Technical Completion Report
Project C-7232

INPUT/OUTPUT MODELS AS DECISION CRITERIA FOR LAKE RESTORATION

by

Paul D. Uttormark[1]
Mark L. Hutchins[1]

April 1978

The work upon which this publication is based was supported in part by funds provided by the United States Department of the Interior, Office of Water Research and Technology, as authorized under the Water Resources Research Act of 1964, P.L. 88-379, as amended. Agreement No. 14-34-0001-6230.

[1]LAND AND WATER RESOURCES INSTITUTE
11 Coburn Hall
University of Maine at Orono
Orono, Maine 04473

WATER RESOURCES CENTER
1975 Willow Drive
University of Wisconsin
Madison, Wisconsin 53706

ABSTRACT

Over the past several years, input/output models have been used increasingly as decision-making aids in the design of lake restoration activities because they provide an approximation of the link between nutrient influx and lake trophic status. To evaluate the applicability of these models as design tools, a study was conducted in which "before" and "after" data were obtained for twenty-five lakes which experienced reductions in nutrient inflow, and comparisons were made of measured and predicted changes in lake conditions. Four input/output models were used as predictive tools to describe lake response: those reported by Dillon and Rigler (1974) and Vollenweider (1975, 1976), and a model developed in this study in which cellular biomass, rather than total phosphorus, is used as the trophic state indicator. Comparisons of measured and predicted responses were based on general descriptions of trophic status; Secchi depth, including the Trophic State Index (TSI) reported by Carlson (1977); and a Lake Condition Index (LCI) reported by Uttormark and Wall (1975).

Based on described trophic states of oligotrophic, mesotrophic, and eutrophic, it was found that all four models yielded accurate predictions for at least 70% of the study lakes; however, the model of Vollenweider (1976) and the biomass model yielded somewhat better predictions, with 82% correct. Also, the biomass model theoretically extends predictive capabilities to lakes with high flushing rates where cellular washout becomes an important consideration. A lack of data prevented adquate testing of this capability.

Comparisons of measured and predicted responses based on other measures of lake condition were less definitive. Though a reduction in phosphorus input generally led to improved water quality, data scatter using both the TSI and the LCI made further interpretation difficult. Also, estimates of improvements in transparency were found to be generally optimistic, with measured Secchi depths reaching only 50-80% of predicted values for most of the study lakes.

It was concluded that the input/output models examined are best applied to those restoration techniques which curb nutrient influx and where long-term average conditions can be reasonably approximated. The models were also used as a basis for discussing restorative techniques designed to disrupt internal nutrient cycles and accelerate nutrient outflow. This exercise provided some insight into the potential effects of nutrient cycling and accelerated nutrient outflow on overall water quality; however, the results must be viewed with caution, since the analyses involve assumptions which are not consistent with all restrictions placed on the models.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

ACKNOWLEDGEMENTS

The work upon which this report is based was supported in part by funds provided by the U.S. Department of the Interior, Office of Water Research and Technology, as authorized under the Water Resources Research Act of 1964 (P.L. 88-379) as amended. Support also was provided by the University of Maine and by the University of Wisconsin.

Data necessary to conduct this project was generated primarily by contributions from an international group of scientists. Their participation in the successful completion of this project is gratefully acknowledged.

SECTION I

INTRODUCTION

Over the past several years, major steps have been taken to expedite restoration of the nation's lakes, as well as to protect those remaining high-quality lakes from future degradation. The state/federal cost-sharing program for lake renewal and protection included in the 1972 Amendments to the Water Quality Act (P.L. 92500) has been an important stimulus. This act authorizes the expenditure of $300 million for the implementation of lake improvement activities. Lake renewal and protection legislation has been enacted, or is under consideration, in a number of states. These legislative acts are evidence not only of mounting public concern for water quality management in lakes, but also of the recognition that responsibility for lake quality extends beyond local riparians to include the general public.

Implicit in each of the above-mentioned acts is the assumption that if funds are available present technology can be applied to solve most lake problems. Unfortunately, this is true only in part. Lake renewal is an emerging science which includes few proven approaches, several potentially useful techniques which have undergone limited field testing, and some "laboratory methods" which are theoretically feasible but have yet to be tested.

Literature reviews dealing with lake renovation are not lacking; three independent reviews have been prepared in recent years: Dunst *et al.* (1974), Tenney *et al.* (1974), and EPA (1973). However, each of these reports is limited to a summary of individual lake renewal experiences which have been reported in the literature. To date, no serious attempt has been made to analyze and compare the results of these experiences within a common, quantified frame of reference. Such information would be particularly helpful now, because both state and federal agencies are moving rapidly into full-blown lake renewal programs, and quantitative information relating to the predictability of results-- and thus the likelihood for success-- is needed.

For purposes of this report, "lake renewal" is defined as the range of activities dealing with the prevention, amelioration, or reversal of eutrophication. In addition, it is considered that all lake renewal techniques may be grouped into three general categories: (a) those which deal with reducing nutrient influx; (b) those which accelerate or expedite nutrient outflow; and (c) those which are intended to disrupt or control internal nutrient cycling. Within this definition and frame-

work, the two-fold objective of this report is

1. to present quantitative information relating to lake renewal experiences and define criteria for estimating the "likelihood of success" of those techniques for which sufficient data are available; and

2. to identify areas of needed research and development that would lead either to a refinement of provisional renewal criteria, or to the formulation of guidelines for those techniques which presently are not well understood and for which comparable data are lacking.

The formal study of limnology dates back to the early 1900's and has been underlain by a history of descriptive studies documenting the complexity of lake environments and the unique characteristics of specific lakes. In more recent years, emphasis has been placed on developing quantitative information relating to similarities among lakes, and attention has been focused on developing simplified relationships between nutrient influx and trophic status of lakes. These relationships are particularly important for the development of lake restoration methods because they provide guidelines and serve as a decision-making aid for lake improvement projects.

On the basis of water analyses from 17 Wisconsin lakes, Sawyer (1947) suggested that if, at time of spring overturn, concentrations of inorganic phosphorus and inorganic nitrogen (ammonia plus nitrate nitrogen) exceeded 10 and 300 mg/m^3 respectively, a lake may be expected to produce excessive growth of algae or other aquatic plants. Vollenweider (1968) conducted a statistical analysis of data reported by Thomas (1953) and concluded that the critical levels suggested by Sawyer generally were borne out by the condition of lakes in Central Europe.

The critical concentrations suggested by Sawyer, although not to be construed as rigid lines of demarcation, do provide target values for lake renewal efforts. However, it is difficult to relate these values directly to reductions in nutrient input, because the relationship between nutrient influx and in-lake nutrient concentrations is not clear.

Vollenweider (1968) suggested provisional nutrient loading criteria for lakes in which the rate of nitrogen and phosphorus influx to lakes (expressed as $gm/m^2/yr$) was related to subsequent trophic status. "Acceptable" and "excessive" loading rates were defined. These loading criteria were developed empirically by comparing the loading values to the trophic state of about 30 large lakes in North America and Europe. For the most part, the criteria have been upheld by other investigators; however, specific values may have to be modified somewhat to account for local differences (Shannon and Brezonik, 1972).

Table 1: SPECIFIC NUTRIENT LOADING LEVELS FOR LAKES (EXPRESSED AS TOTAL NITROGEN AND TOTAL PHOSPHORUS IN $g/m^2/yr$)*

Mean depth up to	Permissible loading up to:		Dangerous loading in excess of:	
	N	P	N	P
5 m	1.0	0.07	2.0	0.13
10 m	1.5	0.10	3.0	0.20
50 m	4.0	0.25	8.0	0.50
100 m	6.0	0.40	12.0	0.80
150 m	7.5	0.50	15.0	1.00
200 m	9.0	0.60	18.0	1.20

*from Vollenweider (1968)

SECTION II

INPUT/OUTPUT MODELS

In recent years a number of attempts have been made to develop improved nutrient loading/lake condition relationships based on simple input/output models. (Vollenweider 1975, 1976; Dillon and Rigler 1974) In each of these cases, the models are restricted to phosphorus-limited lakes, and it is assumed that, on a long-term basis, lakes may be approximated by completely mixed flow-through reactors. It is further assumed that the influx of phosphorus is constant, that phosphorus losses occur through the outlet and through internal losses (sedimentation), and that the net internal loss is directly proportional to the amount of phosphorus in the lake. Under these assumptions, the resulting steady-state concentration of phosphorus in the lake has been selected as an indicator of a lake's trophic status.

Model equations are then developed by calculating a phosphorus mass balance for the simplified system. Thus,

$$\text{change in total-P} = \text{inflow} - \text{sedimentation} - \text{outflow.}$$

$$V\frac{d[P]}{dt} = Q[P_0] - \sigma[P]V - Q[P] \qquad (1)$$

where V = lake volume, L^3

$[P]$ = in-lake total phosphorus concentrations, ML^{-3}

Q = annual water flow rate, L^3T^{-1}

$[P_0]$ = inflow total phosphorus concentration, ML^{-3}

σ = specific sedimentation rate, T^{-1}

At steady-state, temporal changes are zero, and the in-lake phosphorus concentration may be expressed by

$$[P] = [P_0]\frac{\rho}{\sigma + \rho} \qquad \text{where } \rho = \frac{Q}{V} = \text{flushing rate, } T^{-1} \qquad (2)$$

Alternately, Eq.(2) may be expressed in terms of phosphorus loadings rather than average input concentrations,

$$[P] = \frac{L}{\bar{z}(\rho + \sigma)} \tag{3}$$

where L = specific areal phosphorus loading, $ML^{-2}T^{-1}$
$\bar{z}$ = mean lake depth, L

The major difficulty in utilizing either Eq.(2) or Eq.(3) comes about because of the inability to specify appropriate values of σ, the specific sedimentation rate, for different lakes. Because "sedimentation" is used to describe all net internal losses of phosphorus (i.e. all processes by which phosphorus is retained within lakes), it is extremely difficult if not impossible to determine experimentally. Thus, attempts have been made to estimate values of σ on the basis of other known lake parameters. It should be noted that the phosphorus loading/lake condition relationships presented by Vollenweider (1975 and 1976) and Dillon and Rigler (1974) are all based on Eq.(3) and differ only because of the way in which the specific sedimentation rate was estimated.

Vollenweider (1975) used Eq.(3) to calculate values of σ for a known set of lake data, and by plotting specific sedimentation rate versus mean depth he deduced that

$$\sigma \simeq \frac{10}{\bar{z}} \tag{4}$$

where $\bar{z}$ is measured in meters and σ in $years^{-1}$

Then by substitution in Eq.(3)

$$[P] = \frac{L}{10 + \bar{z}\rho} \tag{5}$$

Maximum acceptable specific loadings were defined as the levels which would result in a steady-state in-lake phosphorus concentration of $10mg/m^3$. In-lake values of twice that amount, $20mg/m^3$, were judged to be excessive or dangerous. Using subscripts to indicate in-lake concentrations associated with given loading rates, "maximum acceptable" and "excessive" specific loadings are given by

$$L_{10} = .01(10 + \bar{z}\rho) \tag{6a}$$

$$L_{20} = .02(10 + \bar{z}\rho) \tag{6b}$$

Although somewhat arbitrary, the values of 10-20mg-P/m^3 appear to be reasonable and are supported by the findings of Sawyer (1947), insofar as theoretical steady-state phosphorus concentrations are analogous to concentrations of inorganic phosphorus at time of spring overturn.

A plot depicting phosphorus loading/lake condition relationships as presented by Vollenweider (1975) is shown in Fig.1. This graph has been used widely as a decision-making tool for estimating the extent to which the phosphorus loadings of eutrophic lakes should be reduced so that the lakes would revert to a more "desirable" trophic state.

Dillon and Rigler (1974) developed a similar relationship based on Eq.(3) and used an indirect approach to avoid some of the difficulties associated with selecting appropriate values for the specific sedimentation rate. They modified the analysis to include a phosphorus retention coefficient, R, which is defined as that portion of the total phosphorus input which is retained within a lake.

$$R = \frac{P_{in} - P_{out}}{P_{in}} \tag{7}$$

Also, from Eq.(2)

$$R = \frac{\sigma}{\sigma + \rho} \tag{8}$$

Eq.(3) may then be expressed in terms of the phosphorus retention coefficient by

$$[P] = \frac{L(1 - R)}{\bar{z}\rho} \tag{9}$$

Dillon and Rigler recommended plotting $L(1-R)/\rho$ versus $\bar{z}$ as shown in Fig.2. Values of 10 and 20mg-P/m^3 were again used to define acceptable and excessive loading values. This method of plotting has the advantage that the loci of all constant in-lake phosphorus values are depicted by straight, parallel lines on the graph. In addition, the approach circumvents the difficulties of specifying σ by incorporating an alternative parameter, R, which is more easily measured.

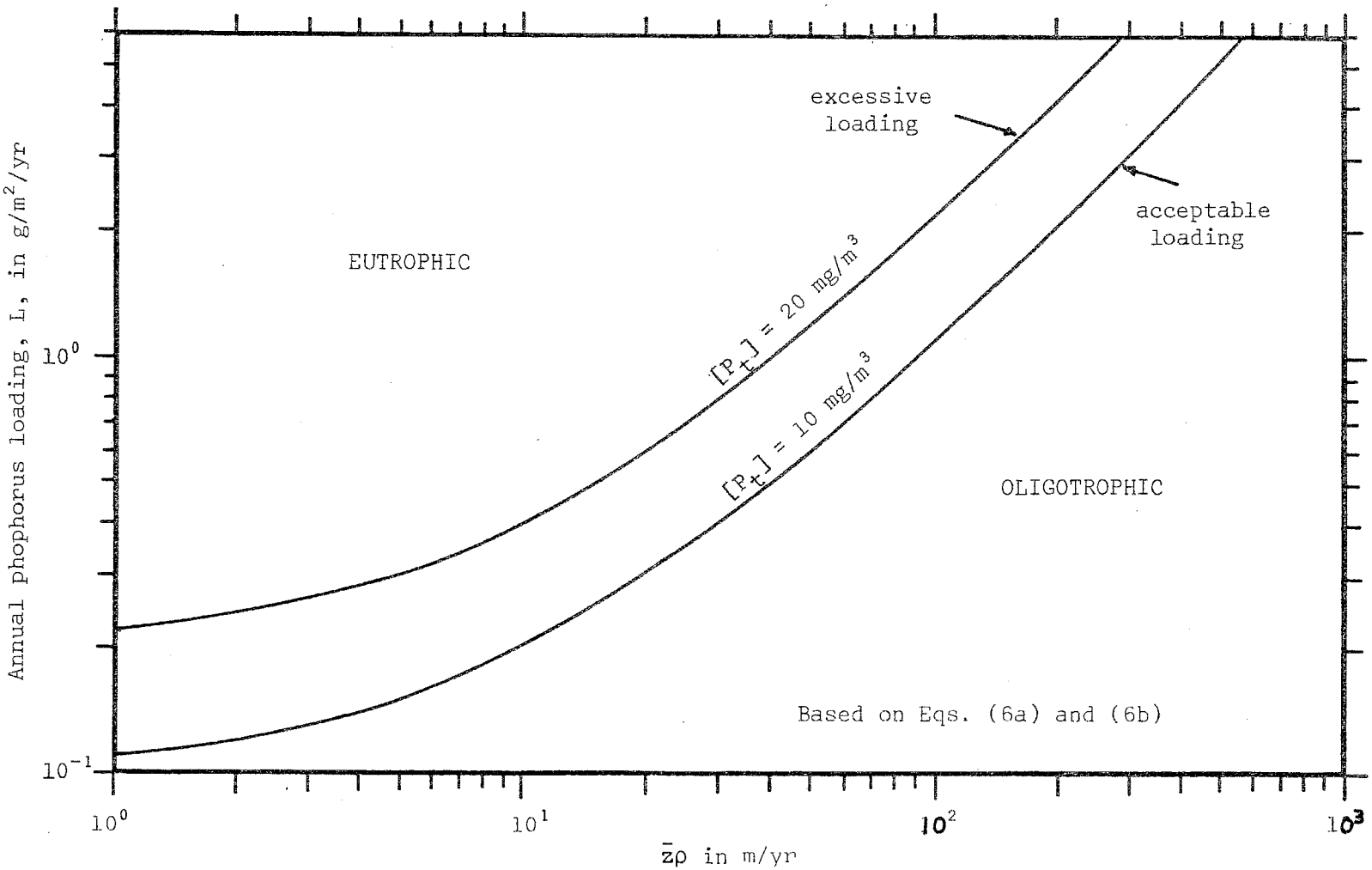

Fig. 1 : Nutrient loading/lake trophic condition after Vollenweider (1975)

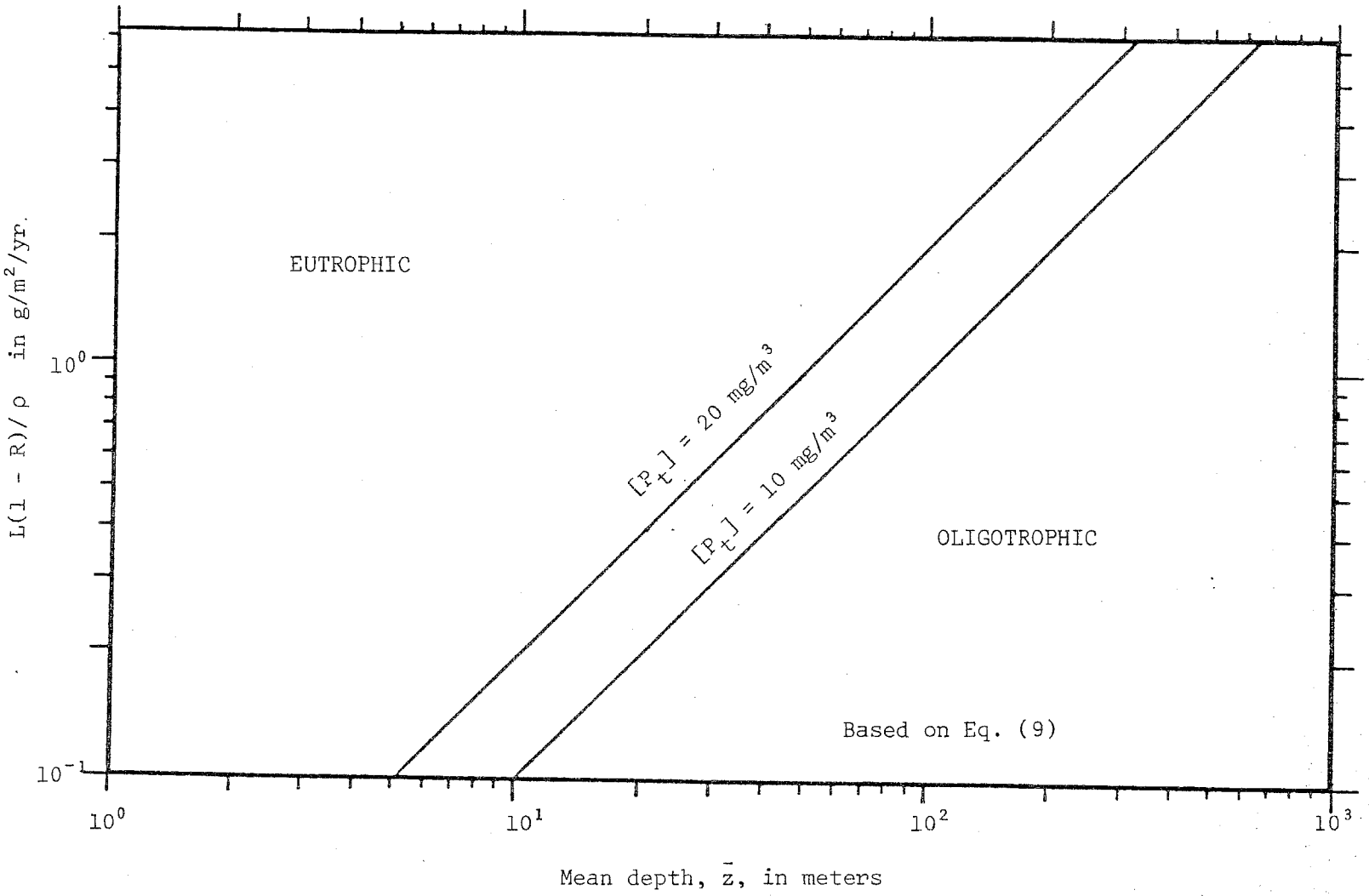

Fig. 2: Nutrient Loading/Lake Trophic Condition after Dillon and Rigler (1974)

It is interesting to note that both Eqs.(5) and (9) contain flushing rate only as a product with mean depth, i.e. only as "$\bar{z}\rho$". And

$$\bar{z}\rho = \frac{V}{A} \cdot \frac{Q}{V} = \frac{Q}{A} \tag{10}$$

The quantity Q/A is the hydraulic loading-- the amount of water added annually per unit area of lake surface. This combination of terms effectively cancels out the effect of flushing rate in the analysis and, consequently, both Eqs.(5) and (9) lead to the interpretation that lakes with the same hydraulic and phosphorus loadings should have the same in-lake phosphorus concentration regardless of differences in flushing rates. A major stimulus for developing input/output models came from the recognition that static loading criteria (Table 1) did not adequately describe lakes with high flushing rates, and that flushing rate should be incorporated into the criteria. Although this was accomplished only in part-- hydraulic loading, not flushing rate, was built into the models-- the results nevertheless represent a distinct improvement over the static loading criteria.

