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PREDICTING TROPHIC RESPONSE TO PHOSPHORUS ADDITION IN A CAPE BRETON ISLAND LAKE

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Freshwater Lake in Cape Breton Island is characterized by clear water (2-8 Hazen u), and high water temperature (10-12°C) and low oxygen levels (0-20% air saturation) in the hypolimnion in late summer. The lake receives ca. 27 mgP/m^2/y from developments and sea spray in addition to the natural, edaphic phosphorus load of 106 mgP/m^2/y. The lake is considered oligo-mesotrophic based on transparency (Secchi depth 7 m), total phosphorus (7.6 mg/m^3), annual mean and peak chlorophyll (2.5 and 6.4 mg/m^3, respectively), low hypolimnetic oxygen levels and relatively dense growth of macrophytes in shallow areas. A proposed development would increase the phosphorus load by ca. 5 mgP/m^2 during the summer which would increase the epilimnetic total phosphorus concentration to 8.6 mg/m^3 and peak chlorophyll to 9.8 mg/m^3, assuming an average lake response. These changes would place the lake into the mesotrophic category. Close to the outflow of the secondary treatment discharge, nuisance levels of algal response and macrophyte growth could be expected.

Vers la fin de l'été, le lac Freshwater, situé dans l'île du Cap Breton, est caractérisé par une eau claire (2-8 Hazen u), une température de l'eau élevée (10-12°C) et de faibles niveaux d'oxygène (0-20% de saturation d'air) dans l'hypolimnion. Le lac reçoit environ 27 mg P/m^2/ an des diverses exploitations et de l'embrun marin en plus de la charge naturelle de phosphore édaphique de 106 mg P/m^2/an. Ce lac est considéré oligo-mésotrophe basé sur la transparence (profondeur du disque de Secchi 7 m), le phosphore total (7.6 mg/m^3), la moyenne annuelle et le maximum de chlorophylle (2.5 et 6.4 mg/m^3 respectivement), le faible taux d'oxygène de l'hypolimnion et la croissance relativement dense des macrophytes en eaux peu profondes. Une proposition d'exploitation augmenterait la charge de phosphore de 5 mg P/m^2 pendant l'été, ce qui aurait pour effet d'augmenter la concentration totale de phosphore de l'épilimnion à 8.6 mg/m^3 et le maximum de chlorophylle à 9.8 mg/m^3, en supposant une reponse moyenne pour le lac. Ces transformations placeraient le lac dans la catégorie des lacs mésotrophes. Une croissance nuisible d'algues et de macrophytes peut survenir près de la bouche d'écoulement du traitement secondaire des eaux.

Introduction

Freshwater Lake (46° 38' 40''N, 60° 23' 45'' W) is the second largest lake in Cape Breton Highlands National Park and the largest boulder-beach (barachois) pond in the National Parks in Canada. Its location near the Park entrance, makes it highly visible and it is used for swimming. This necessitates that the lake and its catchment be managed to ensure its unimpaired recreational and aesthetic values.

Recently a development site on the northwest shore of the lake near the park entrance has been proposed as a preferred location for several reasons. Concerns have been raised about possible detrimental impact of the facility on the lake, which is already showing some signs of man-made eutrophication, unlike the other pristine, oligotrophic lakes nearby.

The freshwaters of Cape Breton Highlands National Park were surveyed during 1976 and 1977 and the information thus obtained was used in combination with some of the findings (Vollenweider & Kerekes 1980) of the Organization for Economic Co-operation and Development (OECD) Cooperative Programme on Monitoring of Inland Waters (Eutrophication Control) to evaluate the possible impact of phosphorus addition on Freshwater Lake which might result from the proposed facility.

Methods

Sampling procedures and methods of measurements are given in detail by Kerekes et al. (1978).

Water temperature, dissolved oxygen, hydrogen ion concentration and specific conductance (low-range probe) were measured in situ using a Hydrolab Surveyor II instrument equipped with a 20 m cable. Chlorophyll-a and phaeophytin were determined by the fluorometric method of Yentch and Menzel (1963) as modified by Holm-Hansen et al. (1965). Total phosphorus was determined on unfiltered duplicate samples, digested with potassium persulfate (Menzel & Corwin, 1965). The phosphate thus produced was then estimated, along with inorganic phosphate originally present in the sample, by the method of Murphy and Riley (1962).

Annual total phosphorus loading and annual mean total phosphorus inflow concentration were estimated from lake concentration using the formula and its derivations developed by Vollenweider (1976).

$$(L(P)/q_a)/(1 + \sqrt{T(w)}) = [\overline{P}]_i/(1 + T(w))$$

$$[\overline{P}]_i \approx [\overline{P}]_\lambda \cdot (1 + \sqrt{T(w)});$$

$$L(P) = [\overline{P}]_i \cdot q_a$$

where $L(P)$ = specific loading of total phosphorus per unit lake surface area ($mg\ P/m^2/y$)

$[\overline{P}]_i$ = average annual inflow concentration of total phosphorus ($mg\ P/m^3$)

$[\overline{P}]_\lambda$ = average annual concentration of total phosphorus in the lake ($mg\ P/m^3$)

$T(w)$ = water residence time (y)

q_a = hydraulic load (m/y).

