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Internal Phosphorus Loading From the Sediments and the Phosphorus-Chlorophyll Model in Shallow Lakes

by

© Edward T. Riley

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

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Abstract

Data from the literature were used to calculate separate regressions of summer chlorophyll a (Chla) concentration on spring total phosphorus (TP) concentration for deep lakes (i.e., lakes which remain thermally stratified during the summer) and shallow lakes (i.e., lakes which mix intermittently during the summer). Significant differences were found in the spring [TP]-summer [Chla] relationship for the two lake types ($P < 0.05$). The mean ratio of summer [TP] to spring [TP] was also significantly different in deep and shallow lakes ($P < 0.001$). This difference in the summer [TP] to spring [TP] ratio is the explanation offered for why the spring [TP]-summer [Chla] relationship was different in the two lake types. Internal loading of phosphorus from the sediments to the surface water in shallow lakes was suggested as the cause of the difference in the summer [TP] to spring [TP] ratio in the two lake types.

The contribution of internal loading from the sediments to the TP budget and to the [TP] in the surface water was investigated from May to November in Nakamun and Halfmoon Lakes, two shallow, productive lakes in Alberta. During the summer, Nakamun Lake was intermittently stratified and Halfmoon Lake was weakly, thermally stratified. While the lakes were stratified, the water overlying the sediments was anoxic and TP levels increased in the deep water. During the stratified periods, the sediments were the main source of

TP, contributing 1468 and 147 kg of TP to Nakamun and Halfmoon Lakes, respectively, During these same periods, external loading to Nakamun and Halfmoon Lakes was insignificant (37 and 5 kg, respectively). Average release rates of TP calculated from the in-lake TP budgets for Nakamun and Halfmoon Lakes (12.7, 15.6 mg/m²/day, respectively) were slightly higher than the rates predicted from laboratory experiments on sediment cores (9.7 and 7.2 mg/m²/day, respectively). Quantitative estimates of vertical water exchange in Nakamun Lake and in-lake TP budgets for both lakes indicated that phosphorus released from the sediments was transported to the surface water during mixing. After eight of the nine mixing events which immediately followed stratified periods, the [TP] increased 3-43% and 31-52% in the surface water of Nakamun and Halfmoon Lakes, respectively.

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I. Introduction

The nutrient phosphorus (P) is the primary factor which limits summer algal biomass in north temperate lakes (Schindler 1977). Consequently, total phosphorus (TP), often measured at spring overturn, is a good predictor of summer chlorophyll a (Chla) concentrations (Sakamoto 1966; Dillon and Rigler 1974; Oglesby and Schaffner 1978; Smith 1982; Prepas and Trew 1983). There are suggestions that the summer [Chla] to spring [TP] ratio is higher in shallow lakes (i.e., lakes which mix intermittently during the summer) than in deep lakes (i.e., lakes which remain thermally stratified during the summer) (Oglesby and Schaffner 1975; Schaffner and Oglesby 1978; Prepas and Trew 1983).

The proposed explanation for the higher summer [Chla] per unit of spring [TP] in shallow lakes is that TP concentrations increase from spring to summer in the surface water of shallow, but not deep, lakes (Prepas and Trew 1983). External loading cannot account for the observed TP increases in many shallow lakes during summer (Larsen et al. 1975; Stevens and Gibson 1977; Reynoldson and Hamilton 1982). Internal P loading is often considered responsible for these increases, usually through P release from profundal sediments when the overlying water is anoxic, with subsequent transport of this P to the surface water (Larsen et al. 1981; Stefan and Hanson 1981).

Alberta has many shallow, productive lakes. In these lakes, TP concentrations in the surface waters increase throughout the summer (Prepas 1983; Prepas and Trew 1983). Prelimnary studies on some of these lakes suggest release of phosphorus from the sediments under anoxic conditions is the most significant source of internal phosphorus loading (Prepas and Wisheu unpublished data).

In this study, I used data gathered from various sources to compare the spring [TP]-summer [Chl*a*] and summer [TP]-spring [TP] relationships in deep and shallow lakes. It has been suggested these relationships are different in the two lake types, but these differences have not been tested statistically. I also examined the P loading on two shallow, productive lakes in Alberta and conducted laboratory studies on P release from the sediments to determine the importance of internal loading from the sediments on the TP budget and [TP] in the surface water of shallow lakes. This is the first attempt to quantify the input of P release from the sediments in Albertan lakes.

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II. A Comparison of the Phosphorus-Chlorophyll Relationships in Shallow and Deep Lakes

A. Introduction

The relationship between the total phosphorus (TP) and chlorophyll a (Chla) concentrations in lakes has been examined by a number of authors (Sakamoto 1966; Dillon and Rigler 1974; Oglesby and Schaffner 1978; Smith 1982; Prepas and Trew 1983). This relationship is fairly consistent when spring or winter [TP] is used to predict the average summer [Chla] for a lake (Nicholls and Dillon 1978). The spring [TP]-summer [Chla] relationship has been used as a simple, yet valuable tool in lake management (Dillon and Rigler 1975).

The applicability of models to predict summer [Chla] (or some other estimate of the phytoplankton standing crop) would be improved if the residual variance in these models were reduced (Nicholls and Dillon 1978; Smith 1982). There are suggestions that the variation in the spring [TP]-summer [Chla] model would be reduced if the lakes were divided into two categories: deep lakes (i.e., lakes which remained thermally stratified during the summer) and shallow lakes (i.e., lakes which mix intermittently during the summer) (Oglesby and Schaffner 1975; Schaffner and Oglesby 1978; Prepas and Trew 1983).

Further analysis of Prepas and Trew's data shows that the summer [Chla] to spring [TP] ratio is higher in shallow lakes than in deep lakes. The measured Chl*a* concentrations in six of the eight shallow lakes in their study were greater than the values predicted by Dillon and Rigler's (1974) spring [TP]-summer [Chl*a*] model. The measured summer Chl*a* concentrations in only 7 of the 18 deep lakes in their study were greater than the predicted values.

Oglesby and Schaffner (1975) calculated separate linear regressions of summer [Chl*a*] on winter [TP] for deep and shallow lakes. They assumed that the spring [TP]-summer [Chl*a*] relationships were different in the two lake types. Oglesby and Schaffner's regression line for shallow lakes has a greater slope and intercept than the regression line for the deep lakes. However, their data sets were too small to test whether these differences were significant.

During summer, the [TP] in the trophogenic zone increased in shallow lakes and decreased in deep lakes in Prepas and Trew's study. Differences in summer [TP] to spring [TP] ratios in the two lake types could explain why shallow lakes often have higher summer [Chl*a*] than deep lakes, relative to spring [TP].

To examine whether the differences in the spring [TP]-summer [Chl*a*] relationships in deep and shallow lakes were significant, I calculated separate regression lines for summer [Chl*a*] on spring [TP] for both lake types. I then compared the regression lines for deep and shallow lakes with each other and with Dillon and Rigler's (1974) regression line by analysis of covariance. I treated Dillon and Rigler's regression line as a model for deep lakes because most of the lakes in their data set were deep. The results support the hypothesis that the spring [TP]-summer [Chl*a*] relationships are different in deep and shallow lakes. Differences in the summer [TP] to spring [TP] ratios in the two lake types offer the best explanation for the differences in the spring [TP]-summer [Chl*a*] relationship.

B. Methods and Materials

The data for the regression lines were gathered from several sources: Dillon and Rigler (1974), Oglesby (1977), Oglesby and Schaffner (1978), Prepas and Trew (1983), C.E. Gibson (University of New Ulster, Coleraine, Northern Ireland, pers. comm.), and E. Mills (Cornell Biological Field Station, Bridgeport, N.Y., pers. comm.) (Table 1). The data consisted of:

1) Spring [TP] i.e., the lake [TP] at spring overturn. Phosphorus data collected in late winter (Oglesby and Schaffner 1978) were treated as spring values since they are comparable (Nicholls and Dillon 1978).

2) [Chl*a*] i.e., average lake concentration of chlorophyll *a* during the summer.

3) Summer [TP] i.e., the average summer [TP] in the trophogenic zone. The trophogenic zone was defined as the water above the depth of 1% surface-penetrating irradiance.

I did not use some data from the original data sets in our analyses. Mills (pers. comm.) and Oglesby and Schaffner

(1978) both provided data for Oneida Lake in 1975. Mill's data were used for the calculations because they were based on a much larger sample size than Oglesby and Schaffner's (23 versus 2 samples for spring [TP] and 65 versus 2 samples for [Chl*a*], respectively). Three lakes from Prepas and Trew's data set were excluded from the calculations. The spring [TP] values in two lake's (Joseph and Cooking) were well beyond the range of the other lakes in Table 1 (706 and 303 mg/m^3, respectively). A third lake, Hasse, was excluded because it could not be clearly classified as either a deep or shallow lake.

The data were transformed to $\log_{10}$ before regression analyses as in other spring [TP]-summer [Chl*a*] models (Dillon and Rigler 1974; Prepas and Trew 1973). The regression analyses were performed with BMDP statistical packages (Dixon 1981) on the Amdahl model 580/5860 computer at the University of Alberta. The other statistical analyses were from Zar (1974).

The data in Table 1 were used to calculate the regressions of summer [Chl*a*] on spring [TP] for the two lake types. A regression line based on Dillon and Rigler's (1974) data set was also included in the analysis of covariance. The spring TP concentrations in 5 shallow lakes were higher than for any deep lakes. The spring [TP] in eight deep lakes were below the range of values for shallow lakes (Table 1). In analysis of covariance the range of the independent variable should be similar for all data sets. Thus lakes with more than than 10 mg/m³ or less than 100 mg/m³ of spring [TP] were excluded from the analysis of covariance. A range of 10 to 100 mg/m³ of spring [TP] was chosen because it did not reduce the size of the data sets too much and there were no extreme outliers within this range.

To compare the relationship between summer [TP] and spring [TP] in the trophogeni zone, and summer total nitrogen concentration ([TN]) and summer [TP] in the trophogenic zone of the two lake types, I calculated the summer [TP] to spring [TP] and summer [TN] to summer [TP] ratios for individual lakes. I then calculated mean ratios for deep and shallow lakes and compared the means with a Mann-Whitney test. This method was used instead of analysis of covariance for three reasons: (1) significantly more variance was associated with the summer [TP] to spring [TP] relationship in shallow lakes as compared to deep lakes ($F = 11.5$, $P < 0.001$), (2) the data sets were small, and (3) ratio data are often not normally distributed. Therefore parametric statistical techniques such as analysis of covariance, which assume homogeneity of variances and normal distributions, were inappropriate.

C. Results and Discussion

The relationship between spring [TP] and [Chla] was highly significant ($P < 0.001$) for both deep and shallow lakes (Fig. 1 and 2). The spring [TP]-summer [Chla] relationship for shallow lakes (Table 1) was:

$$\log_{10}[\text{Chl}\underline{a}] = 1.251 \log_{10}[\text{TP}]\text{sp} - 0.680 \quad (r=0.83,\ n=25) \qquad (1)$$

and for the deep lakes it was:

$$\log_{10}[\text{Chl}\underline{a}] = 1.015 \log_{10}[\text{TP}]\text{sp} - 0.555 \quad (r=0.80\ n=31) \qquad (2)$$

where [TP]sp is the [TP] at spring overturn.

The correlation coefficients for these regressions (Eq. 1 and 2) were not as high as for Dillon and Rigler's line:

$$\log_{10}[\text{Chl}\underline{a}] = 1.449 \log_{10}[\text{TP}]\text{sp} - 1.136 \quad (r=0.95,\ n=46) \qquad (3).$$

A p ial explanation for why Eq. 1 and 2 had lower correlation coefficients than Eq. 3 is that the data sets for Eq. 1 and 2 covered a narrower range of spring TP concentraions than Dillon and Rigler's data set. Spring [TP] values ranged from 13.9 to 152, 7.7 to 79.9, and 3.0 to 180 (mg/m^3) in Eq. 1, 2, and 3, respectively.

For analysis of covariance, I calculated a second set of regression lines. Only lakes with spring [TP] concentrations between 10 and 100 mg/m^3 were used. The spring [TP]-summer [Chl<u>a</u>] relationship for the shallow lakes in this range was:

$$\log_{10}[\text{Chl}\underline{a}] = 1.299 \log_{10}[\text{TP}]\text{sp} - 0.751 \quad (r=0.77,\ n=22) \qquad (1a)$$

and for deep lakes it was:

$$\log_{10}[\mathrm{Chl}\underline{a}] = 0.996 \log_{10}[\mathrm{TP}]\mathrm{sp} - 0.528 \quad (r=0.75,\ n=27) \qquad (2a)$$

The equation for the lakes in this range from Dillon and Rigler (1974) was:

$$\log_{10}[\mathrm{Chl}\underline{a}] = 1.389 \log_{10}[\mathrm{TP}]\mathrm{sp} - 1.052 \quad (r=0.90,\ n=30) \qquad (3a).$$

When Eq. 1a, 2a, and 3a were compared by analysis of covariance, the residual variances and slopes were not significantly different (Table 2, Fig. 3). However, the adjusted means for Eq. 1a and 2a, and 1a and 3a were different, although the adjusted means for Eq. 2a and 3a were not different (Table 2, Fig 3.). Thus the spring [TP]-summer [Chla] relationships were different in deep and shallow lakes, but the two sets of deep lakes (Eq. 2a and 3a) were similar. Because of this difference in the spring [TP]-summer [Chla] relationship in deep and shallow lakes, Eq. 1 should be used to predict [Chla] in shallow lakes and Eq. 2 or 3 should be used for deep lakes. When more data are available, Eq. 1 should be compared with regression models for other shallow lakes to evaluate whether the spring [TP]-summer [Chla] relationship is consistent for shallow lakes.

I did not attempt to incorporate total nitrogen (TN) (e.g., Smith 1982) into my models because my data set was too small for multivariate analyses. However, I had TN data for one portion of my data set (Table 1, data from Prepas and Trew 1983). I used these data to test whether the mean summer [TN] to [TP] ratios were different in deep and shallow lakes. The ratios were different ($P < 0.01$). The mean [TN] to [TP] ratio was smaller in the shallow lakes than in the deep lakes (27 and 44, respectively) which according to Smith (1982) means the shallow lakes should have a lower summer [Chla] to spring [TP] ratio, than the deep lakes. Since the shallow lakes had a higher summer [Chla] to spring [TP] ratio, I concluded [TN] to [TP] ratios in the shallow and deep lakes were not responsible for the differences found here. However, incorporation of [TN] into empirical models to predict summer [Chla] in deep and shallow lakes could reduce the residual variation.

The higher elevation of the spring [TP]-summer [Chla] relationship for shallow lakes as compared to deep lakes (Fig. 3) supports the hypothesis that shallow lakes are more productive per unit of spring [TP] than deep lakes. The difference in elevation looks small when the lines are plotted together on a log-log scale. However when the regression lines are plotted in the arithmetic scale (Fig. 4) the differences between the two models increase as spring [TP] increases. This trend suggests that shallow lakes respond more strongly than deep lakes to increases in spring nutrient concentrations.

The differences between the predictions made by the spring [TP]-summer [Chla] models for deep and shallow lakes have important implications for lake management. For instance, Eq. 1 and 2 predict a [Chl<u>a</u>] of 28 and 15 mg/m³, respectively for a lake with a spring [TP] of 50 mg/m³. According to Dillon and Rigler (1975), a lake with a [Chl<u>a</u>] of 15 mg/m³ could support a warm-water fishery whereas a lake with a [Chl<u>a</u>] of 28 mg/m³ may not be able to.

A partial explanation for the higher summer [Chl<u>a</u>] to spring [TP] ratio in the shallow lakes as compared to deep lakes is the relationship between the spring [TP] and the average summer [TP] in the trophogenic zone of these two lake types. The mean ratios of summer [TP] to spring [TP] in shallow and deep lakes were 1.57 and 0.87, respectively (Table 1). Thus [TP] increases in the shallow lakes and decreases in deep lakes from spring to summer. The difference between the mean summer [TP] to spring [TP] ratios was significant ($P < 0.001$). Since phosphorus is generally the limiting nutrient in north temperate lakes (Schindler 1977) and [TP] increases in shallow lakes and decreases in deep lakes from spring to summer, the higher algal biomass per unit of spring [TP] in shallow lakes is reasonable.

Clearly more information is needed on the cause of the increased summer [TP] in shallow lakes. Recycling of phosphorus due to lake mixing is one explanation for why the [TP] increases in shallow lakes (Oglesby and Schaffner 1975). Phosphorus that would sediment out of the water column in a deep lake during the summer is resuspended in a shallow lake.