A further modification of the input/output approach was presented by Vollenweider (1976). Through statistical considerations, a relationship was developed between the specific sedimentation coefficient and the hydraulic residence time of lakes, which may be expressed in terms of the flushing rate by

$$\sigma = \sqrt{\rho} \tag{11}$$

(An expression identical to Eq.(11) was developed independently by Larsen and Mercier (1976).)

Thus, from Eq.(3)

$$[P] = \left(\frac{L}{\bar{z}\rho} \frac{\rho}{\sqrt{\rho} + \rho}\right) = [P_0] \frac{\rho}{\sqrt{\rho} + \rho} \tag{12}$$

Or, based on the selection of 10 and 20mg-P/m^3 as acceptable and excessive concentrations respectively,

$$\left[\frac{L}{\bar{z}\rho}\right]_{10} = [P_0]_{10} = .01\left(1 + \frac{1}{\sqrt{\rho}}\right) \tag{13a}$$

$$\left[\frac{L}{\bar{z}\rho}\right]_{20} = [P_0]_{20} = .02\left(1 + \frac{1}{\sqrt{\rho}}\right) \tag{13b}$$

A graphical representation of these equations is given in Fig.3. The dashed lines shown at the left side of the figure were suggested by Vollenweider to describe the condition of "cellular washout"-- a condition which might be expected when the flushing rate approaches the mean life span of phytoplankton populations. This condition cannot be described by the input/output models discussed above, and it is shown on the plot to indicate a zone in which the model equations are likely to be inadequate. As part of this project, an analysis of washout conditions was undertaken in an attempt to eliminate this shortcoming.

To examine cellular or "biomass" washout, a modeling approach very similar to previous work was taken. However, the model contains an additional step which describes the incorporation of phosphorus into biomass. Not all phosphorus is converted to biomass; thus total phosphorus was divided into two components: (1) that fraction which is incorporated into biomass, and (2) that fraction which remains in solution. Biomass concentration (expressed as P), rather than total phosphorus concentration, was selected as the trophic state indicator. It was anticipated that improvement in present modeling capabilities would result, since biomass concentration may be representative of trophic state over a broader range of lake conditions, particularly when cellular washout is approached.

It was assumed that the kinetics of phosphorus uptake by biomass could be described adequately by the Michaelis-Menten relationship (Michaelis-Menten, 1913; Monod, 1949). Specifically, the Michaelis-Menten relationship describes the specific growth rate, μ, as a function of substrate concentration such that

$$\mu = \hat{\mu} \frac{[S]}{k_s + [S]} \tag{14}$$

where $\hat{\mu}$ = maximum specific growth rate attainable for a given organism at infinite substrate concentration, T^{-1}

$[S]$ = substrate concentration, ML^{-3}

k_s = half-saturation constant = the substrate concentration at which specific growth rate equals one-half the maximum specific growth rate, ML^{-3}

In developing the model equations, it was convenient to define both a

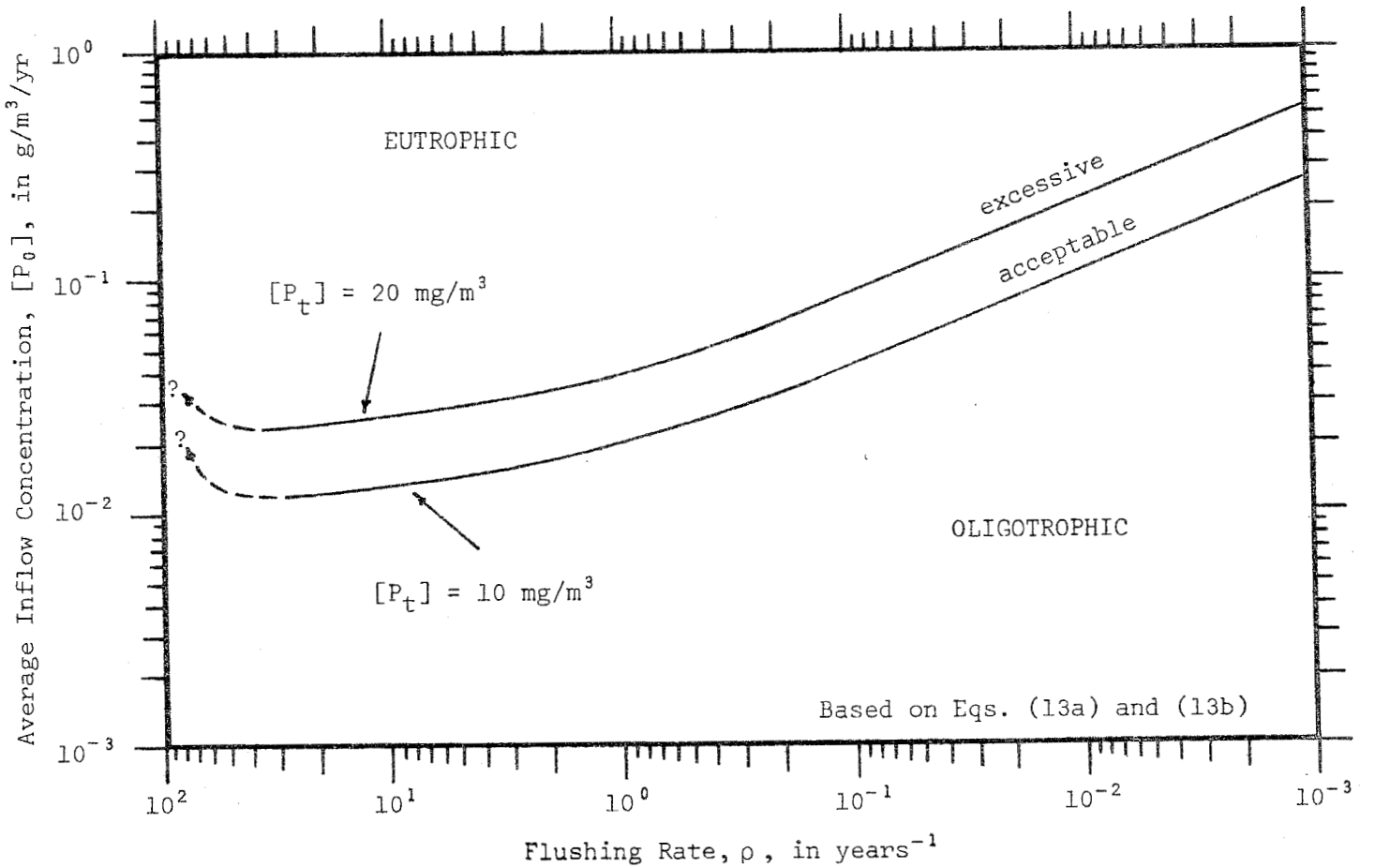

Fig. 3: Nutrient Loading/Lake Trophic Condition after Vollenweider (1976)

biomass balance and a nutrient balance for lake systems. At steady-state, the biomass balance requires that

$$\mu = \rho + \sigma \left\{ \frac{1}{\bar{t}_j} + K \right\} \qquad (15)$$

and the nutrient mass balance yields

$$\frac{[X]}{Y} = ([P_0] - [P_S])\frac{\rho}{\rho + \sigma} \qquad (16)$$

where $[X]$ = concentration of in-lake biomass, ML^{-3}

Y = yield coefficient = biomass produced per nutrient incorporated, dimensionless

$[P_S]$ = phosphorus concentration remaining in solution, ML^{-3}

As with the other models described above, an indirect approach was used to characterize the sedimentation coefficient. Using the nutrient retention concept discussed by Dillon and Rigler (1974), a retention coefficient was defined such that

$$R = \frac{\sigma \frac{[X]}{Y} V}{[P_0]Q} \qquad (17)$$

The simultaneous solution of Eqs.(14), (15), (16), and (17) results in an expression for biomass concentration, the model trophic indicator. Also, knowing that $[P_0] = L/(\bar{z}\rho)$, it can be shown that

$$\left[\frac{[X]}{Y}\right]^2 \rho(\hat{\mu} - \rho) + \frac{[X]}{Y}\left[\frac{L}{\bar{z}} R\left(\hat{\mu} - 2\rho - \frac{1}{R}\hat{\mu}\right) + \rho\left(\frac{L}{\bar{z}} + \rho k_s\right)\right] - R\frac{L}{\bar{z}}\left[\frac{L}{\bar{z}}(R - 1) - \rho k_s\right] = 0 \qquad (18)$$

The model equation, though cumbersome, can be solved for biomass concentrations using the quadratic formula. (For a more complete development of Eq.(18), refer to Appendix 1.) It should also be mentioned that, because Eq.(18) is a quadratic, there are two real solutions to the equation. However, because conditions described by the second root-- low

biomass and high phosphorus concentration-- are not generally observed in natural lakes, the second solution will not be discussed here. For further discussion of the biomass model and implications thereof, the reader is referred to Hutchins (1977).

The solution of Eq.(18) requires that values be chosen for kinetic parameters, maximum specific growth rate, and half-saturation constant. Furthermore, values for the retention coefficient must be specified. Based on literature values, it was assumed that lake conditions could be approximated by values of $0.3 day^{-1}$ and $0.005 g/m^3$ for maximum specific growth rate and half-saturation constant, respectively. The retention coefficient was defined as a function of flushing rate after Vollenweider (1976) and Larsen and Mercier (1976), and it was assumed that this relationship applies regardless of trophic state. However, it should be pointed out that any relationship for determining retention coefficients may be used.

For convenience, Eq.(18) can be expressed in graphical form as shown in Fig.4. In this figure, biomass is plotted as a function of flushing rate. A family of curves is plotted in which volumetric loading is constant along each line. This plotting format was selected because it provides the user with a continuous-scale trophic state indicator on the ordinate axis, and therefore a given trophic state is represented by a straight horizontal line.

It should also be pointed out that, in the lower right-hand corner of Fig.4, a region exists within which there are no steady-state solutions to the model equation. This region represents washout conditions, i.e. the loss of biomass through the outlet and through sedimentation exceeds biomass production through growth, and steady-state conditions cannot be maintained under the constraints of the model.

As a final point, it is instructive to compare the results obtained from the biomass model with those of Vollenweider (1976). Direct comparisons can be made (see Fig.5) because both models use phosphorus as the trophic indicator; however, the latter uses total phosphorus and the former uses biologically-bound phosphorus. As shown in Fig.5, this distinction between phosphorus forms is negligible over a broad range of flushing rates, and the model equations plot as a single line; only when washout conditions are approached do the models yield different results. The differences occur because of the influence of flushing rate on phosphorus uptake kinetics as described by the biomass model. At high flushing rates, uptake is incomplete and biologically-bound phosphorus represents only a fraction of total phosphorus. When a critical flushing rate is exceeded, washout occurs and biologically-bound phosphorus approaches zero, even though theoretically a supply of available phosphorus remains in solution. Critical flushing rates, plotted as a function of volumetric loading (and average input concentration), are shown in Fig.6.

A more general depiction of the similarities and differences between

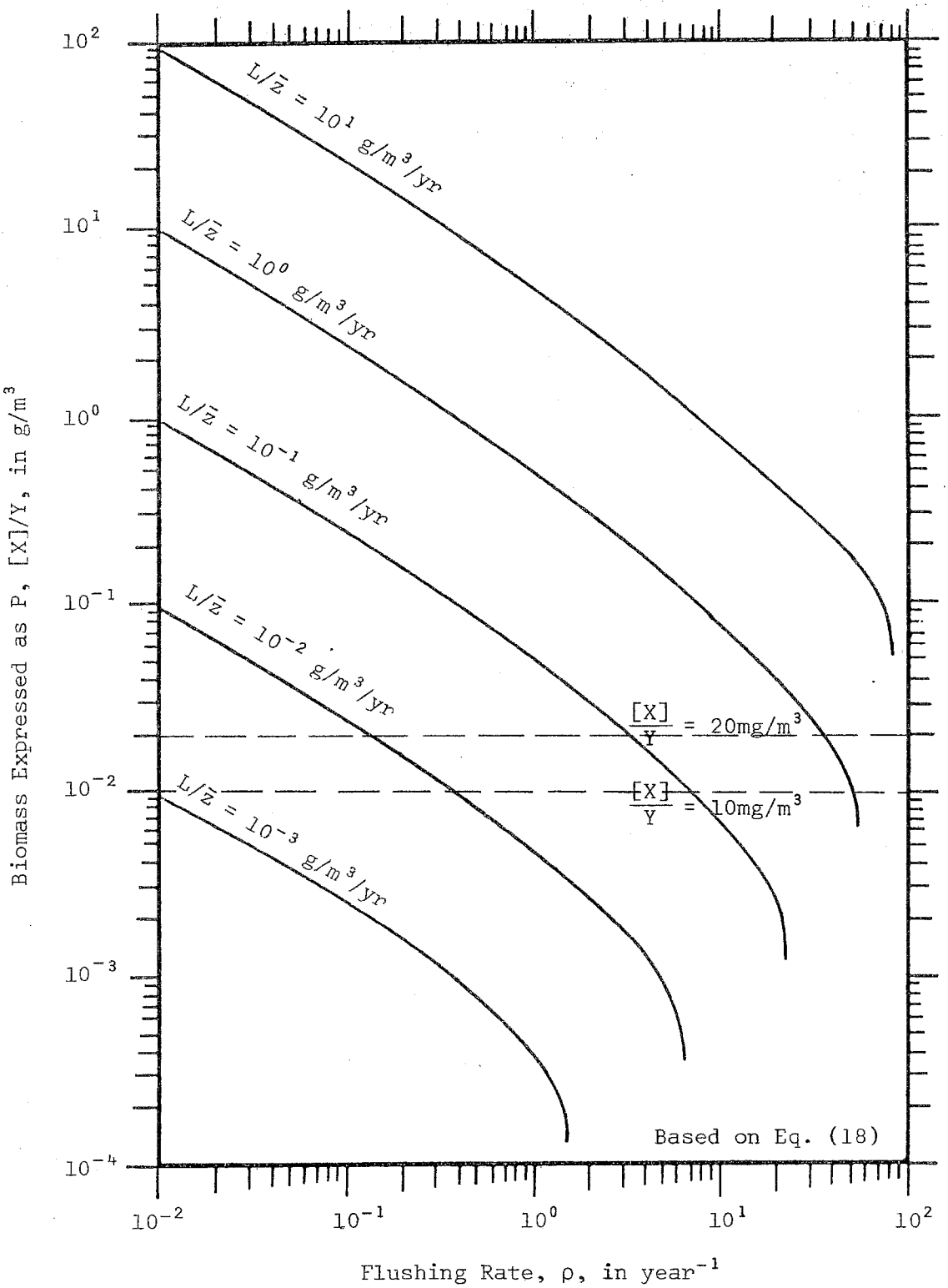

Fig. 4: Predicted Biomass Concentration as a Function of Flushing Rate and Volumetric Loading

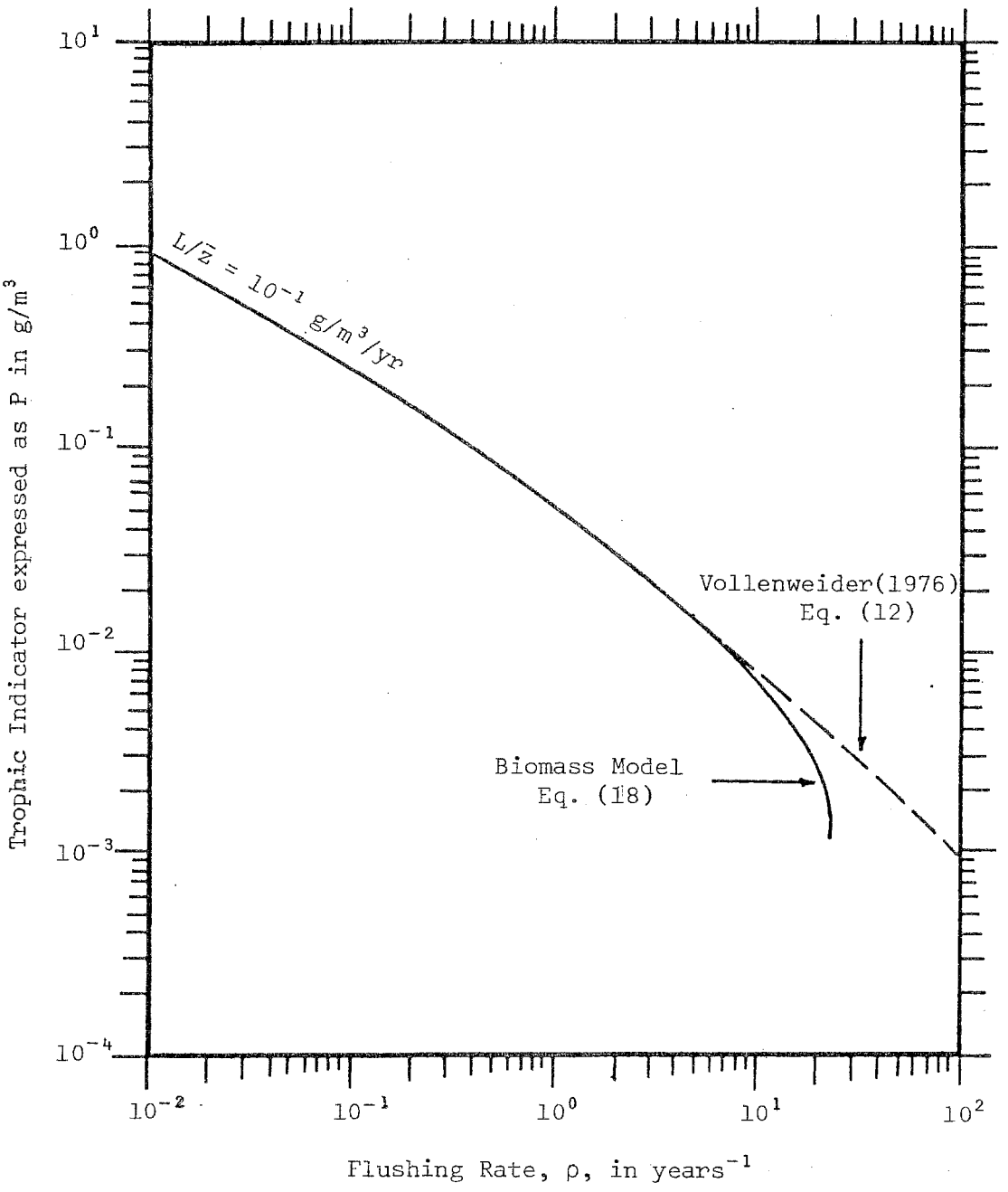

Fig. 5: Comparison of Biomass Model with that of Vollenweider (1976)