The validity of the estimated annual mean inflow concentration of total phosphorus (13.7 mg P/m^3) was checked by examining the available total phophorus concentration measurements taken once a month between April, 1976 and March, 1977 in one of the major inflow streams. The annual mean total phosphorus concentration of the inflow was found to be 9.5 mg P/m^3 ((range 4.8 to 15.0 mg P/m^3) monthly values). Occasional measurements taken in a minor inflow stream gave similar results.

Mean chlorophyll-a and peak chlorophyll-a concentrations were predicted from lake total phosphorus concentrations using the formulae developed by Vollenweider and Kerekes (1981):

$$[\overline{Chl}] = 0.28\,[P]_\lambda^{0.96}$$

$$[Chl]^{max} = 0.64\,[P]_\lambda^{1.05}$$

where $[\overline{Chl}]$ = average annual concentration of chlorophyll-a in the euphotic zone (mg/m^3)

$[Chl]^{max}$ = annual peak concentration of chlorophyll-a in the euphotic zone.

Description of Freshwater Lake

Freshwater Lake (Fig 1, Table I) is a barachois pond separated from the sea by a pebble barrier which forms Ingonish Beach. A public beach is located at the northeast corner of the lake. The National Park Headquarters and staff residences are on the northwest side. Residential and commercial developments (part of the village of Ingonish Beach) and various roads on the drainage basin, all lie close to the lake. Beyond this area of development around the lake, the drainage basin is covered by white spruce, maple and balsam fir forest, underneath which lies compacted glacial till. Approximately 60% of the lake volume lies below MSL.

There is some evidence from specific conductance measurements that a small influx of saline water occurs during the winter (Fig 2), but in the spring and fall it mixes with the overlying water.

After spring breakup and a brief isothermal period, a layer of cold, dense, oxygen-poor water remained below 15 m depth, while water in the lake above it circulated freely (Fig 3). The epilimnion reached temperatures over 22°C while the hypolimnion was between 10-12°C. The volume of the hypolimnion decreased from 13% of the total lake volume in June (depth >10m) to 5% in September (>13m). During autumn mixing, the water gradually cooled off to around 1°C before freezing and warmed somewhat under ice by late March. Because long, windy, cool springs and autumns lead to long mixing periods, such relatively high hypolimnetic and cold under-ice temperatures are common in lakes in Atlantic Canada.

