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The Application of the Phosphorus-Loading Concept to Eutrophication Research

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P.J. Dillon



SCIENTIFIC SERIES NO. 46
(Résumé en français)

INLAND WATERS DIRECTORATE,
CANADA CENTRE FOR INLAND WATERS,
BURLINGTON, ONTARIO, 1975.

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The Application of the Phosphorus-Loading Concept to Eutrophication Research

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This report was prepared on the initiative of Dr. R. A. Vollenweider for the National Research Council Associate Committee on Scientific Criteria for Environmental Quality—Subcommittee on Water.

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Abstract

Recent advances in the study of eutrophication include the improvement of Vollenweider's original phosphorus-loading–mean depth relationship to take into account the water retention time of the lake. In addition, the relationship between phosphorus loading and phosphorus concentration has been investigated, and correlations between phosphorus loading and primary production for the Great Lakes and between spring phosphorus concentration and summer chlorophyll concentration for a wide variety of lakes have been developed. A number of lakes have undergone reductions in phosphorus load; in those where the reduction was significant, the lakes have responded favourably.

Résumé

Les derniers progrès obtenus dans l'étude de l'eutrophisation comprennent l'amélioration de la relation de Vollenweider entre la charge primitive de phosphore et la profondeur moyenne, pour tenir compte de la durée de séjour de l'eau dans le lac. On a de plus étudié la relation existant entre la charge de phosphore et la concentration en phosphore. On a établi des corrélations entre la charge de phosphore et la production primaire des Grands lacs et entre la concentration en phosphore et la concentration estivale en chlorophylle pour un grand nombre de lacs. Un certain nombre de lacs ont subi des réductions des charges de phosphore; dans ceux où la réduction a été notable, on a observé une amélioration de leur état.

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List of Symbols

Symbol	Definition	Dimension
L	areal loading	$M\ L^{-2}\ T^{-1}$
$\bar{z}$	mean depth	L
τ_w	residence time of water	T
ρ	flushing rate $= 1/\tau_w$	T^{-1}
R	retention cœfficient	—
A_o	lake surface area	L^2
A_d	area of land drainage	L^2
V	lake volume	L^3
Q	outflow volume	$L^3\ T^{-1}$
r	areal runoff of watershed	$L\ T^{-1}$
J	supply	$M\ T^{-1}$
σ	sedimentation rate cœfficient	T^{-1}
q_s	areal water loading to lake $= \bar{z}/\tau_w$	$L\ T^{-1}$
m_w	amount of a substance in the lake	M
$[m_w]$	concentration of m	$M\ L^{-3}$
L_{int}	internal loading from sediments to water column	$M\ L^{-2}\ T^{-1}$
E_s	export cœfficient from the soil	$M\ L^{-2}\ T^{-1}$
E_c	per capita discharge of an element	$M\ T^{-1}$
C	basin population	

The Application of the Phosphorus-Loading Concept to Eutrophication Research

P.J. Dillon

INTRODUCTION

The concept of nutrient loading or "specific surface loading," the amount of a nutrient added per unit of lake area per unit time (Vollenweider, 1968), was first used by Sawyer (1947) in his investigation of the fertilizing effects of agricultural and urban drainage on the Madison Lakes, Wisconsin. Sawyer found that Lake Waubesa, which received the greatest quantity per acre of both phosphorus and nitrogen of the three lakes that he investigated, also experienced the most frequent algal blooms. Conversely, Lake Monona, which received the least nutrients on an areal basis, experienced the least number of algal blooms. Further use of the areal loading concept was made by Bartsch and Lawton (1949) and Thomas (1955, 1957), who attempted to relate nitrogen and phosphorus inputs to the degree of eutrophication of Lake Mendota and several Swiss Lakes, respectively.

A different approach was taken by Edmondson (1961) who argued that computation of nutrient input on an areal basis was unsatisfactory because it did not allow for the depth of the lake, and thus for the degree of dilution and the resulting concentration of nutrients in the water. Edmondson therefore expressed the nutrient income on the basis of the volume of the lake and termed the resulting parameter the "potential concentration" which could be called, in fact, the volumetric loading. This had the added benefit of accounting for the different effects that would be felt by a lake from receiving a given amount of nutrient supplied in concentrated form (e.g., in sewage) or in dilute form (as dilute runoff).

One purpose of each of these studies was to provide a standard means of expressing nutrient input so that the inputs to different lakes could be compared on a common basis, hopefully leading to relationships between this standard measure of nutrient supply and the degree of eutrophication of the lakes. It was not until several years later that such a relationship, for which these studies laid the groundwork, was actually postulated.

In reality, it is recognized that nutrient concentration rather than nutrient supply controls the standing crop of phytoplankton (and macrophytes) in a lake, and therefore the eutrophication process, although the two are obviously closely interrelated (Vollenweider):



It is also obvious that loading is inherently a simpler (in the sense of more easily predicted) parameter than concentration and that for rough estimates of a lake's trophic state, loading is useful as a first step.

Although the concept of loading is applicable to any element or compound, subsequent emphasis has continued to be directed primarily to nitrogen and phosphorus, undoubtedly because these two elements are accepted widely as the chemical factors most often determining the productivity of lakes, and hence, the extent of the eutrophication of lakes.

Phosphorus, in particular, has been singled out for attention, partly because it is generally believed to be the nutrient most frequently controlling eutrophication (National Academy of Sciences, 1969; Likens, 1972; Schindler *et al*, 1971), and partly because its input will, for most lakes, be easier to control than will the input of nitrogen (Vollenweider, 1968). The latter results from the fact that much of the phosphorus supplied to lakes is supplied via point sources (sewage, detergents and industrial wastes), while nitrogen, although also supplied from point sources, is supplied often in large quantities from diffuse sources (agricultural runoff, nitrogen fixation, precipitation) that are much more difficult to regulate (International Joint Commission, 1969). Thus the control of phosphorus input is not only desirable but practical, as the case histories later described demonstrate.

VOLLENWEIDER'S PHOSPHORUS-LOADING–MEAN DEPTH RELATIONSHIP

The first attempt to unify all of the nutrient budget data available in the literature was undertaken by Vollenweider in 1968. He found that when the areal total phosphorus loading was plotted against mean depth on a log-log scale (Fig. 1), straight lines or bands could be arbitrarily drawn separating the lakes into the three standard lake types in terms of the degree of eutrophy:

oligotrophic, mesotrophic and eutrophic lakes. A summary of the phosphorus budgets of these lakes is given in Table 1.

