.923e 09	10.350e 08	-1.645e 09	21.533e 09
F	19.189e 09	-4.565e 08	36.184e 08	16.027e 09
M	53.602e 09	-1.278e 09	10.543e 09	44.337e 09
A	81.776e 09	-9.331e 08	12.515e 09	70.193e 09
M	37.476e 09	-1.116e 09	38.800e 08	34.712e 09
J	11.531e 09	28.631e 06	-3.171e 08	11.819e 09
J	97.795e 08	32.405e 07	28.173e 08	66.382e 08
A	69.642e 08	33.708e 07	-3.363e 07	65.607e 08
S	20.701e 09	-8.992e 08	19.514e 08	19.649e 09
O	19.845e 09	48.387e 06	-3.920e 09	23.716e 09
MEAN	27.219e 09	-2.314e 08	16.379e 08	25.812e 09

SOUTH BASIN

MO	INFLOW	STORAGE	NET SED	OUTFLOW
D	35.162e 09	13.621e 09	73.180e 08	14.223e 09
J	28.602e 09	14.290e 09	-1.852e 09	16.164e 09
F	21.033e 09	79.089e 08	32.361e 08	98.880e 08
M	54.855e 09	-1.033e 10	33.693e 09	31.492e 09
A	82.649e 09	-3.037e 09	40.259e 09	45.427e 09
M	42.259e 09	-8.283e 09	24.743e 09	25.804e 09
J	16.085e 09	10.624e 08	45.192e 08	10.503e 09
J	15.172e 09	12.398e 09	-3.958e 09	67.325e 08
A	16.206e 09	-1.590e 09	10.037e 09	77.585e 08
S	30.178e 09	-6.846e 09	20.222e 09	16.803e 09
O	32.134e 09	83.984e 07	93.782e 08	21.916e 09
MEAN	34.031e 09	18.206e 08	13.418e 09	18.792e 09

Table 15. continued

CENTRAL BASIN

MO	INFLOW	STORAGE	NET SED	OUTFLOW
D	18.365e 09	30.101e 09	-3.287e 10	21.133e 09
J	20.016e 09	31.520e 09	-3.433e 10	23.324e 09
F	12.313e 09	71.942e 08	-6.375e 09	11.494e 09
M	38.097e 09	-4.719e 10	49.369e 09	35.922e 09
A	55.294e 09	-4.710e 10	53.540e 09	48.853e 09
M	30.986e 09	-3.971e 10	44.871e 09	25.826e 09
J	12.834e 09	10.150e 10	-9.890e 10	10.235e 09
J	10.993e 09	57.419e 09	-5.558e 10	91.552e 08
A	12.540e 09	-2.712e 10	28.922e 09	10.735e 09
S	22.852e 09	17.099e 09	-1.539e 10	21.057e 09
O	27.465e 09	59.803e 07	-4.598e 09	31.464e 09
MEAN	23.796e 09	76.647e 08	-6.523e 09	22.654e 09

NORTH BASIN

MO	INFLOW	STORAGE	NET SED	OUTFLOW
D	25.953e 09	24.638e 09	-2.119e 10	22.510e 09
J	27.280e 09	80.303e 08	-1.233e 10	31.582e 09
F	13.827e 09	57.354e 08	-6.700e 09	14.792e 09
M	44.569e 09	-3.557e 09	-1.935e 09	50.061e 09
A	64.549e 09	-6.779e 08	-8.659e 09	73.887e 09
M	32.400e 09	-2.424e 10	13.947e 09	42.693e 09
J	12.603e 09	-8.031e 09	56.769e 08	14.957e 09
J	13.021e 09	16.819e 09	-1.256e 10	87.608e 08
A	15.328e 09	-1.052e 10	14.693e 09	11.152e 09
S	27.712e 09	-1.538e 10	22.503e 09	20.585e 09
O	37.963e 09	34.525e 07	14.203e 09	23.415e 09
MEAN	28.655e 09	-6.210e 08	69.472e 07	28.581e 09