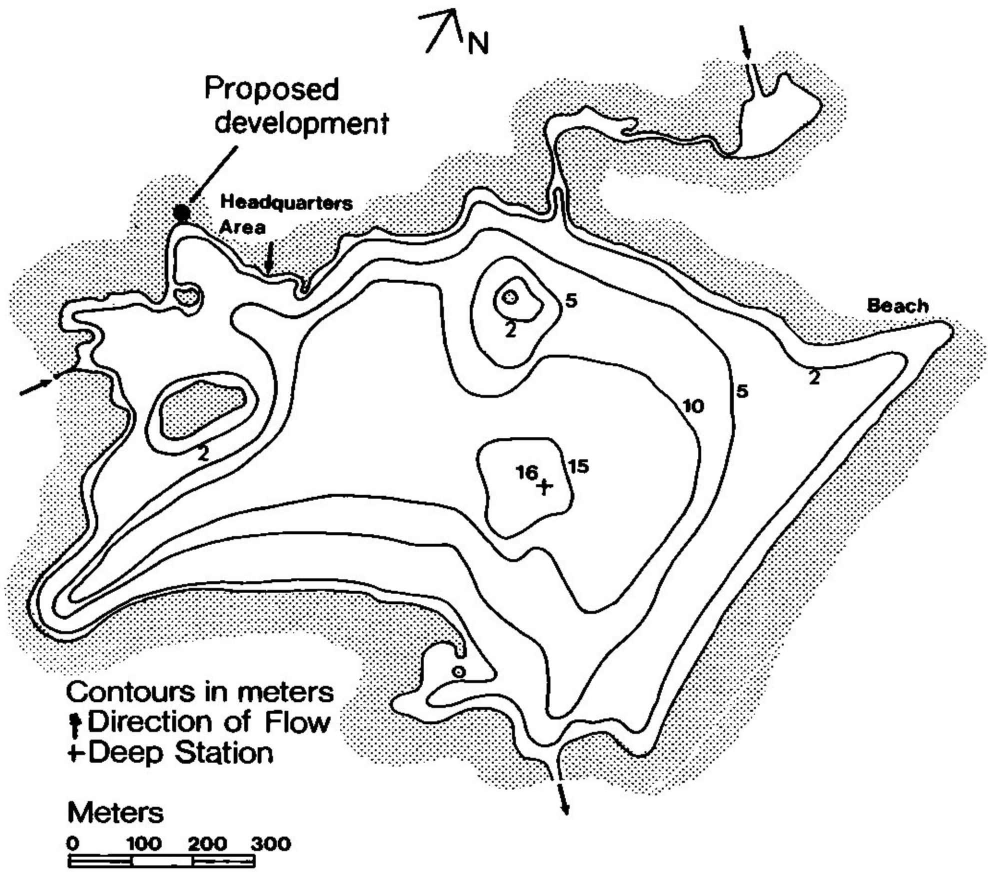

Fig 1. Bathymetric map of Freshwater Lake, Cape Breton Highlands National Park, Nova Scotia.

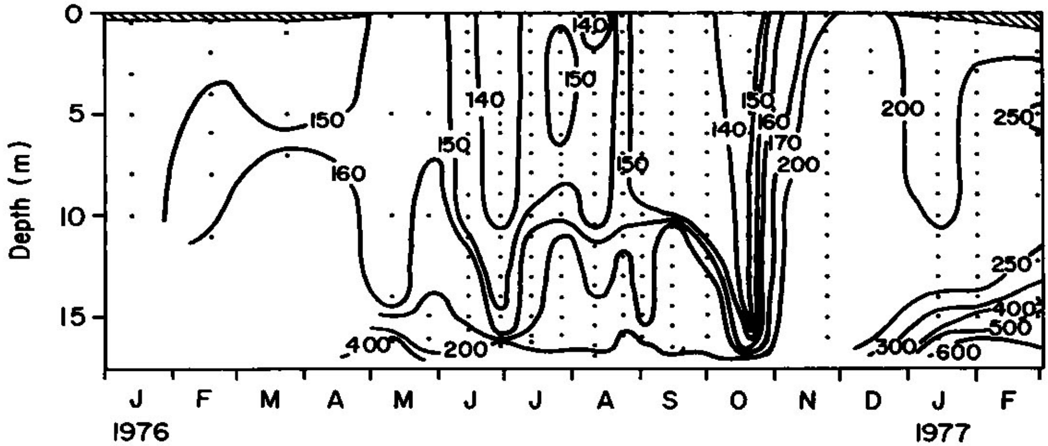

Fig 2. Isopleths of specific conductance µhmos/cm in Freshwater Lake. Dots in panel indicate depths of measurements on which the graph is based. Ice cover shown to scale.

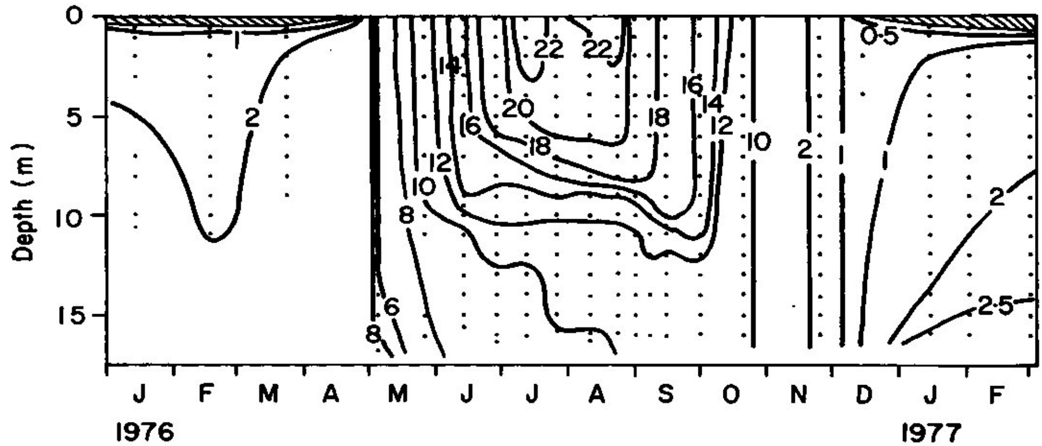

Fig 3. Isotherms °C of Freshwater Lake. See Fig. 2.

Dissolved oxygen concentrations in the euphotic zone were high throughout the study period, often exceeding air saturation (Fig 4). Hypolimnetic oxygen levels declined steadily throughout the summer and almost disappeared by mid-September. They remained above 50% air saturation during winter in all but the bottom meter of water.

The clarity of water in terms of both colour and turbidity, allowed the euphotic zone to extend to a maximum of 12 m depth with an ice-free seasonal mean of slightly over 11 m (Kerekes et al. 1981). Thus the tropholytic zone was restricted to the lower hypolimnion.

Table I. Selected morphometric and chemical features of Freshwater Lake, Cape Breton Highlands National Park, Nova Scotia.

