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Use of Vollenweider-OECD Modeling to Evaluate Aquatic Ecosystem Functioning

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ABSTRACT: The Vollenweider-Organization for Economic Cooperation and Development (OECD) models are statistical relationships that describe the functioning of aquatic ecosystems in the use of aquatic plant nutrients (nitrogen and phosphorus) for the production of planktonic algae. These models were developed on the basis of data from several hundred bodies of water throughout the world; those discussed herein define the relationships between normalized phosphorus loads to lakes and reservoirs and the planktonic algal chlorophyll, algal productivity, algal-related water clarity, hypolimnetic oxygen depletion rate, and fish yield. Guidance is provided on the use of these relationships for assessing the overall functioning of an aquatic ecosystem.

KEY WORDS: hazard evaluation, ecosystem functioning, ecosystem modeling, phosphorus, algae, chlorophyll

One approach to the evaluation of whether an aquatic ecosystem is functioning as it should or the functioning has been altered, is to compare the functioning of the ecosystem of concern to some norm. In making this comparison, several issues must be addressed: what does "functioning of an ecosystem" mean; what parameters are used to assess this functioning; what is a "norm" for the particular type of system; what is the expected range of variability among "normally" functioning ecosystems of this type; and how far from the norm or normal range does the functioning of an ecosystem have to be before it is judged to be different enough from the norm to he of concern? In the case of ecosystem evaluation associated with water quality management, is being that different from the norm something of sufficient concern to society to justify contaminant control; can the same level of deviation from the norm perhaps occur through natural events unrelated to contaminant input?

There are various ways in which ecosystems and their functioning have been evaluated. For example, these evaluations have often been tied to the numbers and diversity of organisms included in a survey of a system. Other approaches focus on conducting specific laboratory tests, such as enzyme production or activity, to assess how well a particular part of a component of the system is operating. Other approaches attempt to develop, through laboratory microcosms, appropriate replicates of a full-scale ecosystem for study. A number of papers describing these types of approaches are presented in this volume.

The focus of this paper is on the application of the Vollenweider-Organization for Economic Cooperation and Development (OECD) modeling approach to the assessment of overall aquatic ecosystem functioning. These models describe, in a normalized statistical modeling framework,

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ecosystem functioning as described by the utilization of phosphorus load in the production of planktonic algal chlorophyll, primary productivity, water clarity as controlled by primary production, hypolimnetic oxygen depletion rate, and overall fish yield. The basis for these empirical models is the functioning of several hundred ecosystems; they serve as a reasonable description of a "norm" and range of expected ("normal") conditions.

Vollenweider-OECD Models

During the mid-1970s the Organization for Economic Cooperation and Development (OECD) sponsored a five-year study of the relationships between nutrient loading and eutrophication-related water quality response in bodies of water in the United States, Canada, Australia, Japan, and 14 countries in Western Europe. Vollenweider, one of the principal individuals directing this OECD study and the overall study coordinator, had already begun to investigate, quantify, and mathematically describe the factors influencing how planktonic algae in a water body utilized the nutrient input, based on a group of about 20 lakes, primarily European [1-3]. He found that the water body mean depth, surface area, and hydraulic residence time play critical roles in the amount of planktonic algal biomass that develops within a water body for a given phosphorus load to that water body. On the basis of the data on the group of European water bodies, he defined a statistical regression between the epilimnetic planktonic algal chlorophyll concentration and the phosphorus load normalized by mean depth, hydraulic residence time, and surface area. The phosphorus loading is normalized in accordance with the following formulation

$$\frac{L(P)/q_s}{1 + \sqrt{\tau_w}} \tag{1}$$

where

$L(\mathrm{P})$ = the areal annual total phosphorus load, mg P/m^2/year,
q_s = the mean depth, m, divided by the hydraulic residence time, year, and
τ_w = the hydraulic residence time, year.