Internal loading from the sediments is an additional explanation for the increase of [TP] in shallow lakes. Some authors suggest that internal phosphorus loading contributes significantly to the phosphorus budget of shallow lakes during summer (Lie 1977; Larsen et al. 1981; Reynoldson and Hamilton 1982; Hanson and Stefan 1982; Landers 1982). However, the mechanism for internal loading to shallow lakes is still unclear. For example, Lie (1977) and Larsen et al. (1981) studied the same lake during the same time period; Larsen et al. reported that phosphorus release from the sediments during periods of temporary stratification accounted for most of the internal loading to the lake whereas Lie found phosphorus release from macrophytes was the major internal loading source.

Clearly, more research on the processes controlling the [TP] in shallow lakes is needed. In particular phosphorus loading to shallow lakes needs better quantification. A clear understanding of these processes in shallow lakes will enhance our knowledge of these same processes in all lakes. It will also help to explain why the spring [TP]-summer [Chl*a*] relationship is different in deep and shallow lakes.

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TABLE 1. Spring or winter total phosphorus concentration ([TP]), summer chlorophyll _a_ concentration. ([Chl_a_]), summer [TP] in the trophogenic zone, and mixing regimes (D = deep, S = shallow) for the lakes used in the analyses.

Lake	Spring [TP] (mg/m³)	Summer [Chl_a_] (mg/m³)	Summer [TP] (mg/m³)	Mixing Regime	Reference
Amnisk North	66.0	21.6	37.9	D	Prepas and Trew (1983)
Amnisk South	68.7	21.0	38.6	D	
Baptist N.	57.8	34.1	65.6	S	
Baptist S.	79.9	50.9	55.3	D	
Birch	45.2	21.7	53.8	S	
Bourque	16.4	4.8	19.1	D	
Eden	28.7	9.2	19.6	D	
Ethel	34.6	6.3	19.9	D	
Hastings	152.0	80.6	156	S	
Hilda	28.3	5.6	25.7	S	
Hubbles 1980	27.1	10.4	15.8†	D	
Hubbles 1981	26.2	7.6	20.7	D	
Marie	15.8	5.5	16.0	D	
Mink	24.7	5.3	26.9	S	
Moore	33.9	4.7	23.6	D	
Nakamun 1980	53.1	41.7	155	S	
Nakamun 1981	78.4	150	155	S	
Narrow 1981	11.1	3.4	11.8	D	
Roi	13.4	5.8	14.8	D	
Sauer	33.0	18.6	31.7	D	
Star	28.8	5.4	21.2	D	
Tucker	29.1	30.0	58.9	S	
Twin 1980	21.4	1.7	12.0	D	
Twin 1981	16.3	2.3	12.8	D	
Wizard	36.3	26.4	44.2	S	
Wolf	39.4	7.3	21.3	D	
Lough Neagh					C. E. Gibson (pers. comm.)
1978	96	58	75 *	S	
1979	98	100	105 *	S	
1980	114	77	90 *	S	
1981	123	103	126 *	S	
Oneida					
1975	17.4	11.4	87.8*	S	E. L. Mills (pers. comm.)
1976	28.8	9.0	25.3*	S	
1977	31.3	12.8	30.5*	S	
1978	26.2	6.9	37.2*	S	
1979	35.8	7.2	40.2*	S	
1980	46.1	12.0	67.1*	S	
1981	44.2	11.9	72.1*	S	
1982	28.9	8.4	51.2*	S	

(Table 1 cont'd)

Lake	Spring [TP] (mg/m³)	Summer [Chl a] (mg/m³)	Summer [TP] (mg/m³)	Mixing Regime	Reference
Canadarago	39.5	22.5‡	----	S	Oglesby and Schaffner (1978)
Canandaiqua	10.1	2.6‡	----	D	
Canadice	9.2	4.4‡	----	D	
Cayuga 1972	20.7	9.7‡	----	D	
Cayuga 1973	22.2	7.8‡	----	D	
Cayuga 1974	20.5	8.7‡	----	D	
Conesus	17.6	5.6‡	----	D	
Hemlock	10.9	5.8‡	----	D	
Honeoye	16.2	13.2‡	----	S	
Keuka	15.1	3.3‡	----	D	
Lamoka	13.9	7.3‡	----	S	
Oneida 1973	42.0	29.0‡	----	S	
Otesego	8.4	2.2‡	----	S	
Otisco	8.4	2.2‡	----	D	
Owasco	14.7	6.2‡	----	D	
Seneca	17.5	7.1‡	----	D	
Skaneateles	7.7	1.5‡	----	D	
Waneta	24.0	20.8‡	----	S	

* Integrated concentration for the whole water column. This data was not used to compare the relationship between summer [TP] and spring [TP].

† Summer [TP] of the trophogenic zone not available for Hubbles in 1980. Data for the [TP] of the epilimnetic zone was used instead.

‡ Chlorophyll a plus pheopigments.

Table 2. A comparison of three regression lines (Eq. 1a, 2a and 3a) by analysis of covariance (* indicates significant difference ($P \leq 0.05$)).

COMPARISON OF THE THREE REGRESSION LINES	
Bartlett's Test for Homogeneity of Variances	
$P > 0.50$	
Comparison of Slopes	
$P = 0.23$	
Comparison of Intercepts	
$P = 0.01$ *	
Pairwise Comparison of Intercepts (Newman-Kuels test)	
Shallow vs. Deep	$P < 0.05$ *
Shallow vs. Dillon and Rigler's	$P < 0.05$ *
Deep vs. Dillon and Rigler's	$P >> 0.50$

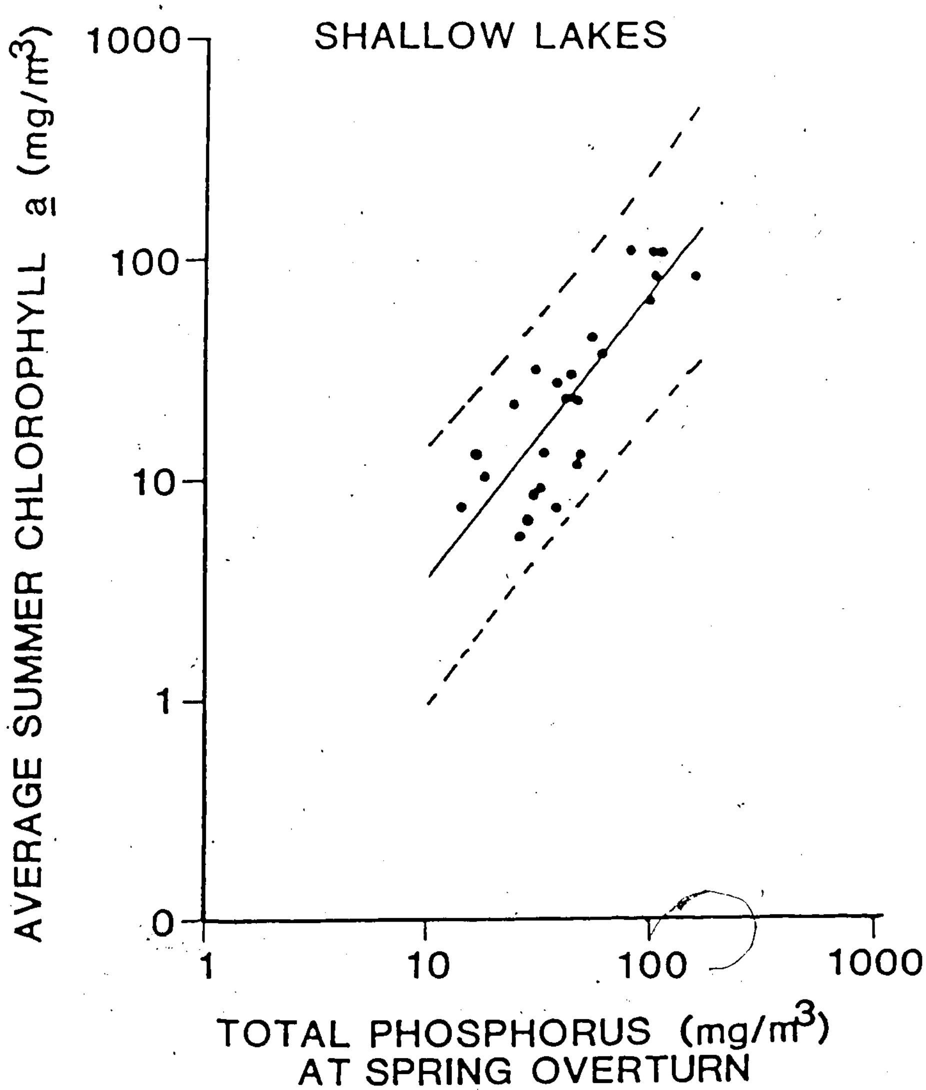

Figure 1. Summer chlorophyll a concentration vs. spring total phosphorus concentration in the sample of shallow lakes. Dashed lines are the 95% confidence intervals for lakes outside the original data set.

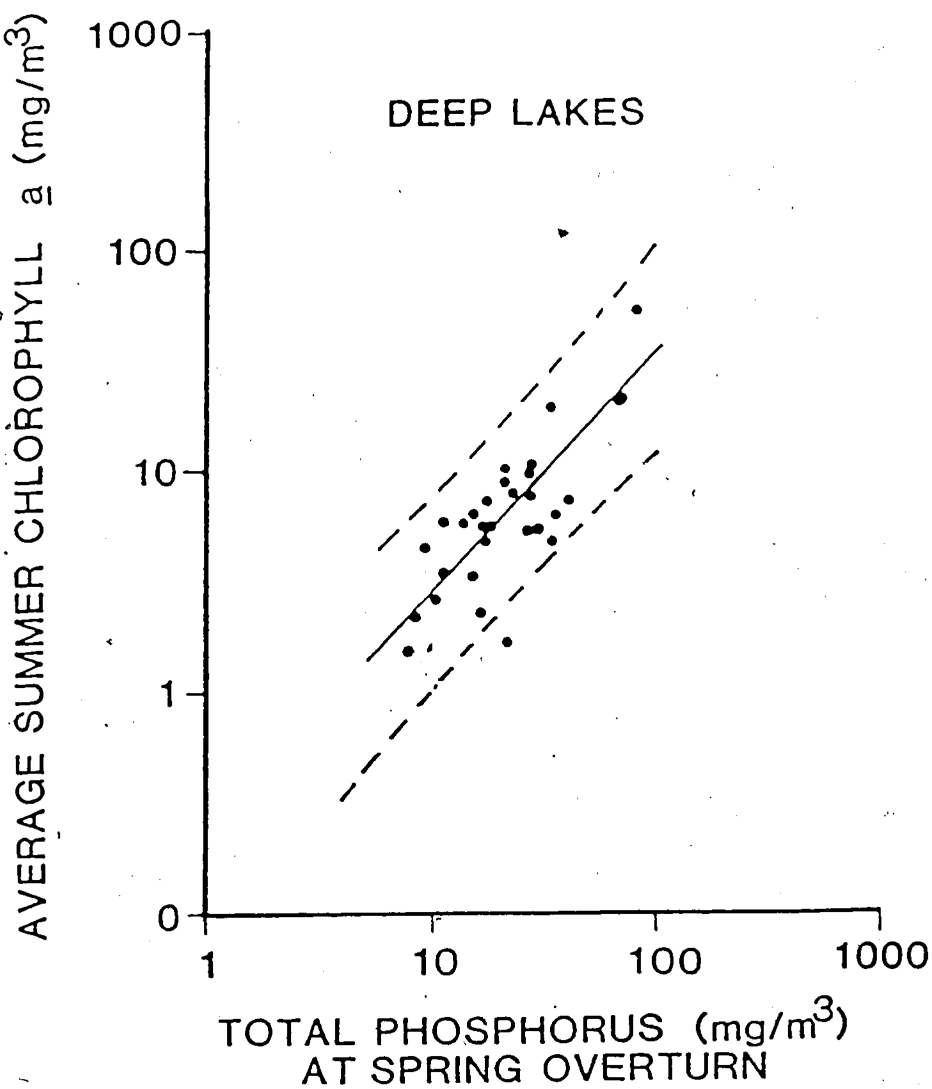

Figure 2. Summer chlorophyll a concentration vs. spring total phosphorus concentration in the sample of deep lakes. Dashed lines are the 95% confidence intervals for lakes outside the original data set.

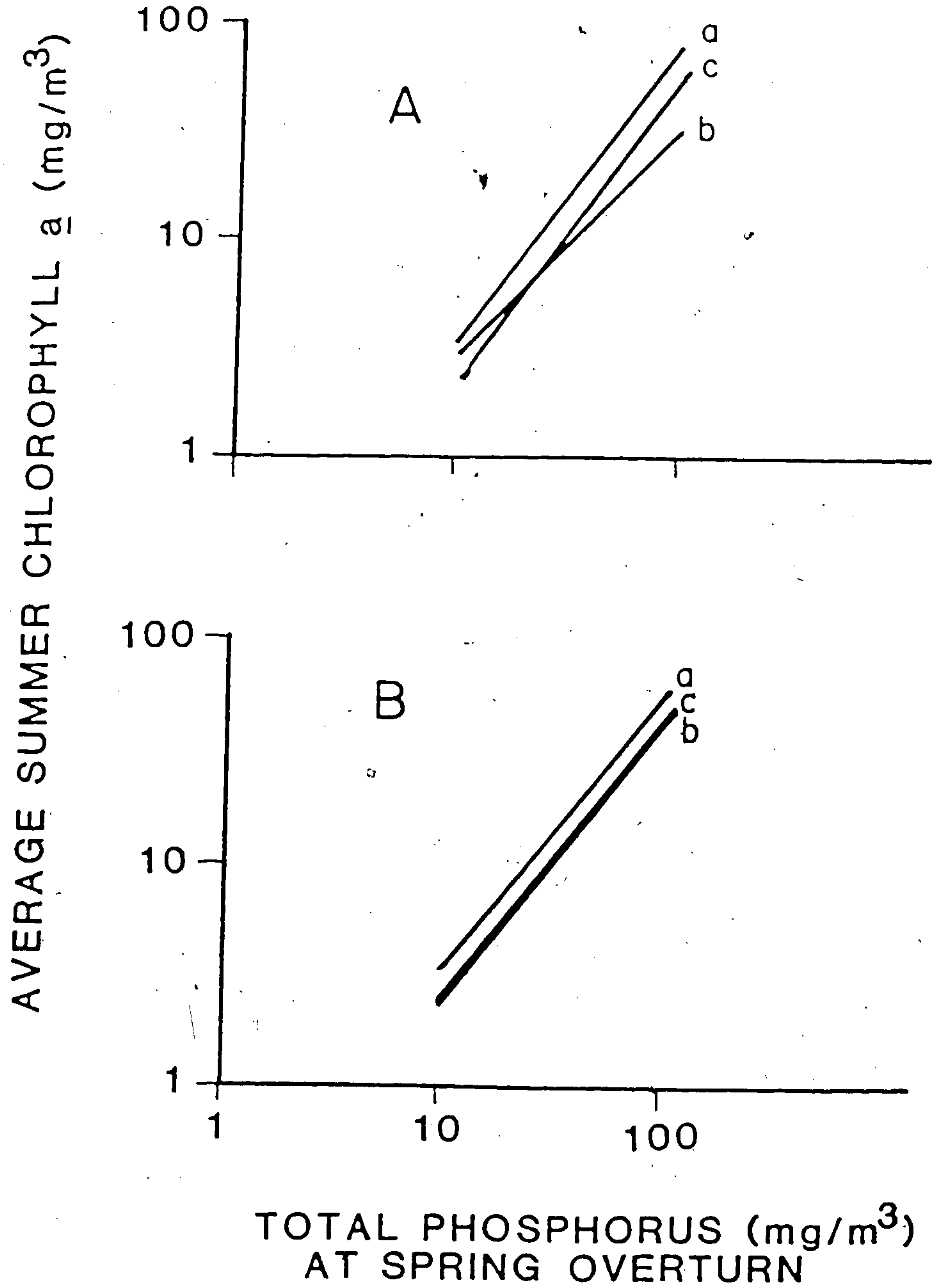

Figure 3. Summer chlorophyll a concentration vs. spring total phosphorus concentration for: (a) shallow lakes (Eq. 1a), (b) deep lakes (Eq. 2a), and (c) Dillon and Rigler's (1974) model (Eq. 3a) plotted together with the: (A) original slopes, and (B) slopes averaged.