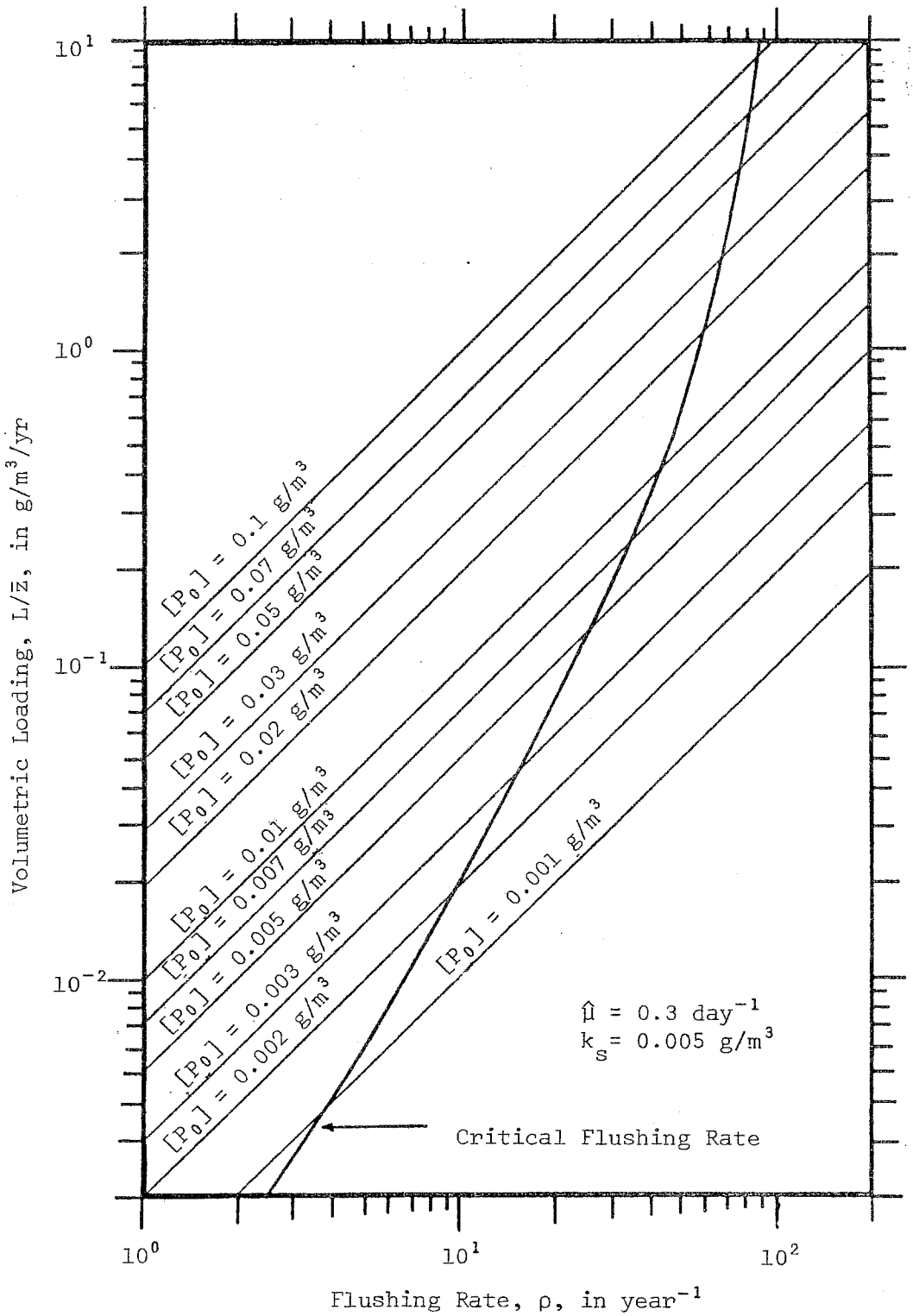

Fig. 6: Predicted critical flushing rates as a function of volumetric loading

the two models is shown in Fig.7. In this case, the graph is divided into three zones: in Region I the models yield identical results for all practical purposes; in Region III, washout conditions are predicted by the biomass model and the models are not comparable; Region II is a transition zone in which phosphorus uptake is incomplete, and while some biologically-bound phosphorus is predicted by the biomass model, it is always less than 90% of total phosphorus as predicted by Eq.(12). The distinction between these three zones may be important when a biomass-related parameter (such as Secchi depth) is used as an indicator of trophic state. In this case, it is anticipated that the biomass model would yield better results for lake conditions described by Regions II and III. However, for lake conditions described by Region I-- which includes most lakes-- a biomass model offers no advantage, and identical results can be obtained more simply with Eq.(12). However, the plotting format used in Fig.4 would be advantageous for comparing lake data and developing an improved understanding of lake loading/lake condition relationships.

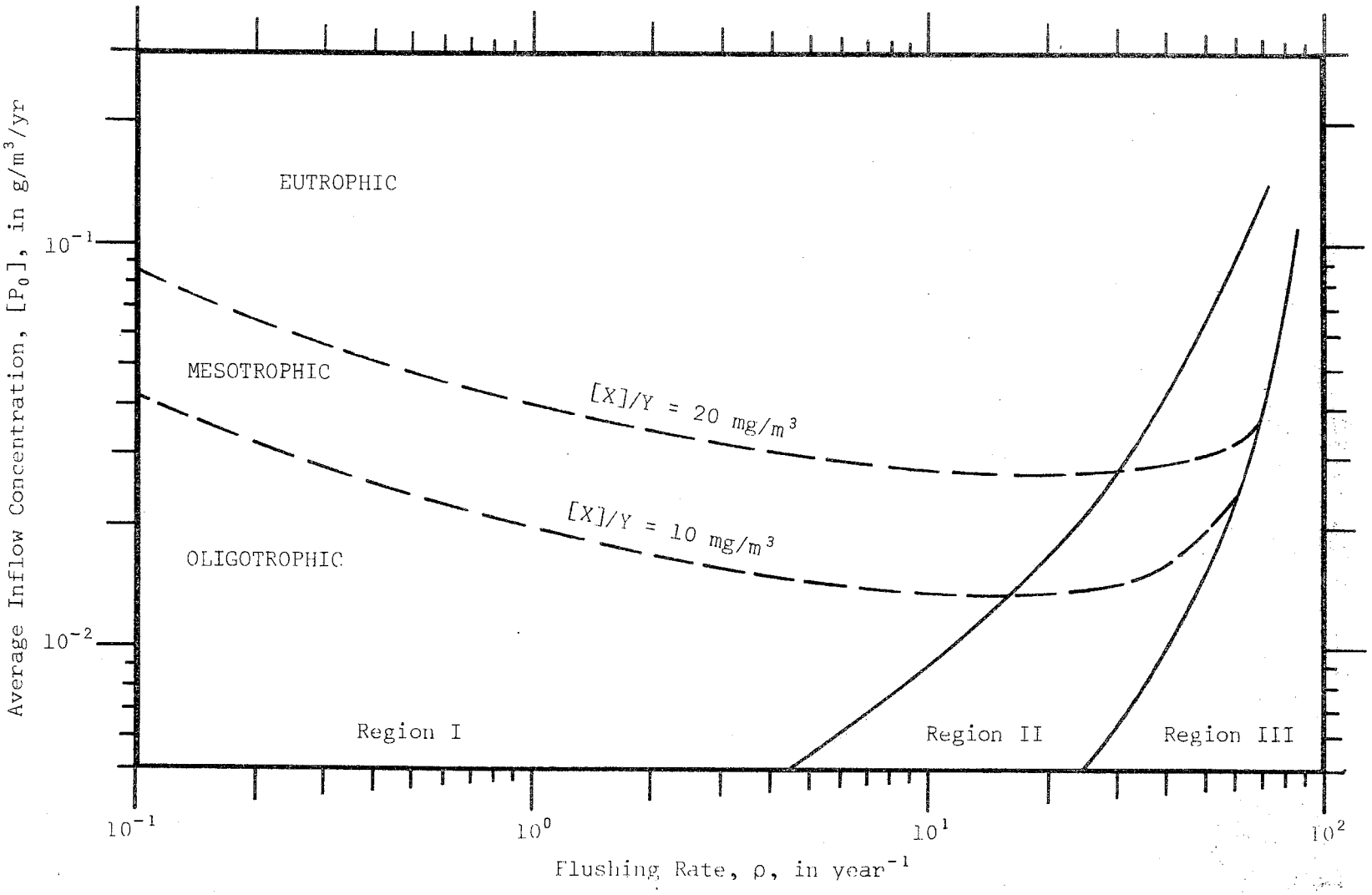

Fig. 7: Comparison of Biologically Bound Phosphorus as given by the Biomass Model, to Total Phosphorus as Defined by the Model Reported by Vollenweider (1976)

SECTION III

APPLICABILITY OF MODELS

The four models presented above are all of the same general form and are based on similar assumptions and approximations. They all include assumptions of steady-state and complete mixing, and are applicable to lakes only with respect to long-term average conditions, not short-term variations. The models have been "verified" only in the sense that if lake data are plotted as suggested in Figs.1-4 there tends to be a separation of lakes according to perceived trophic status-- eutrophic lakes are separated from those which are oligotrophic, and mesotrophic lakes blend in between. In all cases there are some lakes which do not plot according to the predicted pattern, but the models appear to yield reasonable results for most lakes.

When using these models as guides for lake restoration, it is assumed that differences in nutrient input which give rise to lakes of differing trophic status are also indicative of the change in trophic status a given lake will undergo if a comparable change in nutrient input is experienced. That is, for a lake with a given size, mean depth, and flushing rate, it is assumed that the models may be used to define the reduction in phosphorus influx necessary to reduce in-lake phosphorus concentrations to acceptable levels. The validity of this assumption has not been established, and examination of this hypothesis is one of the primary objectives of this report.

The applicability of the models to lake restoration activities is, of course, limited by the assumption of steady-state conditions. Transient conditions are not described, but the models may be useful in describing "before" and "after" conditions for some techniques. For discussion purposes, it is convenient to express the model equations by the general form

$$\begin{matrix}\text{change in lake} \\ \text{trophic state}\end{matrix} = \begin{matrix}\text{external} \\ \text{loading}\end{matrix} \pm \begin{matrix}\text{internal} \\ \text{recycling}\end{matrix} - \text{outflow} \qquad (19)$$

Similarly, lake restoration techniques can be divided into three general groups (see Table 2), each represented by one of the three terms in the trophic state equation.

The first group of restoration techniques is designed to improve water

Table 2: LAKE RENEWAL TECHNIQUES

1. Techniques to Reduce Nutrient Inflow

   a) Wastewater treatment
   b) Wastewater/stormwater diversion
   c) Land treatments (primarily agricultural)
   d) Treatment of inflow
   e) Product modification (i.e., detergents)

2. Techniques to Disrupt Internal Nutrient Cycles

   a) Dredging
   b) Destratification/aeration
   c) Hypolimnetic aeration
   d) Nutrient inactivation/precipitation
   e) Bottom sealing

3. Techniques to Accelerate Nutrient Outflow

   a) Biotic harvesting
   b) Selective discharge
   c) Dilution/flushing

quality in lakes by reducing nutrient influx. This reduction may be accompanied by significant changes in water inflow (stormwater diversions), or the water flow may not be greatly affected (advanced wastewater treatment). In general, the input/output models are suitable for evaluating techniques of this type, and it is not necessary to deal with each technique separately-- they may be treated as a single group, since they have the common effect of reducing external loadings. More complete treatment of this topic can be found in SECTION IV.

Techniques in the second group are intended to accomplish water quality improvements by disrupting the internal movement or recycling of nutrients within lakes. The ultimate objective is to restrict the nutrient supply to epilimnetic waters during the growing season, but this is usually accomplished indirectly as a result of altering in-lake conditions. For example, hypolimnetic aeration may reduce the transport of nutrients from sediments to overlying waters by maintaining aerobic conditions in the bottom waters; however, the resulting effect on the nutrient content of surface waters cannot be quantified readily because internal transport processes are poorly understood. Likewise, dredging may reduce internal cycling by removing nutrient-rich sediments and exposing sediments containing fewer nutrients, but the overall effect on a lake's nutrient budget cannot be quantified adequately at present.

Because of difficulties in quantifying the effects of restoration techniques which disrupt nutrient cycling, it does not appear that the input/output models cited above will be particularly useful for assessing or predicting lake trophic changes resulting from this particular group of restoration techniques. Although the models include a provision for an in-lake phosphorus reaction, they account for cycling only in a gross sense by assuming a net annual loss to the sediments-- seasonal changes are not addressed. However, by specifying how the net annual phosphorus loss is altered, this group of restoration techniques can be qualitatively evaluated by input/output models. If it is assumed that the sedimentation rate can be increased by a factor "a" (where "a" is greater than unity), then a new steady-state phosphorus concentration, [P]', can be defined by

$$[P]' = [P_0]\frac{\rho}{a\sigma + \rho} \tag{20}$$

Also, assuming that the sedimentation rate is a function of flushing rate after Vollenweider (1976) and Larsen and Mercier (1976), the modified in-lake phosphorus concentration can be compared to concentrations before, and it can be shown that

$$\frac{[P]'}{[P]} = \frac{1 + \sqrt{\rho}}{a + \sqrt{\rho}} \tag{21}$$

The ratio of "before" and "after" phosphorus concentrations provides a measure of the relative reduction in lake trophic state that can be anticipated from restoration techniques which disrupt internal nutrient cycling. Fig.8 is a plot of relative reduction versus flushing rate for selected values of "a". It can be seen that, in theory, increased sedimentation rates produce the greatest relative reductions at low flushing rates, and have the least effect at high flushing rates. This occurs because, when the flushing rate is low, the primary loss of phosphorus is through sedimentation-- phosphorus loss through outflow is minimal. Therefore, an increase in the sedimentation rate affects the dominant mode of phosphorus loss and has a major impact on in-lake concentrations. Conversely, for lakes with high flushing rates the major phosphorus loss is through outflow, and changes in sedimentation have a minimal effect on the overall phosphorus balance. For example, the theory indicates that a doubling of sedimentation rate will decrease in-lake phosphorus concentrations by nearly 50% at a flushing rate of $.01yr^{-1}$, and by less than 10% at a flushing rate of $100yr^{-1}$. Reductions on the order of 20-40% are estimated for most flushing rates commonly encountered, provided that a doubled sedimentation rate could be maintained an an annual basis.

In-lake nutrient reduction on the order discussed above may or may not be significant, depending upon specific restoration objectives. Often in-lake concentrations of 10 or $20mg/m^3$ are used as target values for restoration efforts, and it is interesting to note how lines representing these "permissible" and "critical" concentrations are repositioned on a plot of input concentration versus flushing rate, when the sedimentation rate is doubled but the other parameters remain unchanged. The dashed lines in Fig.9 are plots of Eq.(20) where in-lake phosphorus concentrations are constant at 10 and $20mg/m^3$ and $a = 2.0$. The solid lines represent identical concentrations as predicted by the model of Vollenweider (1976). It can be seen that a doubling of the sedimentation rate results in an upward displacement of the lines, with the greatest change occurring at low flushing rates. Theoretically, for those situations in which a lake is represented by a point within the shaded zone of displacement, it would be possible to achieve the target concentration through the disruption of internal phosphorus cycles-- provided that this disruption has the net effect of doubling the sedimentation rate. If a lake point lies above the displaced lines, then a net effect in excess of a doubling would be required to achieve the target values.

Although it might be interesting to speculate on the values of "a" which would be associated with the various restoration techniques listed in Group 2 of Table 2, there presently is insufficient information available to permit the selection of appropriate values. In any event, the use of such values would probably have only limited practical value. Before an evaluation of Group 2 techniques can be accomplished with input/output models, the models will have to be reformulated to provide a more detailed accounting of internal phosphorus cycling. Some progress has been made in this direction by treating sedimentation and release from sediments as separate (but not totally independent) processes (Lorenzen,

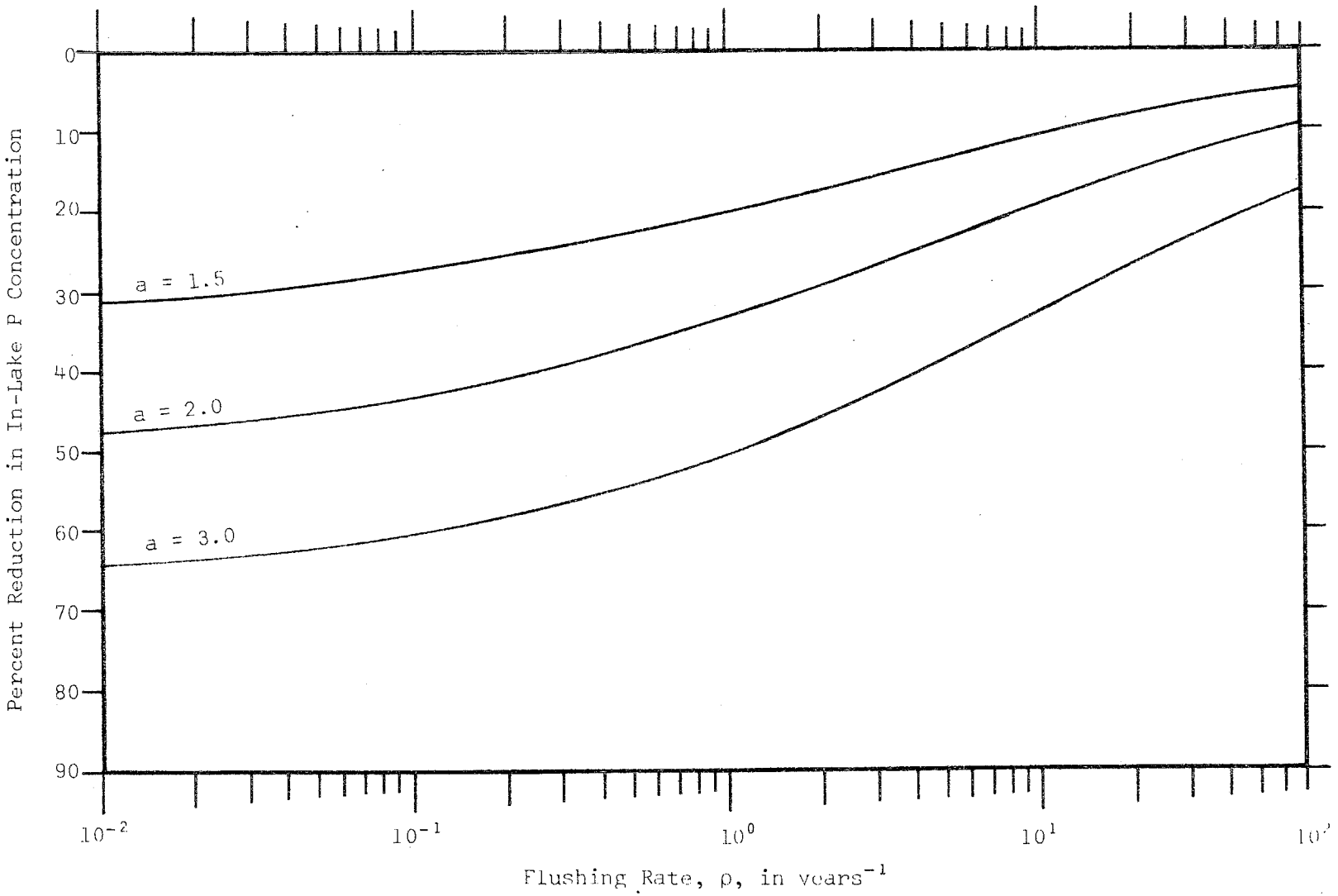

Fig. 8: Theoretical Reductions in In-Lake P Concentrations by Increasing Sedimentation by a Factor of "a"