Inherent in the mathematical/theoretical formulation of the normalization of the phosphorus load are the interactions of nutrients with the sediments and particulate matter in the water body, the availability of the phosphorus input (most of the water bodies included had on the order of 75% of the input phosphorus load in available forms), and the grazing of the phytoplankton. The normalized phosphorus loading term developed is theoretically equivalent to the average in-lake phosphorus concentration; based on data available on U.S. and international OECD water bodies, the in-lake phosphorus concentration can be mathematically described asa function of normalized phosphorus loading. Thus, the model simply mathematically describes the relationship between the nutrients available and the phytoplankton that develop, that is, algal stoichiometry. Similar stoichiometric relationships are reflected in the correlations between the phytoplankton biomass and the higher trophic levels described further on in this paper.

With the data for the OECD water bodies in the United States [4] and the international OECD water bodies [5] and the results of studies conducted since by the authors and their associates [6, 7], the basis for Vollenweider's empirical relationship has been expanded to more than 750 water bodies throughout the world (Fig. 1). These water bodies include lakes, reservoirs, and an estuarine system. They include shallow and deep, large and small, temperate and antarctic, and ultraoligotrophic and eutrophic water bodies, as well as those in between. These water bodies would, in general, be considered to he unaffected by toxic chemicals that would cause the overall aspects of their ecosystem functioning to be adversely affected.