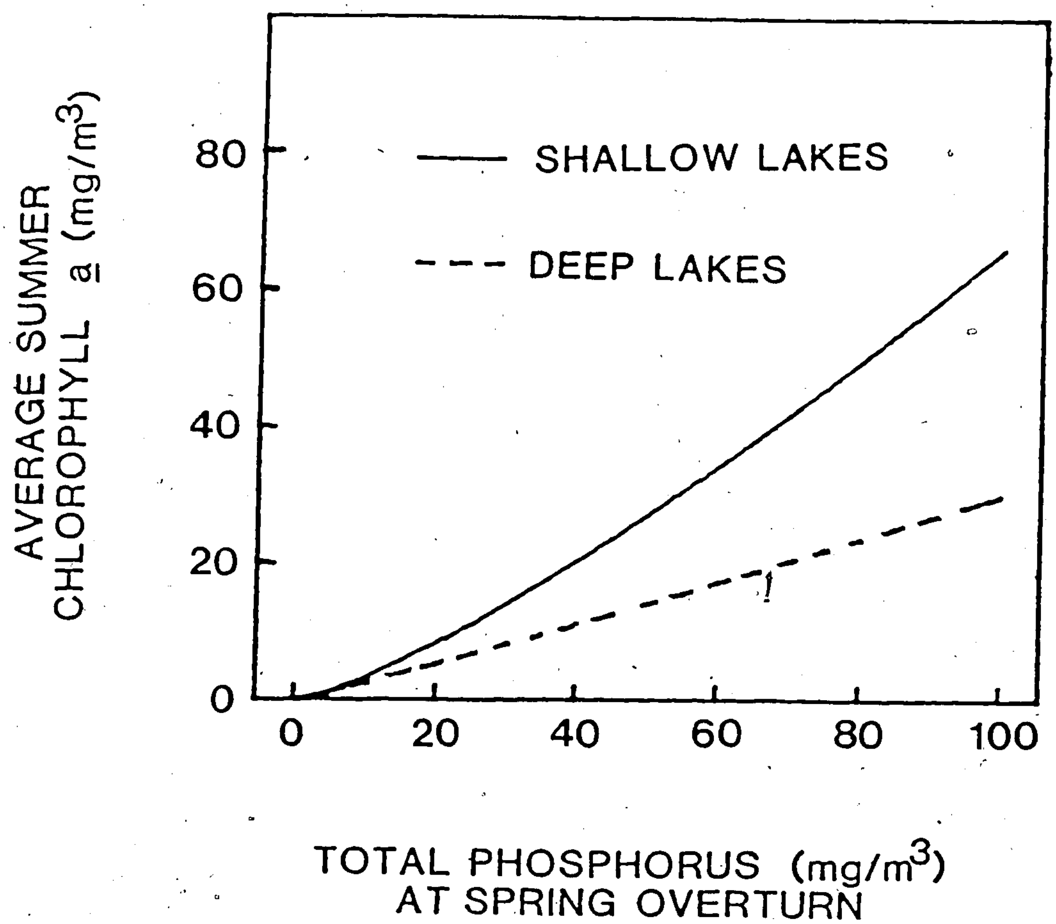

Figure 4. The regression equations of summer chlorophyll a concentration vs. spring total phosphorus concentration for the samples of deep and shallow lakes (Eq. 1 and 2) in the arithmetic scale.

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III. The Role of Internal Phosphorus Loading in Two Shallow, Productive Lakes in Alberta, Canada

A. Introduction

During summer, total phosphorus (TP) concentrations increase in the surface water of many shallow lakes (Larsen et al. 1975; Stevens and Gibson 1977; Reynoldson and Hamilton 1982; Prepas and Trew 1983). These increases occur when external phosphorus (P) loading is low. Thus, in shallow lakes, internal loading is often cited as the cause of the increased TP levels in the surface water.

Three mechanisms for internal P loading to the surface water in shallow lakes have been suggested: (1) release of P from profundal sediments when the overlying water is anoxic, with subsequent transport of this P to the surface water (Larsen et al. 1981; Stefan and Hanson 1981); (2) resuspension of lake sediments during mixing (Reynoldson and Hamilton 1982); and (3) release of P from healthy and scenescing macrophytes (Lie 1977; Carpenter 1980; Landers 1982).

Numerous laboratory studies have shown that P is released from lake sediments when the overlying water is anoxic (Mortimer 1941 and 1942; Theis and McCabe 1978; Holdren and Armstrong 1980) and release rates increase with higher water temperatures (Banoub 1975, Holdren and Armstrong 1980). Field studies have shown that P release from profundal sediments is an important source of loading to the deep water of shallow lakes (Stevens and Gibson 1977; Larsen et al. 1981; Stefan and Hanson 1982). The link between deep water buildup of TP and fluctuations of [TP] in the surface water is less clear. Only one field study (Larsen et al. 1981) has shown that the [TP] increased in the surface water after mixing. However, in that study, TP increases in the surface water after mixing were 139-1000% greater than the losses from the deep water. To demonstrate that the P released from the sediments is transported to the surface water during mixing, exchanges of TP between deep and surface waters need to be quantitatively balanced.

Alberta has many shallow, productive lakes (Prepas 1983). Total phosphorus concentrations in the surface water of these lakes increase during summer (Prepas and Trew 1983; Prepas and Wisheu unpublished data). To evaluate the contribution of the sediments to the TP levels in the surface water of these lakes, detailed studies were undertaken on Nakamun and Halfmoon Lakes. At Nakamun Lake, data were collected on the external TP loadings, vertical distributions of temperature, TP, total dissolved phosphorus (TDP), and dissolved oxygen (DO), and trophogenic concentrations of TP and chlorophyll _a_ (Chl_a_). At Halfmoon Lake, similar data on temperature, TP, DO, and Chl_a_ were collected. Both lakes were sampled throughout the ice-free season. Also, sediment cores from Nakamun Lake were taken to the laboratory and incubated under oxic and anoxic conditions at three temperatures. These data were used to:

(1) evaluate the effect of water temperature and DO levels in the water overlying the sediments on P release rates in shallow Alberta lakes; (2) quantify the relative importance of internal and external P loading to these lakes; (3) compare sediment release rates measured in situ and in cores; and (4) quantify the exchange of TP between the deep and surface waters during mixing and determine the effect of this input on TP and Chl*a* levels in the surface water.

B. Description of the Study Lakes

The two study lakes, Nakamun and Halfmoon, are located in the boreal mixed-wood biome in central Alberta. Nakamun Lake is 70 km northwest of Edmonton and Halfmoon Lake is 20 km east of Edmonton. Nakamun is a shallow (mean depth, 4.5 m)(Fig. 1A), medium-sized lake (surface area, 3.5 km^2), draining an area of 48.2 km^2, 42% of which is used for grazing and cereal crops. The mean depth of Halfmoon lake is similar (4.8 m)(Fig. 1B), but the surface area is smaller (0.4 km^2), and the drainage basin, 57% of which is used for grazing and cereal crops, is the same relative size (3.3 km^2). Both Nakamun and Halfmoon Lakes are eutrophic, the average summer Chl*a* concentrations in 1981 were 150 and 46.2 mg/m^3, respectively (Prepas and Trew 1983). Both lakes have relatively small littoral zones (< 20% of the sediment area) but the macrophyte beds in these areas are dense. Baseline chemical information on both lakes is in Prepas and Trew (1983).

C. Materials and Methods

To determine how oxic and anoxic conditions in the water overlying the sediments and water temperature influenced P release from the sediments of Nakamun Lake, sediment cores were collected with a multiple corer (Hamilton et al. 1970). At the lake, all but the top 20 cm of sediment was released from the bottom of the core and the tubes were filled with lake water. The cores were transported to the laboratory and incubated at one of three temperatures (3, 10, 25°C) under oxic or anoxic conditions for periods of 14 to 21 days. To maintain oxic (DO > 4 mg/L) and anoxic (DO < 1 mg/L) conditions, the water in the tubes was bubbled with air and nitrogen gas, respectively. Residual oxygen in the nitrogen was removed by passing the gas through a column of Catalyst R3-11 (Chemical Dynamics Corporation). To evaluate changes in TP levels in the water overlying the sediments, duplicate 5 mL subsamples were removed every three to five days and made up to 50 mL with double distilled water and stored for analysis. Water removed for analyses was not replaced.

Bathymetric maps for both lakes were constructed from data collected with a Furuno model FE-400 depth sounder. Lake surface areas were determined from aerial photographs and lake watershed areas from 1:50,000 topographic maps and aerial photographs. Lake volumes were determined from bathymetric maps with a Tallos digitizer connected to a Hewlett-Packard model 9825B desk-top computer.

The TP loading to Nakamun Lake from terrestrial sources and losses via the outflow were determined from discharge and [TP] in the six inlet and the outlet streams. Stream discharge was determined by the dye dilution technique (Dillon 1974); the dyes used were Flourescein and Rhodamine WT. Water samples for TP analysis were collected midstream and placed in a 1-L Nalgene bottle. Loadings for the 20% of the watershed area with no streams, were estimated from runoff coefficients (kg/km²/day) from adjacent watershed areas with streams.

Aeolean P inputs to Nakamun Lake were estimated with a collector located in the lake, on a raft. The collector consisted of a Nalgene funnel leading into a 2-L Nalgene bottle (Gomolka 1975). To exclude insects, 250-µm netting was secured to the bottom of the funnel (Dillon and Rigler 1974b). To discourage birds from perching on the funnel, plastic straws were taped to the outside rim. Every one to two weeks the bottle was taken to the laboratory, the volume of water was recorded, and the water was analysed for TP. Aeolean samples collected in May and June were fouled by insects, birds, and humans. For this period, data collected for Wabamun Lake (25 km southwest of Nakamun Lake) were used to estimate aeolean loading (P. Mitchell, pers. comm.).

Nakamun Lake was visited every three or four days and Halfmoon Lake was visited every two weeks during the ice-free season (between 11 and 13 May, and 10 and 15 November, 1982). Vertical profiles of TP were determined on water samples collected at 1-m intervals from the surface to the sediment water at up to three stations in Nakamun Lake (8.5, 6.5 and 4.5 m deep; Fig. 1A) and over the deepest part of Halfmoon Lake (8.5 m deep; Fig. 1B). More than one station was sampled at Nakamun Lake to evaluate if distance from the sediments was an important factor determining the TP level. At stations 1 and 3 in Nakamun Lake (Fig 1A), water samples from depths of 1, 3, 5, 6, and 8 and 1, 3, 5, and 6 m, respectively were analyzed for TDP. At all three stations in Nakamun Lake and at the one station in Halfmoon Lake, DO was determined on samples collected at 1-m intervals from the sediment-water interface until well-oxygenated water (DO > 4 mg/L) was encountered. Water samples for vertical profiles were collected with a 1.5-L drop-sleeve aluminum water bottle. Vertical profiles of temperature were measured at stations 1 and 3 in Nakamun Lake and at the one station in Halfmoon Lake at 1-m intervals with a Montedoro Whitney (model TC-5C) thermistor thermometer accurate to 0.1 °C. The epilimnion was defined according to Hutchinson (1957). The trophogenic zone was estimated as two times Secchi disk depth (Dillon and Rigler 1974a). Trophogenic TP and Chl<u>a</u> levels representative of the whole lake were collected at 5 to 10 stations in Nakamun and Halfmoon Lakes. Samples were collected from the surface to the bottom of the trophogenic zone with a polyethylene tube and pooled in 2-L opaque Nalgene bottles. In Nakamun Lake, this water was also used to determine the phytoplankton species composition. All Nalgene bottles used for transporting samples back to the laboratory were treated as outlined in Prepas and Rigler (1982).

Total phosphorus was determined on 50 mL subsamples with the potassium persulfate technique described by Prepas and Rigler (1982), with one modification. Since the *Aphanizomenon* colonies in Halfmoon Lake did not pass through a 250-μm net, the samples were not filtered. Water for TDP analysis was filtered through a pre-rinsed 0.45-μm Millipore HAWP membrane filter and analysed as for TP. Duplicate subsamples were analyzed from water over the sediment cores and for TDP; the remaining analyses were in triplicate.

Dissolved oxygen was determined on water samples which were fixed in the field and analyzed by Carpenter's (1965) modified Winkler technique. For the water overlying the sediment cores, DO was determined by a micro-Winkler technique (Burke 1962). Chlorophyll a was determined with the ethanol extraction method described in Bergmann and Peters (1980), with one exception. I used a Bausch and Lomb Spectronic (Spec) 710 spectrophotometer instead of a Spec 100. When Chla samples were read on both machines, the Spec 710 consistently gave higher readings. To make my data comparable with those reported from Spec 100s, my Chla values were corrected based on a comparison using Chla from Sigma Chemical Co.:

$$[\mathrm{Chl}\underline{a}](\mathrm{Spec}\ 100) = 0.88\ ([\mathrm{Chl}\underline{a}](\mathrm{Spec}\ 710)) + 0.28$$
$$(r = 0.98,\ n = 8,\ P < 0.01)$$

Phytoplankton counts were determined by the inverted microscope method described by Lund et al. (1958).

To estimate stratum and whole-lake masses of TP, profiles were collected at three stations in Nakamun Lake. The lake was divided into three sections corresponding to the depths of Stations 2, 3, and 1: areas over maximum depths of 0 to 5 m, 5 to 7 m, and 7 to 8.5 m, respectively. Masses of TP were calculated for each stratum, over each section, and summed for whole-lake masses. Masses of TDP were calculated in a similar manner, except the lakes was divided into two sections: areas over maximum depths of 0 to 7 and 7 to 8.5 m.

To calculate P loading to the deep water from the sediments and to the surface from the deep waters, the lakes were divided into deep and surface strata. The division was at 2.5 m because water above this depth was always well oxygenated and the trophogenic zone was generally in this region (average depths of the trophogenic zone during the summer for Nakamun and Halfmoon Lakes were 1.6 and 2.0 m, respectively).

The net external loading (NEL) to Nakamun Lake between two sampling dates, *t* to *t+n* (where *n* is the number of days), was calculated with the mass balance equation:

$$NEL = TP_{in} - TP_{out} \quad (1)$$

where TP_{in} is the TP entering the lake from runoff and aeolean loading, and TP_{out} is the amount of TP lost from the lake via the outflow from *t* to *t+n*. External loading to Halfmoon Lake was estimated from coefficients calculated with data from Nakamun Lake. Net internal load (NIL) to Nakamun Lake from *t* to *t+n* was calculated from the mass balance equation:

$$NIL = \triangle TP - NEL \quad (2)$$

where $\triangle TP$ is the change of TP in the whole lake from *t* to *t+n*. The units for NEL and NIL are kg. During periods when the lakes were stratified, release rates of TP and TDP (RR_{TP}) from the sediments (mg/m²/day) were calculated with the equation:

$$RR_{TP} = TP_{rel} \;/\; (n \;/\; As) \quad (3)$$

where TP_{rel} is the change in TP or TDP (mg) below 2.5 m, *n* is the number of days the lake was stratified, and As is the surface area (m²) of the sediments which were anoxic. Release rates from the cores were calculated with a modified Eq. 3: TP_{rel} was the increase of TP in the water above the core, *n* was the number days this water was bubbled with nitrogen gas, and As was the area inside the core (11 cm²).

Thermal budgets were constructed for Nakamun Lake to provide independent estimates of TP movement from the deep water to the surface water during mixing events. The volume of the epilimnetic water required to raise the temperature of a deep water stratum (e.g., 4.5 to 5.5 m) from that measured at *t* to that measured at (*t+n*) (V_{mix}) was calculated:

$$V_{mix} = V_d \left(\frac{T_{d,t+n} - T_{d,t}}{T_{epi} - T_{d,t}} \right) \qquad (4)$$

where V_d is the volume (m^3) of the deep water stratum, $T_{d,t}$ and $T_{d,t+n}$ are the temperature (°C) of the stratum on *t* and *t+n*, respectively, and T_{epi} is the volume-weighted temperature of the epilimnion at *t*. The estimated volume of water exchanged between *t* and *t+n* and the TP concentrations at time *t* in the two strata, were used to estimate the vertical flux of TP between *t* and *t+n*. This flux was estimated for each stratum below the eplimnion where the temperature had increased from *t* to *t+n*. The total flux was used to calculate a predicted [TP] in the surface water at *t+n*. These budgets assume that during mixing, all exchange was between the deep water and the epilimnion (i.e., water did not mix between the deeper strata). Thermal budgets were calculated for periods of mixing in which the thermal mass (temperature x volume) of the lake did not change significantly (< 5%) between *t* and *t+n*.

