# THE RELATIVE MAGNITUDE OF PHOSPHORUS SOURCES FOR SMALL, OLIGOTROPHIC LAKES IN ONTARIO, CANADA

OCTOBER 1992

Ontario

Environment
Environnement

ISBN 0-7778-0168-X

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PIBS 2120
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OCTOBER 1992

**ABSTRACT**

Mass balances for total phosphorus (TP) were measured for a minimum of 9 years in 8 lakes located near the southern boundary of the Canadian Precambrian Shield in Ontario. The lakes ranged from having no shoreline development to having intensive development. Potential inputs of TP from anthropogenic activities ranged from 0% (in the undeveloped lakes) to about 60% of the TP load. In all the lakes, internal sources of TP were small (generally less than 10% of the total TP load). Atmospheric deposition was a major source of TP (approximately 21 $mg/m^2/yr$) in those lakes with small catchments relative to lake area. Export of TP from the watershed was important in those lakes with large catchment: lake area ratios.

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## INTRODUCTION

It has been demonstrated on numerous occasions that phosphorus is the nutrient most often determining trophic status in north temperate lakes (Schindler *et al.* 1971, Dillon and Rigler 1974). As a result, attempts to measure input/output budgets for total phosphorus (TP) in lakes are abundant in the literature (Malueg *et al.* 1975, Larsen *et al.* 1981, Cross and Rigler 1983, Garber and Hartman 1985, Caraco *et al.* 1988). However, because of the inherent difficulty and time involved in constructing accurate mass balances (Labaugh and Winter 1984), many studies suffer from poor quality or incomplete data. This is unfortunate because accurate mass balance data can be used to assess the relative importance of the different sources of TP to a lake and then to predict lakewater TP concentrations as a function of input source strength.

The purpose of this paper is to describe TP mass balances for 8 lakes located in the Precambrian Shield region of Ontario, Canada, and to assess the relative magnitude of the different sources.

## STUDY AREA

The 8 study lakes (Table 1) are located in the Muskoka-Haliburton region of Ontario, Canada, about 200 km north of Toronto and 250 km southeast of Sudbury, the closest centres of industrial activity. All are situated on the Canadian Precambrian Shield and are underlain by metamorphic and plutonic silicate rocks. The lakes' catchments have been substantially altered by glacial processes. Their unconsolidated surficial deposits are dominated by till plains (continuous moraine deposits >1 m thick) and thin till and rock ridges (<1 m thick). In some of the lakes' watersheds there are extensive pockets of peat (Dickie Lake) or small accumulations of outwash and sand (Blue Chalk, Red Chalk and Harp Lakes).The catchments of the lakes are primarily forested (mixed deciduous/coniferous). Cottage development ranges from none (in Plastic Lake) to 125 cottages/homes around Dickie Lake. Sewage disposal is accomplished either using septic tank/tile field systems or by storage of the sewage in holding tanks and removal from the catchment.

All the lakes are small (21 to 94 ha), with mean depths ranging between 3.3 and 14.2 m and maximum depths ranging between 5.8 and 38 m. Six of the lakes are dimictic, with the two shallowest (Heney and Dickie Lakes) being only weakly stratified or not stratified at all. Seven of the lakes are headwater with the exception of Red Chalk Lake, which is downstream of Blue Chalk Lake. Red Chalk Lake consists of two discrete basins connected by a shallow (<2 m) channel.

## METHODS

Details of the methods used for determining the hydrologic budgets (hydrologic year June 1 - May 31) are described in Scheider *et al.* (1983) and Locke and Scott (1986). Similarly, the methods, equipment and sampling regimes employed for the collection of bulk precipitation, stream and lakewater samples for TP analyses are described in Scheider *et al.* (1981, 1983), Locke and Scott (1986) and Dillon *et al.* (1986). Phosphorus was measured in all precipitation, lake and streamwater samples using an automated ascorbic acid reduction, ammonium molybdate colorimetry technique or (prior to March 22, 1979), an automated stannous chloride, molybdate reduction technique (MOE 1983).

The procedure for calculating the inputs of TP to the lakes from precipitation ($L_{PR}$ and the watershed ($L_{TERR}$) is described in Scheider *et al.* (1979).

Internal loadings of TP ($L_{INT}$ mg/m$^2$/yr) to the lakes with hypolimnia were estimated from:

$$L_{INT} = \Delta\,[TP]_{hypo} \bullet V_{hypo} / A_o + \Delta\,[TP]_{IC} \bullet V/A_o \qquad (1)$$

where $\Delta\,[TP]_{IC}$ and $\Delta\,[TP]_{hypo}$ are the changes in the TP concentrations in the whole lake during the ice-covered period and in the hypolimnion during summer stratification, respectively (mg/m$^3$/yr ), V and $V_{hypo}$ are the lake volumes and hypolimnetic volumes respectively (m$^3$) and $A_o$ is the lake surface area (m$^2$).