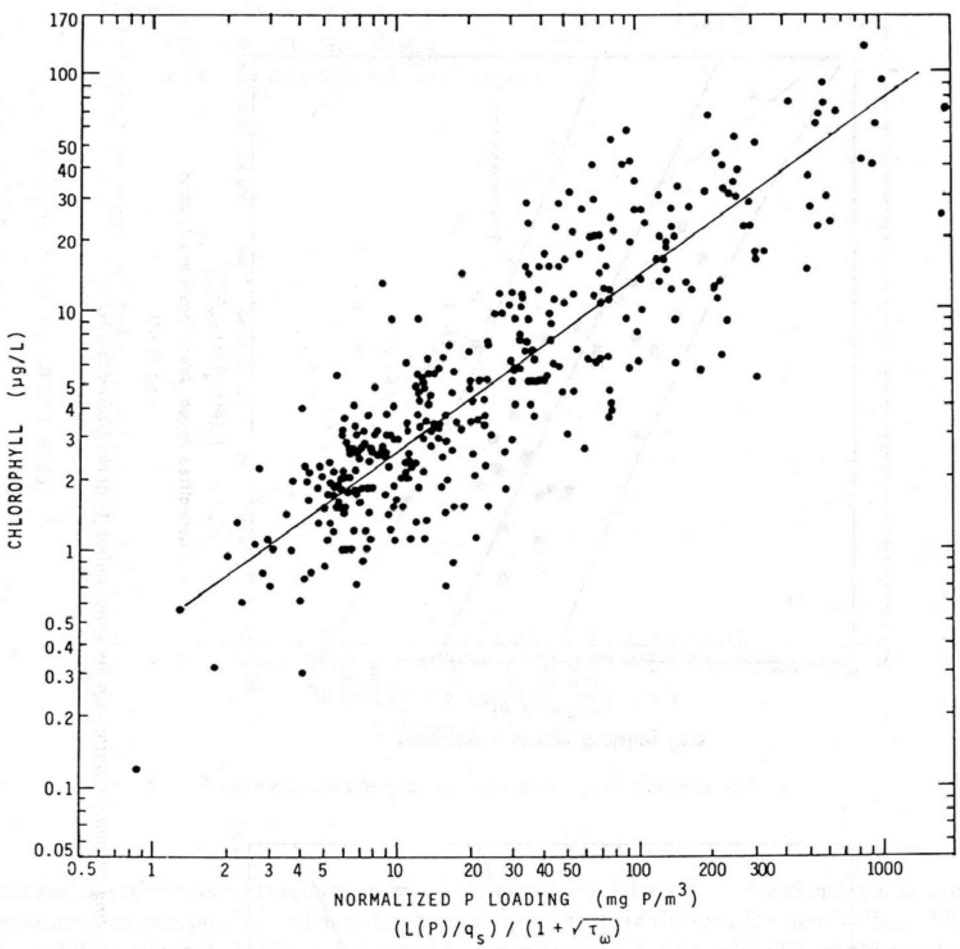

FIG. 1—*Updated Vollenweider-OECD normalized phosphorus loading–chlorophyll response relationship* [7] *for bodies of water throughout the world.*

With their definition of the empirical relationship between normalized phosphorus loading and planktonic algal chlorophyll for the OECD water bodies in the United States, Rast and Lee [4] expanded the approach and developed analogous relationships between the normalized phosphorus load and the Secchi depth (for water bodies with moderate or little inorganic turbidity or color) and also between the normalized phosphorus load and the hvpolimnetic oxygen depletion rate. Jones and Lee [6] updated these statistical relationships to include data from other water bodies on which data were available; Fig. 2 shows these relationships.

In addition to the relationships shown in Figs. 1 and 2, work was being conducted independently to relate the planktonic algal biomass to the overall yield of fish in water bodies. Based on information from the literature [8, 9] and the normalized phosphorus load-response relationships in Figs. 1 and 2, Lee and Jones [10] found and described the statistical relationship shown in Fig. 3 between the normalized phosphorus load and the overall fish yield. While the data base for this relationship is smaller than those for the other models, the trend found is as would be expected: the greater the phosphorus loading, the greater the chlorophyll-algal biomass, and the greater the overall fish yield. Lee and Jones [10] and Jones and Lee[7] discussed the development and interpretation