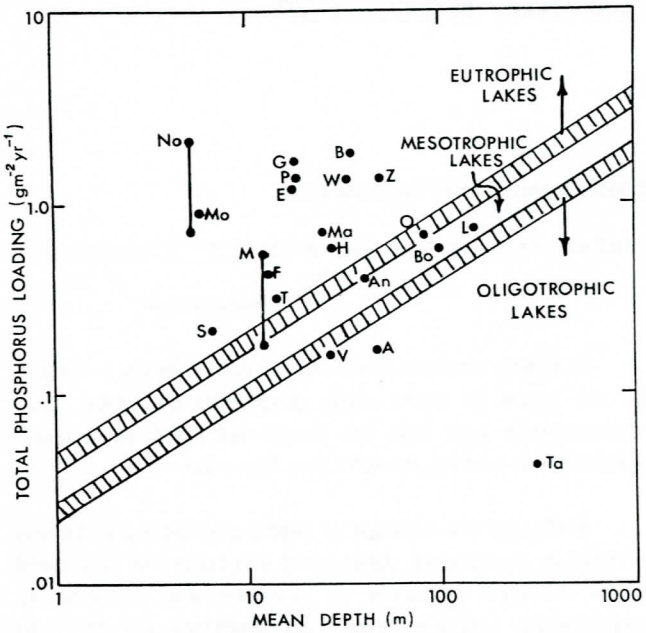


Figure 1. Vollenweider's total phosphorus-loading–mean depth relationship. Lower bar line is limit of "permissible" loading; upper is "critical" loading. Lakes: Ta–Tahoe, A–Aegerisee, V–Vänern, L–Léman, O–Ontario, Bo–Constance, (Bodensee–Obersee), An–Annecy, Ma–Mälaren, T–Türlersee, F–Furesø, S–Sebasticook, H–Hallwilersee, M–Mendota, Mo–Moses, No–Norrviken, E–Erie, P–Pfäffikersee, G–Greifensee, B–Baldeggersee, W–Washington, Z–Zürichsee. These bands were arbitrarily chosen by Vollenweider to separate lakes into three trophic types.

The lower line separating oligotrophic and mesotrophic lakes was termed "permissible loading," since it represented the upper loading level as a function of mean depth that could be permitted without having the lakes revert beyond the oligotrophic state; the upper line, termed "critical loading," represented the level above which a lake could be characterized as eutrophic. A similar relationship was derived for nitrogen loading, assuming a tolerable N/P ratio of 15:1 (by weight).

This simple model was dependable since for lakes with phosphorus-loading data available, the predicted status in most cases matched the observed status exemplified by the standard (but arbitrary) criteria of lake condition: transparency (Secchi disc depth), chlorophyll concentration, oxygen concentration in the hypolimnion, frequency of algal blooms, etc. This simple relationship, which, in effect, filled a vacuum in eutrophication studies, was accepted widely both as an indication of the degree of eutrophy of lakes and, more importantly, as a guide to the permissible and dangerous loading levels of phosphorus to lakes (Schindler and Nighswander, 1970; Schindler *et al*, 1971; Gächter and Furrer, 1972; Patalas, 1972; Patalas and Salki, 1973; Stumm and Stumm-Zollinger, 1972; Ahl, 1972; International Joint Commission, 1969). Perhaps the most important use of this relationship was to provide a rationale for the removal of phosphorus from sewage treatment effluent in the Great Lakes Basin. Lake Ontario, in the mesotrophic category according to its estimated total phosphorus loading for 1967 (Fig. 1) would, in 1986, fit into the oligotrophic range of the graph, if 95% of the phosphorus was removed from all of the municipal and industrial wastes. Without phosphorus control, however, it would be well into the eutrophic category by 1986 (Fig. 1). By a similar argument, Lake Erie, advanced in the eutrophic range in 1967, would be improved almost to the mesotrophic category in 1986 with phosphorus control or would be even more eutrophic without control.

Vollenweider, however, stressed that this loading–mean depth relationship was very approximate and that other parameters should also be included in these considerations, notably water renewal time (flushing rate of the lake), internal loading, extent of the shoreline and littoral area. Edmondson (1970), in discussing the usefulness of the phosphorus-loading–mean depth relationship, mentioned that the effect of a doubled phosphorus loading from a doubled flow rate into the lake must be different from the effect caused by a doubled phosphorus concentration in the inflow and concluded that a study of nutrient loading vs water loading might be useful.

INCORPORATION OF FLUSHING RATE INTO THE LOADING–MEAN DEPTH MODEL

Vollenweider (1973) modified his simple loading–mean depth relationship to include the mean residence time of water (τ_w) so that lakes with unusually high or low flushing rates have this feature taken into account in any consideration of their trophic state. By plotting loading against $\bar{z}/\tau_w$ (Fig. 2), a more realistic representation was attained that had a basis in theoretical considerations of nutrient budget modelling (Vollenweider, 1973). The parameter $\bar{z}/\tau_w$ (m yr^{-1}) is equivalent to the areal water loading, i.e., the height of the water load that is supplied to the lake in one year.

A specific case of a lake's predicted status affected by this alteration is Lake Tahoe. Since the loading is very low (40 mg P m^{-2} yr^{-1}) and the mean depth extremely large (~300 m), Vollenweider's original plot (Fig. 1) predicted that Lake Tahoe would be ultra-oligotrophic as determined by the great distance below the line of permissible loading. The water replacement time (τ_w) of Lake Tahoe, however, is about 700 years. Thus it would be expected that a

Table 1. Phosphorus Budget Parameters of Lakes Reported in the Literature (from Dillon, 1974; Vollenweider, 1968)

Lake	Symbol	L_p ($g\ m^{-2}\ yr^{-1}$)	R	ρ (yr^{-1})	$\bar{z}$ (m)	Reference
Aegerisee	A	0.16	0.68	0.115	49	(Vollenweider, 1969)
Türlersee	T	0.30	0.80	0.465	14	(Vollenweider, 1969)
Hallwilersee	H	0.55	0.36	0.260	28	(Vollenweider, 1969)
Bodensee-Obersee	Bo	4.065	0.65	0.205	100	(Vollenweider, 1969)
Pfäffikersee	P	1.36	0.77	0.385	18	(Vollenweider, 1969)
Zürichsee	Z	1.32	0.25	0.680	50	(Vollenweider, 1969)
Greifensee	G	1.565	0.62	0.490	19	(Vollenweider, 1969)
Baldeggersee	B	1.75	0.61	0.220	34	(Vollenweider, 1969)
Tahoe	Ta	0.042	0.93	0.0014	303	(Vollenweider, 1969)
Norrviken 1961-62	No	4.03	0.49	1.75	5.4	(Ahlgren, 1967)
1970		2.1				(Ahlgren, 1972)
Sebasticook	S	0.209	0.48	0.39	6.0	(Mackenthun *et al*, 1968)
Clear	C	0.040	0.80	0.13	12.5	(Schindler and Nighswander, 1970)
Erie	E	1.06	0.84	0.40	18	(Anon., 1969)
		0.98				(Patalas, 1972)
Ontario	O	0.65	0.78	0.152	84	(Anon., 1969)
		0.86				(Patalas, 1972)
Superior	Su	0.03	0.9	0.0053	148	(Patalas, 1972; Rainey, 1967)
Michigan	Mi	0.29	0.9	0.032	84	(Patalas, 1972; Rainey, 1967)
227 (ELA)	227	0.34	0.89	0.238	4.4	(Schindler *et al*, 1971)
Okanagan	OK	0.39	0.95	0.017	75.3	(Patalas, 1973)
Skaha	SK	2.2	0.65	0.89	26.5	(Patalas, 1973)
Kalamalka	Ka	0.32	0.90	0.009	58	(Patalas, 1973)
Wood	Wo	0.50	0.90	0.0092	21	(Patalas, 1973)
Menona	Me	2.14	0.71	0.833	7.8	(Vollenweider, 1968)
Waubesa	Wa	9.93	0.00	3.33	4.8	(Vollenweider, 1968)
Kegonsa	Ke	6.64	0.09	2.86	4.6	(Vollenweider, 1968)
Léman	L	0.70	0.20	0.083	155	(Vollenweider, 1968)
Zellersee	Ze	1.20	–	0.37	37	(Liepolt, 1966)
Washington	W	1.34	–	0.313	33	(Edmondson, 1961)
Mendota	M	0.174	–	0.083	12	(Sawyer, 1947)
Moses	Mo	0.90	–	–	5.6	(Sylvester and Oglesby, 1964)
Vättern	V	0.065	–	0.018	39	(Ahl, 1970)
Vänern	Va	0.15	–	0.12	25	(Ahl, 1970)
Hjälmaren	Hj	0.30	–	0.28	6	(Ahl, 1970)
Mälaren	Ma	0.70	–	0.37	12.5	(Ahl, 1970)