Table 16. The nitrogen budget for Lake Memphremagog from December 1974 to October 1975

NEWPORT BAY

MO	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
D	17.620e 09	17.489e 09	99	13.065e 07	1	.000e 00	0
J	20.923e 09	20.723e 09	99	20.006e 07	1	.000e 00	0
F	19.189e 09	19.051e 09	99	13.765e 07	1	.000e 00	0
M	53.602e 09	53.380e 09	100	22.164e 07	0	.000e 00	0
A	81.776e 09	81.647e 09	100	12.890e 07	0	.000e 00	0
M	37.476e 09	37.310e 09	100	16.623e 07	0	.000e 00	0
J	11.531e 09	11.410e 09	99	12.015e 07	1	.000e 00	0
J	97.795e 08	94.483e 08	97	33.129e 07	3	.000e 00	0
A	69.642e 08	65.991e 08	95	36.512e 07	5	.000e 00	0
S	20.701e 09	20.391e 09	99	31.029e 07	1	.000e 00	0
O	19.845e 09	19.635e 09	99	20.997e 07	1	.000e 00	0
MEAN	27.219e 09	27.008e 09	99	21.108e 07	1	.000e 00	0

SOUTH BASIN

MO	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
D	35.162e 09	37.821e 08	11	27.315e 08	8	28.649e 09	81
J	28.602e 09	28.866e 08	10	41.826e 08	15	21.533e 09	75
F	21.033e 09	21.283e 08	10	28.778e 08	14	16.027e 09	76
M	54.855e 09	58.838e 08	11	46.338e 08	8	44.337e 09	81
A	82.649e 09	97.609e 08	12	26.949e 08	3	70.193e 09	85
M	42.259e 09	40.723e 08	10	34.753e 08	8	34.712e 09	82
J	16.085e 09	17.540e 08	11	25.120e 08	16	11.819e 09	73
J	15.172e 09	16.078e 08	11	69.263e 08	46	66.382e 08	44
A	16.206e 09	19.114e 08	12	76.335e 08	47	66.607e 08	41
S	30.178e 09	40.424e 08	13	64.873e 08	21	19.649e 09	65
O	32.134e 09	40.279e 08	13	43.899e 08	14	23.716e 09	74
MEAN	34.031e 09	38.052e 08	11	44.132e 08	13	25.812e 09	76

Table 16. continued

CENTRAL BASIN

MØ	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
D	18.365e Ø9	26.409e Ø8	14	15.Ø15e Ø8	8	14.223e Ø9	77
J	2Ø.Ø16e Ø9	15.529e Ø8	8	22.991e Ø8	11	16.164e Ø9	81
F	12.313e Ø9	84.3Ø4e Ø7	7	15.819e Ø8	13	98.88Øe Ø8	8Ø
M	38.Ø97e Ø9	4Ø.576e Ø8	11	25.471e Ø8	7	31.492e Ø9	83
A	55.294e Ø9	83.852e Ø8	15	14.813e Ø8	3	45.427e Ø9	82
M	3Ø.936e Ø9	32.719e Ø8	11	19.1Ø3e Ø8	6	25.8Ø4e Ø9	83
J	12.834e Ø9	95.Ø15e Ø7	7	13.8Ø8e Ø8	11	1Ø.5Ø3e Ø9	82
J	1Ø.993e Ø9	45.335e Ø7	4	38.Ø73e Ø8	35	67.325e Ø8	61
A	12.54Øe Ø9	58.542e Ø7	5	41.96Øe Ø8	33	77.585e Ø8	62
S	22.852e Ø9	24.829e Ø8	11	35.66Øe Ø8	16	16.8Ø3e Ø9	74
O	27.465e Ø9	31.356e Ø8	11	24.131e Ø8	9	21.916e Ø9	8Ø
MEAN	23.796e Ø9	25.781e Ø8	11	24.258e Ø8	1Ø	18.792e Ø9	79