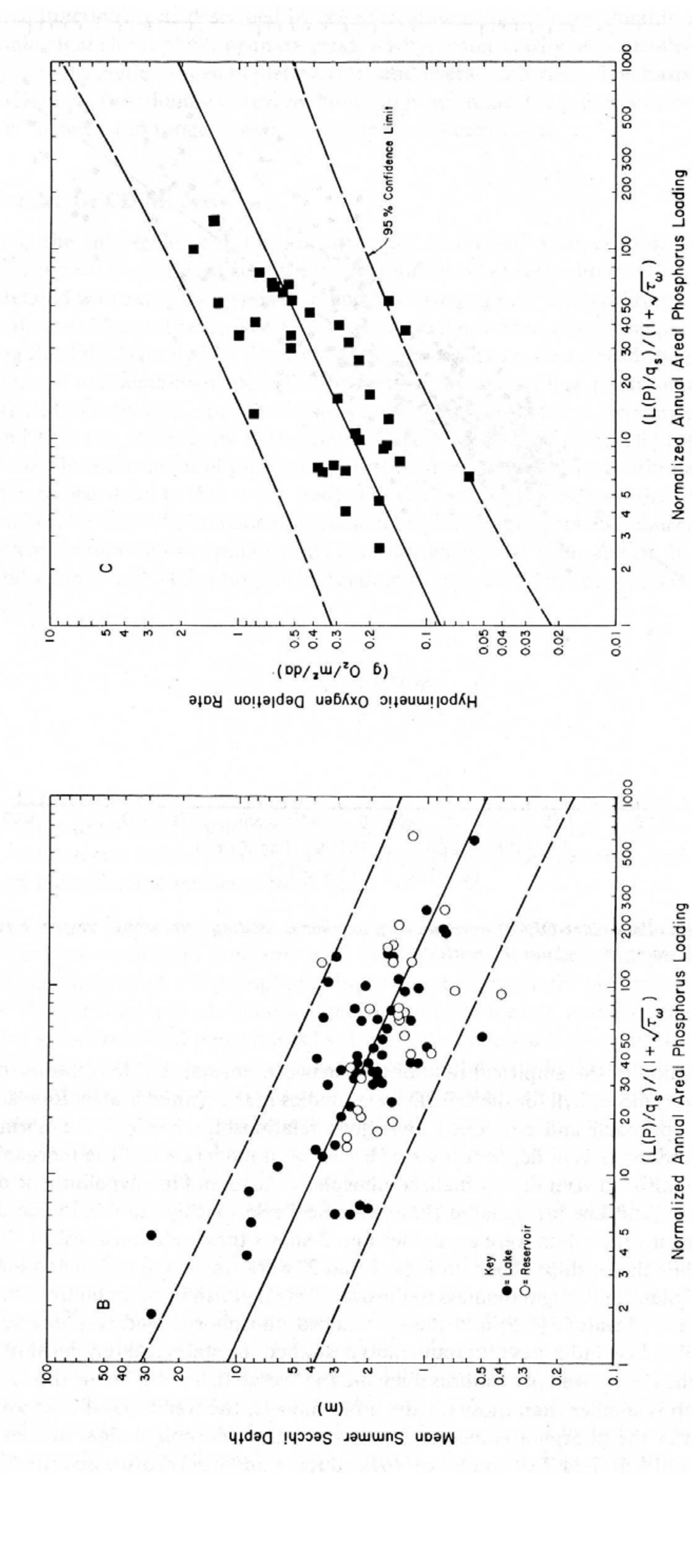

FIG. 2—*Normalized phosphorus loading–response relationship for water bodies [6] in the United States.*

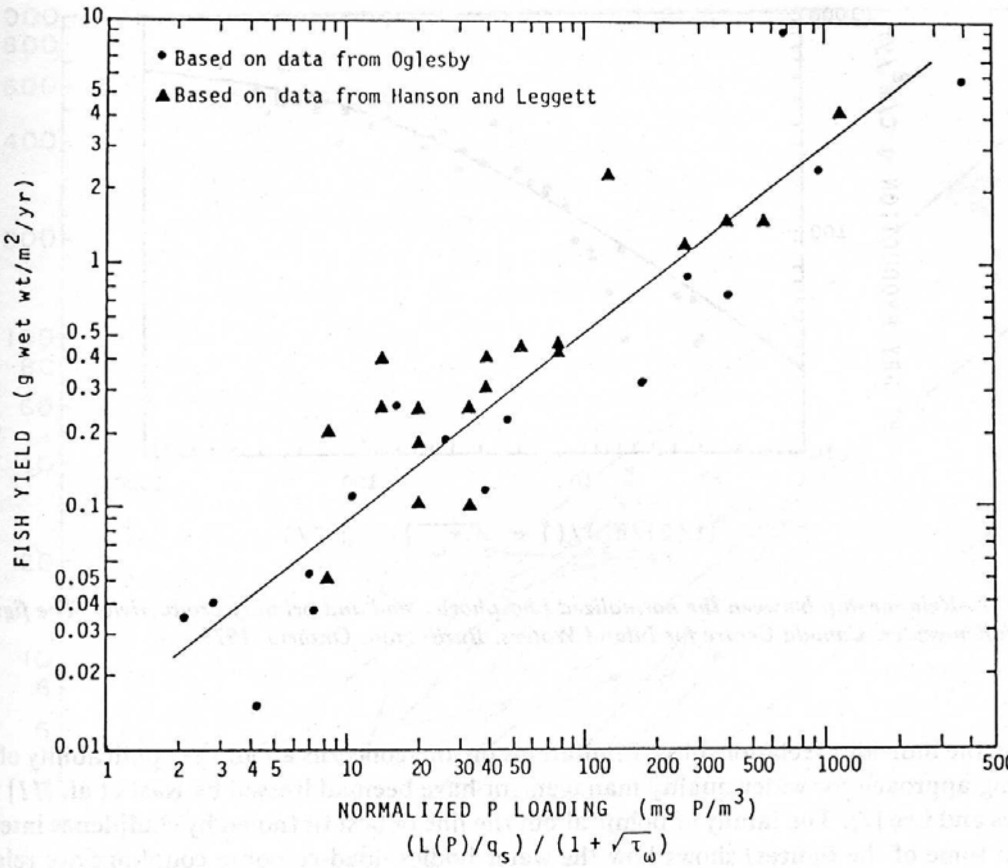

FIG. 3—*Normalized phosphorus loading–fish yield relationship* [10].