For the lakes with shoreline development, the potential anthropogenic inputs of TP from private sewage disposal systems ($L_A$ mg/m$^2$/yr) were calculated as:

$$L_A = \#\text{ of units} \bullet 0.80 \bullet 10^6 \bullet 0.75 \bullet (1 - f_h) / A_o \qquad (2)$$

where 0.80 is the input of TP in kg/capita/yr and 0.75 is the cottage usage in capita yr/yr/unit. The quantification of the number of cottage units and $f_h$ (the fraction of the units using holding tanks) was determined from surveys conducted by the Ontario Ministry of Housing from 1976-78 which have been updated recently (P. Dillon, unpubl. data).

## RESULTS AND DISCUSSION

A summary of the magnitude of the sources of TP to each of the study lakes is given in Table 2. The total input of TP ($L_T$) ranged between 36 and 203 mg/m$^2$/yr, assuming that groundwater inputs of TP were negligible. This is a reasonable assumption given the paucity of surficial material in most of the study watersheds and the impervious nature of the granitic bedrock.

Internal inputs of TP ($L_{INT}$) were generally small (about 3-6 mg/m$^2$/yr), averaging about 8% of $L_T$ (note that $L_{INT}$ for Heney Lake = 0 because the lake did not stratify). However, relatively high values of 26.2 and 14.3 mg/m$^2$/yr (22.1 and 12.6% of $L_T$) were measured in Chub and Crosson Lakes, respectively as a result of the extensive duration of summer anoxia. While $L_{INT}$ in these 8 small oligotrophic study lakes is generally low, it has been shown to be a significant source of TP in some shallow and/or eutrophic lakes, contributing as much as or more to $L_T$ than external TP sources (Riley and Prepas 1984, Premazzi and Provini 1985, Garber and Hartman 1985). $L_{INT}$ may be particularly important in meso/eutrophic lakes which have undergone reductions in external TP inputs as a result of lake recovery programmes (Larsen *et al.* 1981, Rossi and Premazzi 1991). On the other hand, negligible release of TP from the sediments was observed in oligotrophic Lake 303 following the termination of phosphorus fertilization (Levine and Schindler 1989).

In our study lakes, potential anthropogenic inputs of TP ($L_A$) were variable (0 to 57.5% of $L_T$), depending on the extent of shoreline development. Comparisons of $L_A$ with data from other studies are difficult to make because potential anthropogenic inputs of TP often are not included in the overall TP budget (e.g., Moeller and Wetzel 1988). This is unfortunate because from Table 2, it is evident that $L_A$ can be a significant source of TP to lakes.

The relative importance of TP input from the catchment ($L_{TERR}$) generally increased as the ratio $A_d/A_o$ increased. In 6 of the lakes, more than 50 mg TP/m$^2$ of lake surface/yr was supplied from the watershed. In 4 of these lakes (Chub, Crosson, Heney and Red Chalk), this represented at least half of $L_T$, while in the 2 extensively developed lakes (Dickie and Harp), $L_{TERR}$ represented about one third of $L_T$. In Blue Chalk and Plastic Lakes, $L_{TERR}$ was only 10.8 and 13.6 mg/m$^2$/yr respectively, (21.9 and 37.3% of $L_T$, respectively). The relatively low value of $L_{TERR}$ in these 2 lakes was a result of the small $A_d/A_o$ ratio (Table 1).

Atmospheric deposition of TP directly onto the lakes' surfaces ($L_{PR}$) was uniform among the 8 study lakes averaging 20.7 ± 1.5 mg/m$^2$/yr. Atmospheric deposition was a major source of TP (11 - 53% of LT) to all the lakes, but especially to Blue Chalk and Plastic Lakes, which have the largest $A_d/A_o$ ratios. Similarly, $L_{PR}$ was found to be an important source of TP to small, oligotrophic Mirror Lake, New Hampshire (Caraco *et al.* 1988), Bob Lake, Ontario (Cross and Rigler 1983) and mesotrophic Piburger See, Austria (Psenner 1984). Comparisons of our $L_{PR}$ values with those in the literature are difficult because of the numerous variables involved (e.g., collector type, location, period of operation, etc.), but $L_{PR}$ is potentially important to a wide range of lake types.