D. Results

Sediment Core Experiments

In the sediment core experiments, TP was released when the overlying water was anoxic (Fig. 2). However, when the same water was aerated, TP levels decreased in the water column (Fig. 2). Release rates (RR_{TP}) increased proportional to water temperature (Table 1, Fig 2B):

$$RR = 0.51\,\theta + 1.78 \quad (r = 0.98,\ n = 11,\ P < 0.001) \qquad (5)$$

where θ is temperature (°C). These results suggest that: (1) when the water overlying the sediments in Nakamun Lake is anoxic, TP will increase in this water; and (2) in individual lakes, release rates are temperature dependent. Although core experiments were not run on sediments from Halfmoon Lake, I expected similar results since both lakes have similar mean depths (Fig. 1), superficial sediment type (black, organic material), levels of productivity, and water chemistry (Prepas and Trew 1983).

Phosphorus Loading to Nakamun Lake

Nakamun Lake had 12 successive periods of water stagnation and mixing between 17 May and 2 November, 1982. These periods of stagnation and mixing were divided into three categories: (1) stratification, when the water next to the sediments was anoxic and the chemocline or thermocline was not depressed from the previous sampling day; (2) complete mixing, when chemical or thermal stratification was not evident; and (3) partial mixing, when the thermocline or chemocline was depressed from the previous sampling day, but the water over the sediments was anoxic.

Nakamun Lake was stratified four times between 25 May and 23 August (Table 2); one of these periods lasted 34 days and the other three lasted 6 or 7 days. During these stratified periods, DO was rapidly depleted in the water over the sediments (Fig. 4B). For instance, on 22 July, the [DO] at 8 m at Station 1 was 5.4 mg/L; on 26 July, the [DO] was 0.3 mg/L at the same location. As DO levels approached 0 mg/L, the TP and TDP concentrations increased near the sediments (Fig. 4C and D), TP and TDP mass increased in the deep water, and the net internal load (Eq. 2) was positive (Table 2, Fig. 3A). Total phosporus levels in the surface water did not change more than 5% during any stratified period (Table 2).

During seven periods from 17 May to 2 November, Nakamun Lake mixed completely or partially. To facilitate the analysis, the period from 23 August to 2 November was divided into two periods (23-26 August and 26 August-2 November). Thus, Table 2 lists eight periods of complete or partial mixing. During the two periods of complete mixing which directly followed other periods of complete mixing (17-25 May and 26 August-2 November) (Table 2), the [TP] was constant throughout the water column (Fig 4C), the water over the sediments was well oxygenated (Fig. 4B), and the net internal load was negative (Table 2). During these two periods, the loss of TP from the whole lake was 6 and 2%/day, respectively. The remaining six periods of complete or partial mixing were between 28 June and 26 August (Table 2). Prior to each of these six periods, the water next to the sediments was anoxic and TP and TDP levels were high in the deep water (Table 2, Fig. 4). When the lake mixed, the P-rich deep water exchanged with the relatively dilute surface water. Consequently, during five of these periods, TP increased 3-43% in the surface water (Table 2, Fig 3A). During the sixth period (9-16 August), the TP level in the surface water decreased. Total dissolved P levels in the surface water remained constant throughout the summer (Fig 4D). During mixing events, TDP which was transported to the surface water, was probably incorporated immediately into the particulate P pool by the phytoplankton (Lehman and Sandgren 1982).

There were four periods of complete mixing between 15 July and 26 August (Table 2). During three of these periods, both TP and TDP levels decreased in the deep water and the net internal load was negative (Table 2). During these periods, the loss of TP from the deep water was greater than the increase in the surface water (Table 2). Thus, some of the P lost from the deep water went to the sediments. During the fourth period of complete mixing (23-26 August) the TP increased in both the deep and surface water and the net internal load was positive (Table 2). During the two periods of partial mixing in Nakamun Lake, TP and TDP continued to increase in the water over the sediments (Fig. 4C and D). Consequently, losses from the deep water were less than increases of TP in the surface water during the first period of partial mixing (28 June-5 July) and TP increased rather than decreased in the deep water during the second period of partial mixing (Table 2). During these two periods, the net internal load was positive.

Terrestrial loading to Nakamun was low, 39 kg between 17 May and 2 November. When the terrestrial loading estimates collected between 17 May and 2 November were extrapolated to a full year, the coefficient for the watershed was 1.9 mg/m². Between 17 May and 2 November, aeolean sources contributed a similar amount of TP to the lake, 43 kg. When the lake was stratified, the net external load (Eq. 1) was insignificant compared to the net internal load (Eq. 2) (37 and 1468 kg, respectively). During the four periods of stratification and the second period of partial mixing (5-15 July), release rates of TP and TDP from the sediments ranged from 10.5 to 19.6 and 8.1 to 28.0 mg/m²/day, respectively.

Phosphorus loading to Halfmoon Lake

Halfmoon Lake was thermally stratified in late May and by early July, partial mixing was evident (Fig. 5A). However, the mixing in Halfmoon was weaker than in Nakamun

Lake. Halfmoon Lake did not completely mix until 25 September. Consequently, the water overlying the sediments in Halfmoon Lake was anoxic from 27 May until 25 September. Based on thermal patterns, the study on Halfmoon Lake was broken into five periods: (1) a stratified period; (2) and (3) two consecutive periods of of partial mixing (the first was much weaker); and (4) and (5) two consecutive periods of complete mixing (the first followed a TP buildup in the deep water).

During the period when Halfmoon Lake was stratified (27 May-25 June), TP levels decreased 2%/day in the surface water and TP increased (78) kg in the deep water (Table 2, Fig 3B). During the first period of partial mixing (25 June-8 August), TP increased 36% in the surface water as the result of P-rich deep water mixing with the relatively dilute surface waters (Table 2, Fig. 3B). During this period, TP continued to increase in the deep water since the water overlying the sediments remained anoxic (Table 2, Fig. 3B, 4B and C). Mixing was stronger from 8 August to 10 September. Total phosphorus increased 52% in the surface water and a net loss of TP was registered from the deep water (Table 2, Fig 3B). However, the mixing was still incomplete during this period and TP levels remained high in the deep water (Fig 5C). From 10 to 25 September, the lake mixed completely, the TP resevoir in the deep water was distributed throughout the water column, the TP level in the surface water increased 31%, and the TP level of the deep water decreased (Table 2, Fig 3B and 5). During this period, TP increases in the surface water accounted for only one third of the losses from the deep water (Table 2). The lake continued to mix from 25 September to the end of the study (29 October). Total P decreased during this period, at a rate of 1%/day (Table 2).

When the water next to the sediments in Halfmoon Lake was anoxic, the net increase of TP was 147 kg (Table 2). Runoff and aeolean loading coefficients for Nakamun Lake (0.0051 and 0.065 $mg/m^2/day$, respectively) were used to estimate external loading to Halfmoon Lake. From 27 May to 10 September, external loading supplied an estimated 5 kg of TP to Halfmoon Lake. As in Nakamun, external loading was insignificant in Halfmoon Lake compared with internal loading.

Thermal Budgets

Thermal budgets were used to predict TP concentraions in the water above 2.5 m in Nakamun Lake on three occasions: 1, 5, and 15 July. The predicted TP concentrations were all higher than the measured values (Table 3). However, the predicted TP values assume no sedimentation. When a sedimentation rate of 1.5%/day (Rigler 1974) was applied, the predicted and measured values were much closer (Table 3). One predicted value was still overestimated (15 July) and another was underestimated (5 July). These calculations assume that the lake mixed immediately after the previous sampling day. Thus, the calculations are only approximate, but they suggest that sedimentation rates were variable in Nakamun Lake.

Chlorophyll a and Total Phosphorus in the Trophogenic Zone

In both lakes, TP and Chla concentrations in the trophogenic zone were correlated on a day to day basis from May to August ($r = 0.80$, $n = 28$, $P < 0.001$ and $r = 0.76$, $n = 7$, $P < 0.05$ for Nakamun and Halfmoon Lakes, respectively) (Fig. 6). As well in Nakamun Lake, TP and Chla levels were correlated during the fall (September to November, $r = 0.98$, $n = 10$, $P = 0.001$). However in Halfmoon Lake, TP increased in the fall due to lake mixing, while Chla levels decreased (Fig. 6). Thus, P transported to the surface water during the growing season (May-August) was incorporated by the phytoplankton, whereas P transported to the surface water during the fall was not.

E. Discussion

The data from Nakamun and Halfmoon Lakes support the original hypothesis that P is released from lake sediments when the overlying water is anoxic. During these periods, internal loading contributed 1468 and 147 kg of TP to Nakamun and Halfmoon Lakes, respectively. The sediments were likely the source of this internal loading: (1) the buildup of TP and TDP began and was always greatest at the sediment-water interface (Fig. 4C, 4D, and 5C); (2) in

Nakamun Lake, where both TP and TDP were measured, the build-up in the deep water was TDP not particulate P (during the four periods of stratification, TDP were 77-226% of the increased TP in deep water); (3) in four out of five cases when the lakes were stratified, increases of TP in the deep water could not be accounted for by losses of TP from the surface water (Table 2). Although groundwater is a potential P source, it was not monitered in either lake. However, loading patterns to the lakes indicate that the sediments, rather than groundwater, were the major TP source. If groundwater had been the major P input, the net internal load should have been positive throughout the summer, not just during stratified periods (Table 2).

When Nakamun and Halfmoon Lakes were stratified, external loading was insignificant (37 and 5 kg, respectively) compared with internal loading (1468 and 147 kg, respectively). These differences were not due to an underestimation of external loading. Aeolean loading coefficients from this study were similar to those for Wabamun Lake (25 km southeast of Nakamun) (P. Mitchell, pers. comm.) and Lake St. Nora, Ontario (Gomolka 1975).

Aeolean TP Loading

($mg/m^2/day$)

	Nakamun	Wabamun	St. Nora
12 Jul-12 Aug	3.24	3.08	2.78
23 Aug-23 Sep	1.43	2.20	2.03

The yearly terrestrial loading coefficient calculated for Nakamun Lake was lower than those measured for 10 other central Albertan (P. Mitchell, per. comm.) and 31 Ontario (Dillon and Kirchner 1975) watersheds with similar land use (1.9, 12.5, and 28.8 $mg/m^2/yr$, respectively). Our coefficient was low, partly because spring runoff can account for up to 70% of terrestrial loading to local lakes (Mitchell and Hamilton 1982) and only the last part of spring runoff was measured in my study. But even with a correction for spring runoff, my loading value was only half the amount for the other Albertan watersheds. However, this difference was too small to affect the relative difference between external and internal loading in Nakamun and Halfmoon Lakes.

The in-situ TP release rates estimated for Nakamun and Halfmoon Lakes were higher than those predicted from the sediments incubated in the laboratory (Eq. 5) (Table 1). However, there are inevitable errors associated with extrapolating release rates estimated from a 11 cm^2 microcosm to whole-lake release rates: (1) there was no sedimentation of organic material to the water overlying the cores; (2) adsorption of P by biota on the walls of the tube housing the core (Rigler 1956); and (3) imprecise measurement of the sediment area of the lake. Considering the possible errors, the predicted and measured rates are reasonably close (Table 1). In-situ release rates of TDP in Nakamun Lake were less than for TP on three occasions and more than for TP on two ocassions (Table 1). These differences are less than 40%, except for the period of 22 to 29 July (Table 1). During this period the TDP release rates were 228% higher than the TP release rates. Small differences are expected since TDP was not measured at as many depths or stations as TP. However, the differences for the period of 22 to 29 July were due to a large loss of particulate P throughout the water column.

Losses of TP from the surface water to the deep water were quite low in Nakamun Lake during the stratified periods (< 1%/day). The sedimentation rate was much higher in the mixing period of 17 to 25 May (6%/day) and somewhat higher in the mixing period of 26 August to 2 November (2%/day). One explanation for low sedimentation rates from the surface water during stratified periods, is that P can be transported from the deep, to the surface waters by eddy diffusion when vertical TP gradients are high (Larsen et al. 1981). Lower sedimentation rates would also be expected from June to November than from 17-25 May in Nakamun lake because of differences in the algal commun y composition. Diatoms were the dominant algal group in May, when sedimentation was high. Whereas cyanophytes, which have lower sedimentation rates, were dominant for the rest of the study (Fig. 7) (Reynolds et al. 1982).

This study supports the hypothesis that much of the P which is released from the sediments under anoxic conditions is transported to, and remains in, the surface water when the lake mixes. In both lakes, TP increased in the surface water during eight of nine mixing events, which followed a build-up of TP in the deep water. During periods of complete mixing, increases in the surface water could not be accounted for by external loading. However, these increases could be accounted for by a transfer of TP from the deep water, in all but one case. During periods of partial mixing, increases in the surface water were greater than losses from the deep water because P release from the sediments continued. Independent estimates of TP movement between the deep and surface waters (thermal budgets) also indicated that lake mixing caused the TP increases in the surface water. For most of the study period, macrophyte release and resuspension of sediments during mixing do not appear to be important P sources. If these sources were important, net internal P loading should have been positive rather than negative during periods of complete mixing. However, during one period of complete mixing in Nakamun Lake, the net internal load was positive rather than negative (23-26 August) (Table 2). During this period, TP increased in the surface water (as expected during mixing), but a corresponding decrease was not registered in the deep water. The P input to Nakamun lake for this period could have come from a source other than sediment release, such as senescence of macrophytes in the littoral zone (Carpenter 1980; Landers 1982).

The data from Nakamun and Halfmoon Lakes clearly illustrate the importance of P release from the sediments on the TP budget and [TP] in the surface water in shallow lakes. The data also illustrates the importance of the increased TP levels in the surface water on algal biomass (Fig. 6). Further studies are needed on the factors that control TP and Chl*a* levels in shallow lakes on a year to year basis. For example, summer Chl*a* concentrations in Nakamun Lake in 1980 through 1982 were 42, 150 (Prepas and Trew 1983), and 60 mg/m^3, respectively; and for Lough Neagh, Ireland in 1978 through 1981 average summer Chl*a* concentrations were 58, 100, 77, and 103 mg/m^2, respectively (C.E. Gibson pers. comm.). These differences may be due to variations in mixing patterns and release rates from year to year. For instance, had strong mixing occurred during June instead of July in Nakamun Lake, temperatures at the sediment-water interface would have been higher and more P would have released into the deep water. When the lake mixed, TP increases in the surface water would have been even greater and Chl*a* concentrations may have been higher. The importance of DO levels and temperature on P release rates were also demonstrated in this study. Further studies are needed on the factors which control between lake differences in P release rates. As the factors controlling year to year variation in productivity and lake to lake variation in P release rates are established, management tactics for shallow lakes will improve.

F. Acknowledgements

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Table 1. A comparison of release rates of total phosphorus (TP) from Nakamun Lake sediments incubated at three temperatures in the laboratory and from in-lake TP budgets for Nakamun and Halfmoon Lakes during periods of chemical stratification in 1982. Measured (Meas) release rates of TP for both lakes are compared with release rates predicted from incubated sediment cores (Eq. 5). The difference between measured and predicted (Diff) and the measured release rates of total dissolved phosphorus (TDP) for Nakamun Lake are also given.

Date		Temperature (°C)	Release Rate (mg/m²/day) TP Meas	TP Pred	TP Diff	TDP Meas
Mar†	Cores	3	3.6			
Apr	Cores	10	6.9			
Mar†	Cores	25	14.6			
25 May-28 Jun	Nakamun	14	10.5	8.9	1.5	8.1
05 Jul-15 Jul	Nakamun	17	19.6	10.5	9.1	12.5
22 Jul-29 Jul	Nakamun	17	12.3	10.5	1.8	28.0
03 Aug-09 Aug	Nakamun	19	14.7	11.5	3.2	8.9
16 Aug-23 Aug	Nakamun	17	12.2	10.5	1.7	16.0
27 May-25 Jun	Halfmoon	10	13.2	6.9	6.3	
11 Jun-08 Aug	Halfmoon	11	17.3	7.4	9.9	

† These cores collected in 1983.

TABLE 2. Changes in the mass of total phosphorus (TP) above and below the depth of 2.5 m in Nakamun and Halfmoon Lakes and changes in the mass of total dissolved phosphorus (TDP) in Nakamun Lake in 1982 during periods of stratification (Strat), partial mixing (Part Mix), and complete mixing (Tot Mix). Also presented are the net external and internal TP loads to Nakamun Lake and the changes in the mass of TP in Halfmoon Lake.