of this relationship. Vollenveider[2] [5] described a relationship between the normalized phosphorus load and the primary productivity of the OECD water bodies. This relationship is presented in Fig. 4. Vollenweider[2] has indicated that a straight line could equally well be used to describe the function shown.

One of the most important aspects of the Vollenweider-OECD modeling approach is the demonstration and verification of the predictive capability of the relationships. Rast, Jones, and Lee [11] undertook a study to evaluate the data from studies of nutrient load and planktonic-algal-related response for water bodies that had undergone phosphorus load reductions, in order to evaluate the predictive capability of the models. They examined and plotted the data that described the load-response couplings before and after substantial phosphorus loading alterations had occurred in about a dozen water bodies for which appropriate data were available. The results of this evaluation for the chlorophyll response are shown in Fig. 5, which demonstrates that, in general, with alteration in their normalized phosphorus loadings, water bodies track parallel to the line of best fit through the body of data upon which the relationship was developed (Fig. 1). For essentially all of the water bodies evaluated, the predicted response values and the measured response values after the loading change were within a factor of 1.5 of each other. Rast et al. [11] and Jones and Lee [7] provide a discussion of these results and their interpretation for water quality management.

In the use of the Vollenweider-OECD modeling approach for evaluating overall ecosystem functioning, it is important to understand the variability of the data about the lines of best fit

[2]Vollenwelder, R. A., Canada Centre for Inland Waters, Burlington, Ontario, Canada, personal communication, 1986.

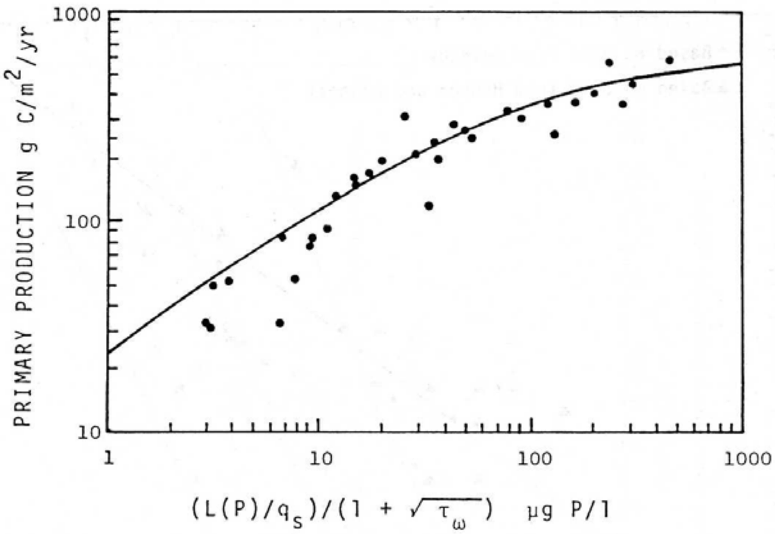

FIG. 4—*Relationship between the normalized phosphorus load and primary productivity. The figure is from Vollenweider. Canada Centre for Inland Waters. Burlington. Ontario. 1979.*

defining the individual relationships. Limitations on and concerns about the applicability of the modeling approach for water quality management have been addressed by Rast et al. I11] and by Jones and Lee [7]. The family of points about the line of best fit (noted by confidence interval lines on some of the figures) shows how the water bodies' load-response couplings are related and also how they vary.