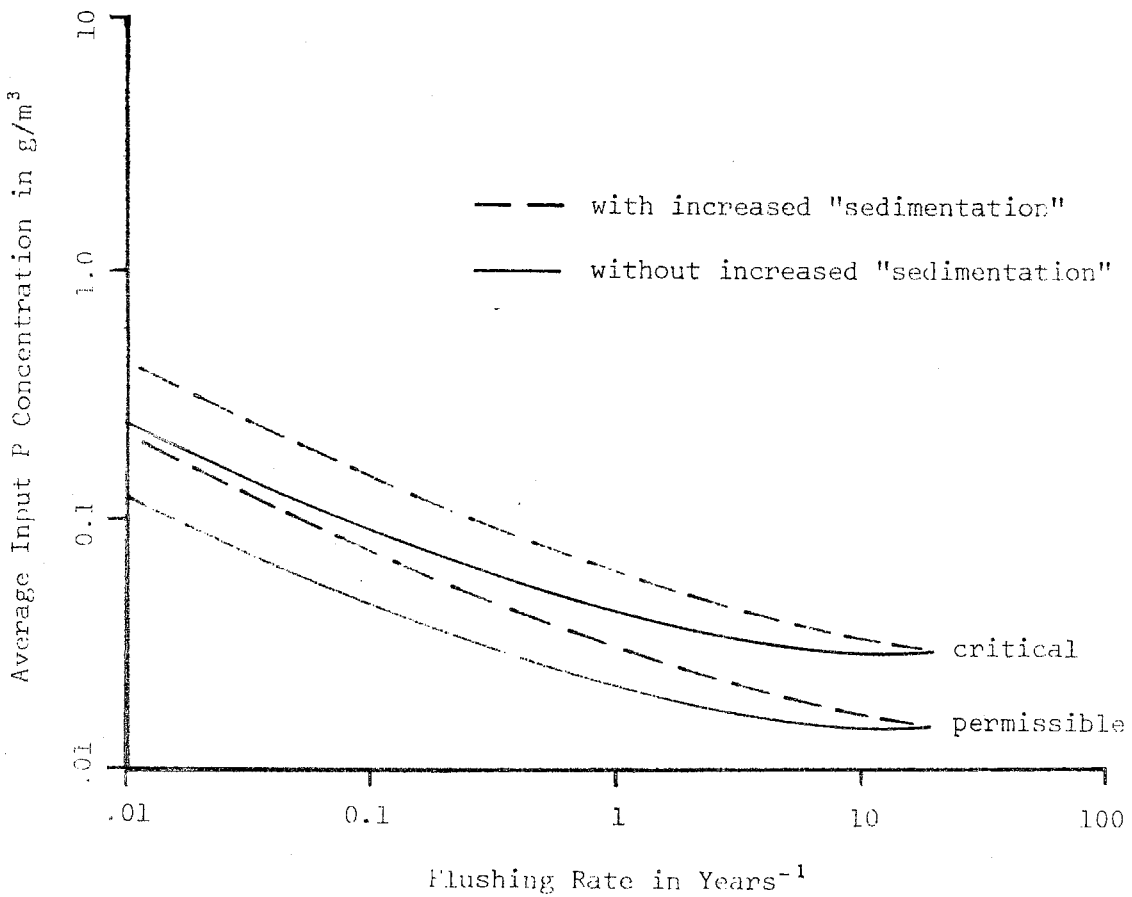

Fig. 9: Theoretical Effect of Increasing Sedimentation Rate by a Factor of Two

1973), but further work is needed, particularly relating to internal transport processes. Also, restoration criteria applicable to destratification techniques have been reported by Lorenzen and Fast (1977); however, these criteria are based on considerations of light limitation rather than phosphorus availability.

The third group of restoration techniques deals with the accelerated outflow of nutrients. Included are such diverse methods as selective discharge, dilution/flushing, and biomass harvesting. With all techniques, the objective is to artificially force nutrients to leave the lake at a rate greater than that which would occur naturally. However, the nutrient pathways differ considerably among the various techniques, and therefore the models are more applicable to some techniques than to others.

In all of the models, phosphorus outflow is coupled with the discharge of water (i.e., rate of phosphorus outflow is represented by the product of the volumetric flow rate and the average in-lake phosphorus concentration). This makes the models readily applicable for assessing long-term dilution/flushing as a renewal technique, since for this approach restoration is undertaken by increasing the removal of phosphorus through the outlet with water as the carrier, and by decreasing the input phosphorus concentration. Because significant quantities of nutrient-poor water are needed to augment the normal inflow, this technique probably is applicable in only a very limited number of situations; however, it could be used to advantage when adequate supplies of supplemental water are available.

If the inflow to a lake is supplemented with water from an auxiliary source which has a low (but not zero) phosphorus content, then the following changes are imposed on the system:

1. the areal and volumetric phosphorus loading are increased;

2. the average phosphorus concentration in the inflowing waters is decreased;

3. the flushing rate is increased.

As a corollary to item 3, it might be expected that the percentage of incoming phosphorus retained within the lake would decrease because, as shown by Vollenweider (1976) and Larsen and Mercier (1975), the specific sedimentation rate (and therefore the phosphorus retention coefficient) is inversely related to flushing rate. Thus, the effect of dilution on in-lake phosphorus concentration is complex and may be influenced by potentially offsetting factors: a reduction in the influent concentration tends to reduce in-lake concentrations, but a reduction in phosphorus retention tends to increase in-lake concentrations. Some interesting results are obtained when input/output models are used to describe the net effect of the countervailing factors.

An expression relating average influent concentration and flushing rate to in-lake concentration can be developed from Eq.(12):

$$[P] = [P_0]\frac{\rho}{\rho + \sqrt{\rho}} \tag{12a}$$

Then, based on this equation, an expression may be derived which compares predicted in-lake concentrations following dilution, [P]', to those which existed before supplemental waters were added, such that

$$\frac{[P]'}{[P]} = \left[1 + \frac{\rho_2[P_0]_2}{\rho_1[P_0]_1}\right]\left[\frac{\rho_1 + \sqrt{\rho_1}}{\rho_1 + \rho_2 + \sqrt{\rho_1 + \rho_2}}\right] \tag{22}$$

where the subscript 1 refers to conditions prior to dilution and the subscript 2 refers to the supplemental flow

Given the quantity of supplementary water available and its average phosphorus concentration, Eq.(22) may be solved to yield the relative change in in-lake phosphorus concentration that might be expected due to the addition of dilution waters. Two special cases based on this equation are shown in Figs.10 and 11.

Fig.10 gives the theoretical percent reduction in phosphorus concentration that can be accomplished with differing flows of supplementary water with the assumption that this water contains no phosphorus. The normal flushing rate without dilution is given on the abscissa, and the lines on the plot represent flushing rates due to the supplemental flow only, expressed as a constant portion of the normal, undiluted flow. For example, given a normal flushing rate of $1.0yr^{-1}$, and a supplemental flow equal to one-half the normal flow (i.e. $\rho_2 = 0.5\rho_1$), it is theoretically possible to achieve a 27% reduction in the in-lake phosphorus concentration. If a 60% reduction were desired, then, as taken from the plot, a supplemental flow somewhat in excess of twice the undiluted flow would be required. It is clear from this plot that, even when the supplemental flow is void of phosphorus, large quantities of dilution water are necessary to have a significant impact on in-lake concentrations.

If large volumes of dilution water are necessary, it is perhaps more realistic to examine the situation in which the supplemental flow contains some phosphorus; a concentration equal to 40% of the normal, undiluted flow was selected for purposes of illustration as shown in Fig.11. This family of curves is remarkably different from those in Fig.10. First, it may be noted that progressively larger quantities of dilution water do not necessarily produce progressively greater reductions of in-lake phosphorus concentrations. Also, for a given specific flushing rate before dilution, a theoretical value for the best

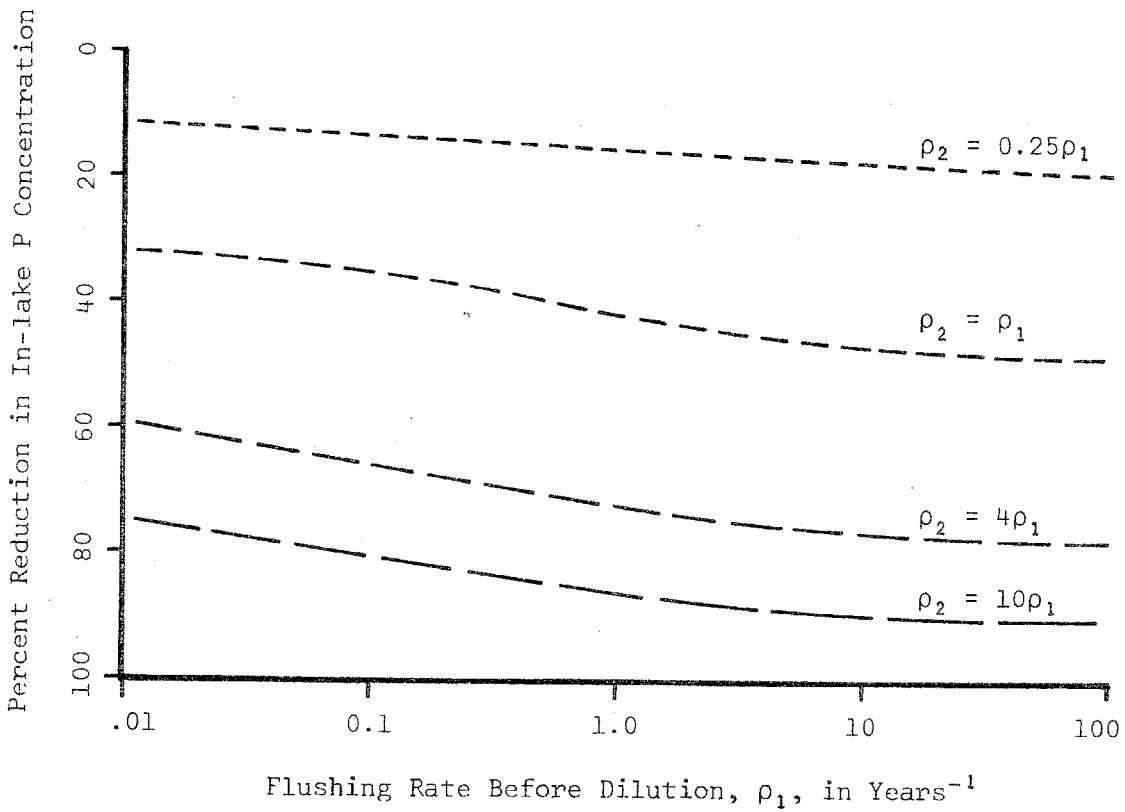

Fig. 10: Theoretical Effect of Dilution When Supplementary Waters Contain No Phosphorus

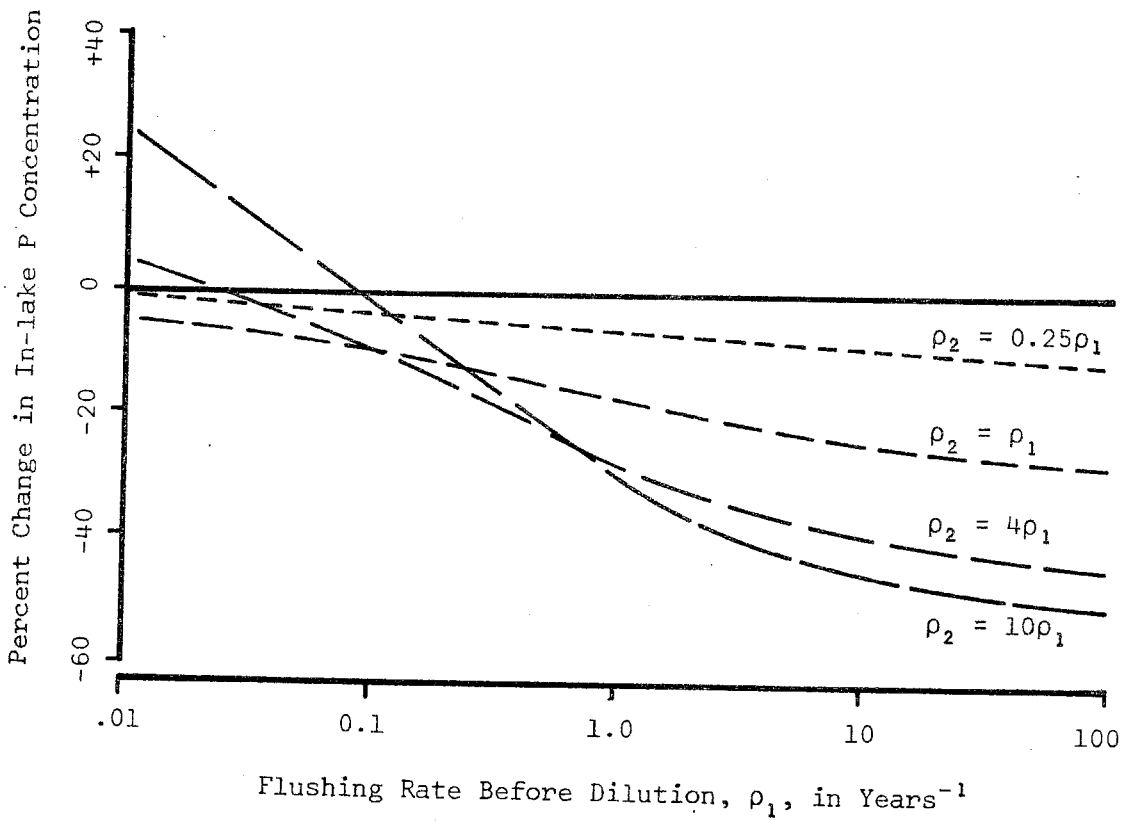

Fig. 11: Theoretical Effect of Dilution When the Phosphorus Concentration in Supplementary Water is 40% of Normal Inflow Concentration

possible relative reduction can be defined. For example, if the original flushing rate for a lake is 1 yr^{-1}, a 30% reduction in in-lake phosphorus concentrations is, theoretically, the best one could achieve even with unlimited quantities of dilution water. The maximum relative reduction is nearly achieved when the supplemental flow is four times the volume of the original inflow, and additional dilution has virtually no effect. If a relative reduction in excess of 30% is deemed necessary to produce significant improvement in water quality, then dilution would not be a viable lake restoration technique.

Secondly, it is theoretically possible to increase in-lake phosphorus concentrations by adding phosphorus-poor dilution waters as indicated in the upper left of Fig.11. Based on the models, at low original flushing rates, lake responses will be influenced more by increases in loading rate than by decreases in input concentrations, and dilution could be a counter-productive restoration technique. At high original flushing rates, input concentrations would be of greater importance, but large volumes of supplemental water may be necessary to produce significant changes. For intermediate ranges of flushing rate, both parameters play important roles, and successful restoration would depend on effective coupling of reduced input concentrations and increased flushing rates to optimize reductions in in-lake phosphorus concentration.

This discussion is not intended to suggest that input/output models can be used to predict phosphorus reductions to within a few percent when dilution waters are added to lakes. That is not the case. However, the models do provide a basis for considering changes in several parameters simultaneously, and it is felt that the general trends defined by the models are realistic. Lakes with low flushing rates are identified as the worst candidates for improvement by dilution, and unless the supplemental water is virtually void of phosphorus, in-lake concentrations could very well increase rather than decrease as a result of dilution. Also, given a specific dilution water, a point of maximum nutrient reduction may exist for which both greater and lesser quantities of dilution water may cause lesser reductions in in-lake phosphorus concentrations.

In the above discussion, the effect of flushing rate on phosphorus retention was taken into account, but possibilities of cellular washout were not considered. However, for lake conditions represented by Regions II and III in Fig.7, the biomass model could be used to estimate the effects of washout associated with dilution/flushing experiences.

While the models appear to be reasonably well-suited for assessing dilution/flushing as a restoration method, they apply less well to other techniques in Group 3 because of the model requirement that nutrient outflow and hydraulic discharge be coupled. Thus the models are not suitable for evaluating procedures (such as harvesting) in which the nutrient "outflow" is independent of the hydraulic flow rate. Selective discharge represents an intermediate situation in which the models may be used qualitatively in a manner similar to the analysis described above

for techniques designed to disrupt internal nutrient cycling.