In conclusion, mass balance data from 8 lakes in Ontario indicated that inputs of TP from the catchment were significant in those lakes with large $A_d/A_o$ ratios, while inputs from precipitation were important in those lakes with small $A_d/A_o$ ratios, provided shoreline development was not extensive. Internal sources of TP were generally low, but anthropogenic inputs of TP were potentially as high as 57.5% of the total TP load in lakes with significant shoreline development.

## ACKNOWLEDGEMENTS

We thank D. Jeffries, J. Findeis, R. Girard and L Scott for assistance with this study.

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**Table 1.** Locations and morphometric characteristics of the 8 study lakes. $A_d$ = watershed area, $A_o$ = lake area, $\overline{z}$ = mean depth, $z_{max}$ = maximum depth, V = lake volume.

| Lake | Latitude (N) | Longitude (W) | $A_d$ (ha) | $A_o$ (ha) | $\overline{z}$ (m) | z, (m) | V ($10^5 m^3$) |
|---|---|---|---|---|---|---|---|
| Blue Chalk | 45°12' | 78°56' | 135 | 52.4 | 8.5 | 23 | 44.7 |
| Chub | 45°13' | 78°59' | 286 | 34.4 | 8.9 | 27 | 30.4 |
| Crosson | 45°05' | 79°02' | 501 | 56.7 | 9.2 | 25 | 52.2 |
| Dickie | 45°09' | 79°05' | 449 | 93.6 | 5.0 | 12 | 46.7 |
| Harp | 45°23' | 79°08' | 509 | 71.4 | 13.3 | 38 | 95.1 |
| Heney | 45°08' | 79°06' | 72 | 21.4 | 3.3 | 5.8 | 7.05 |
| Plastic | 45°10' | 78°48' | 89 | 32.1 | 7.9 | 16 | 25.2 |
| Red Chalk | 45°11' | 78°56' | 435 | 57.1 | 14.2 | 38 | 81.1 |

**Table 2.** The relative magnitude (± s.d.) of TP sources to the study lakes in $mg/m^2/yr$. The % of $L_T$ (the total TP input) for each source is given in brackets. $L_{TERR}$ = catchment input, $L_{PR}$ = precipitation input, $L_{INT}$ = internal input, $L_A$ = potential anthropogenic input from private sewage disposal systems.

| Lake | $L_{TERR}$ | $L_{PR}$ | $L_{INT}$ | $L_A$ | $L_T$ |
|---|---|---|---|---|---|
| Blue Chalk | 10.8 ± 2.69 | 21.7 ± 7.60 | 5.6 ± 2.5 | 11.6 | 49.7 |
| (%) | (21.7) | (43.7) | (11.3) | (23.3) | |
| n | 12 | 12 | 11 | | |
| Chub | 62.3 ± 19.5 | 21.7 ± 7.60 | 26.2 ± 10.4 | 15.7 | 125.9 |
| | (49.6) | (17.2) | (20.8) | (12.4) | |
| | 12 | 12 | 12 | | |
| Crosson | 74.2 ± 12.2 | 18.8 ± 3.44 | 14.3 ± 11.6 | 5.7 | 113.0 |
| | (65.6) | (16.6) | (12.7) | (5.0) | |
| | 9 | 9 | 12 | | |
| Dickie | 60.5 ± 28.4 | 21.7 ± 7.63 | 5.3 ± 4.2 | 86.2 | 173.7 |
| | (34.8) | (12.5) | (3.1) | (49.6) | |
| | 12 | 12 | 12 | | |
| Harp | 61.5 ± 14.5 | 21.7 ± 7.63 | 3.0 ± 7.5 | 116.8 | 203.0 |
| | (30.3) | (10.7) | (1.5) | (57.5) | |
| | 12 | 12 | 12 | | |
| Heney | 54.3 ± 25.3 | 18.8 ± 3.46 | 0 | 25.3 | 98.4 |
| | (55.2) | (19.1) | (0) | (25.7) | |
| | 9 | 9 | | | |
| Plastic | 13.6 ± 3.67 | 19.1 ± 3.34 | 3.5 ± 2.6 | 0 | 36.2 |
| | (37.5) | (52.8) | (9.7) | (0) | |
| | 10 | 10 | 9 | | |
| Red Chalk | 50.5 ± 14.0 | 21.7 ± 7.65 | 3.1 ± 2.4 | 1.1 | 76.4 |
| | (66.1) | (28.4) | (4.1) | (1.4) | |
| | 12 | 12 | 12/8* | | |

* 12 years of data for the Main basin and 8 years for the East basin.