moderate phosphorus loading would affect Lake Tahoe much more severely than many other lakes. In the new formulation (Fig. 2), Lake Tahoe remains in the oligotrophic region, but it is now much closer to the limit of permissible loading. This is consistent with present limnological experience concerning this lake (Vollenweider, 1969).

The first reported case of lakes which clearly did not fit into Vollenweider's original phosphorus loading–mean depth categorization scheme was described by the author (1974). In a study of the total phosphorus budgets of 19 lakes in southern Ontario (Table 2), the author found that a number of the lakes had very high phosphorus loadings (five lakes with $L > 1\ g\ m^{-2}\ yr^{-1}$). According to Vollenweider's relationship, many of these lakes should have been eutrophic, yet in all cases the chlorophyll *a* concentration was low (summer averages between 0.8 mg m^{-3} and 2.7 mg m^{-3}), Secchi disc depth was large (summer

Table 2. Phosphorus Budgets of Lakes in Southern Ontario (Dillon, 1974)

Lake	L_p ($g\ m^{-2}\ yr^{-1}$)	R	ρ (yr^{-1})	$\bar{z}$ (m)
Cameron	2.21	0.30	18.9	7.1
Four Mile	0.11	0.82	0.26	9.3
Raven	0.22	0.55	14.9	0.73
Talbot	0.10	0.69	4.9	0.85
Bob	0.16	0.71	0.37	18.0
Twelve Mile – Boshkung	0.35	0.33	2.4	18.1
Halls	0.22	0.53	0.96	27.2
Beech	1.68	0.07	22.7	9.8
Maple	0.86	0.26	8.0	11.6
Green	1.77	–	38.5	6.1
Pine	1.06	0.01	18.5	7.4
Cranberry	1.28	-0.07	62.7	3.5
Eagle–Moose	0.23	0.36	2.03	12.8
Haliburton	0.12	0.72	0.32	17.7

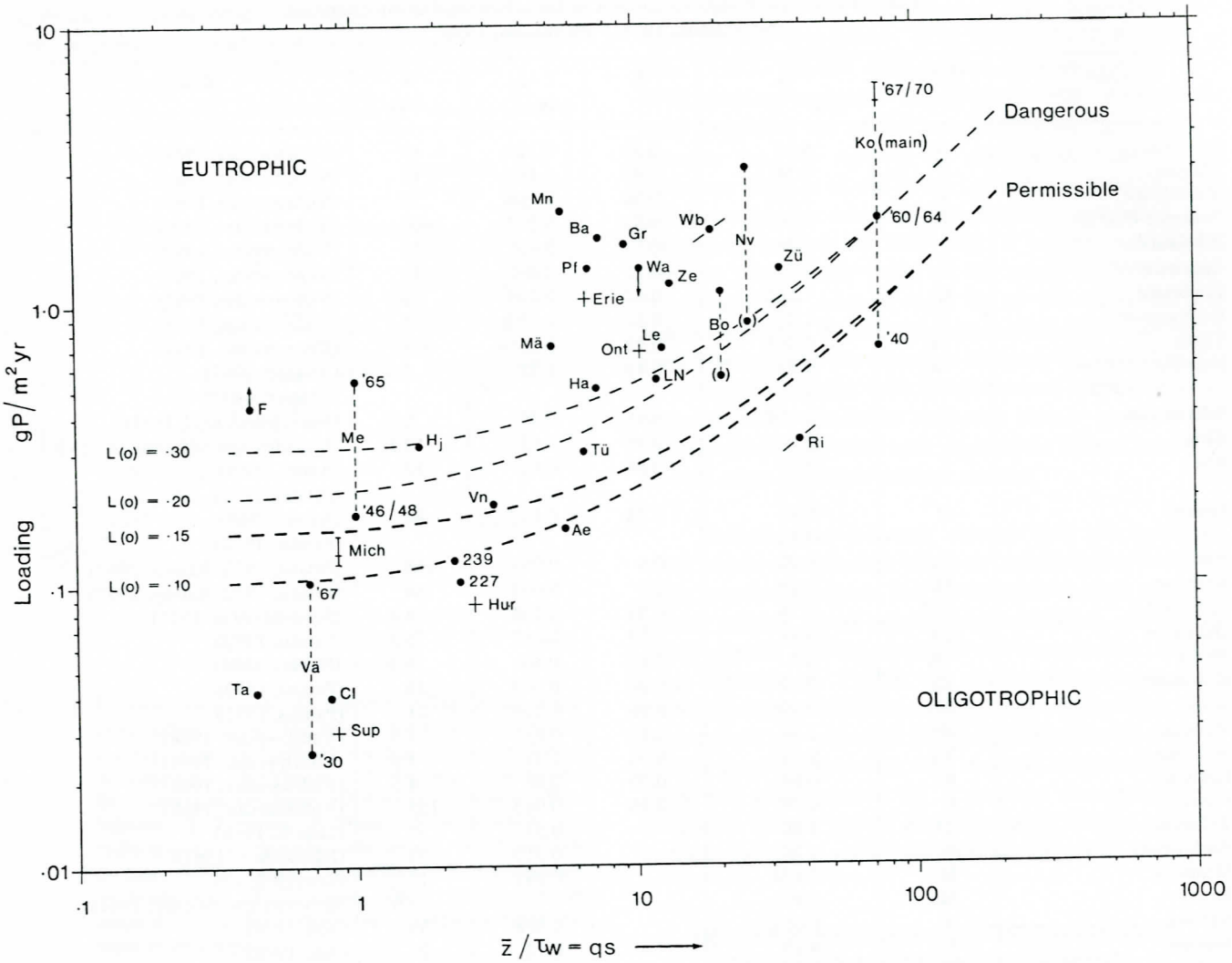


Figure 2. Vollenweider's total phosphorus loading vs mean depth ÷ water residence time ($\bar{z}/\tau_w$) relationship (from Vollenweider, 1973).

averages 3.5 – 8.7 m) and significant hypolimnetic oxygen deficits were not formed. The reason for this discrepancy was undoubtedly that many of these lakes had very high flushing rates as a result of the large drainage area–lake area ratios (Table 2). Consequently, it was proposed by the author that a plot of $L(1-R)/\rho$ vs $\bar{z}$ where ρ, the flushing rate = $1/\tau_w$, was a good method of treating the data. The significance of this parameter is discussed later. It can be noted, however, that (1-R) is the fraction of the loading that is not retained in the lake, but is lost by way of the outflow.