Selective discharge is based on the presence of nutrient stratification within lakes, and the management strategy is to discharge water from the zone of highest nutrient content. While water is still the nutrient carrier, the discharge concentration is not represented by the average in-lake concentration as described by the models. However, the effectiveness of selective discharge as a lake restoration technique can be evaluated qualitatively by the models by assuming that the outflow phosphorus concentration is some multiple of the average concentration in the lake. This relationship can be expressed as

$$[P]_{outflow} = b[P]_{in\text{-}lake} \tag{23}$$

where b = a constant > 1.0

A nutrient loading/lake trophic state relationship can be derived such that

$$[P]' = [P_0]\frac{\rho}{\sigma + b\rho} \tag{24}$$

where $[P]'$ = the modified in-lake phosphorus concentration which results from selective discharge

Again, assuming that the sedimentation rate is a function of flushing rate as described by Vollenweider (1976) and Larsen and Mercier (1976), the in-lake phosphorus concentrations after selective discharge can be compared to unaltered concentrations, and it can be shown that

$$\frac{[P]'}{[P]} = \frac{1 + \sqrt{\rho}}{1 + b\sqrt{\rho}} \tag{25}$$

The ratio of the "before" and "after" in-lake phosphorus concentrations is an approximation of the relative reduction in nutrient concentration that could be anticipated due to selective discharge. In Fig.12, relative reduction has been plotted as a function of flushing rate for three values of b-- 1.5, 2.0, and 3.0-- which probably span the range of effectiveness of selective discharge for most lakes. It can be seen that selective discharge is predicted to have the greatest effect on lakes with high flushing rates, and the least for lakes with low flushing rates. For example, if a discharge concentration can be maintained at a level twice the in-lake concentration ($b = 2.0$), the in-lake phosphorus con-

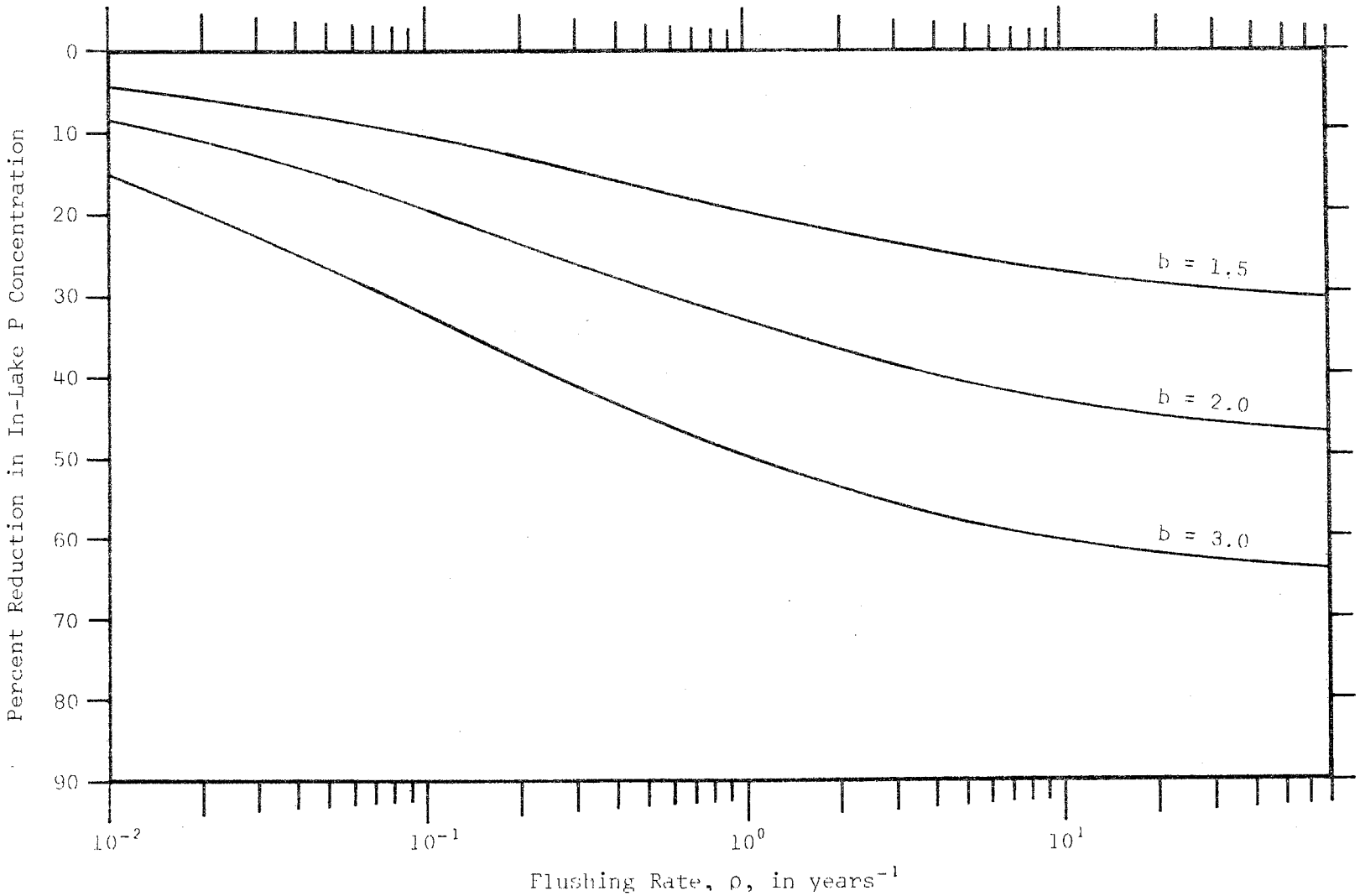

Fig. 12: Theoretical Reductions in In-Lake P Concentrations by Increasing Nutrient Outflow by a Factor of "b"

centration is predicted to decrease by about 10% at the lower flushing rates and by about 45% at high flushing rates. Reductions of approximately 20 to 40% are estimated for flushing rates in the range from 0.1 to $10yr^{-1}$, which would include most lakes.

Figure 13 illustrates the extent to which in-lake phosphorus concentrations could theoretically be altered if the discharge concentration could be maintained at a level twice the average for the lake. For convenience, only lines of 10 and $10/mg/m^3$ are shown. The solid lines are based on Eq.(12) (Vollenweider, 1976), and the dashed lines represent the condition in which the output concentration is doubled, i.e. b = 2.0. It may be seen that these "lines" of "acceptable" and "excessive" concentrations are displaced upward, with the greatest change occurring at high flushing rates. The area between the dashed and solid lines includes all combinations of input concentration and flushing rate for which in-lake concentrations of 10 and $20mg/m^3$ could theoretically be achieved by a doubling of the discharge concentration.

This analysis can only be expected to give a rough approximation of the impact of selective discharge as a tool for reducing phosphorus concentrations in lakes. However, it is suggested that lakes with high flushing rates have the best potential for improvement via this approach, and unless the average annual discharge concentration can be maintained at levels in excess of twice the average for the lake, reductions in in-lake concentrations on the order of 20-40% are about the maximum that could be expected.

In summary, it appears that the models are potentially useful as decision-making tools when the restoration approach is aimed at reducing the input of phosphorus to lakes from external sources. Also, the models handle some approaches to accelerating phosphorus outflow reasonably well and may provide useful guides. When the restoration approach involves manipulation of conditions within the lake proper to disrupt internal nutrient cycles, input/output models are likely to be of only minimal value, and other types of models are needed.

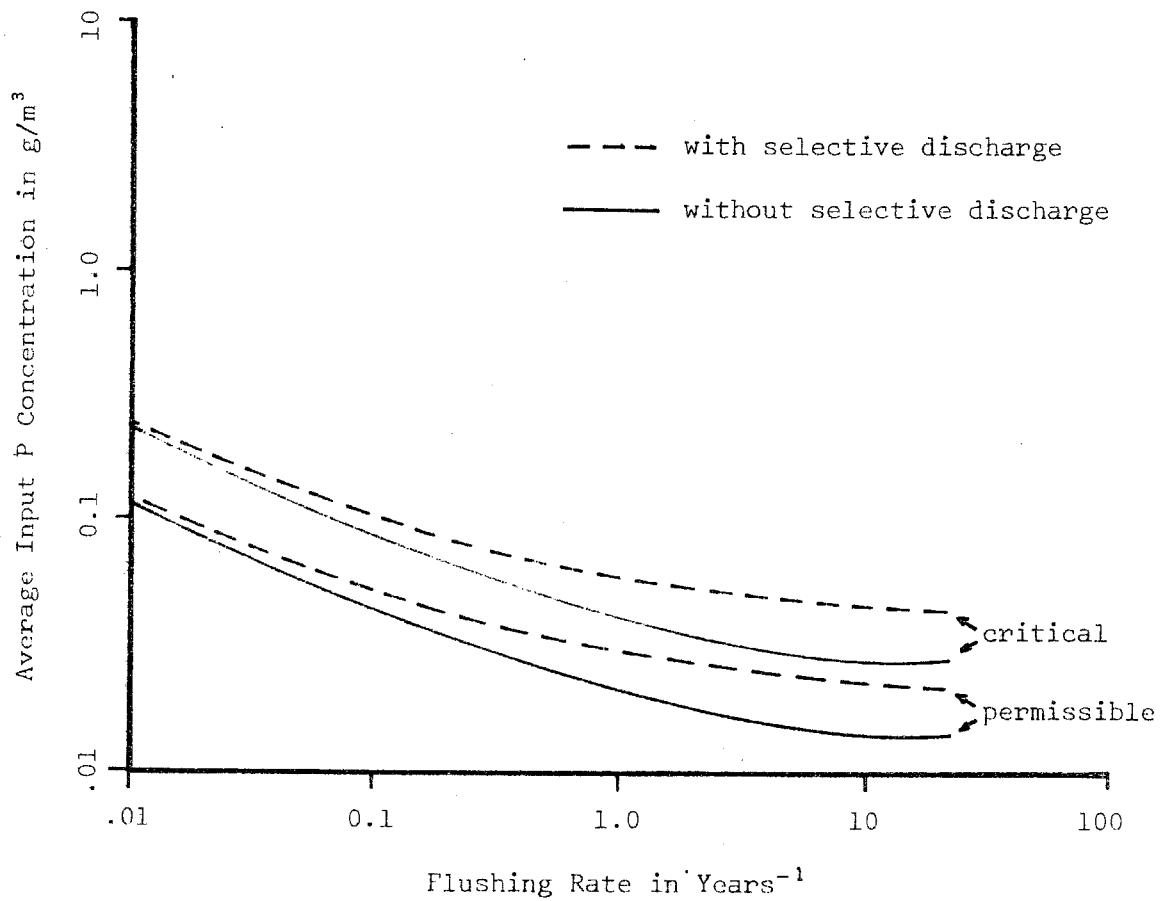

Fig. 13: Theoretical Effect of Selective Discharge if P Concentration in Outflow is Twice the Average Concentration in the Lake

SECTION IV

DATA COMPILATION AND MODEL COMPARISON

One of the major difficulties associated with the development of criteria for lake restoration is the lack of comparable data on which to base judgment. Although the input/output models cited above are judged to provide a potentially useful frame of reference for comparing and quantifying some types of lake renewal results, the data necessary for verification are not readily available. In an attempt to offset this difficulty, data compilation was undertaken as an integral part of this project. This was accomplished by personal communication with scientists and managers located throughout the United States, Canada, and several European countries.

A list of potential data sources was developed based primarily on the summary of lake renewal experiences reported by Dunst *et al.* (1974). Letters were written to 34 investigators in 13 countries, and data were requested regarding a total of 52 lakes where reductions in nutrient loading were reported to have occurred, or would be occurring within the near future (since 1974). To maximize returns, only minimal data were requested; however, care was taken to ensure that the data obtained would be sufficient for the construction of nutrient loading/lake trophic state plots after Vollenweider (1975, 1976) and Dillon and Rigler (1974). Data describing conditions both before and after restoration were requested.

A total of 22 replies were received regarding 43 lakes. Three additional data sets were generated from known sources. Unfortunately, not all responses yielded usable data. Several projects had not proceeded at the rate reported earlier, and were still in the planning stages. For others, nutrient reductions were so recent that "after" data had not yet been compiled. In one case, "after" data was available, but "before" data was missing. Also, data had not been collected for some lakes even though nutrient reductions had occurred. Thus, though data were compiled for 46 lakes, a number of these sets were incomplete and were not sufficient to permit all the planned analyses. Table 3 gives the number of data sets which were adequate for the desired usages, and a summary of tabulated data is listed in Appendix 2.

In addition to the data necessary for the input/output models, information was requested to permit the calculation of a Lake Condition Index (LCI) as reported by Uttormark and Wall (1975), and a Trophic State Index (TSI) as suggested by Carlson (1977). These systems were devised to provide a quantitative measure of "trophic status" and, importantly, to treat trophic state as a continuum rather than as three separate categories-- oligotrophic,

Table 3: SUMMARY OF DATA AVAILABILITY, GIVING THE NUMBER OF LAKES FOR WHICH DATA WERE COMPILED

Model or Usage	Time Relative to Input Reduction		
	-before-	-after-	-both-
Dillon *et al.* (1974)	18	11	10
Vollenweider (1975)	39	24	23
Vollenweider (1976)	39	24	23
Biomass Model	39	24	23
Trophic Status Index	30	20	19
Lake Condition Index	24	14	13

mesotrophic, and eutrophic. It was felt that this latter aspect might be helpful in defining water quality improvements in lakes when the basic trophic character remained unchanged. Even though a lake may be considered "eutrophic" both before and after renovation, water quality improvements could accrue, and it would be useful to have some measure of the change.

It should be noted that the trophic indicators cited above were selected primarily because of their simplicity-- the TSI is based solely on Secchi depth data, and the LCI incorporates hypolimnetic oxygen conditions and severity of algal or macrophyte growth along with Secchi depth-- and their use is not meant to imply that they are generally accepted techniques, or that they may be applied universally to lakes. However, both of these indices have been shown to be useful in some situations, and a generally accepted, universally applicable index does not presently exist. Also, there are no standard definitions for the terms "eutrophic", "mesotrophic", and "oligotrophic", and their usage does not convey the same information to all persons. Nevertheless it was necessary to use this terminology, and the reader is referred to Appendix 2 for a listing of the trophic categories assigned to each of the lakes in the data set for both "before" and "after" conditions. The categories listed are based on published trophic descriptions for most lakes. When published descriptions were lacking, a selection was made based on the data compiled as part of this effort.

Nutrient loading data compiled during this project are used to compare predictive capabilities of nutrient loading/lake trophic state relationships developed by Dillon and Rigler, Vollenweider, and this project. Specifically, the data were plotted using graphical techniques suggested by the respective authors. On all plots, closed circles represent lake conditions prior to reduction in nutrient input; open circles are indicative of conditions after reduction had taken place. When both "before" and "after" data could be plotted, the points are connected. The letters "O", "M", and "E" adjacent to data points represent oligo-, meso-, and eu-trophic lake conditions as reported.

Figure 14 is a plot of the lake restoration data using the graphical technique suggested by Dillon and Rigler (1974). In this case only 10 complete data sets (both "before" and "after") could be plotted, because measured values for the phosphorus retention coefficient, R, often were lacking. Since an objective of this analysis is to evaluate the usefulness of input/output models as predictive tools for estimating "after" conditions based on "before" data, only values of R determined prior to restoration were used in plotting the data. (Measured values of R determined both before and after reductions in phosphorus influx were available for only six lakes. Of these, five showed a reduction and one was found to increase.)

Of the 10 data sets plotted in Fig.14 which depict lakes which experienced reductions in phosphorus input, seven are judged to be described "accurately" by the model. All of the seven were eutrophic initially; four had insufficient reductions to induce significant changes, and three had major reductions which caused the lakes to approach oligotrophic conditions. The remaining three lakes-- Shagawa, Gjersjøen, and Sammamish-- had sufficient

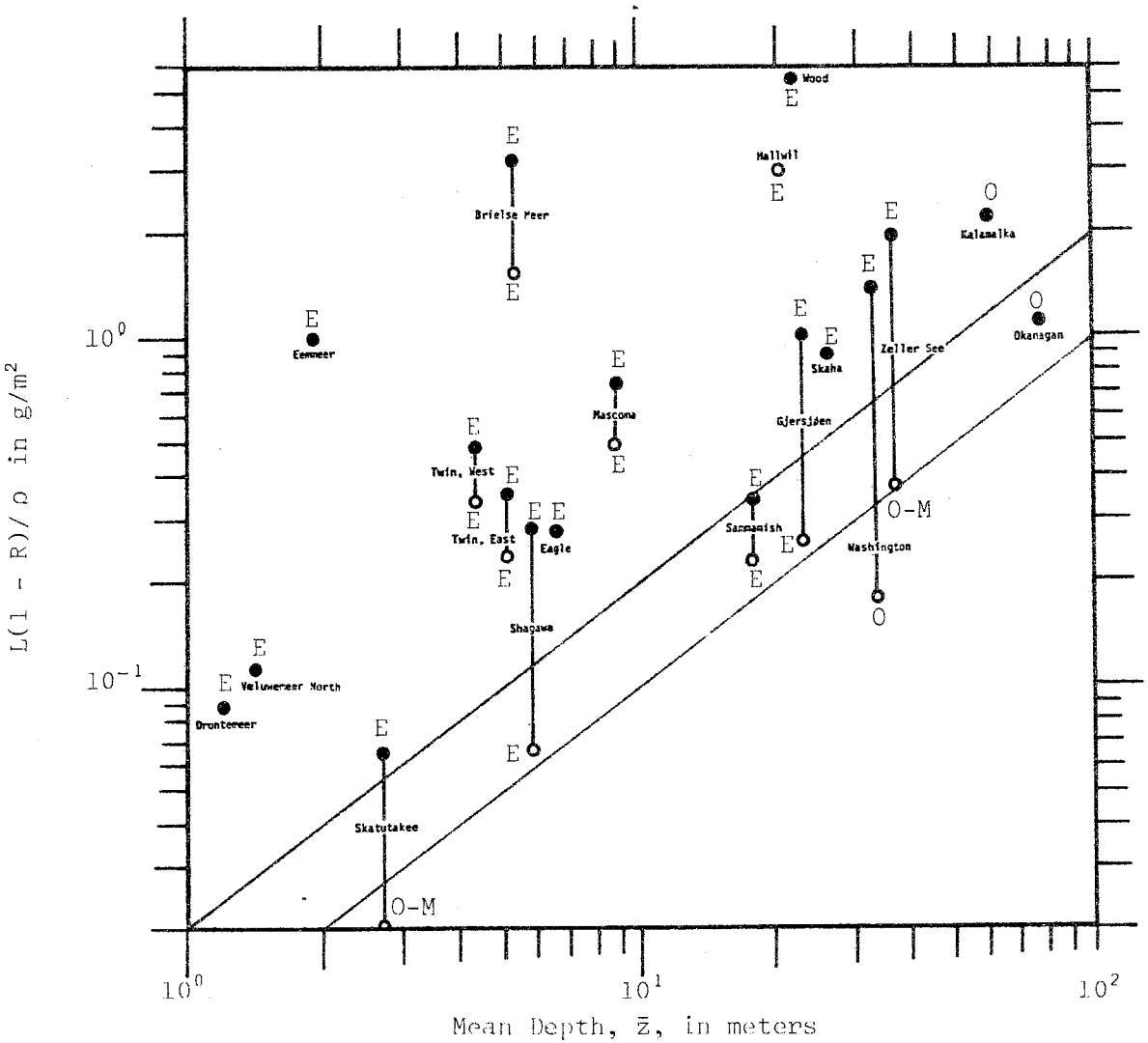

Fig. 14: Trophic Status of Lakes after Nutrient Input Reduction as Predicted by the Model of Dillon and Rigler (1974)

loading reductions that, based on the model results, a change from eutrophic to mesotrophic would be expected. However, for practical purposes, trophic conditions remained unchanged.

Figure 15 is a similar plot using the graphical techniques described by Vollenweider (1975). Because it is not necessary to know specific retention coefficients in this instance, data could be plotted for 23 lakes which experienced nutrient reduction. Of these, 16 are judged to be accurately described by the model. All 16 were eutrophic initilly; 10 remained eutrophic, one became mesotrophic, and five reached oligotrophic conditions. For each of the 16 lakes, predicted trophic state and measured trophic state compared favorably both before and after restoration.

Results for the remaining seven lakes are somewhat varied. All seven were eutrophic initially; after nutrient reduction, oligotrophic conditions were predicted for three lakes (Shagawa, Stone, and Uttran), but each remained eutrophic; mesotrophic conditions were predicted for Washington but it became oligotrophic; and for three lakes nutrient reductions were small and eutrophic conditions were predicted to prevail, yet Worthersee and Ossiacher See became mesotrophic and Millstatter See is now considered oligotrophic. Thus the degree of improvement was underestimated in four instances, and overestimated in three.

A third graph, Fig.16, is plotted using the format suggested by Vollenweider (1976). Of the 23 lakes which could be plotted in this instance, 19 were judged to be described accurately by the model. Of these 19, 12 remained eutrophic, one became mesotrophic, and six approached oligotrophic conditions following restoration. The predicted trophic state failed to correspond to reported after-reduction conditions for only four lakes. Of these, Shagawa was predicted to become oligotrophic but remained eutrophic; no trophic change was predicted for Ossiacher See and Worthersee, yet both became mesotrophic; and mesotrophic conditions were anticipated for Millstatter See but oligotrophic conditions were observed.

Figure 17 is a plot using the graphical techniques developed by this study for describing the biomass model. As discussed previously, there are no significant differences in predictive capabilities between this model and that of Vollenweider (1976) unless flushing rate is high. With the exception of Vaseux Lake, which had not received a reduction in nutrient input, none of the lakes have high flushing rates; thus, trophic state predications using the biomass model are virtually identical to those in Fig.18 (Vollenweider, 1976) and consequently will not be discussed separately.