Lake Surface, A_o 0.422 km^2; Drainage Area, A_d 3.4 km^2

Mean Depth, 6.49m; Max Depth, 16.3m; Cryptodepression Depth, 13.3m

**Water Residence Time, T(w) 0.67y; Water Surplus (runoff), ws 1.2m

Hydraulic load, q_a 9.69 m/y

*pH (range) 7.1 - 7.6; *Colour, 2 - 8 Hazen u

*Specific Conductance, 138 - 200 μmhos/cm, $\bar{x}$ = 164 μmhos/cm

*Secchi depth, 4.6 - 9.3m, $\bar{x}$ = 6.98m

Cations (mg/l)	Anions (mg/l)	(August 10, 1976)
Ca^{++} 11.0	HCO_3^- 15.1	SiO_2 0.2 mg/l
Mg^{++} 1.8	$SO_4^{=}$ 18.1	
Na^+ 19.5	Cl^- 28.0	
K^+ 0.7		

*Surface, ice-free period in 1976.
**T(w) = z/q_a
***q^a = z/T(w) or $1_y/A_o$ where Q_y = $A_d \cdot$ ws

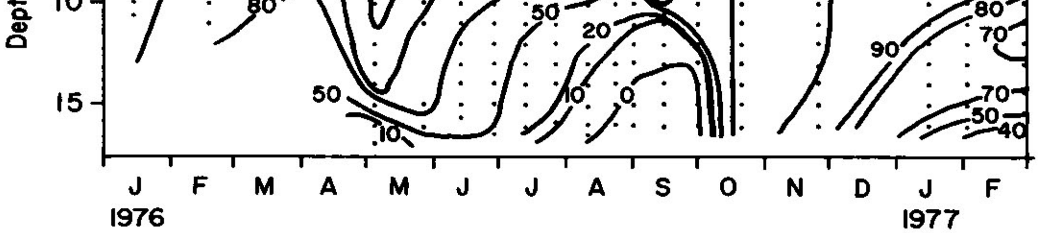

Fig 4. Isopleths of dissolved oxygen as air saturation in Freshwater Lake, January, 1976 - March, 1977. See Fig. 2.

The influx of some sea water either as salt spray or directly through the outlet stream during storms affects the water chemistry of the lake. Na^+ and Cl^- are the dominant ions and the specific conductance (Table I) is much higher than in the other lakes in the Park, with the exception of two ponds also located close to the sea. Winter salting of the highway in the lake's catchment also contributes to the

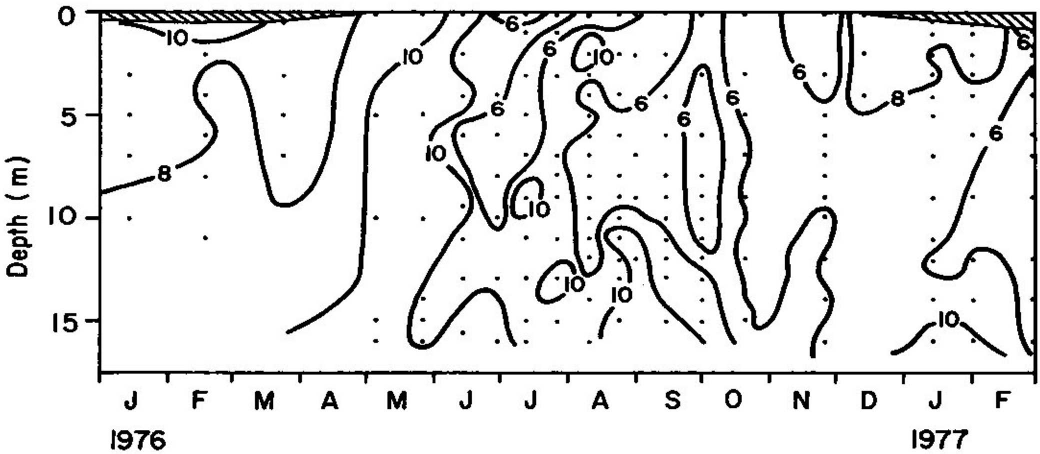

Fig 5. Isopleths of total phosphorus concentration (mg P/m³) in Freshwater Lake. See Fig. 2.

high conductance. Specific conductance of 470 μmhos/cm was measured in one of the inflows in early March, 1976. Specific conductance through the water column increased considerably during the fall and remained high through the winter of 1976, higher than in the previous year (Fig 2). The winter influx of some sea water into the deepest part of the lake gave a specific conductance near the bottom of 680 μmhos/cm by March, 1976.

Total phosphorus concentrations were the highest after breakup in May (Fig 5). The mean annual total phosphorus concentration in the lake (7.6 mg P/m³) is higher than in other Park lakes which were deep enough to stratify, including two pristine lakes (6.0 mg P/m³) located approximately 5 km from Freshwater Lake. The somewhat elevated phosphorus concentration is presumably the result of human activity on the drainage basin and of the seawater influx into the lake. Total phosphorus concentrations remained low, about 10 mg P/m³, in the deeper part of the lake at the end of the summer and during winter stagnation periods.