Use of Models for Evaluation of Overall Aquatic Ecosystem Functioning

The Vollenweider-OECD load-response models can he used to address and integrate several levels of overall "ecosystem functioning" by indicating whether the normalized phosphorus load-response coupling for a water body falls within the family of couplings for the several hundred water bodies unaffected by toxicant input, upon which the models were developed. They can indicate whether the phosphorus loading supports the amount of planktonic algal biomass and productivity expected based on the morphologic and hydrologic characteristics of the water body, whether the rate of bacterial decomposition in the hvpolimnion (oxygen depletion rate) is as expected based on the amount of algal growth, and whether the fish yield is as expected based on the amount of algal biomass in the water body. They can also indicate whether the water body responds to phosphorus load alterations as expected [11].

In order to apply this approach, the phosphorus loading must be determined. This can be done, as described by Rast and Lee [12], based on land use and phosphorus export coefficients or on measurements of water inflow and phosphorus concentrations from the major sources to the water body. (Internal cycling is accounted for in the normalizing.) The mean depth, hydraulic residence time, and surface area must also be estimated. The mean depth is equivalent to the volume of the water body divided by the surface area; the hydraulic residence time can be determined by dividing the volume by the annual water inflow; and the normalized phosphorus loading is computed as indicated in Eq 1.

An estimate of the overall water body ecosystem response must also be made. The best measurement for the purposes of this modeling is usually the average summer epilimnetic planktonic algal chlorophyll. For water bodies that do not have excessive amounts of inorganic turhidity or color, the average summer Secchi depth is also a suitable response parameter, as it is directly related to the planktonic algal chlorophyll. The models themselves can be used to assess whether the