Date	Period of	Change of TP (kg) Above 2.5 m	Change of TP (kg) Below 2.5 m	Change of TDP (kg) Below 2.5 m	Net Internal TP Load (kg)	Net External TP Load (kg)
			Nakamun Lake			
25 May-28 Jun	Strat	-5	+709	+549	+695	+9
22 Jul-29 Jul	Strat	-20	+135	+306	+106	+9
03 Aug-09 Aug	Strat	+33	+105	+115	+135	+4
16 Aug-23 Aug	Strat	-10	+102	+133	+89	+3
28 Jun-05 Jul	Part Mix	+216	-156	-115	+40	+2
05 Jul-15 Jul	Part Mix	+106	+306	+195	+403	+10
15 Jul-22 Jul	Tot Mix	+137	-462	-635	-341	+16
29 Jul-03 Aug	Tot Mix	+23	-134	-308	-109	+2
09 Aug-16 Aug	Tot Mix	-37	-141	-123	-182	+4
23 Aug-26 Aug	Tot Mix	+135	+12	-59	+146	+2
17 May-25 May	Tot Mix	-538	-485	no data	-1034	-11
26 Aug-02 Nov	Tot Mix	-767	-796	-17	-1565	+10

(Table 2 cont'd)

	Period of	Change of TP (kg) Above 2.5 m	Change of TP (kg) Below 2.5 m	Change of TDP (kg) Below 2.5 m	Net Internal TP Load (kg)	Net External TP Load (kg)
		Halfmoon Lake				
27 May-25 Jun	Strat	-87	+78		-9†	
25 Jun-08 Aug	Part Mix	+22	+153		+165†	
08 Aug-10 Sep	Part Mix	+43	-52		-9†	
10 Sep-25 Sep	Tot Mix	+39	-120		-81†	
25 Sep-29 Oct	Tot Mix	-27	-67		-94†	

† Change of TP (kg) in whole lake, not internal load.

Table 3. A comparison of measured and predicted total phosphorus concentrations ([TP]) in the top 2.5 m of the water column of Nakamun Lake after periods of mixing. Predicted values were calculated from thermal budgets (Eq. 4) assuming no sedimentation from the zone above 2.5 m (0% Sed) and sedimentation rates of 1.5%/day (1.5% Sed).

Date	[TP] (mg/m^3) Above 2.5 m		
	Measured	Predicted	
		0% Sed	1.5% Sed
01 Jul	75	80	75
05 Jul	94	97	91
15 Jul	108	122	117

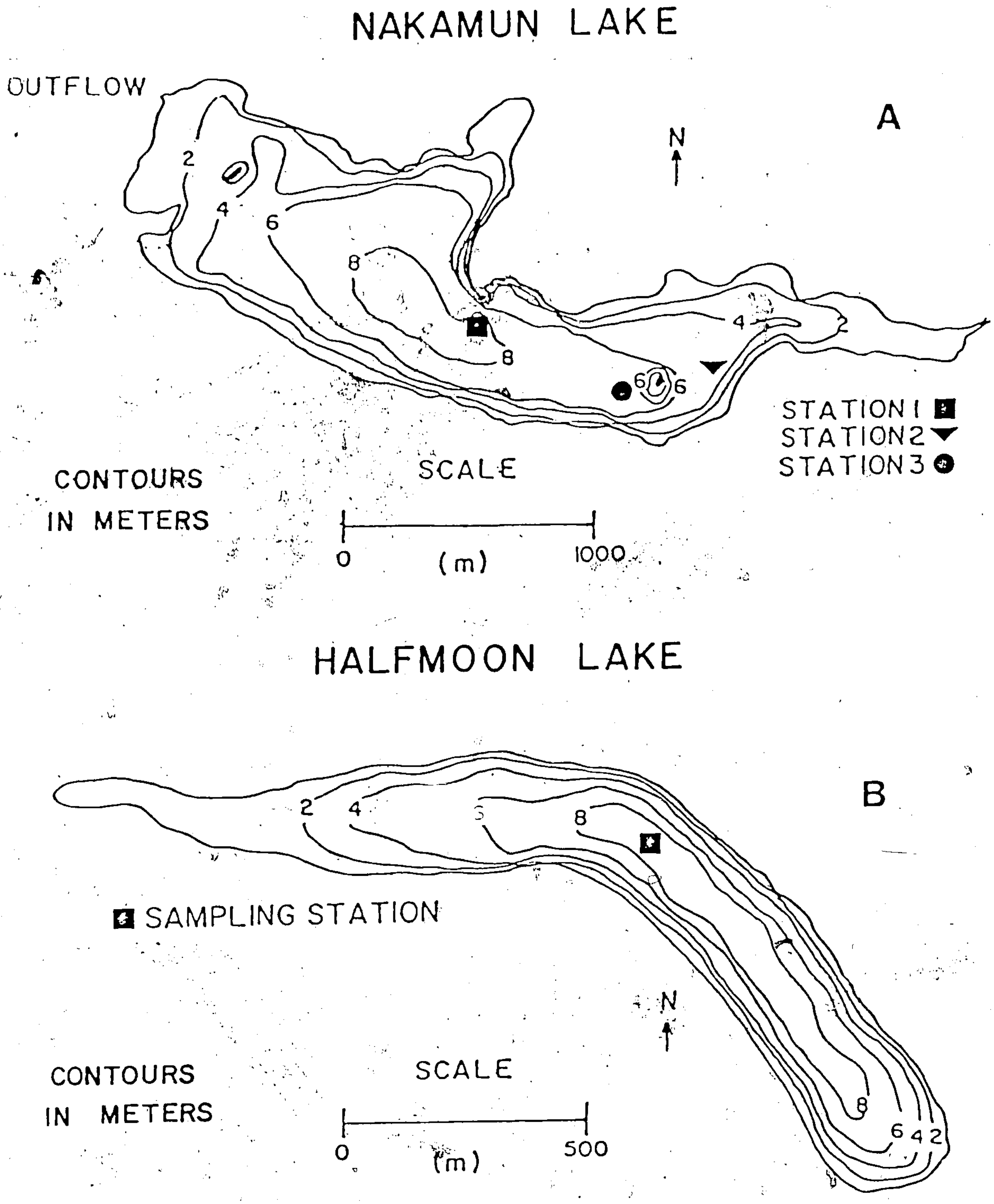


Figure 1. Bathymetric maps of: (A) Nakamun and (B) Halfmoon Lakes.

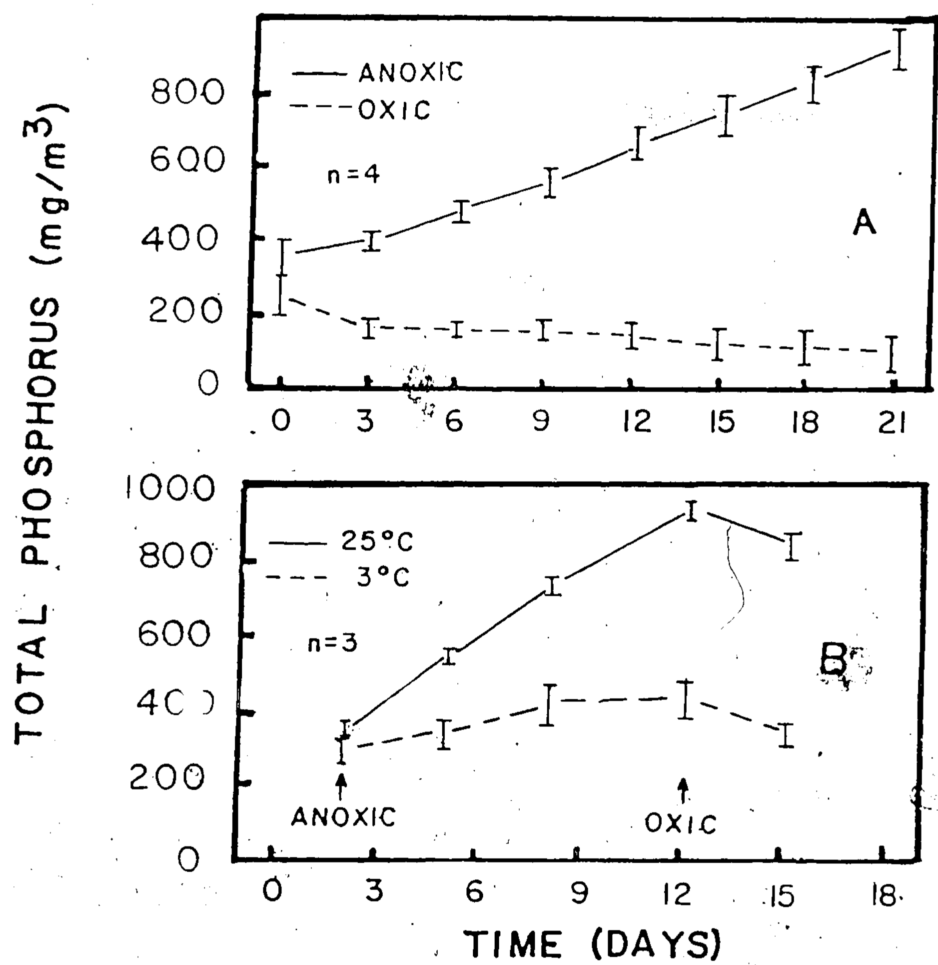
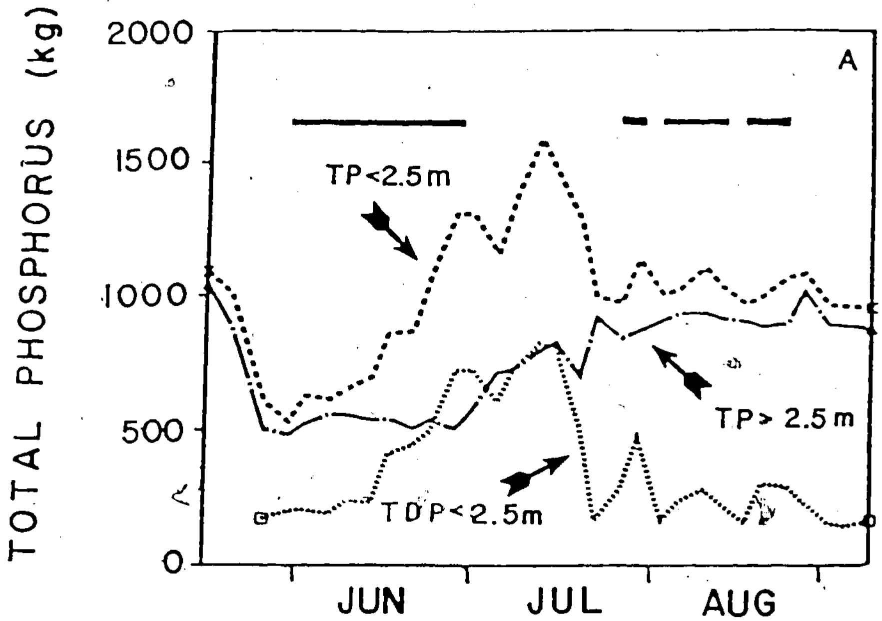


Figure 2. Mean total phosphorus concentration (± SE) of the water over lake sediment cores versus time. Cores were incubated in the dark under: (A) anoxic and oxic conditions at 10° C and (B) under anoxic then oxic conditions at 3° C and 25° C.



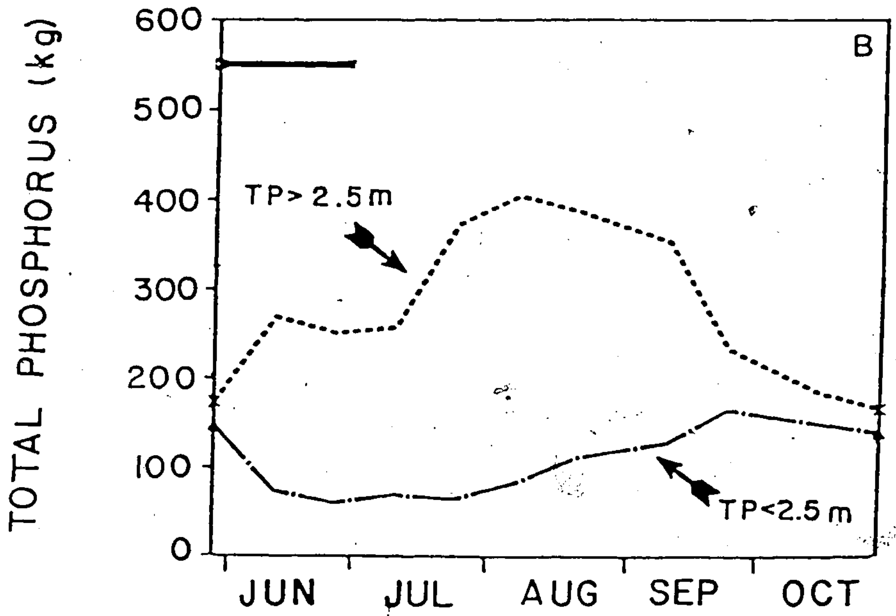


Figure 3. Mass of total phosphorus above (>) and below (<) the depth of 2.5 m versus time in: (A) Nakamun and (B) Halfmoon Lakes. Mass of total dissolved phosphorus (TDP) below 2.5 m also given for Nakamun Lake. Black bars indicate periods of stratification.

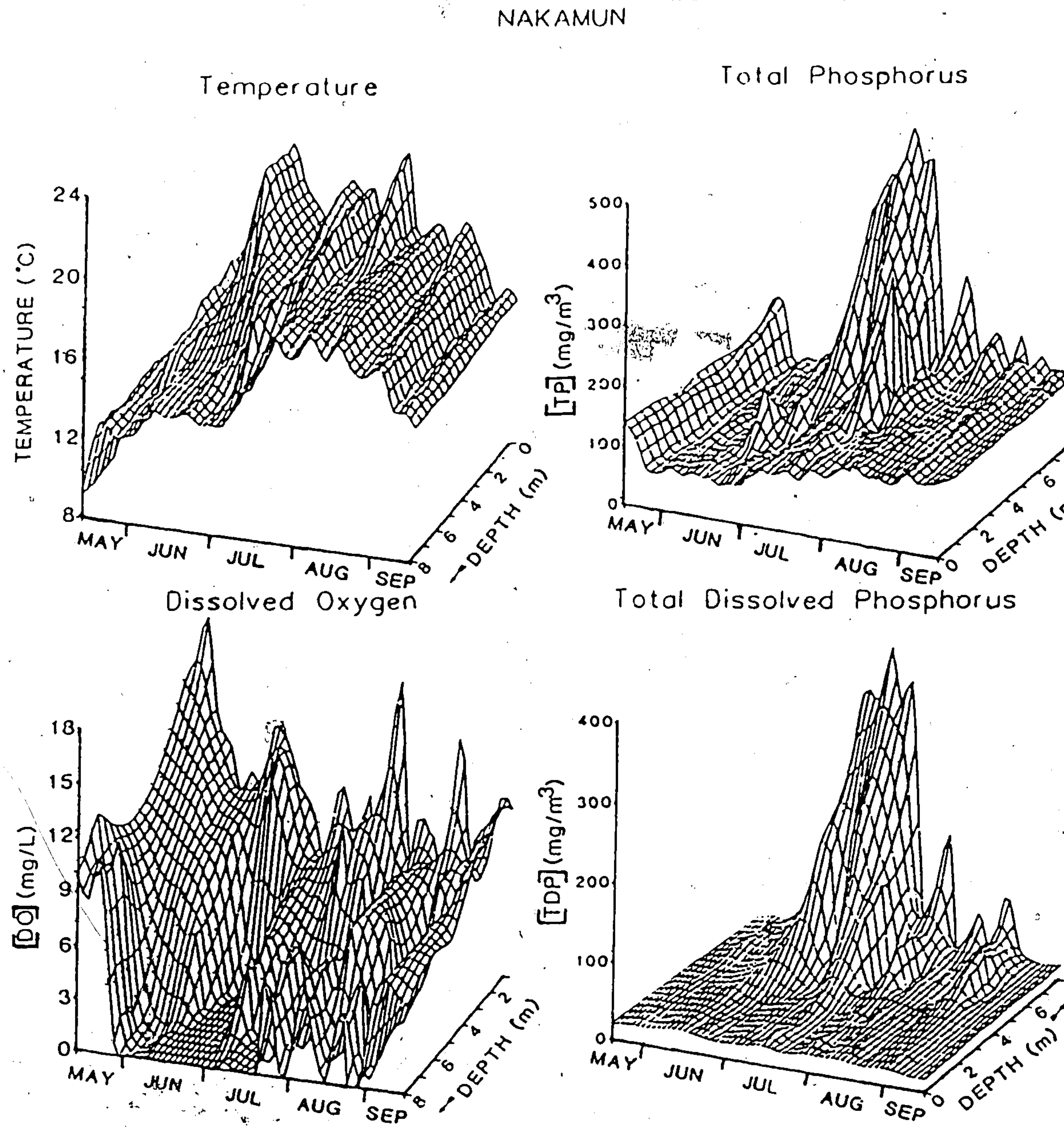


Figure 4. Three dimensional graphs of time versus depth versus: (A) temperature, (B) dissolved oxygen concentration ([DO]), (C) total phosphorus concentration ([TP]), and (D) total dissolved phosphorus concentration ([TDP]) over the deepest station at Nakamun Lake. Note that the depth axes are reversed in C and D.