By plotting $L(1-R)/\rho$ vs $\bar{z}$, both the flushing rate and the retention rate in the consideration of lake trophic state are included. In effect, a plot of L/ρ vs $\bar{z}$ would have the same corrective result as a plot of L vs $\bar{z}/\tau_w$; inclusion of the factor (1-R) simply accounts for one more source of variation.

APPLICATION OF THE SIMPLE MODELS FOR PREDICTION

The L vs $\bar{z}/\tau_w$ Graph

The original L vs $\bar{z}$ graph (Fig. 1), uncorrected for flushing time, was used quite successfully to predict the degree of eutrophy of lakes by several workers. Schindler and Nighswander (1970) demonstrated the oligotrophic nature of Clear Lake, Ontario, while Schindler *et al* (1971) used the "permissible" and "critical" loading lines to calculate the watershed population that Lake 227 in the Experimental Lakes Area could support. Both the International Joint Commission (1969) and Patalas (1972) used the uncorrected graph to describe trophic conditions of the Great Lakes, as outlined previously; Patalas and Salki (1973) made predictions about the future trophic status of several of the Okanagan Lakes in British Columbia from the uncorrected graph, although two of the five lakes studied

had relatively high flushing rates. Other workers in Europe attempted to use the simple model in a similar way (Ahl, 1972; Gächter and Furrer, 1972; Stumm and Stumm-Zollinger, 1972).

The corrected model (Fig. 2) has been used for prediction by Michalski, Johnson and Veal (1973) who investigated the nutrient budgets of several lakes in the Muskoka district of southern Ontario. They made predictions concerning the trophic status of several of the lakes that would result following both changes in the population and the reduction of phosphorus in sewage effluent (Fig. 3).

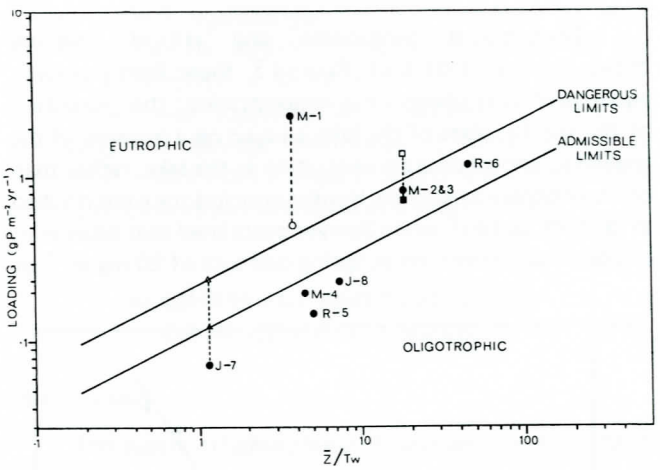


Figure 3. Annual total phosphorus loadings (closed circles) to Lakes Joseph (J-7), Rosseau (R-5) and Muskoka (M2 and M3), Dudley (M-4) and Gravenhurst (M-1) Bays and to Little Lake Joseph (J-8). Loading rates and classification of the degrees of eutrophy (i.e., diagonal lines) are after Vollenweider (in press). Lakes above the upper diagonal are eutrophic in status and lakes below the lower diagonal are oligotrophic. Lakes between the diagonals are mesotrophic. The open circle represents the "measure of eutrophication" for Gravenhurst Bay following 85% reduction of phosphorus from the Gravenhurst and Ontario Hospital Sewage Treatment Plants. The closed and open triangles represent the positions of Lake Joseph following population increases of 1150 and 4400 capita-yrs, respectively. The open square depicts the eutrophic status of Lake Muskoka with twice the current population. The closed square represents a slightly improved trophic status in relation to the lake's present position assuming 85% phosphorus removal for the increased population mentioned as well as for current shoreline residents (from Michalski, Johnson and Veal, 1973).

The L vs $\bar{z}/\tau_w$ model is presently the best method available for obtaining an estimate of the degree of eutrophy of a given lake. The parameter τ_w is easily calculated from the hydrologic budget of the lake as simply V/Q, the lake volume divided by the yearly outflow volume. If the water budget is not available for a particular year, a reasonable estimate of τ_w could be made knowing only A_d, the area of the lake's drainage basin (in m^2) and r, the long-term average unit runoff (m yr^{-1}), as well as V. The product $A_d \cdot r$ would approximate the total inflow to the lake, Q (m^3 yr^{-1}), since precipitation directly onto the lake's surface and evaporation from it approximately balance for temperate lakes. Measurement of the mean depth $\bar{z}$ is, of course, straightforward, but the expression $\bar{z}/\tau_w$ can be calculated without $\bar{z}$ if necessary:

$$\bar{z}/\tau_w = \bar{z} \cdot \frac{Q}{V} = \frac{\bar{z} \cdot Q}{A_o \bar{z}} = \frac{Q}{A_o} = \frac{A_d \cdot r}{A_o} \quad (1)$$

An additional term, A_o (ppt–evaporation), can be added to correct for water falling directly onto the lake.

The other parameter which must either be measured or calculated is the loading, L. This is discussed later in detail.