To facilitate cross-comparisons of model performance, the results depicted in Figs.14-17 are summarized in Table 4. (In this table, differences between predicted and reported results are highlighted by parentheses.) Overall, the models are judged to have performed very well-- both the biomass model and the model reported by Vollenweider (1976) yielded "accurate" results for 82% of the study lakes. The models of Dillon and Rigler (1974)

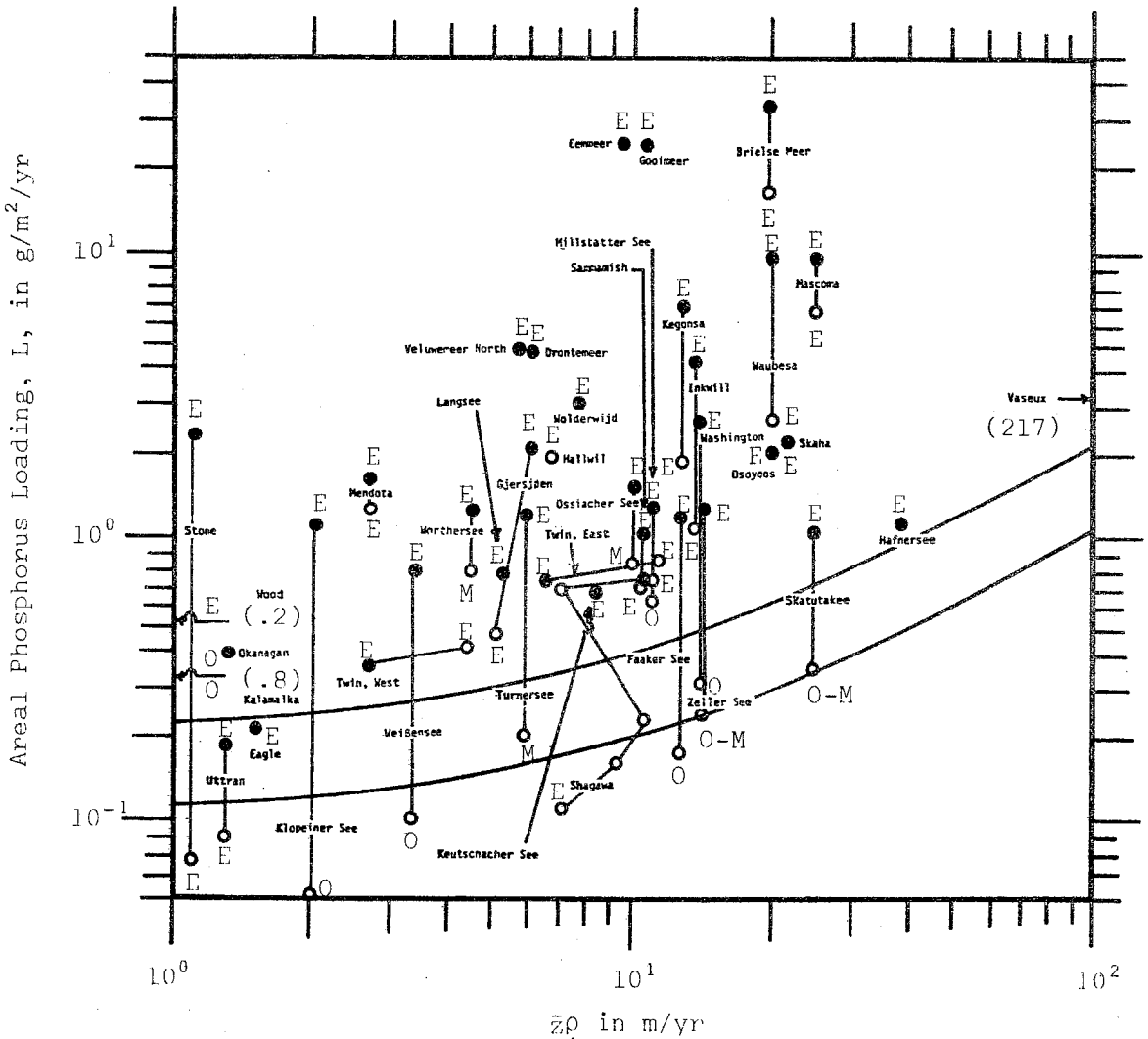

Fig. 15: Trophic Status of Lakes after Nutrient Input Reduction as Predicted by the Model of Vollenweider (1975)

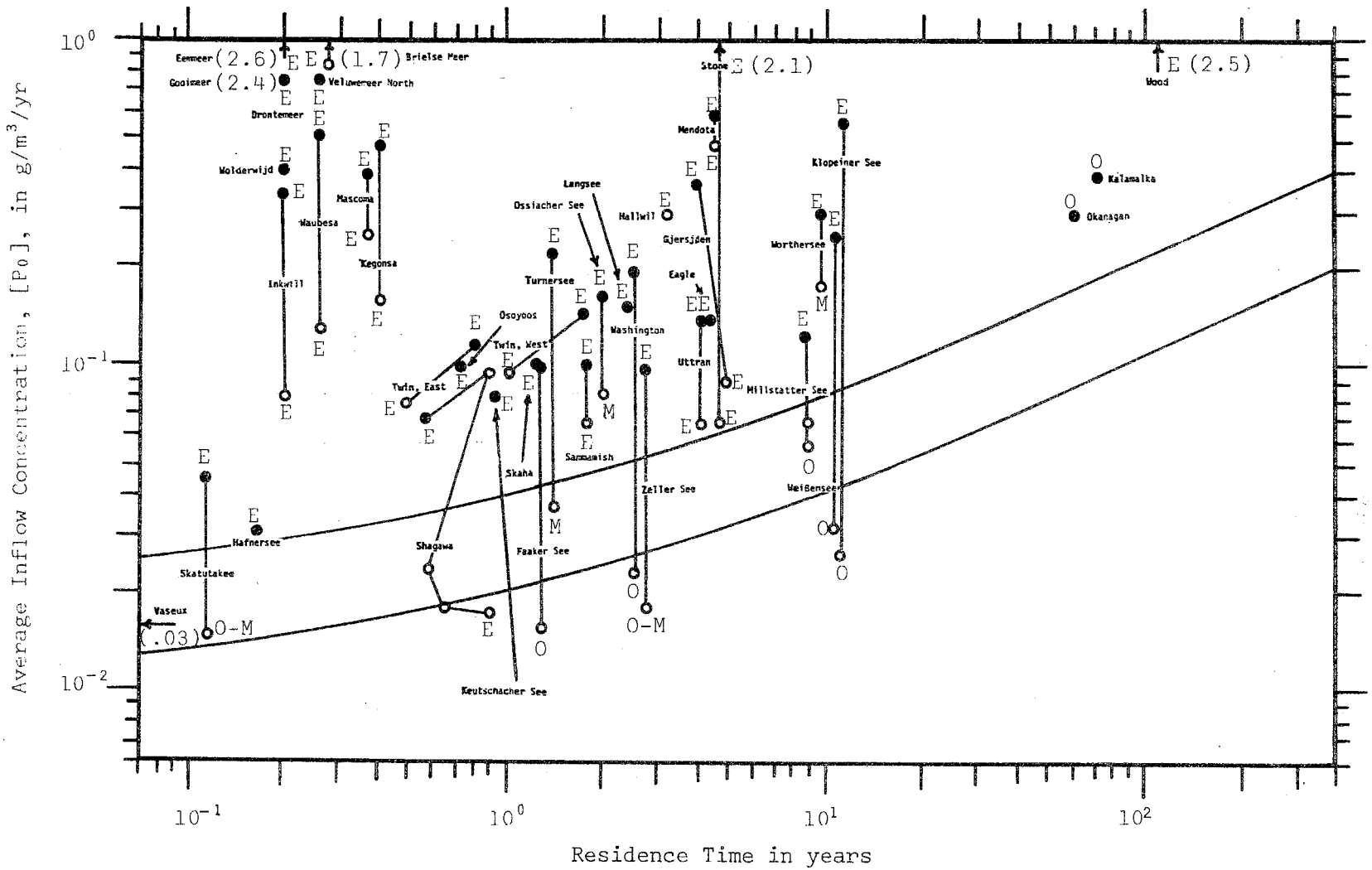

Fig. 16: Trophic Status of Lakes after Nutrient Input Reduction as Predicted by the Model of Vollenweider (1976)

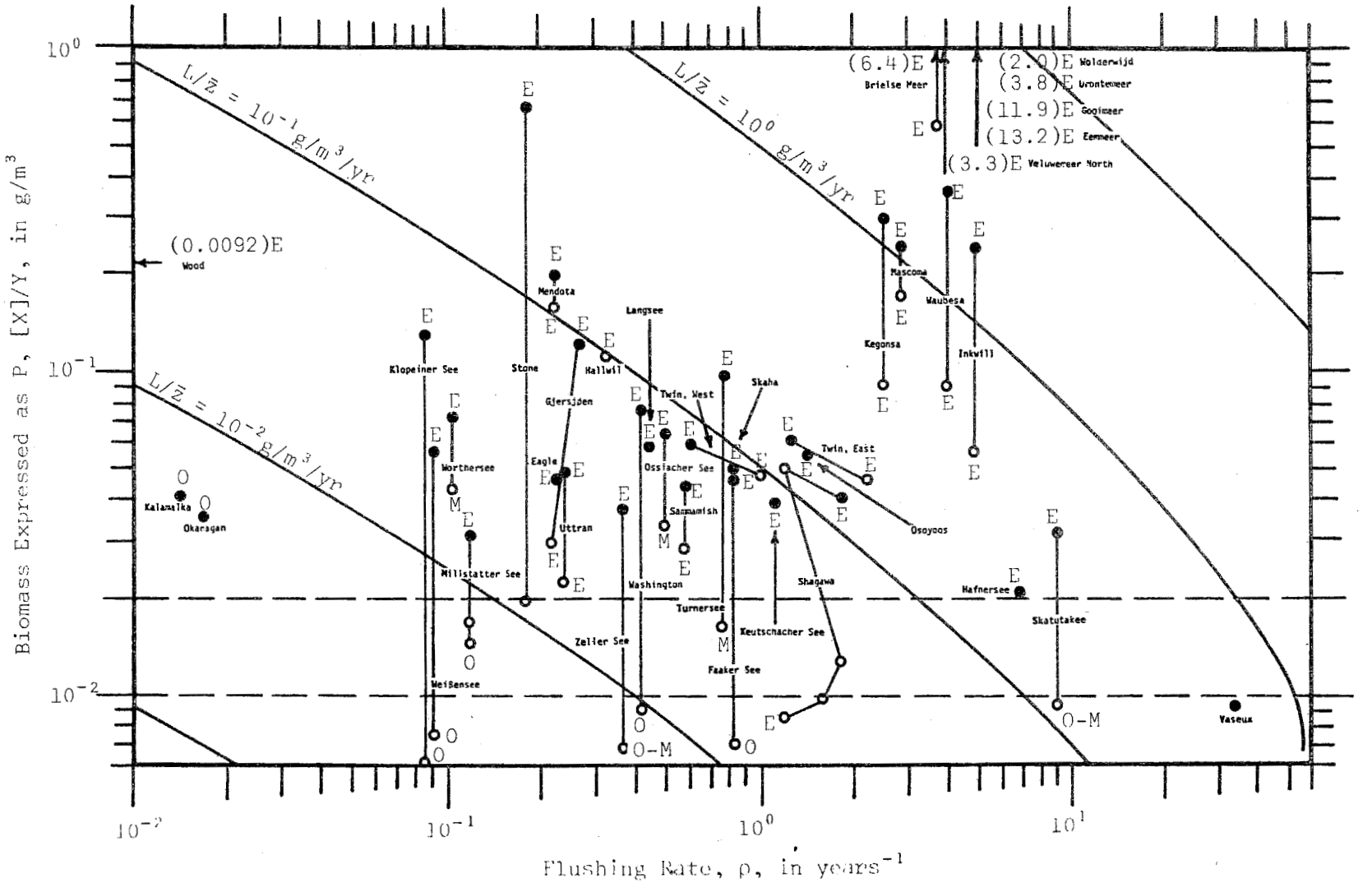

Fig. 17: Trophic Status of Lakes after Nutrient Input Reduction as Predicted by the Biomass Model

Table 4: COMPARISON OF MEASURED AND PREDICTED TROPHIC CONDITION OF LAKES FOR WHICH PHOSPHORUS INPUT WAS REDUCED

Lake Name	Trophic Condition Measured		Predicted* Model 1		Model 2		Model 3		Model 4	
	b	a	b	a	b	a	b	a	b	a
Brielse Meer	E	E	E	E	E	E	E	E	E	E
Faaker See	E	O	-	-	E	O-M	E	O	E	O
Gjersjøen	E	E	E	(M)	E	E	E	E	E	E
Inkwill	E	E	-	-	E	E	E	E	E	E
Kegonsa	E	E	-	-	E	E	E	E	E	E
Klopeiner See	E	O	-	-	E	O	E	O	E	O
Mascoma	E	E	E	E	E	E	E	E	E	E
Mendota	E	E	-	-	E	E	E	E	E	E
Millstatter See	E	O	-	-	E	(E)	E	(M)	E	(M)
Ossiacher See	E	M	-	-	E	(E)	E	(E)	E	(E)
Sammamish	E	E	E-M	(M)	E	E	E	E	E	E
Shagawa	E	E	E	(M)	E	(O)	E	(O)	E	(O)
Skatutakee	E	M-O	E	O	E	M-O	E	M-O	E	M-O
Stone	E	E	-	-	E	(O)	E	E-M	E	E-M
Twin, East	E	E	E	E	E	E	E	E	E	E
Twin, West	E	E	E	E	E	E	E	E	E	E
Turnersee	E	M	-	-	E	M	E	M	E	M
Uttran	E	E	-	-	(M)	(O)	E	E	E	E
Washington	E	O	E	O	E	(M)	E	O	E	O
Waubesa	E	E	-	-	E	E	E	E	E	E
Weißensee	E	O	-	-	E	O	E	O	E	O
Worthersee	E	M	-	-	E	(E)	E	(E)	E	(E)
Zeller See	E	M-O	E	M-O	E	M-O	E	O	E	O
Number of Lakes			10		23		23		23	
Number Accurate			7		16		19		19	
Percent Accurate			70		70		82		82	

*predictions based on
Model 1, Dillon and Rigler (1974)
Model 2, Vollenweider (1975)
Model 3, Vollenweider (1976)
Model 4, Equation (18)

and Vollenweider (1975) worked somewhat less well, but still were found to yield accurate results for 70% of the lakes tested. However, there were no instances in which lake changes described accurately by these two models were described inaccurately by either of the other two. It can also be seen from Table 4 that changes in four lakes-- Millstatter, Ossiacher, Shagawa, and Worthersee-- were not described accurately by any of the models tested. Improvement was underestimated for three of these lakes, which indicates that inaccuracies were not caused by delayed responses to the reduced loadings, but must be due to other factors not adequately handled by the models.

If model performance is based on all the lake data plotted in Figs.14-17, without regard to whether both "before" and "after" data were available, slightly different results are obtained as shown in Table 5. Again, the biomass model and the model reported by Vollenweider (1976) appear to perform slightly better than the other two; however, the performance of all four models was improved when comparisons were based on the expanded data base.

The foregoing evaluation of input/output models was based on the prerequisite condition that lakes can be separated neatly into the three trophic categories "eutrophic", "mesotrophic", and "oligotrophic". Unfortunately, these categories are not defined quantitatively, and their use involves subjective judgment. Furthermore, there is no basis for comparing the relative condition of lakes within these categories. Such information would be desirable for evaluating the overall usefulness of the models. In an attempt to offset these shortcomings and to provide a better perspective of input/output models as decision-making aids, additional analyses were undertaken using trophic state indicators as measures of lake condition. Only the model reported by Vollenweider (1976) was used in these analyses, but the same general conclusions would apply for the other models as well.

A meaningful and easily understood indicator of trophic state is water transparency as measured by a Secchi disc. Shapiro *et al.* (1975) emphasized the need for trophic indicators which are meaningful to the general public, and Carlson (1977) developed an empirical relationship by which total phosphorus concentrations (at time of spring overturn) could be expressed as an equivalent Secchi depth.

$$SD = \frac{64.9}{[P]} \qquad (26)$$

where SD = Secchi depth in meters
[P] = total phosphorus concentration in mg/m^3

This equation is used here as a basis for converting changes in phosphorus concentration (as predicted by the models) to an estimate of changes in Secchi depth, such that

Table 5: SUMMARY OF MODEL PERFORMANCE

Model	Number of Data Points	Number Accurate	Percent Accurate
Dillon & Rigler (1974)	29	24	83
Vollenweider (1975)	61	50	82
Vollenweider (1976)	61	55	90
Biomass (Equation 18)	61	55	90

$$\Delta SD = \left[\frac{[P_1] - [P_2]}{[P_1][P_2]}\right] 64.9 \qquad (27)$$

where the subscripts 1 and 2 refer to "before" and "after" values (mg/m^3) respectively

The predicted Secchi depth following restoration may then be expressed by

$$(SD_2)_{predicted} = (SD_1)_{measured} + \Delta SD \qquad (28)$$

This approach was used because it references predicted Secchi depths to known values which occurred prior to restoration, and because it provides a basis for comparing predicted and measured improvements in transparency as shown in Fig.18. In this graph, the average summer Secchi depth measured after restoration is plotted against the predicted Secchi depth as calculated from Eq.(28). The dashed line on the plot is the theoretical line of perfect agreement between the two values.

It may be seen from Fig.18 that two-thirds of the data points-- 13 of 19-- lie to the right of the dashed line, in the region where predicted improvements exceed measured values. Only six points lie to the left of the line, where improvements are underestimated, and three of these points represent Ossiacher See, Millstatter See, and Worthersee-- lakes which were judged to be handled inaccurately by the models. Based on this analysis it appears that the model yields an optimistic estimate of transparency improvements, and that improvements on the order of 50-80% of predicted values were realized for most lakes in the study set.

Secchi depth data may also be used to assess lake restoration by using the "trophic status index" (TSI) proposed by Carlson (1977), in which

$$TSI = 10[6 - \log_2(SD)] \qquad (29)$$

where SD = Secchi depth in meters

This logarithmic transformation results in a TSI increase of 10 units when the Secchi depth decreases by a factor of two. Corresponding values of Secchi depth and TSI are given in Table 6.