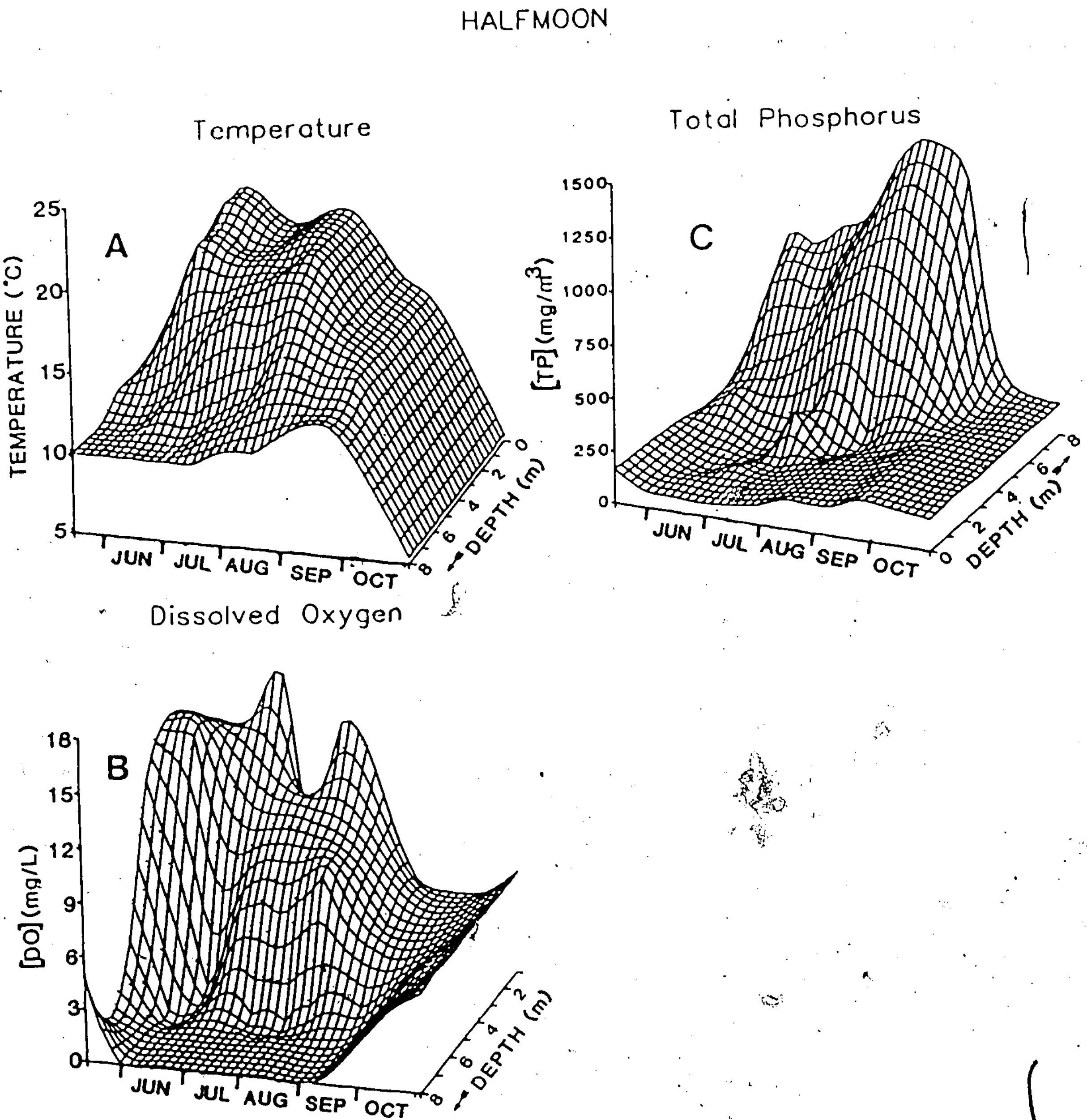
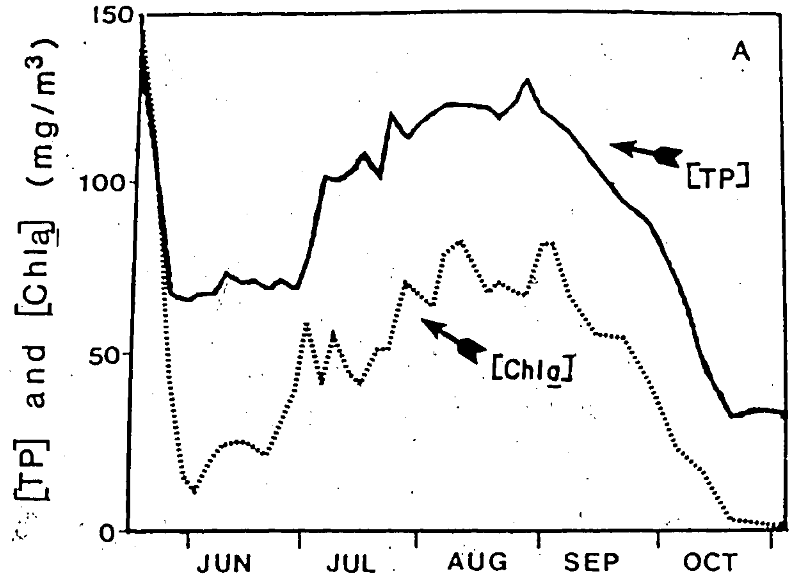


Figure 5. Three dimensional graphs of time versus depth versus: (A) temperature, (B) dissolved oxygen concentration ([DO]), and (C) total phosphorus concentration ([TP]) in Halfmoon Lake. Note that the depth axis is reversed in C.



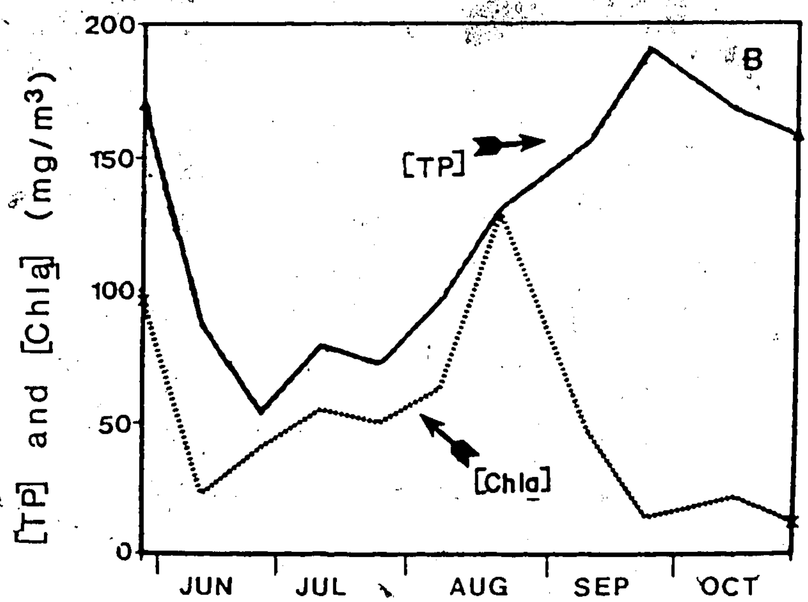


Figure 6. Total phosphorus concentration ([TP]) and chlorophyll a concentration ([Chla]) in the trophogenic zone from May until October, 1982 in: (A) Nakamun and (B) Halfmoon Lakes.

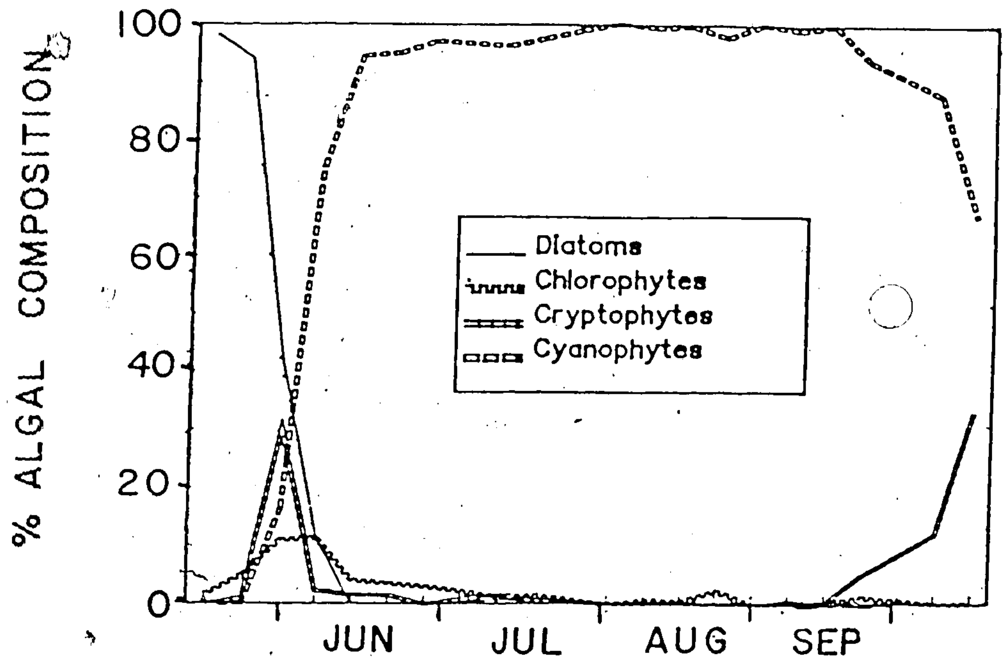


Figure 7. Percent composition of dominant groups in the algal community in the trophogenic zone of Nakamun Lake from May until October, 1982.

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IV. Concluding Discussion

A comparison was made of the relationship between spring total phosporus (TP) and summer chlorophyll a concentrations in deep and shallow lakes. The relationships were different ($P < 0.05$) in the two lake types. Shallow lakes had a higher summer [Chla] per unit of spring [TP] than deep lakes. The suggested reason for this difference was that TP concentrations in the surface water increased from spring to summer in shallow lakes, but decreased in deep lakes. Thus, relatively more phosphorus (P) was available to the phytoplankton community in shallow lakes during the summer than was indicated by spring [TP].

Internal P loading from the sediments is often suggested as the reason for increased surface water concentrations of TP in shallow lakes. The importance of this source was investigated in two shallow lakes in Alberta, Nakamun and Halfmoon. Laboratory experiments on sediment cores indicated P released into the overlying water when this water was anoxic. When the lakes were stratified, dissolved oxygen levels in the water overlying the sediments were low and TP levels increased in this water. During these periods, internal loading contributed 1468 and 147 kg of TP to Nakamun and Halfmoon Lakes, respectively, while external loading only contributed 37 and 5 kg, respectively. Total phosporus release rates, calculated from in-lake budgets for Nakamun and Halfmoon (12.7 and 15.6 mg/m^2/day, respectively), were higher than those predicted from cores incubated in laboratory (9.7 and 7.2 $mg/m^2/day$, respectively). Considering the possible errors in extrapolating laboratory measurments to the field, the predicted and measured rates were reasonably close. Lake mixing transported the P which released from the sediments to the surface water. After eight of the nine mixing events which immediately followed stratified periods, the [TP] increased 3-43% and 31-52% in the surface water of Nakamun and Halfmoon Lakes, respectively. Independent estimates of P movement in Nakamun Lake (thermal budgets) confirmed that TP increases in the surface water were due to lake mixing. The subsequent increase of TP levels in the surface water resulted in increased Chl*a* levels.

Although sediment release was the major source of internal loading, there were other internal inputs of P in Nakamun Lake. The importance of other mechanisms of internal P loading to shallow lakes (macrophytes (Lie 1977; Landers 1982) and sediment resuspension (Reynoldson and Hamilton 1982)) should be studied in conjunction with release from the sediments. Further studies are also needed on internal P loading from the sediments in other shallow lakes. From these studies, the effect of different mixing patterns on P release and transport can be determined. For instance, will more P be transported to the surface water in lakes which mix completely during the summer as compared to lakes which only partially mix? More studies on internal loading from sediments will also determine if P release rates are ignificantly different between lakes. Since internal loading seems to be the important factor influencing summer TP levels in shallow lakes, more productive lakes may have higher release rates. As he relative importance of mixing patterns and release rates are established, management tactics for shallow lakes will improve.

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V. Appendix A: A Test of Two Chlorophyll Models With An Independent Data Set.

Empirical models to predict the growing season mean concentration chlorophyll a ([Chla]su) are based on phosphorus (Nicholls and Dillon 1978). The relationship between total P concentration ([TP]) and ([Chla]su) is quite robust (Prepas and Trew 1983). However, the confidence limits for the models are quite broad (Dillon and Rigler 1974; Nicholls and Dillon 1978). Smith (1982) attempted to improve the predictability of [Chla]su by developing a model based on two variables, TP and total nitrogen (TN) concentrations:

$$\log_{10}[Chla]su = 0.653 \log_{10}[TP]su + 0.548 \log_{10}[TN]su - 1.517 \quad (1)$$

where [TP]su and [TN]su are mean growing season [TP] and [TN], respectively. The model is based on 311 cases.

In order to demonstrate how much variability TN accounts for in the phosphorus-chlorophyll relation, Smith compared his model (Eq. 1) with Dillon and Rigler's (1974) model based on [TP] alone:

$$\log_{10}[Chla]su = 1.449 \log_{10}[TP]sp - 1.136 \quad (2)$$

where [TP]sp is the lake's [TP] at spring overturn. For the test, Eq. 1 and 2 were used to predict [Chla]su for 311 lakes based on [TP]su and [TN]su (Smith 1982). Thus, [TP]su was substituted for [TP]sp in Eq. 2. To compare the accuracy of the models, residual variations (RV) were calculated for each model:

$$RV = (Cobs - Cpred)^2/(n - 1) \qquad (3)$$

where *Cobs* is the observed [Chla]su and *Cpred* is the predicted [Chla]su. For the 311 cases, the RV for Eq. 1 was 1% of the RV for Eq. 2. When only those lakes with a TN to TP ratio > 12 (i.e., lakes which are phosphorus limited according to Dillon and Rigler (1974)) the RV for Eq. 1 was 60% of the RV for Eq. 2.

However, Smith's comparison has a major problem (which he recognized in his paper). Equations 1 and 2 were compared with the same 311 cases used to construct Eq. 1. Thus, it was inevitable that Eq. 1 would be a more accurate predictor of [Chla]su than Eq. 2. The two models should have been tested with an independent data set.

To evaluate both models, I used an independent data set from western Canada consisting of [TP]sp, [TP]su, and [TN]su (Prepas and Trew 1983). For the comparison, I used 20 of the 22 lakes which had sufficient data for this comparison. Two lakes were excluded *a priori* because the [TP]sp in these lakes (303 and 761 mg/m³) were well beyond the range in Dillon and Rigler's study (3 to 180 mg/m³). Three sets of predictions were made: (1) Both [TP]su and [TN]su were used in Eq. 1 to predict [Chla]su, (2) [TP]su was used in Eq. 2 to predict [Chla]su, and (3) [TP]sp was used in Eq. 2 to predict [Chla]su. Contrary to Smith's approach, I calculated RV's for each model based on standard statistical techniques. Thus, the denominator in Eq. 3 was replaced with $n - i$ where i is the number of parameters estimated in the corresponding regression model (i.e., i = 3 and 2 for predictions from Eq. 1 and 2, respecitively).

The RV's from the three sets of predictions were compared pairwise with an F-test. Since three comparisons were made, the chance of committing a type I error was greater than the value given in a standard F table (Zar 1974). Therefore, a probability level of 0.02, rather than the traditional 0.05, was used to distinguish significance.