Mean total phosphorus concentrations in the mixed layer exhibited seasonal trends strikingly similar to that of chlorophyll-a concentration and turbidity (Fig 6). A spring peak of chlorophyll-a appeared in May, throughout the water column (Fig 7). During periods of thermal stratification the highest chlorophyll-a concentrations were found near 1% surface light intensity, i.e., at depths 10 m or greater, or 4 to 5 m under the ice. This condition has been described by Kerekes (1974, 1976) in Atlantic Canada and by Fee (1976) in northwestern Ontario.

Freshwater Lake exhibits annual mean and peak chlorophyll-a levels in relation to total phosphorus concentration that are higher than the "average" described by Vollenwinder and Kerekes (1980). Kerekes (1980) and Janus and Vollenweider (1981) showed among 18 lakes in Atlantic Canada that Freshwater Lake, along with two other clear-water lakes receiving anthropogenic phosphorus, had higher than average chlorophyll-a response to total phosphorus (above the OECD relationship), while the 15 pristine lakes, free from direct human influence, all show average or below average chlorophyll-a response to total phosphorus (Fig 8).

The number of phytoplankton cells/l in an integrated sample from Freshwater Lake (29 June, 1976) was 2.05 x 10^5. The most common species present was the xanthophyte *Chlorochromonas minuta* (9.77 x 10^4 cells/1), a species which con-

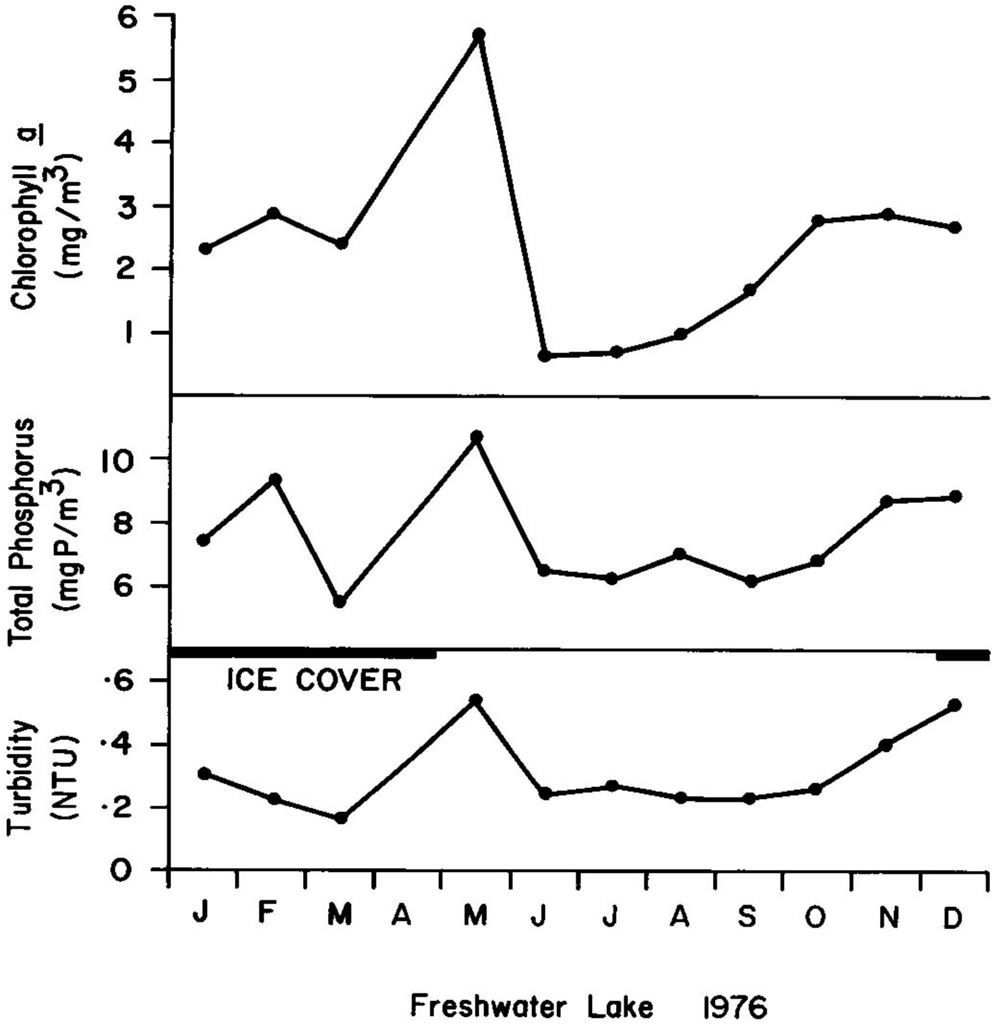

Fig 6. Mean monthly values of turbidity, total phosphorus and chlorophyll-a in Freshwater Lake, in 1976.

tributes to the spring phytoplankton bloom in Lake Mendota (Hutchinson 1967) and may well be responsible for a large part of the high spring chlorophyll-a concentration in Freshwater Lake. Two of the common diatoms, *Cyclotella meneghiniena* (4.31×10^4 cells/1) and *Synedra delicatissima* (2.27×10^5 cells/1), are also known to contribute to spring phytoplankton blooms.