NORTH BASIN

MØ	TOTAL LOAD	RUNOFF	%	PRECIP	%	PREV SEG	%
D	25.953e Ø9	35.18Øe Ø8	14	13.Ø26e Ø8	5	21.133e Ø9	81
J	27.28Øe Ø9	19.6Ø8e Ø8	7	19.946e Ø8	7	23.324e Ø9	86
F	13.827e Ø9	96.1ØØe Ø7	7	13.724e Ø8	1Ø	11.494e Ø9	83
M	44.569e Ø9	64.372e Ø8	14	22.Ø98e Ø8	5	35.922e Ø9	81
A	64.549e Ø9	14.411e Ø9	22	12.852e Ø8	2	48.853e Ø9	76
M	32.4ØØe Ø9	49.174e Ø8	15	16.573e Ø8	5	25.826e Ø9	8Ø
J	12.6Ø3e Ø9	11.7Ø5e Ø8	9	11.979e Ø8	1Ø	1Ø.235e Ø9	81
J	13.Ø21e Ø9	56.259e Ø7	4	33.Ø3Øe Ø8	25	91.552e Ø8	7Ø
A	15.328e Ø9	95.289e Ø7	6	36.4Ø3e Ø8	24	1Ø.735e Ø9	7Ø
S	27.712e Ø9	35.61Øe Ø8	13	3Ø.937e Ø8	11	21.Ø57e Ø9	76
O	37.963e Ø9	44.Ø54e Ø8	12	2Ø.935e Ø8	6	31.464e Ø9	83
MEAN	28.655e Ø9	38.962e Ø8	14	21.Ø46e Ø8	7	22.654e Ø9	79

Table 17. The percent change in concentration of phosphorus, nitrogen, and chloride between the Upper Clyde Station and the station below the Newport sewage treatment plant

MØ	TP	TN	CL
A	1ØØ.64	*******	117.39
S	52.68	*******	117.39
O	223.66	*******	113.64
N	175.92	*******	127.95
D	278.32	92.88	119.28
J	561.22	9Ø.99	119.23
F	1226.83	235.95	211.14
M	266.5Ø	109.43	127.83
A	165.54	1ØØ.29	9Ø.72
M	178.71	1Ø6.47	63.16
J	263.82	136.81	71.49
J	3Ø1.23	121.49	113.97
A	288.46	157.68	125.88
S	2Ø8.69	1Ø9.82	123.17
O	221.85	95.19	97.14
MEAN	3ØØ.94	123.36	115.96

concentration and river concentration are much less for nitrogen than phosphorus, resulting in the lowered effect of the effluent on river nitrogen concentrations.

Mean estimated net sedimentation rates in all four basins are much lower than for phosphorus. For the four basins from south to north, the values are 6%, 39%, 27%, and 2.4%, as compared to phosphorus rates of 27%, 6.2%, 68%, and 16%. Again caution should be exercised in interpreting these values, but since nitrogen is found in 15 times greater quantities than phosphorus in particulate matter, the lower sedimentation rates are striking.

The Predictive Model

The matrix loading model first used the 1974-75 loading data as a test of the model's ability to generate values close to those from which it was originally derived. The results (Table 18) show that it does infact reproduce well the phosphorus and nitrogen values at each station. The values generated tend to reflect early August values in the South Basin and July-August values at Central.

The estimated loadings without the Newport sewage treatment plant were then substituted in for the 1974-75 Segment 1 loadings. The results of this run are also shown in Table 18. The phosphorus values drop considerably throughout the lake, but the nitrogen values decrease only slightly. The minimal change in the nitrogen values is the result of the minor effect the sewage treatment plant has on nitrogen concentrations. The elimination

Table 18. The results of the matrix model for the prediction of phosphorus and nitrogen in Lake Memphremagog