For the western Canadian lakes, Eq. 2 with [TP]su as the independent variable was the best predictor of [Chla]su, followed by Eq.'s 1 and 2 where [TP]sp was the independent variable (Table 1). The accuracy of Eq. 1 and 2 was statistically indistinguishable. (F = 1.7, df = 18,17, P = 0.26 for Eq. 2 based on [TP]sp; F = 2.8, df = 17,18, P = 0.04 for Eq. 2 based on [TP]su). Thus for the 20 lakes from western Canada, the addition of [TN]su does not improve the predictability of [Chla]su over [TP]su or [TP]sp alone. However, Eq. 2 was a better predictor of [Chla] when [TP]su was used rather than [TP]su (F = 4.8, df = 18,18, P =0.002). These results show [TP]su is a better predictor of [Chla]su than [TP]sp.

There are two possible reasons why the addition of TN did not add significant information to the [TP]-[Chla]su relationship for the 20 lakes in western Canada: (1) All these lakes had TNsu to TPsu ratios > 18 (Prepas and Trew 1983). Consequently, nitrogen was probably not limiting algal production (Dillon and Rigler 1974), although Smith argues that nitrogen is limiting even when the TNsu to TPsu ratio is > 18. The addition of nitrogen to the [TP]-[Chla]su model may be significant in lakes where the TNsu to TPsu ratio is < 18 and should be tested with the appropriate data [illegible]. (2) The data set is quite small and only from one [illegible]. Equation 1 should be tested on a larger data set [illegible]uding lakes from several regions.

TABLE 1. Observed average summer chlorophyll a concentration ([Chla]su) and predicted [Chla]su based on Dillon and Rigler's (1974) model using spring total phosphorus concentration ([TP]) (D&Rsp), Dillon and Rigler's model using average summer [TP] (D&Rsu) and Smith's (1982) model using average summer [TP] and total nitrogen concentration (*Cpred* is the predicted [Chla]su and *Cobs* is the observed [Chla]su). All data are from Prepas and Trew (1983).

Lake	Observed [Chla]su (mg/m³)	D&Rsp Predicted [Chla]su (mg/m³)	D&Rsu Predicted [Chla]su (mg/m³)	Smith Predicted [Chla]su (mg/m³)
Birch	21.7	18.3	23.5	21.3
Bourque	4.8	4.2	5.3	7.6
Eden	9.2	9.5	5.5	7.7
Ethel	6.3	12.4	5.6	8.8
Hasse	3.3	8.7	6.2	10.7
Hastings	80.6	106.0	110.1	79.7
Hilda	5.6	9.3	8.1	11.9
Hubbles	7.6	8.3	5.9	9.9
Marie	5.5	4.0	4.1	6.4
Mink	5.3	7.6	8.6	11.8
Moore	4.7	12.1	7.1	11.3
Nakamun	150	40.6	109.1	67.2
Narrow	3.4	2.4	2.6	4.7
Roi	5.8	3.1	3.6	7.6
Sauer	18.6	11.6	10.9	14.2
Star	5.4	9.5	6.1	10.2
Tucker	30.0	9.7	26.8	19.8
Twin	2.3	4.2	2.9	3.9
Wizard	26.4	13.3	17.7	16.8
Wolf	7.3	15.0	6.1	19.2
(*Cpred* *Cobs*)		13484.6	2750.8	7330.4
Degrees of Freedom		18	18	17
Residual Variation		749.2	152.8	431.2

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VI. Appendix B: Chemical and Morphometric Data For Nakamun and Halfmoon Lakes and Total Phosphorus Loading and Phytoplankton Data For Nakamun Lake.

Table 1. Total phosphorus concentration ([TP]), total dissolved phosphorus concentration ([TDP]), dissolved oxygen concentration ([DO]), and temperature profiles for Nakamun Lake (ST = Station).

DEPTH	[TP] (mg/m³)			[TDP] (mg/m³)		[DO] (mg/L)		TEMPERATURE (°C)	
	ST 1	ST 2	ST 3	ST 1	ST 3	ST 1	ST 3	ST 1	ST 3
17 May 1982									
0	138.1								
1	138.1	130.5				16.4			
2	133.5	130.2							
3	123.0	129.7							
4	134.5	136.4							
5	133.8								
6	129.3								
7	141.0					12.4			
8	174.0					10.0			
20 May 1982									
0	115.6							11.2	
1	115.6	108.1				18.8		11.2	
2	115.4	105.3						11.2	
3	117.5	100.4						11.2	
4	114.0	110.2						10.9	
5	107.7							10.7	
6	133.0							9.5	
7	153.0					8.6		9.1	
8	170.0					8.6		[illegible]	
25 May 1982									
0	69.6							13.2	
1	69.6	62.4		22.2		13.5		13.3	
2	67.6	67.4						13.3	
3	68.2	68.7						13.3	
4	74.9	68.2						13.3	
5	74.7							13.1	
6	78.0							12.9	
7	80.5			21.0		11.0		12.9	
8	77.3			21.0		11.0		12.9	
31 May 1982									
0	65.0							14.8	
1	66.0	60.0		24.0		11.5		14.7	
2	63.3	63.6						14.4	
3	61.4	61.7		25.0		10.3		13.7	
4	62.0	66.0						13.5	
5	64.0			22.5		5.7		13.0	
6	64.3			23.3		2.4		12.6	
7	68.6					1.3		12.4	
8	81.0			24.6		0.7		12.2	

(Table 1 cont'd)

DEPTH	[TP] (mg/m³)			[TDP] (mg/m³)		[DO] (mg/L)		TEMPERATURE (°C)	
	ST 1	ST 2	ST 3	ST 1	ST 3	ST 1	ST.3	ST 1	ST 3
3 June 1982									
0	75.2	62.9						16.4	
1	64.4	69.9		24.8		8.9		16.4	
2	76.2	66.3						15.9	
3	80.0	67.0		24.1		8.7		15.7	
4	76.6	65.1						14.9	
5	71.6			24.1		5.6		14.5	
6	83.6			32.0		0.6		13.1	
7	98.2					0.2		12.6	
8	74.9			21.9		0.0		12.4	
7 June 1982									
0	64.7							14.9	
1	69.0		73.3	21.0		10.2		14.8	
2	65.9		76.4					14.7	
3	66.4		81.7			8.5		14.6	
4	60.6		78.8				6.3	14.6	
5	61.6		66.1	19.9		4.3	2.7	14.5	
6	85.0		106.8	25.4	36.6	0.0	0.0	13.4	
7	81.4							12.8	
8	92.4			29.6		0.0		12.7	
10 June 1982									
0	72.3	76.9	72.3					16.0	16.8
1	74.5		72.1	25.7		9.5		16.0	16.8
2	70.4		73.7					15.6	16.4
3	70.6		74.9			8.0	3.9	15.2	15.4
4	71.8		74.2				3.3	14.9	14.6
5	76.6		73.7	23.7		4.4	1.8	14.1	14.4
6	87.2		135.6	26.7	52.5	0.4	0.0	14.0	13.8
7	100.4					0.3		13.8	
8	98.4			40.0		0.0		13.5	
14 June 1982									
0	66.9		69.3						
1	72.4		70.5	26.4		13.0			
2	70.0		71.4						
3	86.4		73.1	25.0		4.7	10.4		
4	79.5		85.2			2.2	7.8		
5	79.3		86.0	27.9		0.2	3.9		
6	80.2		105.5	29.3	41.5	0.0	0.0		
7	94.3			29.7		0.0			
8	123.6			37.5		0.0			

(Table 1 cont'd)

DEPTH	[TP] (mg/m³) ST 1	[TP] (mg/m³) ST 2	[TP] (mg/m³) ST 3	[TDP] (mg/m³) ST 1	[TDP] (mg/m³) ST 3	[DO] (mg/L) ST 1	[DO] (mg/L) ST 3	TEMPERATURE (°C) ST 1	TEMPERATURE (°C) ST 3
17 June 1982									
0	70.0	69.2	59.4					19.9	20.7
1	66.1		80.5	28.3		13.0	12.6	19.9	20.5
2	68.3		70.7					19.8	20.3
3	153.0		80.2	29.3		2.2	6.5	17.0	17.9
4	102.7	80.2	102.0			0.0	1.1	15.2	15.5
5	84.0		88.1	44.5		0.0	0.0	14.3	14.4
6	99.6		90.0	57.7	70.3	0.0	0.0	14.0	14.0
7	138.1		118.7			0.0		13.9	
8	192.3			133.2		0.0		13.6	
21 June 1982									
0	59.2		66.4					22.2	22.3
1	68.8	64.3	66.4	21.6		11.6		22.1	22.3
2	65.9		66.4			10.8		22.1	22.3
3	90.9		69.1	20.9		0.5	10.7	17.4	19.4
4	89.0		78.9			0.0	0.1	15.7	14.8
5	[illegible]		116.3	55.2		0.0		14.3	14.0
6	[illegible]		181.3	60.2	119.5	0.0		14.0	13.5
7	[illegible]					0.0		13.7	
8	229.0			168.0		0.0		13.7	
24 June 1982									
0	65.2		61.3					20.4	19.8
1	77.6	64.6	73.0	24.0		9.6	8.2	20.4	19.7
2	71.1		79.0			8.4		20.3	19.3
3	64.5		81.0	18.6		0.0	0.1	20.1	17.8
4	117.9	160.3	142.8			0.0	0.0	16.0	17.4
5	134.0		96.8	78.7		0.0	0.0	14.7	16.7
6	178.3		187.6	112.5	116.0	0.0		14.5	14.6
7	220.7					0.0		14.0	
8	219.0			153.0		0.0		13.9	
28 June 1982									
0	65.5		60.7					19.4	19.2
1	68.3	62.5	66.7	16.3		8.7	8.4	19.4	19.2
2	64.0		65.3					19.3	18.8
3	68.0		67.6	13.4		4.3	4.3	18.6	18.5
4	75.9	142.5	131.7			0.8	0.0	18.1	16.2
5	144.4		178.4	86.5		0.0	0.0	15.4	14.3
6	231.7		237.7	175.5	178.0	0.0		14.0	13.9
7	375.9					0.0		13.4	
8	394.0			309.0		0.0		13.4	

(Table 1 cont'd)

DEPTH	[TP] (mg/m³)			[TDP] (mg/m³)		[DO] (mg/L)		TEMPERATURE (°C)	
	ST 1	ST 2	ST 3	ST 1	ST 3	ST 1	ST.3	ST 1	ST 3
1 July 1982									
0	80.1		76.5					18.6	18.6
1	70.7	81.3	66.7	18.6		7.7	7.4	18.6	18.6
2	77.9		72.4					18.4	18.5
3	75.3		76.0	16.8		4.9	6.7	18.1	18.5
4	87.8	98.1	80.3			4.1	6.4	18.0	18.4
5	147.2		166.7	61.8		0.8	4.4	17.5	17.3
6	240.8		251.8	160.0	193.5	0.0	0.0	14.2	14.5
7	386.6					0.0		13.6	
8	421.3			341.0		0.0		13.5	
5 July 1982									
0	101.0		92.0					17.7	17.5
1	98.4	93.6	92.4	21.9	22.1	5.7	6.2	17.7	17.5
2	96.5		91.0					17.7	17.5
3	99.2		92.4	19.4	19.4	5.6	6.3	17.6	17.5
4	108.0	90.8	92.4					17.3	17.5
5	112.4		92.4	31.1	31.1	4.6	6.1	17.3	17.5
6	114.3		95.1	40.8	21.0	4.1	6.0	17.2	17.5
7	432.5					0.8		13.8	
8	412.1			334.0		0.0		13.5	
8 July 1982									
0	93.1		94.1					19.3	19.2
1	96.7	96.7	95.3	21.1	19.9	9.6	10.6	19.3	19.2
2	97.7		93.1					18.7	19.1
3	95.3		95.0	21.1	18.8	5.2	8.3	17.9	18.8
4	101.6	101.3	100.1					17.7	17.9
5	100.1		100.8	30.5	30.5	3.4	4.5	17.5	17.7
6	290.0		170.2	190.9	90.1	0.6	0.3	15.8	17.0
7	442.1					0.6		14.1	
8	506.6			399.0		0.5		13.9	
12 July 1982									
0	95.5		98.9					20.6	20.9
1	97.0	105.7	103.7	18.6	22.1	8.9	10.1	20.6	20.9
2	110.7		104.0					19.8	20.8
3	109.5		108.8	18.9	21.0	5.2	5.0	18.9	19.3
4	126.2		112.7					18.1	18.1
5	202.8		119.2	116.5	116.5	0.5	0.1	16.3	17.0
6	274.5		246.0	188.4	164.0	0.2		16.0	16.4
7	360.3					0.0		15.5	
8	446.0			328.0		0.0		15.2	

(Table 1 cont'd)

DEPTH	[TP] (mg/m³)			[TDP] (mg/m³)		[DO] (mg/L)		TEMPERATURE (°C)	
	ST 1	ST 2	ST 3	ST 1	ST 3	ST 1	ST.3	ST 1	ST 3
15 July 1982									
0	103.6		110.8					19.9	20.1
1	112.0	107.7	105.8	29.5	34.8	6.8	7.3	19.9	19.9
2	115.6		102.7					19.2	19.7
3	107.5		107.5	29.8	28.8	4.8	5.0	19.0	19.6
4	143.3	256.1	113.9			2.4	3.4	18.6	19.0
5	166.5		197.8	95.5	95.5	1.0	0.3	17.7	17.7
6	228.9		211.4	131.4	124.0	0.2		17.3	17.5
7	283.8					0.0		15.9	
8	457.3			359.6		0.0		15.5	
19 July 1982									
0	89.6		91.1					20.3	20.4
1	87.9	90.1	89.4	20.7	20.7	9.6	10.1	20.3	20.4
2	87.0		92.5					20.3	20.4
3	89.4		88.5	19.9	19.9	9.5	10.3	20.2	20.4
4	168.7	92.0	89.4			1.1		19.5	20.4
5	318.9		93.0	103.5	19.2	0.3	9.8	18.6	20.4
6	205.6		184.6	129.3	110.5	0.0	0.3	18.0	17.6
7	234.9					0.0		17.4	
8	250.8			178.3		0.0		17.3	
22 July 1982									
0	108.5		129.7					18.2	18.1
1	110.5	139.2	128.7	16.0	19.7	6.3	4.3	18.2	18.1
2	104.4		129.0					18.2	18.1
3	106.1		128.7	17.4	20.7	6.3	4.2	18.2	18.1
4	108.0	127.3	130.9					18.2	18.1
5	114.1		133.8	16.3	28.3			18.2	18.1
6	108.5		143.1	17.0	34.5	5.6	3.5	18.2	18.0
7	114.1					5.5		18.2	
8	121.4			97.5		5.4		18.2	
26 July 1982									
0	106.1		113.6					20.6	20.9
1	107.1	113.2	109.5	19.8	21.3	14.5	15.7	20.2	20.2
2	109.8		108.1					18.9	19.9
3	106.4		105.4	19.1	19.8	6.5	8.1	18.4	19.0
4	100.1	115.6	107.6				7.7	18.3	18.6
5	106.6		108.5	23.1	24.9	4.0	3.1	18.1	18.1
6	120.2		149.7	43.5	60.8	1.8	0.9	17.8	17.9
7	155.1					0.9		17.7	
8	209.4			97.5		0.3		17.3	

(Table 1 cont'd)

DEPTH	[TP] (mg/m³)			[TDP] (mg/m³)		[DO] (mg/L)		TEMPERATURE (°C)	
	ST 1	ST 2	ST 3	ST 1	ST 3	ST 1	ST.3	ST 1	ST 3
29 July 1982									
0	102.1		103.3					22.3	21.8
1	103.7	131.7	113.2	28.6	24.2	16.3	13.8	[illegible]	20.6
2	110.9		118.7					20.1	20.1
3	109.0		115.4	24.7	27.1	2.8	7.3	18.5	19.4
4	153.6	109.7	112.5			1.1		18.1	18.6
5	151.7		105.6	68.7	39.2	0.5	2.4	18.0	18.2
6	139.8		189.6	69.8	106.1	0.6	0.1	18.0	17.7
7	186.3					0.6		17.6	
8	265.1			168.7		0.0		17.4	
3 August 1982									
0	121.9		117.5					18.5	18.8
1	123.4	114.5	115.6	18.8	21.3	5.3		18.5	18.8
2	117.5		118.5					18.5	18.8
3	122.4		115.4	18.0	22.0	5.3	6.7	18.5	18.8
4	124.8	115.8	117.0					18.5	18.8
5	124.6		120.5	18.3	20.6	5.3		18.5	18.8
6	120.7		119.5	19.5	18.3		6.6	18.5	18.8
7	125.1							18.5	
8	127.0			19.5		5.3		18.5	
6 August 1982									
0	122.3		122.1						
1	125.1	119.7	119.3	24.6	24.6	8.5	8.4		
2	122.1		124.0						
3	124.0		124.7	28.7	28.7	6.5	8.3		
4	123.6	124.9	127.0						
5	123.7		129.2	29.5	27.8		7.4		
6	119.5		124.9	29.8	29.9	3.7	6.0		
7	122.6					3.1			
8	120.7			26.4		3.6			
9 August 1982									
0	127.9		121.1					18.7	18.7
1	122.8	119.5	132.4	24.9	26.2	7.9	7.5	18.7	18.7
2	116.2		121.8					18.7	18.4
3	115.7		126.8	23.1	23.5	7.1	5.7	18.7	18.3
4	119.0	143.3	131.3					18.5	18.1
5	119.5		147.3	24.9	40.5	7.1	2.6	18.5	18.0
6	116.9		185.9	23.1	82.5	7.0	0.4	18.5	17.5
7	158.6					1.8		17.8	
8	173.9			70.5		0.7		17.3	