The lake also supports dense growth of submergent aquatic vegetation at the western end in small sheltered embayments with mud bottoms. Twenty-two aquatic plant species were recorded in Freshwater Lake on August, 1976, including *Chara globularis*, five species of *Potamogeton* and two species of *Myriophyllum* (Davis and Wilson 1979).

The trophic characteristics of Freshwater Lake indicate that the lake is in transition between an oligotrophic and a mesotrophic state. According to the "fixed boundary system" for trophic categories developed in the OECD Eutrophication

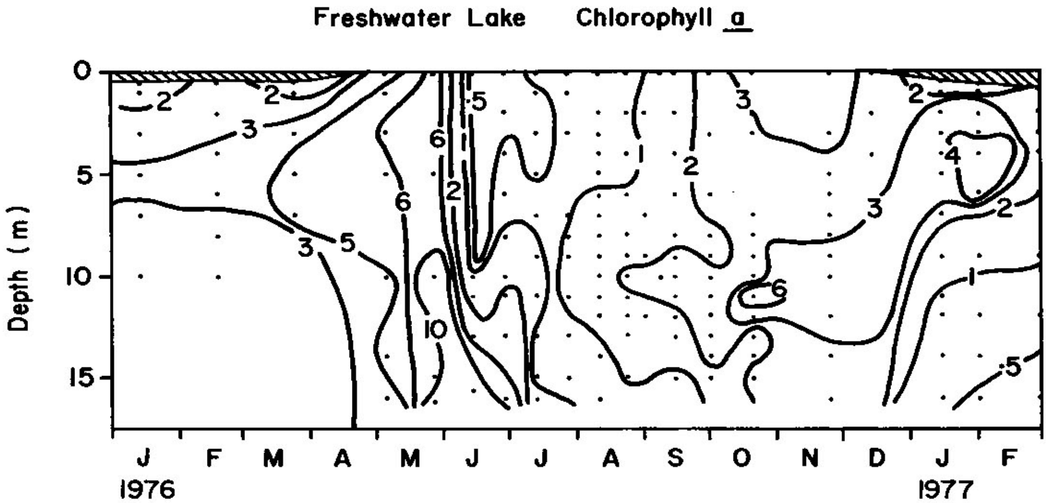

Fig 7. Isopleth of chlorophyll-a concentration (mg Chl/m^3) in Freshwater Lake. See Fig. 2.

Table II. Proposed boundary values for trophic categories (fixed boundary system) based on total phosphorus, chlorophyll-a concentrations and Secchi disc transparency. After Vollenweider and Kerekes (1981).

	Variable (mg/m^3)			Secchi depth (m)	
Trophic Category	$\overline{[P]}_\lambda$	$\overline{[Chl]}$	$\overset{max}{[Chl]}$	$\overline{[Sec]}^{y}$	$\overset{min}{[Sec]}^{y}$
ultra-oligotrophic	4.0	1.0	2.5	9.0	6.0
oligotrophic	10.0	2.5	8.0	6.0	3.0
mesotrophic	10—35	2.5—8	8—25	6—3	3—1.5
eutrophic	25—100	8—25	25—75	3—1.5	1.5—0.7
hypertrophic	100	25	75	1.5	0.7

Program (Table II), the lake could be considered as oligotrophic based on annual mean total phosphorus, Secchi depth and peak chlorophyll, and as oligo-mestrophic based on annual mean chlorophyll. The hypolimnetic oxygen depletion, the relatively high abundance of several species of algae often associated with a higher trophic condition and the relatively dense growth of macrophytes all indicate a higher-than-oligotrophic condition in Freshwater Lake.

The transitional nature of Freshwater Lake between oligotrophy and mesotrophy is also reflected in trophic characteristics expressed in terms of probability, also developed in the OECD Eutrophication Programme. The total phosphorus value of 7.5 mg/m^3 has an attached probability of 22% for ultra-oligotrophic, 65% for oligotrophic, 13% for mesotrophic (Fig 9). The annual mean chlorophyll (2.5 mg/m^3) implies probability of 6% for ultra-oligotrophic, 50% for oligotrophic, 42% for mesotrophic and 2% for eutrophic; for peak chlorophyll (6.4 mg/m^3) 58% for oligotrophic, 36% for mesotrophic, 5% for eutrophic and 1% for hypertrophic conditions.