The loading itself may be used to predict water quality if it can be related to specific measures of the trophic state of lakes. For example, Vollenweider, Munawar and Stadelmann (1974) related the total yearly primary

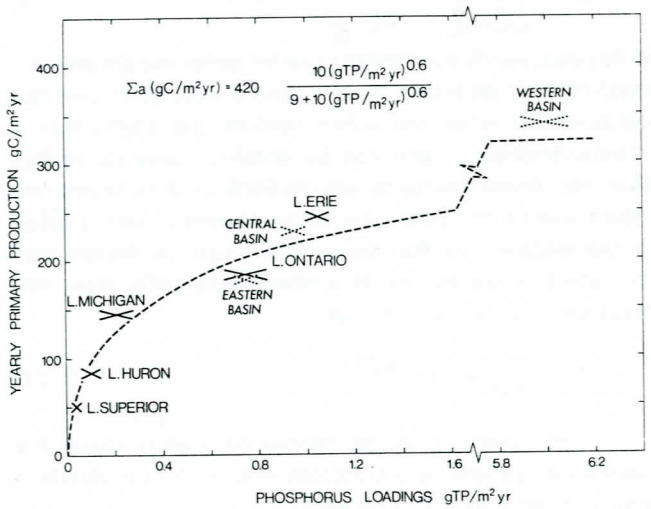


Figure 4. Yearly primary production plotted against total phosphorus loading for the Great Lakes (after Vollenweider, Munawar and Stadelmann, 1974).

production to phosphorus loading for the Great Lakes (Fig. 4).This relationship is especially instructive, since it clearly illustrates that a large reduction in phosphorus loading is needed for Lakes Erie and Ontario to reduce significantly their yearly primary production. For a lake with L = 1 gP m^{-2} yr^{-1}, the estimated primary production would be 220 gC m^{-2} yr^{-1}. To halve this production, the loading must be reduced to 0.15 gP m^{-2} yr^{-1}, i.e., a reduction of 85% is needed according to the simple model. As previously stressed, concentration, not loading, however, controls the standing crop, and this argument will not hold for lakes such as Lake Erie having a relatively rapid renewal rate. This loading vs production relationship is at the same stage in its development as the original loading–mean depth relationship (Fig. 1), i.e., a first approximation.

Significance of the $L(1-R)/\rho$ vs $\bar{z}$ Model

In 1969, Vollenweider devised a simple nutrient budget model from a mass balance equation:

$$\frac{d\, m_w}{dt} = J - \sigma\, m_w - \frac{Q}{V} m_w \qquad (2)$$

where m_w is the amount of a substance m in the lake, J is the yearly supply of m to the lake (kg yr^{-1}), σ is a sedimentation rate cœfficient (yr^{-1}), Q and V are the outflow volume per year and lake volume as before, and $[m_w]$ is the concentration of the substance m in the outflow. The details of the methods of solution and assumptions made in this model are discussed by Vollenweider (1969, 1973) and the author (1974). The steady-state solution to this model, in terms of total phosphorus concentration, is simply:

$$[P] = \frac{L}{\bar{z}\,\sigma + \bar{z}/\tau_w} \qquad (3)$$

If this equation is used for the prediction of the phosphorus concentration of a lake, L, $\bar{z}$, τ_w and σ must be known, but measurement of σ, the sedimentation rate cœfficient, is extremely difficult and can be obtained only indirectly. However, under the same assumptions used to derive the model, among them that the outflow concentration is equal to the average lake concentration, it can be shown that the retention cœfficient, R, a much more easily measured parameter, can be expressed as:

$$R = \frac{\sigma}{\sigma + \rho} \text{ or } \sigma = \frac{R\,\rho}{1-R} \qquad (4)$$

The model, of course, cannot be used to make this calculation; otherwise a tautology results. An independent means of calculating R is necessary:

$$R_{exp} = 1 - \frac{\Sigma\, q_a\, [p]_a}{\Sigma\, q_i\, [p]_i} \qquad (5)$$

where q_a are the outflow discharge volumes (m^3 yr^{-1}), $[p]_a$ the outflow concentrations, q_i the inflow volumes, and $[p]_i$ the inflow concentrations.

Thus equation (3) can be rewritten as:

$$[P] = \frac{L}{\bar{z}/\tau_w + \bar{z}\, R_{exp}\rho/(1 - R_{exp})}$$

or

$$[P] = \frac{L\,(1 - R_{exp})}{\bar{z}\,\rho} \qquad (6)$$

where R_{exp} is calculated as given in equation (5).

Therefore if "permissible" and "critical" lines are drawn on a plot of $L\,(1-R)/\rho$ vs $\bar{z}$, these lines represent equal predicted phosphorus concentration; the prediction of the trophic state of the lake is based on a measure of the predicted phosphorus concentration in the lake, rather than on its phosphorus loading. Similar conclusions were reached as far back as 1947, when Sawyer postulated that lakes with a total P concentration at spring overturn of 20 mg m^{-3} or

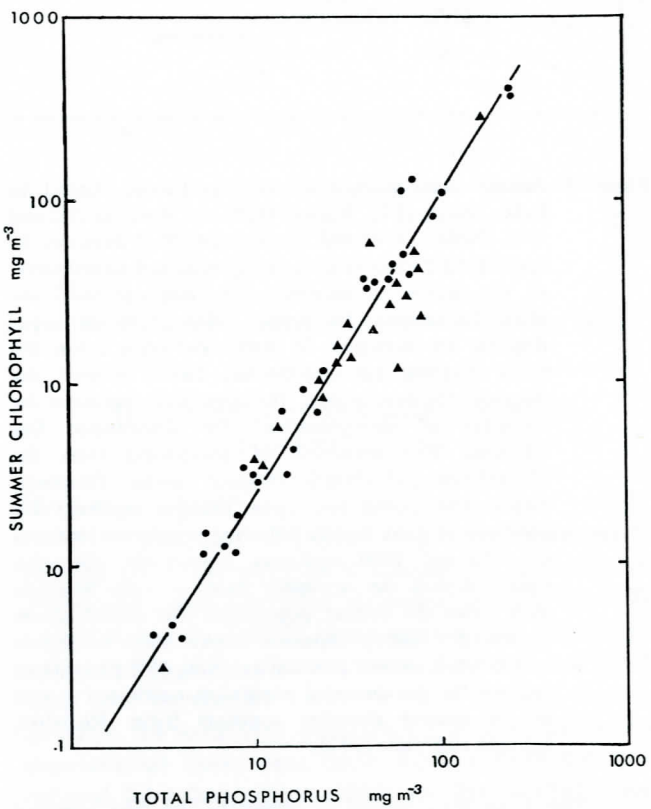


Figure 5. Plot of total phosphorus concentration at spring overturn vs average chlorophyll *a* concentration in summer for a number of lakes. Circles represent data from Sakamoto (1966), triangles are for other lakes in the literature. Line is regression line for Sakamoto's points. Correlation cœfficient (r) is 0.97.

greater would have algal blooms in the following period of stratification. This line of reasoning is consistent with that described in the Introduction; nutrient concentration, itself a function of loading, determines a lake's production and therefore its degree of eutrophication.

By plotting $L\,(1-R)/\rho$ vs $\bar{z}$ and devising "permissible" and "critical" lines, this model could be treated as an alternative method to the L vs $\bar{z}/\tau_w$ plot for predicting the degree of eutrophy of a lake. It will be more useful, however, if treated in its original sense, i.e., a simple method for predicting phosphorus concentration. Phosphorus concentration, in turn, can be related to water quality parameters that reflect lake trophic state, as Sawyer (1947) qualitatively did for frequency of algal blooms and as the author (1974) quantitatively did for summer chlorophyll *a* concentration (Fig. 5). The latter relationship was suggested as a convenient means of predicting the average chlorophyll *a* concentration in summer in a lake from a single measurement or prediction of the phosphorus concentration at spring overturn.