Geometric Mean Concentration		Matrix Model Est.		Vollenweider Model	Elimination of STP Input	
P	N	P	N	P	P	N
31.3	495	30.5	486	36.1	19.3	473
17.0	468	18.6	306	21.6	12.6	299
10.1	298	7.9	330	9.9	5.7	324
9.25	349	7.9	354	7.1	6.2	350

of the plant effluent would cause a 37% decrease in the mean incoming concentration of phosphorus (J/Q) from 42 mg/m^3 to 26 mg/m^3. The percentage change in total phosphorus concentration in the four basins is estimated to be 27%, 23%, 18%, and 12% respectively. This drop even in the North Basin again illustrates the significant effect that loading at Newport has on the entire lake. Whether or not these new values could actually be reached may depend a great deal on whether the sedimentation coefficients will remain the same with new nutrient regimes. As the coefficients used are actually net coefficients, they assume that both sedimentation and nutrient release from the sediments is proportional to the concentration of total phosphorus in the water. If sediment release is an independent function, then the response predicted above may be delayed until the sediment concentrations of nutrients reach a new steady state value.

As a check on the validity of this matrix model, the loading model of Vollenweider (1976) was substituted into the A matrix. Vollenweider's model can be of the form

$$C_L = J/Q_O \frac{1}{1 + \sqrt{V/Q_o}}$$

where

C_L = the mean lake concentration

J = the external loading (mg/yr)

Q_o = the outflow volume of water (m^3/yr)

V/Q_o = the hydrologic residence time

The matrix model is of the form

$$C_L(Q_o + K_1V) = J$$

and the Vollenweider model can be rearranged to the same form

$$C_LQ_o \ (1 + \sqrt{V/Q_o}) = J$$

By rearranging the matrix model, a form equivalent to Vollenweider's formula can be obtained

$$C_LQ_o \ (1 + K_1V/Q_o) = J$$

and Vollenweider's term $(1 + \sqrt{V/Q_o})$ can now be substituted for the matrix model term $(1 + K_1V/Q_o)$.

The results of the run of the Vollenweider model gives excellent predictions of the nutrient concentrations in the four segments (Table 18).

DISCUSSION

The evidence presented in this study indicates that the southern rivers, especially the Clyde, the Black and the Barton, dominate the hydrologic and nutrient forcings to Lake Memphremagog. Through the single inflow at Newport, Vermont flowed 63% of the water, 84% of the phosphorus and 58% of the nitrogen loadings. Although the input of the Newport Sewage Plant was not directly measured, it was estimated, by using differences in loading between the stations above and below the plant, that the plant contributes a minimum of 37% of the phosphorus loading at the Newport inflow. The plant's contribution of nitrogen could not be accurately measured because as mentioned before, the nitrogen concentrations of the effluent did not significantly raise the nitrogen concentration of the Clyde River.

Based on the results of the budgets, the influence of the nutrient-laden water from the southern rivers is felt in every basin of the lake. The total loadings to a segment from both runoff and precipitation seldom contribute more than 20% of the total nutrient load to the segment. Thus, the three major Vermont rivers and the associated sewage treatment plant in Newport must be considered the major nutrient forcing function on the Memphremagog lake system.

The intermixing of the waters from the two major rivers, the Black and the Barton, with the Clyde's high nutrient concentrations, provides a relatively stable nutrient load throughout the year. As loading is both a function of flow and concentration, loadings are high when flow is low because of the increased importance of the high concentrations of the STP, while when flows are high in the spring and fall, the influence of the STP is diminished. The result is no more than a 6-fold difference in monthly loading throughout the year. The result is also that the incoming concentrations of phosphorus at Newport are relatively constant (though highly fluctuating) throughout the year. The importance of this relatively constant input of nutrients is that changes in the concentrations of nutrients within the lake's four major basins cannot easily be ascribed to changes in external loading. It is perhaps the most important finding of this study that internal mechanisms appear to be the major determinants of the seasonal nutrient fluctuations within the lake.