(Table 1 cont'd)

DEPTH	[TP] (mg/m³)			[TDP] (mg/m³)		[DO] (mg/L)		TEMPERATURE (°C)	
	ST 1	ST 2	ST 3	ST 1	ST 3	ST 1	ST 3	ST 1	ST 3
12 August 1982									
0	116.2		117.6					18.7	18.3
1	117.1	119.5	123.2	26.8	23.3	7.6		18.6	18.2
2	122.3		119.9					18.6	18.2
3	120.6		120.2	24.7	20.8	6.7	6.2	18.5	18.2
4	120.6	115.7	119.0					18.4	18.2
5	115.3		127.0	24.7	24.0		5.5	18.4	18.2
6	116.9		122.5	27.8	22.6	5.3	4.6	18.4	18.1
7	162.7					0.7		18.4	
8	169.3			59.7		0.0		18.2	
16 August 1982									
0	117.9		120.6					17.4	17.4
1	113.1	120.1	119.9	17.9	19.7	6.1	6.8	17.4	17.4
2	115.2		114.6					17.4	17.4
3	117.9		118.6	17.5	20.5	5.7	6.1	17.4	17.4
4	116.2	116.4	117.4					17.4	17.4
5	120.1		116.0	17.9	18.7	5.6	5.9	17.4	17.4
6	114.4		114.5	19.4	18.3		5.9	17.4	17.4
7	114.0					5.2		17.3	
8	119.6			19.0		4.2		17.3	
19 August 1982									
0	110.8		109.3					19.1	
1	115.7	110.3	118.7	21.2	20.9	13.4	13.2	18.8	
2	113.2		113.0					17.5	
3	113.0		112.7	22.0	22.7	3.9	4.5	17.3	
4	108.1	144.7	109.5			3.1	3.3	17.1	
5	114.7		120.4	33.0	35.7	2.2	2.0	17.0	
6	128.2		117.7	44.1	35.3	0.4	0.9	16.9	
7	138.8					0.0		16.8	
8	176.7			96.5		0.0		16.7	
23 August 1982									
0	112.9		117.5					18.2	18.5
1	114.1	113.4	115.2	22.2	24.3	8.5	9.5	18.1	18.5
2	112.2		119.7					18.1	18.5
3	113.4		120.9	24.6	22.9	6.9	9.4	18.1	18.5
4	124.5	126.1	126.3			1.7		17.5	18.0
5	124.9		133.8	49.1	44.4	0.9	0.9	17.4	17.5
6	137.5		161.0	59.7	83.1	0.9	0.0	17.4	17.2
7	153.7					0.0		17.0	
8	111.8			31.4		0.0		17.0	

(Table 1 cont'd)

DEPTH	[TP] (mg/m³)			[TDP] (mg/m³)		[DO] (mg/L)		TEMPERATURE (°C)	
	ST 1	ST 2	ST 3	ST 1	ST 3	ST 1	ST.3	ST 1	ST 3
26 August 1982									
0	133.4		138.6					17.1	17.0
1	133.9	125.7	134.9	25.9	25.6	5.3	4.8	17.1	17.0
2	136.4		131.9					17.1	17.0
3	134.1		125.7	24.4	33.4	5.0	4.5	17.1	17.0
4	138.9	120.2	127.9					17.1	17.0
5	132.4		123.4	24.1	28.2	3.8	4.5	17.1	16.9
6	133.6		126.9	25.2	26.3		4.6	17.1	16.9
7	138.9					5.0		17.1	
8	147.1			25.2		4.9		17.1	
30 August 1982									
0	118.7		120.8					15.4	15.3
1	118.4	117.7	114.4	17.3	18.0	6.7	4.2	15.4	15.3
2	120.1		113.3					15.4	15.3
3	118.0		114.7	18.1	19.5	6.3	6.3	15.4	15.3
4	116.8	113.7	114.7					15.4	15.3
5	116.1		118.7	18.8	19.5	6.5	3.3	15.4	15.3
6	115.8		118.4	18.0	18.0	6.3	4.2	15.3	15.3
7	118.0					6.3		15.3	
8	122.7			16.9		6.3		15.3	
3 September 1982									
0	120.1		114.7					16.0	16.0
1	116.5	116.8	114.0	17.3	17.7	10.3	9.3	15.9	15.9
2	114.9		114.7					15.9	15.9
3	114.0		109.7	16.2	18.4	9.5	8.7	15.9	15.8
4	113.3	114.2	114.2					15.9	15.8
5	115.6		114.0	15.8	16.5	6.8	8.2	15.7	15.7
6	122.2		117.3	16.5	17.3		7.9	15.5	15.7
7	129.9							15.5	
8	127.1			18.4		5.6		15.3	
7 September 1982									
0	125.7		118.8					15.4	15.1
1	114.7	117.4	115.2	18.3	19.5	9.7	8.7	15.4	15.0
2	115.5		110.8					15.3	14.9
3	113.7		114.2	20.1	20.1		5.7	15.1	14.8
4	116.4	124.7	115.5					14.9	14.7
5	112.8		115.9	20.1	19.7	6.0	5.4	14.8	14.7
6	114.7		113.3	18.6	20.7			14.7	14.7
7	116.7							14.7	
8	118.4			20.1		5.0		14.6	

Table 2. Total phosphorus concentration ([TP]), dissolved oxygen concentration ([DO]), and temperature profiles for Halfmoon Lake.

DEPTH	[TP] (mg/m^3)	[DO] (mg/L)	TEMPERATURE (°C)
25 May 1982			
0	166.1		11.5
1	166.1	13.4	11.5
2	168.3		11.5
3	163.0		11.5
4	155.9	12.3	11.4
5	136.3		11.1
6	145.6		10.9
7	182.3		10.4
8	229.2	4.9	10.1
11 June 1982			
0	78.4		17.5
1	80.7		17.5
2	91.4		16.8
3	95.6	14.2	15.6
4	120.2	6.8	13.9
5	222.9	0.0	11.3
6	278.8	0.0	10.7
7	627.3	0.0	10.4
8	805.6	0.0	10.1
25 June 1982			
0	70.9		20.7
1	82.1	13.4	20.2
2	51.5		19.8
3	71.2	8.8	19.4
4	91.4	0.8	15.0
5	156.7	0.0	12.5
6	331.0	0.0	11.2
7	663.7	0.0	10.6
8	775.2	0.0	10.2
9 July 1982			
0	62.3		19.7
1	68.9	16.2	19.1
2	98.4		18.6
3	55.4	8.0	18.0
4	59.1	5.3	16.9
5	136.2	1.5	15.2
6	449.5	0.2	11.7
7	644.2	0.0	10.6
8	878.3	0.0	10.2

(Table 2 cont'd)

DEPTH	[TP] (mg/m³)	[DO] (mg/L)	TEMPERATURE (°C)
23 July 1982			
0	69.6		18.2
1	78.5	7.6	18.2
2	69.6		18.2
3	77.0		18.1
4	260.8	5.9	17.9
5	190.9	0.3	16.2
6	609.5	0.0	12.4
7	824.5	0.0	11.7
8	930.1	0.0	10.9
8 August 1982			
0	95.8		19.3
1	97.2	13.7	19.2
2	92.0		19.0
3	97.2	8.3	18.7
4	72.3	6.1	18.3
5	279.9	0.0	16.5
6	721.9	0.0	13.6
7	996.1	0.0	12.3
8	1222.7	0.0	11.4
20 August 1982			
0	139.7		19.5
1	123.5	12.4	19.5
2	118.2		19.4
3	112.5		19.1
4	90.1	7.6	18.7
5	121.1	1.1	17.5
6	644.1	0.0	15.3
7	1076.6	0.0	13.4
8	1349.5	0.0	11.9
10 September 1982			
0	141.4		15.7
1	145.4	5.0	15.7
2	143.5		15.6
3	155.0	4.3	15.6
4	145.9	3.8	15.6
5	210.2	1.3	15.5
6	372.3	0.4	14.5
7	823.4	0.0	13.8
8	1181.2	0.0	13.0

(Table 2 cont'd)

DEPTH	[TP] (mg/m³)	[DO] (mg/L)	TEMPERATURE (°C)
25 September 1982			
0	189.4		14.4
1	185.6		14.4
2	189.7		14.3
3	188.2		14.3
4	183.9		14.2
5	183.2		14.1
6	189.9		14.0
7	284.4		13.5
8	481.1		13.1
15 October 1982			
0	169.3		9.5
1	168.3	4.5	9.5
2	170.2		9.5
3	167.8		9.5
4	168.8		9.5
5	172.9		9.5
6	169.3	4.5	9.5
7	178.2		9.4
8	174.8	4.3	9.4
29 October 1982			
0	151.7		5.4
1	161.6	5.9	5.4
2	157.0	5.8	5.4
3	149.8	5.8	5.4
4	156.3	5.8	5.4
5	151.9	5.8	5.4
6	161.4	5.7	5.4
7	149.8	5.8	5.4
8	152.9	5.6	5.4

Table 3. Total phosphorus concentration ([TP]) and chlorophyll a concentration ([Chla]) of the trophogenic zone, and Secchi disk depth (S.D.) in Nakamun Lake. Trophogenic zone defined as 2 times S.D.

Date	[Chla] (mg/m^3)	[TP] (mg/m^3)	S.D. (m)
May 13	140.0		0.7
17	147.2	136.9	0.8
20	115.5	110.0	0.6
25	42.7	67.5	
31	14.5	65.4	1.3
Jun 03	10.5	67.4	1.5
07	19.5	67.0	1.7
10	24.3	73.0	1.1
14	24.6	70.0	1.0
17	24.1	71.0	0.9
21	21.2	67.6	0.9
24	26.7	71.0	1.0
28	38.7	67.7	0.9
Jul 01	58.6	77.1	0.7
05	40.8	100.6	0.9
08	54.7	100.0	0.8
12	44.4	103.0	0.7
15	41.0	108.0	0.7
19	51.1	100.8	0.7
22	50.9	118.5	0.6
26	69.9	112.2	0.4
29		116.0	0.4
Aug 03	62.7	120.0	0.4
06	77.9	122.0	0.5
09	81.9	121.9	0.5
12			0.5
16	67.2	121.3	0.7
19	69.9	117.8	0.7
23	66.6	123.2	0.5
26	66.2	130.3	0.5
30	80.7	119.5	0.5
Sep 03	80.9	117.8	0.5
07	65.8	114.2	0.5
14	54.9	103.7	0.6
20	54.3	93.7	0.7
28	41.2	87.0	1.0
Oct 05	23.4	71.2	
12	15.8	46.3	2.7
20	2.6	32.0	5.0
27	1.5	34.0	5.5
Nov 02	1.4	33.0	

Table 4. Total phosphorus concentration ([TP]) and chlorophyll a concentration ([Chla]) of the trophogenic zone, and Secchi disk depth (S.D.) in Halfmoon Lake. Trophogenic zone defined as 2 times S.D.

Date	[Chla] (mg/m^3)	[TP] (mg/m^3)	S.D. (m)
May 27	96.0	170.2	0.9
Jun 11	23.1	86.9	1.1
25	40.8	54.1	
Jul 09	54.6	78.7	1.0
23	49.9	72.2	1.4
Aug 05	62.8	95.5	
20	129.4	130.5	0.7
Sep 10	46.9	155.8	1.2
24	14.0	190.2	2.3
Oct 15	21.5	166.9	2.0
29	11.6	157.5	1.5

Table 5. Strata volumes for Nakamun Lake.

Stratum (m)	Volume (m^3)
0-0.5	1767706
1-1.5	3084314
2-2.5	2773344
3-3.5	2483808
4-4.5	1985559
5-5.5	1561066
6-6.5	1190994
7-7.5	771943
8-8.5	253356

Table 6. Strata volumes for Halfmoon Lake.

Stratum (m)	Volume (m^3)
0-0.5	206173
1-1.5	350583
2-2.5	324923
3-3.5	297849
4-4.5	254377
5-5.5	201667
6-6.5	150087
7-7.5	104229
8-8.5	71874

Table 7. Total phosphorus runoff loading, aeolean loading, loss through the outflow, and net external load to Nakamun Lake.

DATE	Runoff of TP (kg)	Aeolean TP (kg)	Outflow TP (kg)	NET TP (kg)
May 13-17	2.22	0.76*	13.26	-10.22
17-20	2.21	0.57*	10.46	-7.62
20-25	4.68	0.95*	11.02	-5.31
25-31	3.07	1.14*	2.49	1.72
May 31-Jun 3	0.94	0.69*	0.00	1.63
Jun 3-7	0.03	0.92*	0.00	0.95
7-10	0.01	0.69*	0.00	0.69
10-14	0.00	0.92*	0.00	0.92
14-17	0.00	0.69*	0.00	0.69
17-21	0.00	0.92*	0.00	0.92
21-24	0.00	0.69*	0.00	0.69
24-28	0.00	0.92*	0.00	0.92
Jun 28-Jul 1	0.00	0.69*	0.00	0.69
Jul 1-5	0.28	1.24*	0.00	1.52
5-8	0.27	0.93*	0.00	1.20
8-12	0.19	1.24*	0.00	1.43
12-15	5.53	1.35	0.00	6.88
15-19	7.07	0.75	0.00	7.82
19-22	7.86	0.39	0.00	8.25
22-26	5.54	0.52	0.00	6.06
26-29	2.11	0.39	0.00	2.50
Jul 29-Aug 3	0.79	1.04	0.00	1.83
Aug 3-6	0.00	0.78	0.00	0.78
6-9	0.00	2.94	0.00	2.94
9-12	0.00	2.94	0.00	2.94
12-16	0.00	1.44*	0.00	1.44
16-19	0.00	1.08*	0.00	1.08
19-23	0.00	1.44*	0.00	1.44
23-26	0.00	1.59	0.00	1.59
26-30	0.00	2.12	0.00	2.12
Aug 30-Sep 3	0.00	0.40	0.00	0.40
Sep 3-7	0.00	0.52	0.00	0.82
7-14	0.00	0.28	0.00	0.28
14-21	0.00	0.28	0.00	0.28
21-28	0.00	1.19	0.00	1.19
Sep 28-Oct 5	0.00	0.21	0.00	0.21
Oct 5-12	0.00	0.21	0.00	0.21
12-19	0.00	1.30*	0.00	1.30
19-27	0.00	1.30*	0.00	1.30
Oct 27-Nov 2	0.00	1.30*	0.00	1.30

* Esitmates from average values from Alberta Environment.

Table 8. Algal counts from Nakamun Lake, summer of 198[illegible].

Date	Cyanophytes Cells/mL x 10^3	Chlorophytes Cells/mL x 10^3	Cryptophytes Cells/mL x 10^3	Diatoms Cells/mL x 10^3
May 17	0.00	2.60	0.00	165.00
25	0.00	5.50	1.00	105.00
31	2.80	1.90	5.20	7.30
Jun 7	37.40	5.60	1.10	5.60
14	229.00	9.70	3.70	0.00
21	325.00	12.00	5.20	0.00
28	305.00	9.40	0.00	0.00
12	222.00	3.10	3.90	1.50
19	250.00	3.90	1.50	0.10
26	524.00	3.90	1.50	0.00
Aug 2	230.00	0.00	0.00	0.00
9	329.00	2.40	0.00	0.00
16	340.00	0.80	0.00	0.00
23	242.00	5.50	0.00	0.00
30	213.00	0.00	0.00	0.00
Sep 7	260.00	0.00	0.00	2.30
14	198.00	0.00	0.00	0.00
20	181.00	2.30	9.50	0.00
Oct 6	115.00	0.00	15.90	0.00
12	15.90	0.00	7.90	0.00