MEASUREMENT AND PREDICTION OF PHOSPHORUS LOADING

Measurement

The supply of phosphorus to any lake can be written as:

$$\sum_{i=1}^{n} q_i\,[p]_i + L_{int}$$

where q_i represents the amount of water supplied by each input, $[p]_i$, the phosphorus concentration of that input, and L_{int} the internal loading from the sediments to the water column. For an accurate budget, every source must be considered: all streams and rivers, industrial waste discharges, sewage and storm outfalls, precipitation, groundwater including marshland drainage, surface flow not in discrete channels, as well as the sediment-to-water flux, if any. In some cases a small number of easily measured sources supply most of the total load, e.g., Lake 227, an artificially enriched lake in the Experimental Lakes Area, Kenora (Schindler *et al*, 1971). For the majority of lakes, especially those not greatly influenced by man, however, measurement of the total phosphorus budget is time-consuming, difficult and expensive. Proper measurement of the water volume of inflowing streams and rivers requires continuous-recording discharge or water level measurement apparatus combined with a good control section and frequent calibration or a calibrated permanent installation (weir, flume, etc.). If possible, continuous-sampling devices for chemical analyses should be used since no study, as yet, has determined either optimum or minimum necessary sampling frequency. The same applies to industrial waste discharges and sewage and storm water outlets. The measurement of phosphorus in precipitation, long overlooked, has been reviewed by Chapin and Uttormark (1973) and it should now be apparent that this will be a very important consideration for many lakes, especially those little affected by man. Automatic sampling equipment is again necessary. The measurement of input via groundwater, marshland drainage, and surface runoff outside of that in discrete channels, is perhaps the most difficult phase of nutrient budget calculations, and very few, if any, reliable measurements are available. In cases where any of these factors are important, it has usually been necessary to resort to very rough estimates of the phosphorus supplied, as in the case of the calculated nutrient budget of Lake Mendota (Nutrient Sources Subcommittee, 1966).

The phosphorus and nitrogen budgets of Lake Mendota are indicated in Table 3. The wide range of values obtained for phosphorus loading gives some idea of the uncertainty, since according to Vollenweider (1968), it is unlikely that these differences exist.

Measurement of L_{int}, the internal loading from the sediments to the water column, is perhaps the most difficult problem in calculating nutrient budgets. One such calculation was made by Vollenweider in 1968, using data from Bachofen (1960) as outlined in Table 4. Very few such estimates are available, but it is apparent that internal loading may, in certain cases, exceed external loading. Such was the case for Lake Erie during the August–September 1970 period of investigation by Burns and Ross (1972). Considerable effort must be expended in investigating this area, especially with the aid of radioactive tracers.

Table 3. Specific Annual Loading of Lake Mendota (in g/m^2/yr) (from Vollenweider, 1968)

Year	Soluble P	Total P	Inorganic N	Organic N	Total N	Reference
1945-47	0.065	0.174	2.24	0.84	3.08	(Bartsch)
1948-49	0.203	0.415	3.12	1.04	4.16	(Emelity)
1948-49	0.198	0.414	2.97	1.01	3.98	(Belter)
1965	–	0.54	–	–	6.4	(Lee)

Table 4. Exchange of $P(PO_4)$ between Water and Sediments in the Baldeggersee (from Vollenweider, 1968)

Period	28.5.58 - 22.10.58	22.10.58 - 5.5.59	5.5.59 - 15.10.59
Days	147	195	163
Hypolimnion oxygen conditions	anaerobic	aerobic	anaerobic
Change in $P(PO_4)$ content per m^2 of representative column of water	+ 1.75 g	− 1.35 g	+ 2.00 g
Lake retention from surface loading	+ 0.35	+ 0.46	+ 0.38
Algebraic difference = amount released by sediments	+ 1.40		+ 1.62
or = amount taken up by sediments		− 1.81	
Mean daily rates of release or uptake (g/m^2/day)	+ 0.0095	− 0.0093	+ 0.0099

Prediction

Since there are many difficulties involved in measuring the phosphorus loading to a lake, some studies have relied totally on estimates of the loading (Patalas, 1972; Patalas and Salki, 1973; Shannon and Brezonik, 1972a, 1972b; Nutrient Sources Subcommittee, 1966). Patalas (1972) proposed equation (7):

$$L_p = E_s \cdot \frac{A_d}{A_o} + \frac{E_c C}{A_o} + 0.15\, L_{pa} \frac{A_o(a)}{A_o} \qquad (7)$$

where: E_s is the export coefficient of phosphorus from the soil in g total P m^{-2} of land drainage yr^{-1}

A_d is the area of the land drainage in m^2

A_o is the area of the lake in m^2

E_c is the per capita discharge of P reaching the lake in g total P/capita/yr

C is the basin population

L_{pa} is the total P loading for the next lake upstream in g m^{-2} yr^{-1}

$\frac{A_o(a)}{A_o}$ is the ratio of the areas of the next lake upstream and the lake considered, and

0.15 is obtained by assuming that 85% of the phosphorus supplied to the upstream lake is retained in that lake.

Table 5. Parameters Used for Calculation of the Total Phosphorus Loadings for St. Lawrence Great Lakes (after Patalas, 1972)

Parameter	Symbol	Superior	Michigan	Huron	Erie	Ontario
Area of the lake in 10^6 m^2	A_o	82,367	58,016	59,570	25,821	19,009
Area of the land drainage in 10^6 m^2	A_d	124,838	117,845	128,464	76,790	64,229
Ratio of land drainage to lake area	$\frac{A_d}{A_o}$	1.5	2.0	2.2	3.0	3.4
Basin population in millions	C	0.9	7.5	2.0	11.8 (6.0)[a]	6.1
Export of phosphorus from the soil, g total P/m^2 of land/yr	E_s	0.010	0.035	0.020	0.050	0.035
Per capita discharge of total phosphorus reaching lake, in g/yr	E_c	1,700	1,700	1,700	1,700(1,000)[a]	1,700
(Calculations of loading in g total P/m^2 of lake/yr)						
P loading from soil ($E_s \cdot A_d/A_o$)		0.015	0.070	0.044	0.150	0.118
Population dependent P loading $\frac{E_c C}{(A_o)}$		0.019	0.219	0.057	0.776(0.232)[a]	0.545
P loading from lake upstream (assuming 85% phosphorus retention in lake upstream) $(0.15\, L_{pa} \cdot \frac{A_o(a)}{A_o})$		0	0	0.046	0.052(0.028)[a]	0.200
Total P loading from all sources (g m^{-2} yr^{-1})	L_p	0.03	0.29	0.15	0.98(0.41)[a]	0.86

a–Calculated for Lake Erie for 1929

He used this equation to calculate loadings for the St. Lawrence Great Lakes (Table 5), and found good agreement between the estimated and measured (International Joint Commission, 1969) loadings for Lakes Erie and Ontario (0.98 vs 1.06 g m^{-2} yr^{-1} and 0.86 vs 0.65 g m^{-2} yr^{-1}, respectively).