Overall, I believe that Freshwater Lake is best classified as oligo-mesotrophic with a definite tendency toward mesotrophy. This is in sharp contrast to the clearly

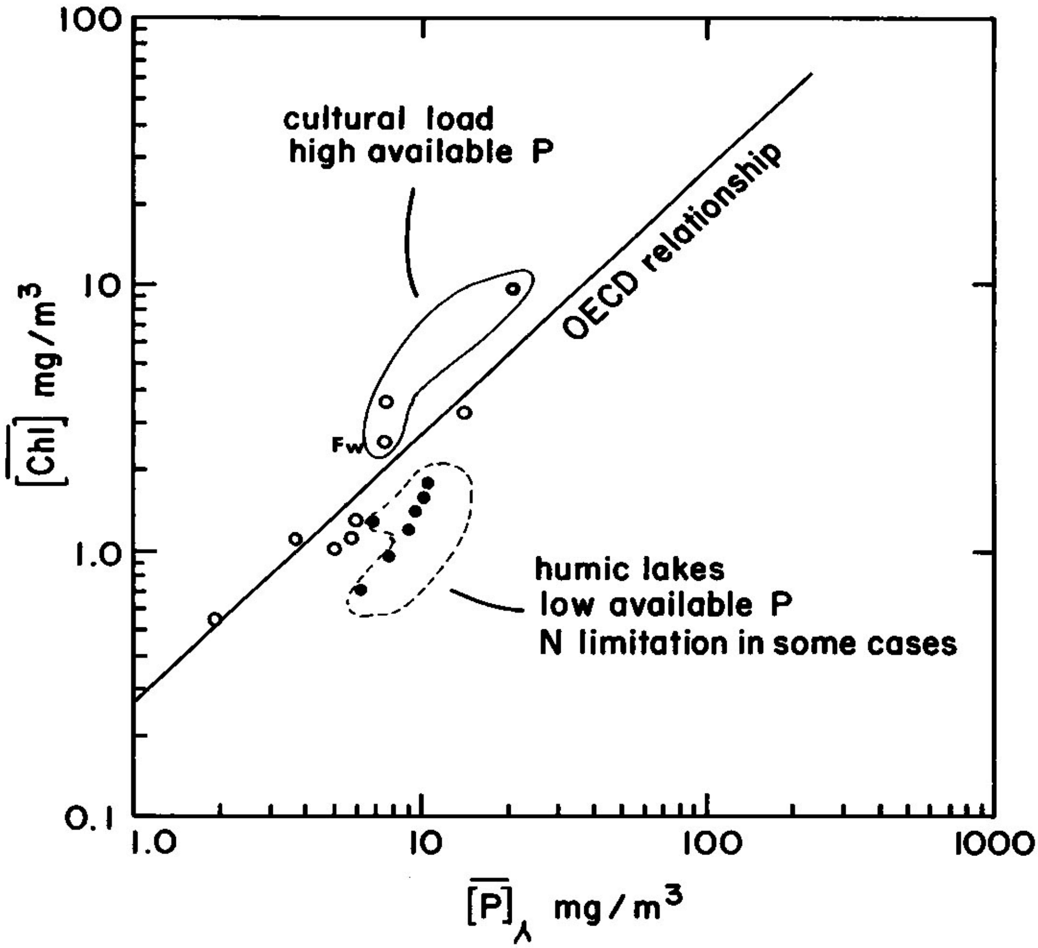

Fig 8. Annual mean chlorophyll-a in relation to annual mean total phosphorus concentration in selected lakes in the Atlantic Region of Canada. Freshwater Lake is indicated by the letters FW (after Kerekes 1980).

oligotrophic conditions found in two pristine, undisturbed lakes nearby (Kerekes *et al*., 1981). It is not possible (see below) to separate the additional natural phosphorus contribution (sea spray) from the anthropogenic contribution (i.e., lawn fertilizers, septic tank leakage). However, it is safe to conclude that without the anthropogenic phosphorus addition, Freshwater Lake would be closer to the oligotrophy, which is the management objective for this particular lake.

Estimation of Loads of Natural and Existing Anthropogenic Phosphorus

Considering the estimated inflow total phosphorus concentration of 13.7 mg/1, it can be assumed that without the contribution of the existing diffuse anthropogenic load and direct sea spray, the total phosphorus concentration in the lake would be about 6 mg P/m^3, like those of two undisturbed pristine lakes nearby. Using this value and the value for total phosphorus concentration in the lake, the annual