It is quite clear that a difference in nutrient concentration does exist from south to north. Whether or not it can be properly called a gradient is an important question. A gradient implies a uniform decrease, as if the water was flowing purely advectively. With a constant sedimentation rate removing nutrients, the nutrient gradient would approach the form of exponential decay. The actual changes in nutrient concentration with distance ressembles more a series of plateaus suggesting completely mixed basins that were hypothesized in the budget model. There is evidence that these basins behave differently with respect to their nutrient dynamics because of their own distinct basin morphometry. As such the lake may be considered a series of connected lakes rather than a trophic continuum.

It is also immediately obvious that nitrogen and phosphorus behave differently within the lake. Phosphorus concentrations decrease down the lake, but total nitrogen concentrations decrease only slightly. In addition, the particulate phosphorus remains at a relatively constant 70% of the total phosphorus, while the fraction of nitrogen found in the particulate form decreases in the northern basin. Apparently nitrogen is behaving more conservatively than is phosphorus.

The fact that the carbon to phosphorus ratio decreases down the lake suggests that the particulate matter is becoming increasingly depleted of phosphorus. The fact that the fraction of particulate nitrogen remains constant relative to carbon but increases relative to phosphorus supports this contention. An atomic N:P ratio of 16:1 or a mass ratio of 7.2:1 is often considered to be a critical value in the determination of whether an algal cell is nitrogen or phosphorus limited (Rast and Lee, 1978). This value is reached within the first 3 km from the inflow at Newport. The maximum N:P mass ratios approach 15 which would make much of the lake decidedly phosphorus limited. Other supporting evidence that phosphorus becomes limited in the north is that the N:P ratio falls during the winter when one would expect less demand for nutrients by the algae for growth.

If phosphorus is limiting to algal growth, then nitrogen would not be required in amounts proportional to its availability and larger and larger fractions would be found in a soluble form. This does not however explain the conservation of nitrogen relative to phosphorus. If the sedimentation of particulates is the only manner to remove nutrients from the water column, then one would expect that nitrogen would be lost at increasingly greater rates than phosphorus because the N:P ratio increases. Instead nitrogen sedimentation rates decrease relative to phosphorus in the northern basins. If on the other hand, the material sedimenting is largely detrital rather than living, Golterman (1972) has shown that phosphorus leaches out of lysed cells more rapidly than does nitrogen. Again, one would expect a greater loss of nitrogen than phosphorus.

We are suggesting that although phosphorus may mineralize more rapidly from dead cells than does nitrogen, it is immediately taken up by another particle, not necessarily an algal cell. Nitrogen however is not taken up. By this mechanism, sedimenting particles tend to retain phosphorus while nitrogen will appear to be lost more rapidly. Evidence that this mechanism does in fact occur is presented in Figure 23. The values presented are the mean annual values at each depth from 0 to 90 meters in the Central Basin. Particulate carbon as well as chlorophyll decreases considerably from the surface to the bottom, while total nitrogen and phosphorus tend to remain at relatively constant levels. However, the fraction of nitrogen and phosphorus in particulate form differs significantly. Particulate phosphorus decreases by approximately 1/2 of its surface values while particulate nitrogen decreases to 1/5 of its surface value. The falling particulates are becoming leached of nitrogen much faster than of phosphorus. This can also be seen in the C/N, N/P, and C/P ratios. The C/P