Figure 19 is a plot of TSI versus a normalized average input concentration, $[P]_n$, which is defined by

$$[P]_n = \frac{[P_0]}{[P_0]_{20}} \qquad \text{where } [P_0] \text{ and } [P_0]_{20} \text{ are given by Eqs.(12) and (13b) respectively} \qquad (30)$$

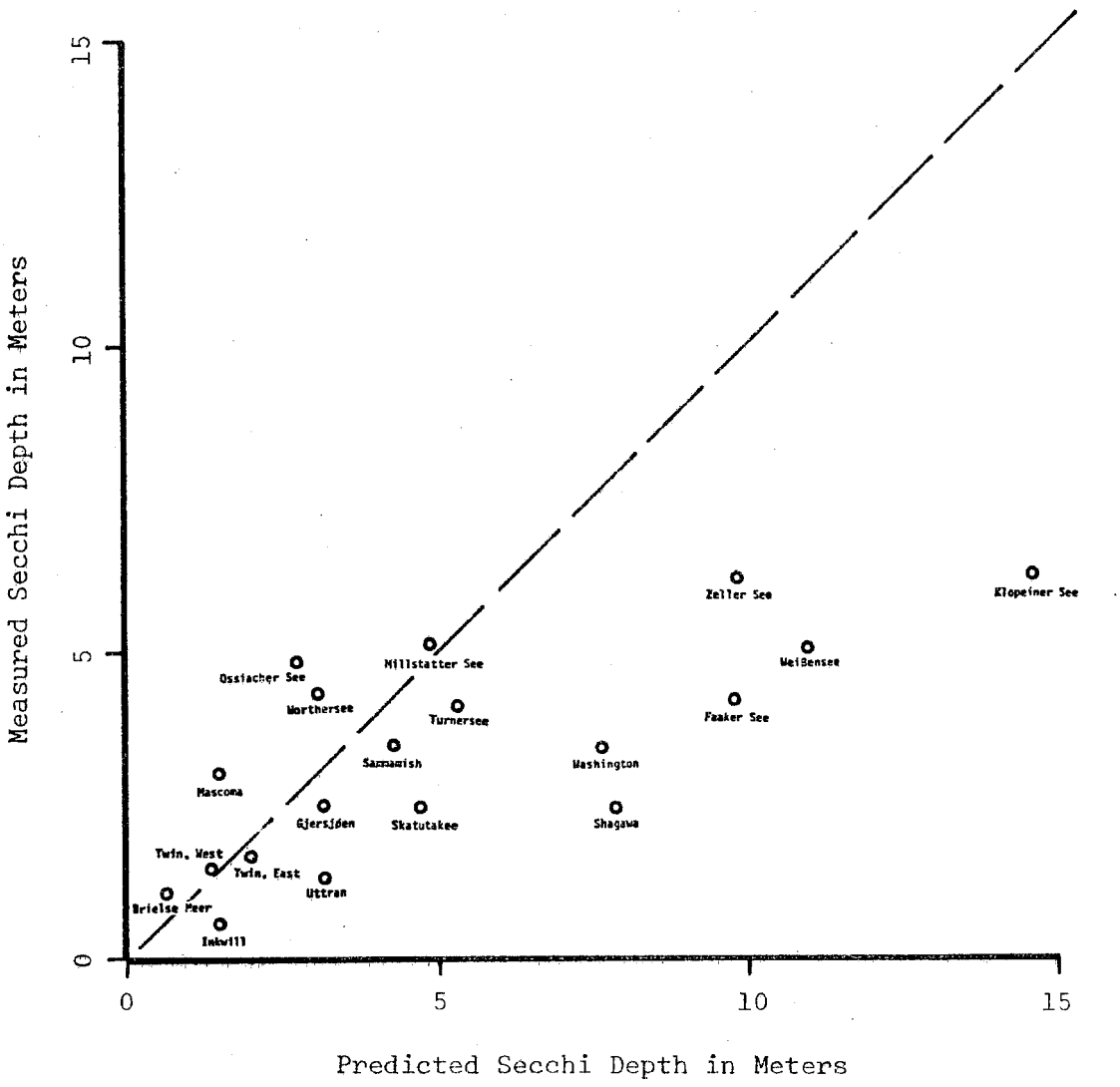

Fig. 18: Comparison of Measured and Predicted Secchi Depths for Lakes Receiving Reduced Phosphorus Input

Table 6: TROPHIC STATUS INDEX VALUES

Secchi Depth (meters)	TSI
64	0
32	10
16	20
8	30
4	40
2	50
1	60
0.5	70

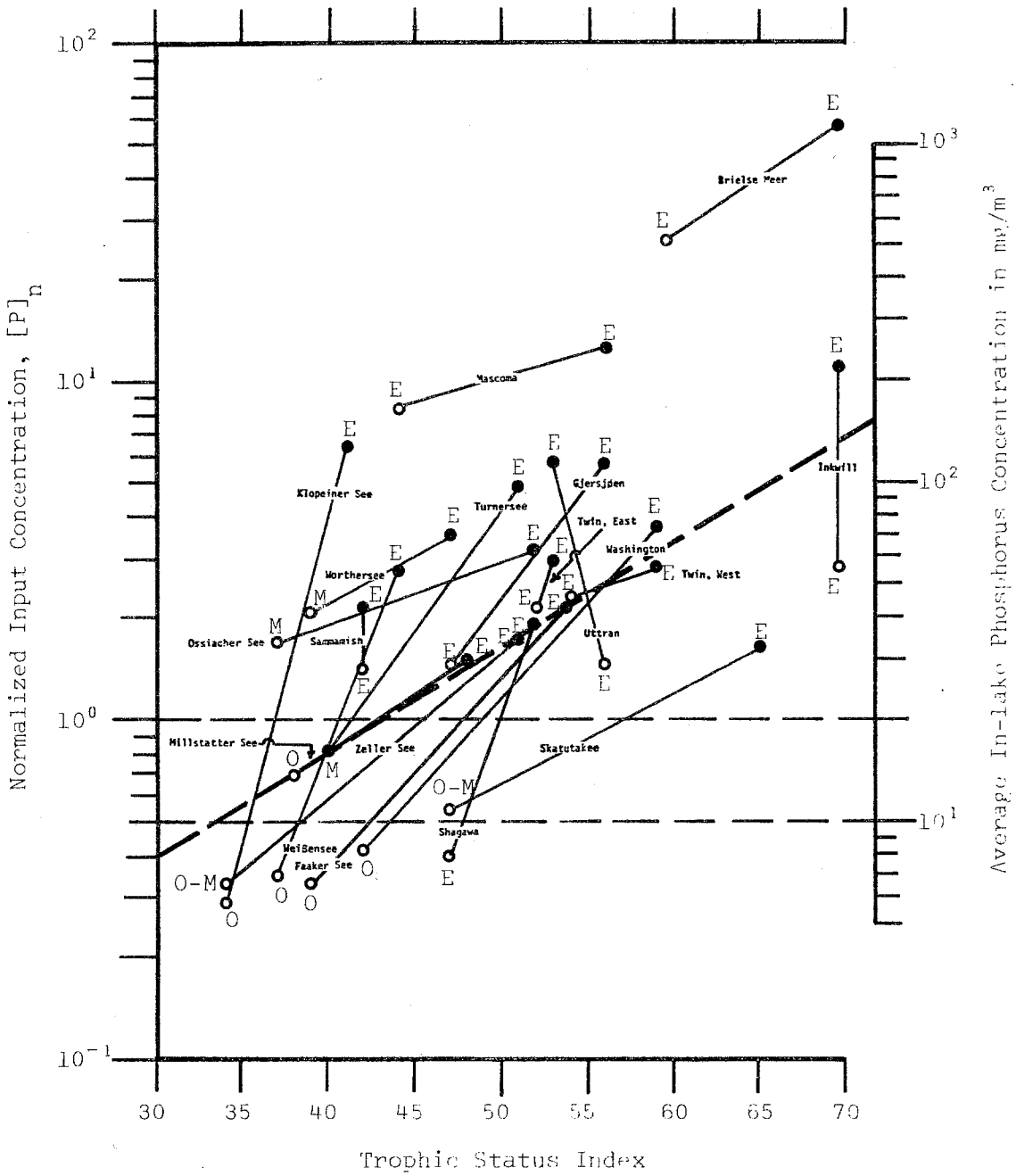

Fig. 19: Relationship Between Normalized Input Concentration and TSI for Lakes Receiving Reduced Phosphorus Loadings (SD = 64.9/[P]is indicated by heavy dashed line)

A value of 1.0 on the ordinate axis corresponds to the "critical" in-lake concentration of 10mg/m^3; likewise, a value of 0.5 corresponds to the "acceptable" level of 10mg/m^3. By normalizing the input concentration in this manner, horizontal lines on the graph represent lines of equal in-lake phosphorus concentration (see auxillary axis on right side of graph), and therefore the ordinate provides a direct measure of trophic state. Also, Eq.(26) was used to define the theoretical relationship between $[P]_n$ and TSI as shown by the dashed line on the plot.

The objective of obtaining a continuous measure of lake condition independent of specific trophic categories was achieved at least in part in Fig.19. Of the 19 lakes represented on the plot, 16 showed improvement in average summer Secchi depth following reductions in phosphorus loadings. (Lakes Sammamish and Inkwill showed no improvement, while a reduction in average Secchi depth was reported for Lake Uttran.) Of the 16 lakes showing improvement, seven lakes (Brielse Meer, Mascoma, Millstatter, Ossiacher, Skatutakee, West Twin, and Worthersee) improved at rates in which the Secchi depth at least doubled when theoretical in-lake concentrations were halved. The remaining nine lakes showed lesser rates of improvement. Data scatter makes further interpretation difficult. Although the data points fall within a band extending from lower left to upper right in Fig.19, there is considerable scatter, which illustrates the uncertainty associated with predicting Secchi depths based on calculated phosphorus values.

Similar difficulties were encountered when an alternative trophic indicator was used as shown in Fig.20. In this case, the normalized input concentration was plotted against the Lake Condition Index (LCI) reported by Uttormark and Wall (1975). The LCI is a composite of several descriptive parameters which include oxygen conditions in the hypolimnion, occurrence of fishkills, degree of algal/macrophyte growths, and Secchi depth information. Possible index values range from 0 to 23, with oligotrophic conditions represented by the lower numbers.

Data for only 13 lakes could be plotted in Fig.20, and seven of these showed no improvement as measured by the LCI. While LCIs were slightly improved for three eutrophic lakes, only those lakes which were predicted to become oligotrophic (with the exception of Shagawa) registered significantly improved LCIs. Though a data trend from lower left to upper right may again be noted, there is considerable scatter, and lake responses are less apparent than those indicated by the TSI.

In summary, the performance analyses described here show that input/output models can be used reliably to predict the general trophic state which occurs in lakes as a result of reductions in phosphorus input. However, when attempts were made to describe changes in water transparency resulting from restoration experiences, the results were less satisfactory, because of uncertainties associated with both the input/output models and the relationships which link phosphorus concentrations to Secchi depth. Refinements are needed in both areas so that restoration guidelines and criteria meaningful to the lay public can be developed.

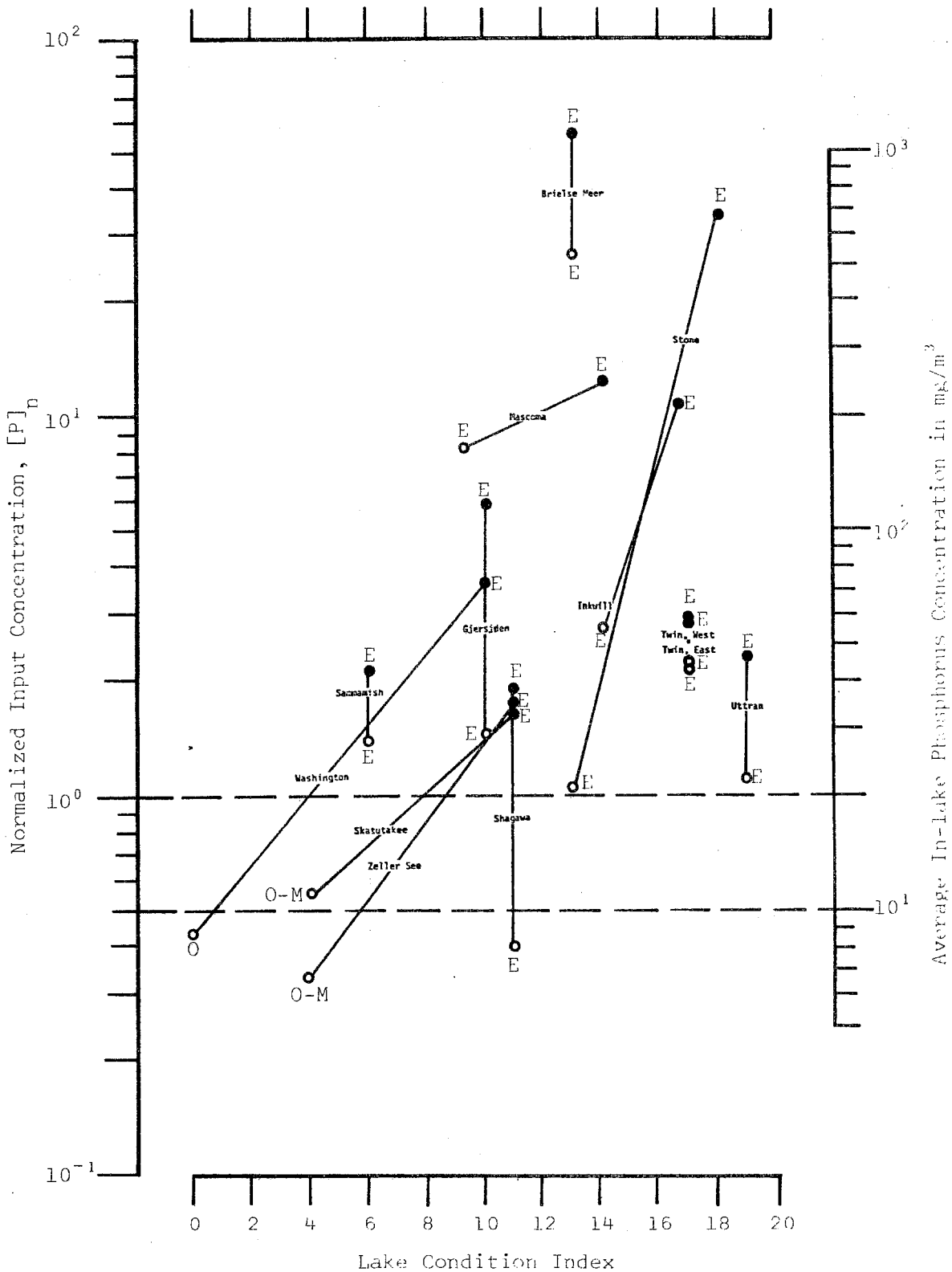

Fig. 20: Relationship Between Normalized Input Concentration and LCI for Lakes Receiving Reduced Phosphorus Loadings

SECTION V

RESEARCH NEEDS

Throughout this study, emphasis has been placed on the decision-making aspects of lake restoration, particularly on the development of guidelines and criteria which relate to the extent of water quality improvement which can be anticipated from a given restoration activity. Input/output models have been emphasized in recognition of their prominence and widespread use among practitioners responsible for lake restoration decisions.

In assessing the overall usefulness of input/output models as decision-making aids for lake restoration and management, several topic areas were identified in which present knowledge is insufficient. In particular, knowledge or information gaps were noted with respect to internal nutrient cycling in lakes; quantitative indices of trophic status; and comparable sets of lake data on which to base management decisions. It is the intent of this section to outline research topics and possible approaches which might lead to a strengthening of present guidelines for lake restoration.

The research topics listed below were developed from the point of view that the prime user of research results would be managers responsible for lake restoration decisions. Emphasis is placed not only on the type of research information that is needed, but also on the format in which results are presented.

--- Virtually all nutrient loading/lake condition models developed to date treat algal concentrations or total phosphorus as indicators of lake quality-- rooted aquatic plants are not taken into account. This is a serious shortcoming affecting many, if not most, restoration decisions. Research is needed to define how changes in nutrient influx or alterations of in-lake conditions affect macrophyte communities. These studies should include analyses of nutrient/algae/macrophyte interactions, and should emphasize mathematical descriptions of the interactive processes.

--- A logical extension of present input/output concepts would be to consider time-varying input parameters and to use maximum in-lake values, rather than steady-state values, as indicators of trophic status. This approach probably will be

mandatory for investigating internal nutrient cycling, and may also result in improved model performance relating to changes in nutrient contributions from external sources.

--- It is questionable whether present knowledge of nutrient dynamics within lakes is sufficient to underpin descriptive models or to provide guidelines for restoration techniques designed to disrupt internal nutrient cycling. Field investigations should be conducted with a "mass balance" perspective, probably with the epilimnion or the photic zone as the volume of interest. Attempts should be made to describe more precisely the transport of phosphorus within lakes, particularly the magnitude and timing of phosphorus releases from sediments in the littoral zone, as well as the effects of aquatic macrophytes on internal phosphorus cycling.

--- It is possible, and perhaps likely, that refinements in present input/output models will come only at the expense of considerable complexity, and that computer models will be necessary. However, to maintain the practical usefulness of model results, research should be undertaken to develop "design curves" so that users could apply the models graphically rather than via custom computer runs.

--- Models of internal phosphorus cycles which account simultaneously for multiple pathways and multiple sources/sinks are likely to be complex and cumbersome to use. One possibility for simplification may be to consider only a single internal source-- e.g. littoral sediments-- and to develop models and corresponding decision guidelines with the understanding that results apply only to lakes in which internal loading from a single source is the dominating and overriding factor. At the same time, it would be desirable to develop relationships between internal nutrient dynamics and readily-measurable limnological characteristics, such that for a given lake the relative importance of various internal sources could be weighed, and the appropriate guidelines could be selected.

--- Although models linking phytoplankton dynamics and nutrient transport have been developed and applied in specific situations-- for example the Sacramento-San Joaquin Delta (DiToro *et al.*, 1971), the Potomac Estuary (Thomann *et al.*, 1974), and Lake Ontario (Thomann *et al.*, 1975)--, models of this type have not impacted significantly on decision-making criteria for lake restoration. Steps should be taken to make better use of these models, perhaps by establishing a service unit at which computer models could be utilized by individuals familiar with their operation, and the output could then be provided to individuals responsible for a given restoration activity. Another alternative would be to utilize these models to develop "design curves," so that model results would be

available in a graphical format.

--- Lake restoration is an emerging science in which full-scale experimentation plays a major role in the development of expertise and the refinement of techniques. This being the case, it is important that information derived from a given restoration experience be applicable and available elsewhere. To expedite this, a centralized data storage and exchange system should be established (perhaps by EPA). This activity should include the specifications for data to be included-- i.e. type and quality-- and should take into account data needs for decision models. As an alternative, a data index might be maintained which would reference, but not store, available data.

--- As qualitative lake descriptors, the terms "eutrophic", "mesotrophic", and "oligotrophic" are meaningful to scientists and lay persons alike. As quantitative descriptors, however, there is little agreement even among scientists. Research is needed to devise improved means for describing "trophic status" (perhaps by indices), to expedite communication not only between scientists and the general public, but also among the scientific community itself. The vague terms presently used are not sufficient to convey necessary information properly or accurately.

--- Most lake restoration approaches are designed to limit the fertility of lakes by curbing nutrient flows from external and/or internal sources. The alternate approach of managing lake environments to channel excess fertility into more desirable end products-- i.e. fish rather than bluegreen algae-- ought to be given more consideration, from the points of view both of field evaluation and of modeling.

BIBLIOGRAPHY

Carlson, R.E., 1977: A trophic state index for lakes.---*Limnol. Oceanogr.* 22(2):361-369.

Dillon, P.J. and F.H. Rigler, 1974: A test of a simple nutrient budget model predicting the phosphorus concentrations in lake water.---*J. Fish. Res. Bd. Canada* 31:1771-1778.

DiToro, D.M., D.J. O'Connor, and R.V. Thomann, 1971: A dynamic model of the phytoplankton population in the Sacramento-San Joaquin Delta. ---*Advances in Chemistry* 106:131-180. American Chemical Society, Washington, D.C.

Dunst, R.C., S.M. Born, P.D. Uttormark, S.A. Smith, S.A. Nichols, J.O. Peterson, D.R. Knauer, S.L. Serns, D.R. Winter, and J.L. Wirth, 1974: Survey of lake rehabilitation techniques and experiences. Wisconsin Department of Natural Resources and the University of Wisconsin, Madison. Technical Bulletin No. 75. 179 pp.

Hutchins, M.L., 1977: Nutrient loading/lake trophic condition relationships with special reference to the influence of flushing rate. Unpublished Master of Science thesis. University of Maine, Orono. 93 pp.

Larsen, D.P. and H.T. Mercier, 1976: Phosphorus retention capacity of lakes.---*J. Fish. Res. Bd. Canada* 33(8):1742-1750.

Lorenzen, M.W., 1973: Predicting the effects of nutrient diversion on lake recovery.---*Modeling the Eutrophic Process*, E.J. Middlebrooks, D.H. Falkenborg, and J.E. Maloney (eds.):205-210. Utah Water Research Laboratory, College of Engineering, Utah State University, Logan.

Lorenzen, M.W. and A. Fast, 1977: A guide to aeration/circulation techniques for lake management. U.S. Environmental Protection Agency, Corvallis Environmental Research Laboratory. Report No. EPA-600/3-77-005. 125 pp.

Michaelis, L. and M. Menten, 1913: Die kinetik der invertinwerkung.---*Biochem. Z.* 49:333.