Table 6. Export Scheme for Total P and $P(PO_4)$ from Various Soil Types (values expressed in mg m^{-2} yr^{-1}) (from Vollenweider, 1968)

P Export	Oligotrophic soils	Mesotrophic soils	Polytrophic soils
Total P	<20	20 – 50	50
$P(PO_4)$	<10	10 – 25	25

Table 7. Ranges and Mean Values for Export of Total Phosphorus from 43 Watersheds; Values Include Results from Southern Ontario Study (results in mg m^{-2} yr^{-1}) (after Dillon and Kirchner, 1974)

Land use	Geological classification	
	Igneous	Sedimentary
Forest		
Range	0.7 – 8.8	6.7 – 18.3
Mean	4.7	11.7
Forest and Pasture		
Range	5.9 – 16.0	11.1 – 37.0
Mean	10.2	23.3
Agriculture		
Range		17 – 113
Mean		46
Urban		
Range		110 – 1660
Mean		1050

Table 8. Per Capita Contribution of Phosphorus (E_c) in Domestic Sewage

From Vollenweider, 1968

E_c (kg P/capita/yr)	Origin and treatment	Reference
0.24 – 0.55	Untreated sewage in the USA	(Rudolfs, 1947)
0.55	Madison, Wisconsin, biologically treated sewage	(Sawyer, 1947)
0.55 – 1.35 (average 0.84)	Minnesota, untreated sewage	(Owen, 1953)
0.66 – 1.75	Illinois (trickling filters) (activated sludge)	(Engelbrecht & Morgan, 1959)
1.61	Madison, Wisconsin, trickling filters	(Mackenthun, Ingram & Porges, 1964)
0.33		(Husmann, 1950)
0.73		(Johansson & Cronholm, 1953)
0.88 – 1.06		(Skulte, 1953)
0.55		(Jansa, 1955)
0.84	(After Ahl, 1963)	(Imhoff, 1958)
0.60		(Klotter & Neussel, 1959)
1.10	Investigation by Lindth in Switzerland	(Marki, 1961)

Additional Data

E_c (kg P/capita/yr)	Year	Reference
0.6	1872 }	(Task Group 2610P, 1967)
1.2	1936 } pre-detergent data	(Task Group 2610P, 1967)
0.4 – 0.5	1938 }	(Task Group 2610P, 1967)
0.4 – 0.5	1947 }	
0.5 – 6.4	1958	(Task Group 2610P, 1967)
1.3 – 1.9	1958	(Task Group 2610P, 1967)
0.8 – 1.9	1959	(Task Group 2610P, 1967)
0.8		(Nutrient Sources Subcommittee, 1966)
0.9		(Lee, 1973)
1.7		(Patalas, 1972)
1.5		(Michalski, Johnson and Veal, 1973)
2.04 – 2.56		(International Joint Commission, 1969)
0.7		(Owens, 1970)

There are, however, a number of potential problems inherent in this model that at present impose severe restriction on its use. Patalas obtained his value for the export coefficient, E_s, from Vollenweider (1968), as outlined in Table 6, but as the author and Kirchner (1974) pointed out, these values are only approximate and their use is subjective. Based on a study of 34 watersheds in southern Ontario, as well as an extensive review of the literature on phosphorus export, they proposed a two-dimensional export scheme that employed land use and geology as the factors on which to estimate the phosphorus export (Table 7). Insufficient data, however, were available for agricultural and urban watersheds to devise a good scheme for these two land use types.

The value used by Patalas for E_c, the per capita discharge of phosphorus reaching the lake, was 1.7 kg yr^{-1}. This is probably reasonable, considering the large quantities of phosphate detergents used in the Great Lakes Basin at the time, but with the recent reductions in the phosphate content of these detergents, a new per capita loading figure is necessary. It is likely that the baseline physiological load (i.e., the baseline per capita discharge of phosphorus in sewage, excluding contributions by detergents) is less than half of that found when detergent contributions are included (Table 8). The range of figures used in the past was quite broad and careful attention must be given to picking a suitable figure in the future.

The third factor that must be considered before applying Patalas' equation to other lakes is that precipitation directly onto the lake is neglected. This can be easily corrected. Although precipitation directly onto the lake will be relatively unimportant for lakes with high population densities in their watersheds, as Lakes Erie and Ontario, it is obvious that for many lakes this will be a significant and sometimes the major source of phosphorus (Schindler and Nighswander, 1970; Armstrong and Schindler, 1971; Chapin and Uttormark, 1973).

Finally, Patalas' choice of 0.85 as the retention coefficient for the Great Lakes is probably reasonable. This cannot be assumed to be generally applicable to other lakes, however, as the data in Table 1 and especially in Table 2, demonstrate. Correlation analysis between R and other parameters demonstrated that for the Haliburton Lakes, R was closely related ($r = -0.90$) to the areal water loading, q_s:

$$R = 0.635 - 0.0032\, q_s$$

In these cases, q_s was large (> 10 for 9 of 13 lakes). Thus the equation is not generally applicable.

Much effort should be directed to the investigation of the factors determining the retention coefficient, so that it may be predicted accurately for a given lake.

THE RESPONSE OF LAKES TO REDUCED PHOSPHORUS LOADING

It is well known that under anaerobic conditions, such as exist in the hypolimnion of a eutrophic lake, substantial quantities of phosphorus are returned from the sediments to the lake. This flux can reach 10 mg m^{-2} day^{-1} (Vollenweider, 1969). It is sometimes argued that a decrease in external loading results in an increased backflow of nutrients from sediments to water. This, of course, counteracts the benefits of a reduction in loading caused by sewage diversion or other remedial measures. Since this question is of vital importance to the concept of eutrophication control, a summary of available case studies follows.

Zellersee

Until 1962, the Zellersee ($A_o = 4.55$ km^2, $\bar{z} = 36.6$ m) received a sizeable phosphorus load ($L_p \sim 1.20$ g m^{-2} yr^{-1}) from the communal sewage of about 7000 inhabitants. At this time the reduction of the load to about 20% of the previous load by sewage diversion was followed by a significant improvement (O_2 concentration > 0 to the bottom) within two years after recovery measures were initiated (Liepolt, 1967).

From the water renewal time of the Zellersee ($\tau_w = 2.7$ yr), it can be calculated that the half-life for the change in concentration from the steady state at one fixed loading to the steady state at a new loading is a minimum of two years. Therefore complete recovery could not be expected for at least eight years or probably longer. Since improvements were noted within two years, the indication is that the sediments have not significantly counteracted the reduction in loading.

Lake Washington

To date, the most comprehensive study of the effects of reduced nutrient load on a lake is that of Lake Washington (Edmondson, 1969a).