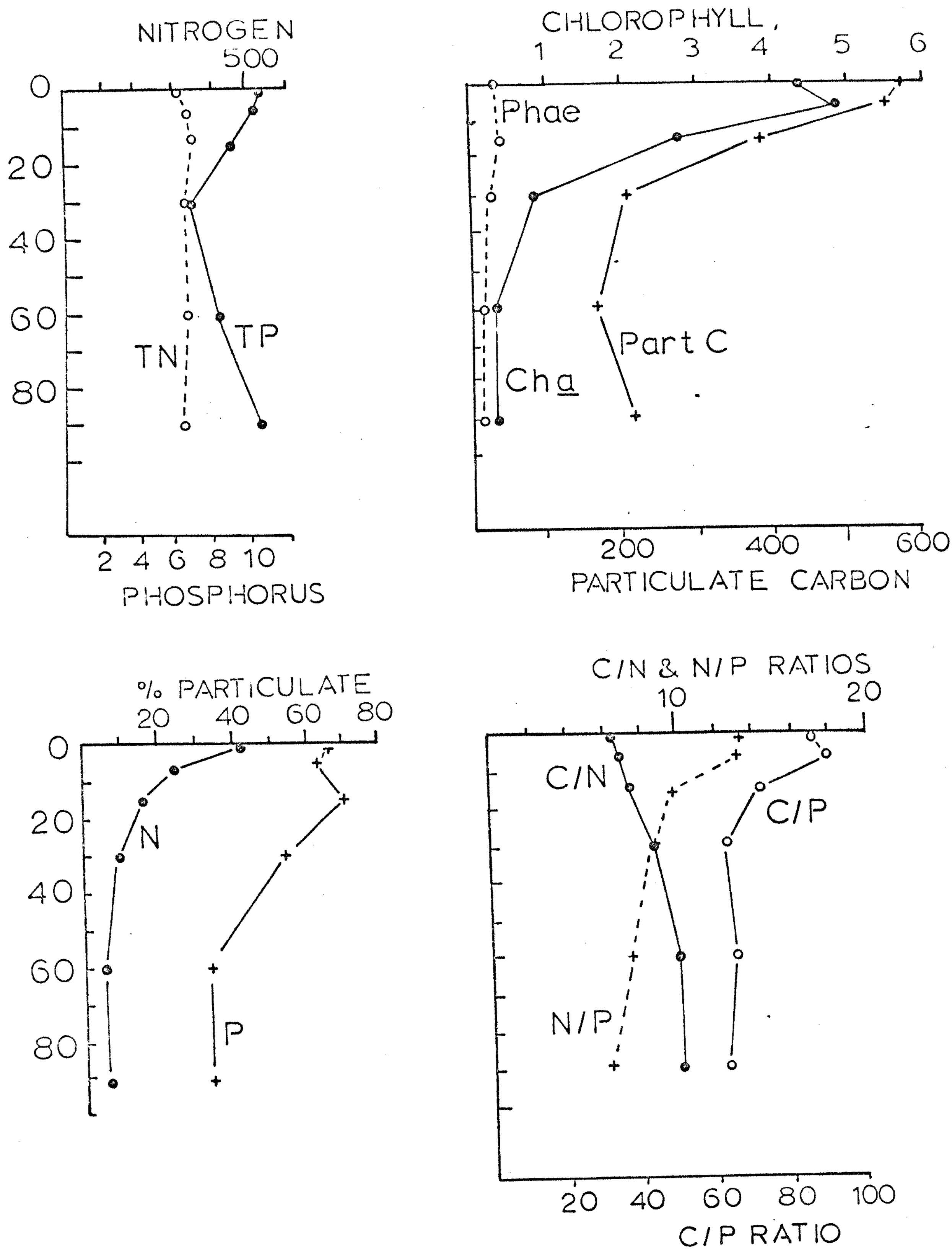

Figure 23. The changes in mean annual carbon, chlorophyll, and elemental ratios at different depths in Central Basin

ratio becomes constant below 30 m, but the N/P and C/N ratios continue to decline.

The evidence is that phosphorus is lost from the lake more rapidly than nitrogen because it is in demand by the living components, whether algae or bacteria, and it remains in the particulate form and is therefore more susceptible to loss by sedimentation. In Lake Tahoe, a system which may be either nitrogen or phosphorus limited (Holm-Hansen, et al., 1978), the C/N ratios remain constant (~6.0) to a depth of 400 meters, while both the C/P and N/P ratios decrease (Holm-Hansen, 1972). Again this suggests that phosphorus is being retained in the particulates, but in this case, carbon and nitrogen are being lost at the same rates. In Memphremagog, for some reason, nitrogen is lost more easily.