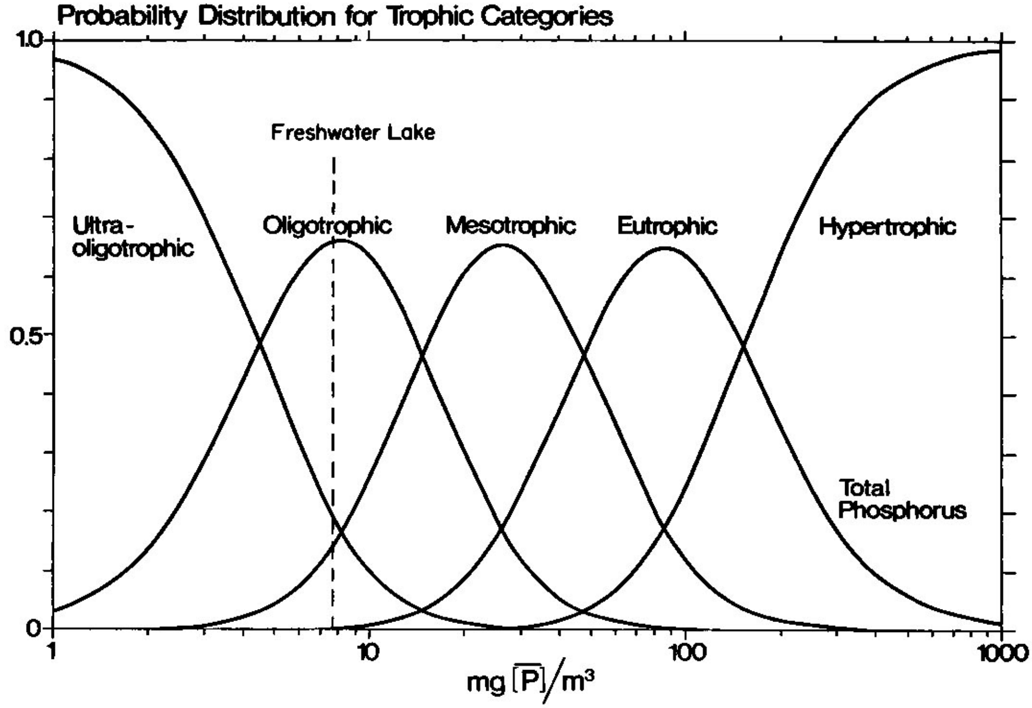

Fig 9. Predicted trophic conditions in terms of probability (5 trophic categories) for annual mean total phosphorus concentrations (after Vollenweider and Kerekes, 1981).

natural (edaphic) background total phosphorus load and the total annual anthropogenic (plus sea spray) phosphorus load can be calculated (Table III). It is reasonable to assume that the anthropogenic phosphorus is proportionately more available biologically than is the natural, phosphorus load. This may explain why the lake has a higher than average chlorophyll-a indicated previously (Fig 8).

The Estimated Impact of Phosphorus from Secondary Sewage Treatment.

The planners estimate that the proposed secondary treatment facility would yield 2.16 kg total phosphorus to Freshwater Lake. The proposed facility would only operate during summer when the lake is thermally stratified and water renewal minimal. It would therefore be misleading to consider the impact of additional total phosphorus load on an average, annual basis. Instead the expected response should be examined as it affects the epilimnion during the summer.

During summer 2.16 kg P added to the mixed layer (2.19×10^7 m^3) would increase the epilimnetic total phosphorus concentration by 1.1 mg P/m^3 (Table III). (On an average annual basis the total phosphorus concentration in the lake would increase only by 0.29 mg P/m^3). This additional phosphorus however is in a form highly available for algal growth. According to the relationship of inorganic phosphorus and total phosphorus relationship given in the OECD Eutrophication study (Vollenweider and Kerekes 1980), the 1.1 mg/m^3 of secondary-treatment phosphorus is approximately equal to 4.0 mg/m^3 of total phosphorus under phosphorus concentration levels applicable to Freshwater Lake. By substituting the

Table III. Selected trophic and hydrological features and phosphorus loading estimates of Freshwater Lake, Nova Scotia. Abbreviations are given in methods.

	Existing Conditions	Natural (edaphic) Conditions	Expected Epilimnetic Concentration After Development
$[\overline{P}]_\lambda$ mg/m^3	7.5	6.0	*8.6
$[\overline{P}]_i$, mg/m^3	13.7	10.9	—
L(P) mg/m^2/y	132.7	105.6	—
Annual total phosphorus load kg/y	56.0	44.6	—
Anthropogenic total phosphorus load kg/y	**11.4	—	(13.56)
T(w) y	.67	.67	—
q_a m/y	9.69	9.69	—
$[\overline{Chl}]$ mg/m^3	2.5	1.6	*3.8
$[\overset{max}{Chl}]$ mg/m^3	6.4	4.2	*9.8

*summer epilimnetic value
**includes sea spray

latter value to the phosphorus-chlorophyll-a relationships (Vollenweider and Kerekes 1980), the expected increase in chlorophyll and peak chlorophyll would be 1.3 and 3.5 mg/m^3 respectively (Table III).

These estimated chlorophyll values would put the lake into mesotrophic category. This is based on the assumption that the lake would respond "normally" without a shift in algal (chlorophyll) response.

The foregoing discussion would apply for the lake as a whole. Close to the outflow of the secondary treatment discharge in a relatively well sheltered, shallow part of the lake, a more dense, nuisance-type algal response and macrophyte growth could be expected.

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