Monod, J., 1949: The growth of bacterial cultures.---*Am. Rev. Microbiol.* 3:371.

Sawyer, C.N., 1947: Fertilization of lakes by agricultural and urban drainage. *New England Water Works Assoc.* 61:109-127.

Shannon, E.E. and P.L. Brezonik, 1972: Eutrophication analysis: a multivariate approach.---*J. of Sanitary Engineering Division, ASCE* 98 (SAL, Proc. Paper 8735):37-57.

Shapiro, J., J.B. Lundquist, and R.E. Carlson, 1975: Involving the public in limnology-- an approach to communication.---*Verh. Internat. Verein. Limnol.* 19:866-874.

Tenney, M.W., S.M. Yaksich, and J.V. Depinto, 1975: Restoration of water bodies.---*Environmental Engineering Handbook*, B.G. Liptak (ed.). Chilton Press, Philadelphia.

Thomann, R.V., D.M. DiToro, and D.J. O'Connor, 1974: Preliminary model of potomac estuary phytoplankton.---*J. Environmental Engineering Division, ASCE* 100(SA3):699-715.

Thomann, R.V., D.M. DiToro, R.P. Winfield, and D.J. O'Connor, 1975: Mathematical modeling of phytoplankton in Lake Ontario. U.S. Environmental Protection Agency, Corvallis Environmental Research Laboratory. Report No. EPA-660/3-75-005. 177 pp.

Thomas, E.A., 1953: Empirische und experimentelle untersuchungen zur konntnis der minimumstoffe in 46 seen der schweiz. und angrenzender gebiete.---*Schweiz. Ver. Gas & Wasserfachm* 2:1-15.

U.S. Environmental Protection Agency, 1973: Measures for the restoration and enhancement of quality of freshwater lakes. Washington, D.C. Report No. EPA-430/9-73-005. 238 pp.

Uttormark, P.D. and J.P. Wall, 1975: Lake classification-- a trophic characterization of Wisconsin lakes. U.S. Environmental Protection Agency, Corvallis Environmental Research Laboratory. Report No. EPA-660/3-75-033. 165 pp.

Vollenweider, R.A., 1968: Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication.---*Organ. Econ. Coop. Dev.* Paris. Technical Report No. DAS/CSI/68.27. 159 pp.

Vollenweider, R.A., 1975: Input-output models with special reference to the phosphorus loading concept in limnology.---*Schweiz. Z. Hydrol.* 37:53-83.

Vollenweider, R.A., 1976: Advances in defining critical loading levels for phosphorus in lake eutrophication.---*Mem. Ist. Ital. Idrobiol.* 33:53-83.

Appendix 1: DERIVATION OF THE BIOMASS MODEL

The development of a cellular or "biomass" model follows a modeling approach very similar to the input/output models of Vollenweider (1975, 1976) and Dillon and Rigler (1974), and several assumptions are common to these models. The model is restricted to phosphorus-limited lakes, and it is assumed that, on a long-term basis, lakes may be approximated by completely mixed flow-through reactors where water inflow equals water outflow. It is further assumed that the influx of phosphorus is constant with time and may be represented by an "average input concentration."

The biomass model extends the theories advanced by Vollenweider (1975, 1976) and Dillon and Rigler (1974) by adding an additional step which describes the incorporation of phosphorus into biomass. All input phosphorus is assumed to be available for biomass growth, but it is not necessary that all phosphorus be converted; thus total phosphorus is divided into two components: (1) that fraction which is incorporated into biomass, and (2) that fraction which remains in "solution."

Fractionalization of total phosphorus leads to several modifications of previous assumptions. Contrary to previous models, biomass concentration (expressed as P), rather than total phosphorus concentration, was selected as the trophic state indicator. Also, phosphorus losses through the outlet may be of two forms, cellular phosphorus and phosphorus in solution. Finally, internal losses of phosphorus ("sedimentation") are assumed to be proportional to biomass concentration instead of to total phosphorus concentration.

In developing the model equations, it was convenient to define both a biomass balance and a nutrient balance for lake systems. The biomass balance can be represented by

$$\text{biomass change} = \text{inflow} + \text{growth} - \text{sedimentation} - \text{outflow}$$

$$V\frac{d[X]}{dt} = 0 + \mu[X]V - \sigma[X]V - Q[X] \qquad (1)$$

where V = lake volume, L^3
$[X]$ = concentration of in-lake biomass, ML^{-3}
μ = specific growth rate, T^{-1}
σ = specific sedimentation rate, T^{-1}
Q = annual water flow rate, L^3T^{-1}

Appendix 1 (Continued): DERIVATION OF THE BIOMASS MODEL

Rate of change per unit volume is given by

$$\frac{d[X]}{dt} = \mu[X] - \sigma[X] - \rho[X] \qquad (2)$$

where $\rho = \frac{Q}{V}$ = flushing rate, T^{-1}

At steady-state, time derivatives are zero and

$$\mu = \rho + \sigma \qquad (3)$$

Similarly, the phosphorus balance can be represented by

change in total phosphorus = inflow - sedimentation - outflow

Assuming that all incoming phosphorus is available for growth and that internal loss of phosphorus occurs only through sedimentation of biomass,

$$V\frac{d[P]}{dt} = Q[P_0] - \frac{\sigma[X]V}{Y} - Q[P_s] - \frac{Q[X]}{Y} \qquad (4)$$

where $[P]$ = total phosphorus concentration, ML^{-3}
$[P_s]$ = phosphorus concentration remaining in solution, ML^{-3}
$[P_0]$ = inflow total phosphorus concentration, ML^{-3}
Y = yield coefficient = biomass produced per nutrient incorporated, dimensionless

Rate of change per unit volume is given by

$$\frac{d[P]}{dt} = \rho[P_0] - \frac{\sigma[X]}{Y} - \rho[P_s] - \frac{\rho[X]}{Y} \qquad (5)$$

At steady-state,

$$\sigma\frac{[X]}{Y} + \rho\frac{[X]}{Y} = \rho([P_0] - [P_s]) \qquad (6)$$

Solving for $\frac{[X]}{Y}$,

$$\frac{[X]}{Y} = ([P_0] - [P_s])\frac{\rho}{\rho + \sigma} \tag{7}$$

A nutrient-biomass linkage was accomplished by assuming that the kinetics of phosphorus uptake by biomass could be described adequately by the Michaelis-Menten relationship (Michaelis-Menten, 1913; Monod, 1949). Specifically, the Michaelis-Menten relationship describes the specific growth rate, , as a function of substrate concentration such that

$$\mu = \hat{\mu}\frac{[S]}{k_s + [S]} = \hat{\mu}\frac{[P_s]}{k_s + [P_s]} \tag{8}$$

where $\hat{\mu}$ = maximum specific growth rate attainable for a given organixm at infinite substrate concentration, T^{-1}
$[S]$ = substrate concentration, ML^{-3}
k_s = half-saturation constant = the substrate concentration at which specific growth rate equals one-half the maximum specific growth rate, ML^{-3}

Solving for $[P_s]$,

$$[P_s] = \frac{\mu k_s}{\hat{\mu} - \mu} \tag{9}$$

Since $\mu = \rho + \sigma$ from Eq.(3),

$$[P_s] = \frac{(\rho + \sigma)k_s}{\hat{\mu} - (\rho + \sigma)} \tag{10}$$

As with the other models described above, an indirect approach was used to characterize the sedimentation coefficient. Using the nutrient retention concept discussed by Dillon and Rigler (1974), the retention coefficient is defined by

$$R = \frac{\sigma \frac{X}{Y} V}{[P_0]Q} \tag{11}$$

Solving for σ,

$$\sigma = \frac{\frac{[P_0]\rho R}{[X]}}{Y} \tag{12}$$

An expression for biomass concentration (expressed as P) can now be derived by the simultaneous solution of Eqs.(7), (10), and (12).

$$\frac{[X]}{Y} = \left[[P_0] - \frac{\left[\rho + \frac{\frac{[P_0]\rho R}{[X]}}{Y}\right] k_s}{\mu - \left[\rho + \frac{\frac{[P_0]\rho R}{[X]}}{Y}\right]} \right] \frac{\rho}{\rho + \frac{\frac{[P_0]\rho R}{[X]}}{Y}} \tag{13}$$

Since $[P_0] = \frac{L}{\bar{z}\rho}$,

$$\frac{[X]}{Y} = \left[\frac{L}{\bar{z}\rho} - \frac{\left[\rho + \frac{\frac{L}{\bar{z}} R}{\frac{[X]}{Y}}\right] k_s}{\mu - \left[\rho + \frac{\frac{L}{\bar{z}} R}{\frac{[X]}{Y}}\right]} \right] \frac{\rho}{\rho + \frac{\frac{L}{\bar{z}} R}{\frac{[X]}{Y}}} \tag{14}$$

Or in a more convenient form,

$$\left[\frac{[X]}{Y}\right]^2 \rho(\hat{\mu} - \rho) + \frac{[X]}{Y}\left[\frac{L}{\bar{z}} R\left(\hat{\mu} - 2\rho - \frac{1}{R}\hat{\mu}\right) + \rho\left(\frac{L}{\bar{z}} + \rho k_s\right)\right] - R\frac{L}{\bar{z}}\left[\frac{L}{\bar{z}}(R - 1) - \rho k_s\right] = 0 \tag{18}$$

This model equation, though cumbersome, can be solved readily for biomass concentration using the quadratic formula.

Appendix 2: DATA SUMMARY

	L ($gms \cdot m^{-2} \cdot yr^{-1}$)	$\bar{z}$ (m)	ρ yr^{-1}	R (dimensionless)	Lake Condition Index	Trophic State Index	Trophic State	Source*
1. Brielse Meer	33.95	5.3	3.70	0.64	13	69	E	R. Peelen, Netherlands
	16.28	5.3	3.70	0.60	13	59	E	R. Peelen
2. Drontemeer	4.0-5.0	1.2	≈5.00	0.9	15	>73	E	W. Segeren, Netherlands
3. Eagle	0.21	6.5	0.23	0.69	11	32	E	J. Latterell, USA
4. Eemmeer	20.0-30.0	1.9	≈5.00	0.8	>11	>73	E	W. Segeren
5. Faaker See	1.2	14.9	0.83	----	--	54.2	E	H. Sampl, Austria
	0.175	14.9	0.83	----	--	39.3	O	H. Sampl
6. Gjersjøen	2.07	23.0	0.26	0.87	10	56	E	H. Holtan, Norway
	0.45	23.0	0.22	0.87	10	47	E	H. Holtan
7. Gooimeer	20.0-30.0	2.1	≈5.00	----	>11	>73	E	W. Segeren
8. Hafnersee	1.15	5.7	6.67	----	--	--	E	H. Sampl
9. Hallwil	----	---	----	----	--	--	-	M. Schmid, Switzerland
	1.94	20.6	0.32	0.5	8	45	E	M. Schmid
10. Inkwill	3.88-4.63	2.7	5.00	----	17	69	E	W. Nef, Switzerland
	0.83-1.33	2.7	5.00	----	14	69	E	W. Nef
11. Kalamalka	0.32	59.0	0.014	0.9	1	28	O	J. Stockner, *et al.* (1974)
12. Kegonsa	6.64	5.0	≈2.50	----	--	--	E	C. Sawyer (1947)
	1.87	5.0	≈2.50	----	--	--	E	W. Sonzogni, USA
13. Keutschacher See	0.65	7.4	1.11	----	--	--	E	H. Sampl
14. Klopeiner See	1.1	22.6	0.087	----	--	41.1	E	H. Sampl
	0.05	22.6	0.087	----	--	33.7	O	H. Sampl
15. Langsee	0.75	12.0	0.435	----	--	--	E	H. Sampl
16. Mascoma	9.78	8.7	2.86	0.78	14	56	E	T. Frost, USA
	6.44	8.7	2.86	0.78	9	44	E	T. Frost
17. Mendota	1.60	12.0	0.22	----	--	--	E	C. Sawyer (1947)
	1.28	12.0	0.22	----	--	--	E	W. Sonzogni
18. Millstatter See	1.30	91.0	0.12	----	--	48.0	E	H. Sampl
	0.70	91.0	0.12	----	--	--	-	H. Sampl
	0.60	91.0	0.12	----	--	36.5	O	H. Sampl
19. Okanagan	0.39	76.0	0.017	0.95	1	30	O	W. Parchomchuk, Canada
20. Osoyoos	2.00	14.0	1.43	----	5	43	E	J. Stockner, *et al.* (1974)
21. Ossiacher See	1.50	19.9	0.5	----	--	51.3	E	H. Sampl
	0.80	19.9	0.5	----	--	37.4	M	H. Sampl
22. Sammamish	1.03	17.7	0.58	0.8	6	42	E	E. Welch, USA
	0.67	17.7	0.58	0.7	6	42	E	E. Welch
23. Shagawa	0.72	5.7	1.82	0.27	11	52	E	K. Malueg, USA
	0.66	5.7	1.205	0.39	--	--	-	K. Malueg
	0.23	5.7	1.82	-1.01	--	--	-	K. Malueg
	0.16	5.7	1.61	-0.46	--	--	-	K. Malueg
	0.11	5.7	1.205	-0.63	11	47	E	K. Malueg
24. Skaha	2.2	26.0	0.83	0.6-0.7	5	42	E	J. Stockner, *et al.* (1974)
25. Skatutakee	1.07	2.7	9.09	0.45	11	65	E	T. Frost
	0.35	2.7	9.09	0.45	4	47.1	O-M	T. Frost
26. Stone	2.30	6.0	0.182	----	18	--	E	M. Tenney, USA
	0.07	6.0	0.182	----	13	--	E	M. Tenney
27. Twin, East	0.71	5.03	1.27	0.354	17	53	E	G. Cooke, USA
	0.84	5.03	2.22	0.210	17	52	E	G. Cooke
28. Twin, West	0.35	4.34	0.61	0.152	17	59	E	G. Cooke
	0.41	4.34	1.01	0.29	17	54	E	G. Cooke
29. Turnersee	1.2	7.5	0.77	----	--	50.7	E	H. Sampl
	0.2	7.5	0.77	----	--	39.6	M	H. Sampl
30. Uttran	0.183	5.4	0.24	----	19	53	E	L. Karlgren, Sweden
	0.086	5.4	0.24	----	19	56	E	L. Karlgren
31. Vaseux	3.2	6.5	33.33	----	--	--	-	J. Stockner, *et al.* (1974)
32. Veluwemeer North	4.0-5.15	1.4	4.00	0.9	15	>73	E	W. Segeren
33. Washington	2.63	32.9	0.42	0.758	10	59	E	W. Edmundson, USA
	0.31	32.9	0.42	0.437	0	42	O	W. Edmundson
34. Waubesa	9.93	5.0	≈4.00	----	--	--	E	C. Sawyer (1947)
	2.64	5.0	≈4.00	----	--	--	E	W. Sonzogni
35. Weißensee	0.775	36.0	0.091	----	--	44.2	E	H. Sampl
	0.10	36.0	0.091	----	--	36.8	O	H. Sampl
36. Wolderwijd	<3.0	1.5	≈5.00	----	>11	>73	E	W. Segeren
37. Wood	0.50	22.0	0.0092	0.90	6	47	E	J. Stockner, *et al.* (1974)
38. Worthersee	1.275	42.0	0.105	----	--	47.4	E	H. Sampl
	0.75	42.0	0.105	----	--	39.0	M	H. Sampl
39. Zeller See	1.28	36.6	0.375	0.41	11	51	E	W. Koucsay, Austria
	0.24	36.6	0.375	0.41	4	34	O-M	W. Koucsay

*by personal communication unless publication date is noted

Appendix 3: LIST OF SYMBOLS

P	total phosphorus
[P]	in-lake total phosphorus concentration, ML^{-3}
[P]'	modified in-lake total phosphorus concentration, ML^{-3}
$[P_o]$	inflow total phosphorus concentration, ML^{-3}
$[P_s]$	phosphorus concentration remaining in solution, ML^{-3}
$[P_n]$	normalized average input total phosphorus concentration, dimensionless
t	time, T
V	lake volume, L^3
Q	annual water flow rate, L^3T^{-1}
L	specific areal phosphorus loading, $ML^{-2}T^{-1}$
$\bar{z}$	mean lake depth, L
σ	specific sedimentation rate, T^{-1}
ρ	flushing rate, T^{-1}
R	phosphorus retention coefficient, dimensionless
μ	specific growth rate, T^{-1}
$\hat{\mu}$	maximum specific growth rate attainable for a given organism at infinite substrate concentration, T^{-1}
k_s	half-saturation constant = the substrate concentration at which specific growth rate equals one-half the maximum specific growth rate, ML^{-3}
[S]	substrate concentration, ML^{-3}
[X]	in-lake biomass concentration, ML^{-3}
Y	yield coefficient = biomass produced per nutrient incorporated, dimensionless
a	sedimentation constant, dimensionless
b	selective discharge constant, dimensionless
SD	Secchi depth
LCI	lake condition index
TSI	trophic status index
E	eutrophic
M	mesotrophic
O	oligotrophic

SUBSCRIPTS

1	refers to conditions before lake restoration
2	refers to conditions after lake restoration
10	refers to input parameters which result in an in-lake total phosphorus concentration of $10mg/m^3$
20	refers to input parameters which result in an in-lake total phosphorus concentration of $20mg/m^3$

SELECTED WATER RESOURCES ABSTRACTS
INPUT TRANSACTION FORM

1. Report No. | 2. | 3. Accession No. W

4. Title: Input/Output Models as Decision Criteria for Lake Restoration

5. Report Date: April 1978

6.

7. Author(s): Paul D. Uttormark and Mark L. Hutchins

8. Performing Organization Report No.

9. Organization: Land & Water Resource Institute, University of Maine at Orono; AND Water Resources Center, University of Wisconsin (Madison)

10. Project No: C-7232

11. Contract/Grant No.: 14-34-0001-6230

12. Sponsoring Organization: Office of Water Research and Technology

13. Type of Report and Period Covered: Technical Completion

15. Supplementary Notes

16. Abstract

A study was conducted to evaluate the applicability of input/output models to the design of lake restoration activities. Four models were evaluated: those reported by Dillon and Rigler (1974) and Vollenweider (1975, 1976), and a model developed in this study in which cellular biomass, rather than total phosphorus, was used as the trophic state indicator. Data were obtained for 25 lakes which had experienced reductions in nutrient inflow. Comparisons of measured and predicted responses were made, based on general descriptions of trophic status; Secchi depth, including the Trophic State Index reported by Carlson (1977); and the Lake Condition Index reported by Uttormark and Wall (1975).

It was found that all four models yielded accurate predictions of general trophic state for at least 70% of the study lakes; the model of Vollenweider (1976) and the biomass model yielded the best predictions, with 82% correct. Comparison of measured and predicted responses based on other indicators of lake condition were less definitive. Estimates of improvements in transparency were found to be generally optimistic, with measured Secchi depths reaching only 50-80% of predicted values for most of the study lakes.

It was concluded that the input/output models examined are best applied to those restorative techniques which curb nutrient influx, and they have only limited application to techniques which disrupt internal nutrient cycling or accelerate nutrient outflow.

17a. Descriptors

Eutrophication, Input-Output Analysis, Lakes, Mathematical Models, Nutrients, Phosphorus, Trophic Level, Water Quality Control

17b. Identifiers

Flushing Rate, Input/Output Models, Lake Restoration Evaluation, Nutrients, Phosphorus, Predicted Lake Response, Trophic State Change, Water Quality Management

17c. COSATI Field/Group

18. Availability

19. Security Class. (Report)

20. Security Class. (Page)

21. No. of Pages: 61

22. Price

Send To:
WATER RESOURCES SCIENTIFIC INFORMATION CENTER
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D.C. 20240

Abstractor: Mark L. Hutchins | Institution: University of Maine at Orono

WRSIC