This mechanism suggests that sedimentation processes may be important in controlling the phosphorus concentrations in each basin. When factors favor sedimentation, phosphorus will be lost at rates greater than it is supplied by inflows and sediment release and the concentration will fall. If sedimentation is decreased, concentrations would rise. This hypothesis would explain some of the seasonal changes seen in the various basins. In Central Basin, the highest phosphorus concentrations are seen in the winter and spring, when particulate phosphorus is low. During this time sedimentation would probably be low and therefore loss rates of phosphorus low. With the oncoming of stratification and increased productivity, sedimentation of particulate phosphorus would increase and concentrations would decrease to new steady state levels.

In the South Basin there are two striking rises in phosphorus concentration. One occurred in February and was associated with a bloom of Glenodinium sp. under the ice. The other occurred both years beginning in late July. The winter bloom with its very high phosphorus concentrations cannot be explained by changes in nutrient inputs. The phosphorus budget shows a negative net sedimentation rate, suggesting that the algae obtained their phosphorus from the South Basin sediments. A possible explanation would be that the algae took up luxury quantities of nutrients from the sediments and then rose to the surface where they reproduced in great numbers. We have no evidence to support this hypothesis other than the absence of any other defined source for the phosphorus.

The summer bloom also cannot be explained by inputs from external sources. The budget again shows a negative net sedimentation rate. Two possible hypotheses are suggested. The first is that if the algae at this time were largely cyanophytes with gas vacuoles, these would not sediment as quickly and the concentrations would rise. The phosphorus increase is associated with large increases in chlorophyll and it may be that the species containing that chlorophyll may in fact be regulating the phosphorus concentration by decreasing the sedimentation rate.

A second hypothesis is suggested by the fact that the commencement of the rise in phosphorus coincides with the breakdown of the thermocline in the South Basin. If the thermocline in fact acts as a trap for particles, its loss may decrease the loss of algae. Exposure of the overlying epilimnion to the sediments could also stir sediments into the water, release interstitial soluble phosphorus, or increase the exchange surface of the sediments, all of which could increase nutrient concentrations in the water. At present, there is no strong evidence to either support or refute any of these hypotheses.

The picture which emerges of the nutrient dynamics in Lake Memphremagog is one of a system or series of systems all having relatively constant seasonal nutrient inputs. A gradient of phosphorus exists down the length of the lake. Nitrogen does not exhibit such a gradient because, it is suggested, that it is not limiting and thus is not so tightly held by particles. Phosphorus is probably limiting in all but the southernmost sections of the lake. The algae perhaps enter the lake saturated with phosphorus. Internal processes, probably sedimentation and perhaps sediment release, rather than external forcings are suggested to be the major source of seasonal fluctuations within the lake. External sources, largely entering at Newport, are only responsible for setting the initial concentration of nutrients at the lake's southernmost end. Internal mechanisms then determine the seasonal changes and the rate of change with distance of the nutrients.

Predictive Modeling of Lake Memphremagog

The matrix model constructed in this study can only be considered a first attempt at predictive modeling within the basin.

The fact that the Vollenweider model did so well when substituted into the matrix gives support to the validity and therefore future usefullness of this model. Apparently the assumption of completely mixed basins with minimal interchange between basins is sufficiently accurate on a yearly basis.

The limitation of the model is of course the fact that it is limited to the prediction of an annual mean concentration. It is largely sensitive to changes in external loadings; the internal mechanisms are considered constant. However, everything we have found so far in this study suggests the importance of internal mechanisms. Mean concentrations do not predict the levels of phosphorus found in late summer in the South Basin. It is these levels that are associated with the algal scums that have gained the notice of the public. A model on a monthly or seasonal basis should be the goal of future investigations.

Utilization of the monthly sedimentation rates to construct a 12 month matrix model could be done, but it would provide little insight into the internal workings of the lake. Just as the present nutrient budget provided evidence that internal mechanisms are important, the next effort should be in defining and quantifying these internal factors. The next model could include stratified and unstratified basins, sedimentation rates, temperature dependent sediment release rates and productivity. Such a model, based on the modest beginnings presented here can be used as a hypothesis generating tool to further research in this lake.

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