By 1952, ten sewage treatment plants discharged directly into the lake. Conditions in the lake (chlorophyll *a* concentration, Secchi disc depth, hypolimnetic oxygen deficit, phosphorus concentration, etc.) gradually became worse (Edmondson, 1961, 1966, 1968, 1969b, 1972; Anderson, 1961) until 1963, the year following the initiation of sewage diversion. Diversion was complete by mid-1968 reducing the phosphorus loading by 55%, at which point improvements were already noticed. Mean

chlorophyll *a* concentration (July and August), which had been about 1.5 mg m^{-3} in 1950 and had risen to about 24 mg m^{-3} in 1964, was reduced to 3.5 mg m^{-3} in 1969. Secchi disc depth, which had fallen from 3.7 m in 1950 to 1.0 m in 1963 and 1964, increased to 3.5 m in 1971. Lake Washington is now no longer considered eutrophic. Again it can be concluded that recovery, once nutrients are diverted, is prompt.

Lake Sammamish

Lake Sammamish, situated near Lake Washington, began to show signs of advanced eutrophication in the mid-1960's, and as a result, sewage diversion was undertaken and completed in 1968. The expected improvements in this lake, however, have not materialized (Welch and Spyridakis, 1972; Emery, Moon and Welch, 1973). There are several reasons for this:

a) the reduction accomplished by diversion amounted to removal of only 39% of the total load with the resultant load still well above Vollenweider's "permissible" level,

b) the mean depth of Lake Sammamish (17.7 m) is considerably less than that of the other two lakes, and

c) its water renewal time is longer (4.8 yr).

In fact, the lack of response of Lake Sammamish was to be expected and it in no way disproves either the hypotheses of Vollenweider or the author.

Lake Norrviken

For many years, Lake Norrviken in central Sweden received both domestic and industrial sewage. In June 1969, all effluents were diverted from the lake, reducing the total phosphorus loading from 4.0 g m^{-2} yr^{-1} to 2.0 g m^{-2} yr^{-1} (Ahlgren, 1972). The lake, however, has not responded to the decreased loading, but this is certainly not surprising considering the continuance of the very high loading of 2.0 g m^{-2} yr^{-1} in relation to the shallow mean depth (5.4 m). Secchi disc depth remained ~ 1 m in 1970 as it was in 1961 and 1969. It is likely that in such a shallow lake the phosphorus in the sediments will be readily remixed into the water column (by wind-generated mixing of the lake) and that recovery, once wastewater is diverted, will not be rapid.

Madison Lakes

The results of diversion of sewage treatment plant effluents from Lakes Monona, Waubesa and Kegonsa are outlined by Edmondson (1968) and Sonzogni and Lee (1972). Complete diversion from Lake Monona was accomplished in 1936; recovery has been slow. Copper sulphate treatments to control algal blooms were necessary for 20 years after the diversion. The remaining Madison Lakes underwent wastewater diversion in 1958, but the response of these shallow lakes has again been slow. For all of these lakes, the phosphorus load remains quite high because of the high contributions from the surrounding agricultural land.

Although improvement has not been outstanding, without diversion, the lakes undoubtedly would have become much worse.

Little Otter Lake

Little Otter Lake, a small Precambrian Shield lake in Ontario ($A_o = 0.665$ km^{-2}, $\bar{z} = 2.7$ m), received a relatively large amount of a polyphosphate de-scaling agent starting in 1971 (Michalski and Conroy, 1973). The lake quickly developed classical symptoms of eutrophy including a dense bloom of *Anabaena limnetica* G. M. Smith, low Secchi disc depths (0.1 – 2.3 m), and high chlorophyll *a* (12-46 mg m^{-3}) and total phosphorus (12-110 mg m^{-3}) concentrations. When the polyphosphate discharges were discontinued, significantly reducing the loading, improvement was rapid. The average Secchi disc depth in 1972 was 3.3 m, chlorophyll *a* concentration was reduced to 2.5 mg m^{-3} and phosphorus concentration was 14 mg m^{-3}. No sign of eutrophy remained. The relatively high flushing rate of Little Otter Lake ($\rho = 9.2$ yr^{-1}) undoubtedly hastened its rapid recovery.

Additional Lakes

In 1933, the sewage was diverted from the Rotsee in Switzerland; nevertheless, the lake continued to produce nuisance algal blooms. The pre-diversion and post-diversion loadings are unknown, however, so it is difficult to evaluate this case. It has been suggested that its small size and agricultural drainage have offset the effect of wastewater diversion, and that the original diversion was insufficient (Edmondson, 1968).

The sewage that was being discharged into Lyngby-Sø in Denmark was diverted in 1959. In the following four years, productivity (as measured by the rate of photosynthesis) decreased. Since 1964, however, macrophytes have become re-established in both of the lakes possibly because of increased light penetration owing to the decrease in phytoplankton population (Emery, Moon and Welch, 1973). Loading data for Lyngby-Sø are not available.

Other lakes which have undergone or are undergoing wastewater diversion or phosphorus removal from effluents

include Lac Annecy in France, Tegernsee and Schliersee in Germany (Hamm, 1971) and Hallwilersee and Zürichsee in Switzerland. The Zürichsee has shown some signs of improvement in recent years. The phosphorus load to Tegernsee and Schliersee was reduced to 10-20% of the original load and the nitrogen load to 25-40% of the original. Although the Tegernsee subsequently showed continued improvement in hypolimnetic oxygen conditions in the following summers, the Schliersee initially showed improvement, but relapsed quickly to a condition of an anaerobic hypolimnion, at least partly because of the partially meromictic nature of the lake. Results are not yet available for most of the other lakes.

SUMMARY

From the preceding case histories, it can be seen that wastewater diversion that resulted in significant reductions (>50%) in the phosphorus loading, improved the trophic state of the lakes. The time required for these changes is a function of the water renewal time and the depth of the lake. Diversion is much less effective for very shallow lakes, since wind action and macrophyte use render the sediment phosphorus pool accessible. The models previously discussed would have effectively predicted the results of the diversions undertaken to date.

FUTURE AREAS OF CONCERN IN PHOSPHORUS-LOADING RESEARCH

A number of critical specific problem areas need to be investigated immediately if these studies are to be advanced. They include:

a) refinement of current knowledge of the relationship between nutrient loading or nutrient concentration and trophic level by finding better relationships between nutrient loading or concentration and various biological parameters,

b) determination of a good means of measurement of L_{int}, the internal loading from the sediments to the lake,

c) clarification of the importance of precipitation and especially dry fallout to the nutrient loadings of lakes,

d) improvement in the measurements of the export coefficient, E_s, for different land uses, especially agricultural and urban watersheds,

e) accurate determination of the per capita supply of phosphorus to lakes in populated watersheds, and

f) further testing of either the L vs $\bar{z}/\tau_w$ or $L(1-R)/\rho$ vs $\bar{z}$ model by observing the effects on the trophic state of a decrease in loading (sewage diversion, tertiary treatment).

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