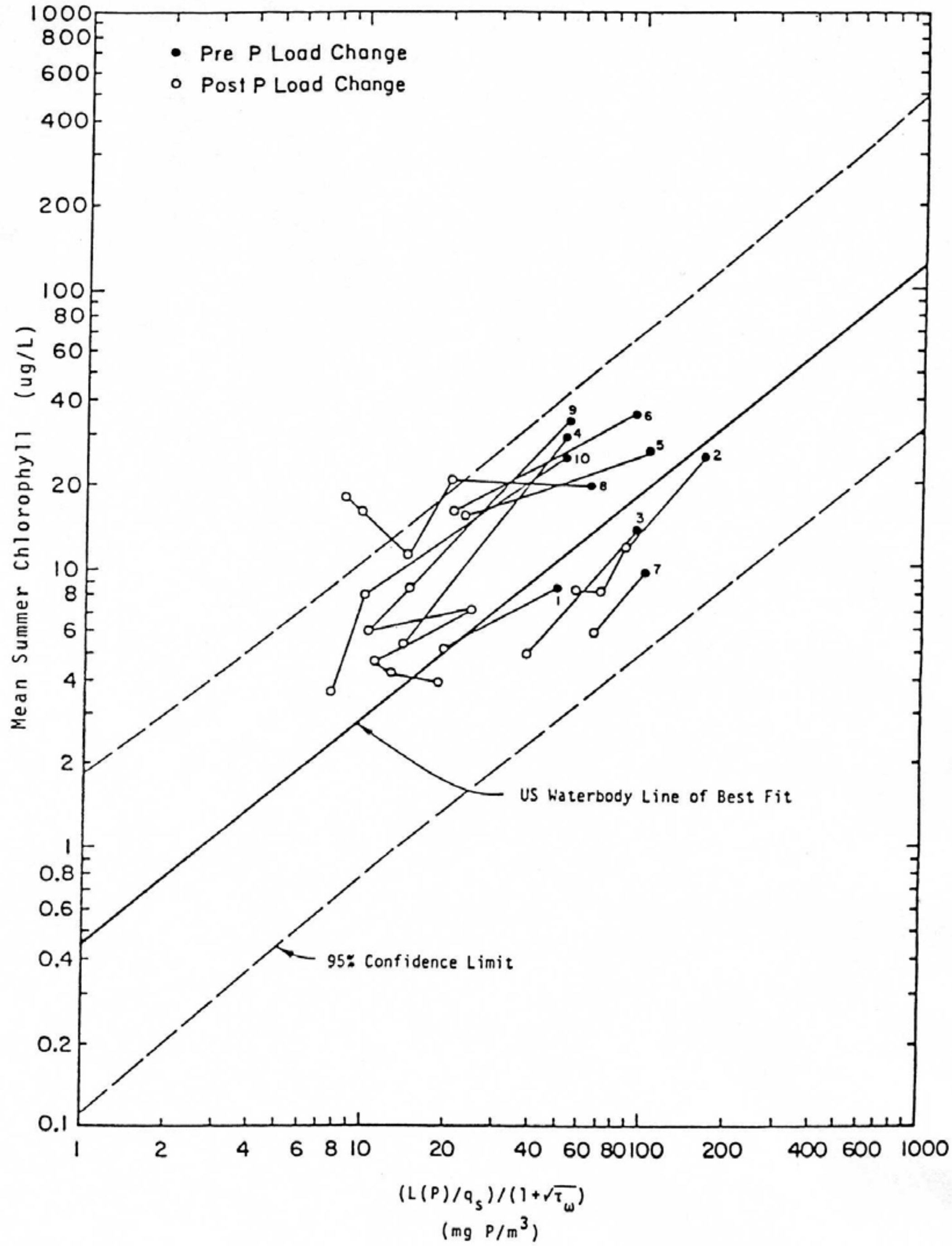

FIG. 5—*Normalized phosphorus loading–chlorophyll response couplings before and after phosphorus load changes* [11].

inorganic turbidity or color is significantly limiting phytoplankton production in a water body [7]. Primary productivity and fish yield can also he utilized as response parameters, but the data bases for the models for these parameters are not as well developed at this time as those for chlorophyll and Secchi depth.

The normalized phosphorus loading and response couplings are then plotted on the appropriate model. If the coupling coordinates are within the family of points that comprise the model, it may be concluded that the aspect of the ecosystem considered is functioning as may be expected based on the norm established by the model. If the coordinates are outside the family of points, the data inputs should be reexamined: First, the reliability of all input data should be examined. Then, each aspect of data input (phosphorus load, morphology, hydrology, and response) should be evaluated to determine whether a factor that would be expected to skew the relationship was overlooked in applying the model. Jones and Lee [6, 7] and Rast et al. [11] discuss the conditions under which the models are not applicable or may need to have input data modified before application. As discussed in those sources, the points of focus should include the following: If the water body has a hydraulic residence time of less than two weeks, if it has a high degree of inorganic turbidity or color (a Seechi depth of less than about 0.5 m during non-algal-bloom periods), or if primary production is significantly manifested as aquatic macrophytes or non plank tonic algae, the models should not be applied directly. If the water body has significant arms or bay areas or is long and thin in shape, with the result that the nutrients added do not rapidly mix throughout the water body, then it should be sectioned and the sections should be evaluated separately for their load-response relationships. If there has been a major perturbation in the phosphorus loading within the recent past (typically during the two to three years prior to the load-response assessment), the water body may not have come to equilibrium with its new loading. In that case, the water body response could be reflecting past loading conditions and not the loading that was measured or estimated at the time of the response assessment. It has been found [11, 13] that a new equilibrium is established after a time period equivalent to about three times the phosphorus residence time of the water body.

If the reevaluation does not reveal conditions that would render the model inappropriate, and the data appear reliable, it may he concluded that something is causing the water body ecosystem to be functioning differently from the approximately 500 water bodies on which the models were formulated. This would suggest that there may have been an impact on the functioning of the aspect of the ecosystem assessed.

Application of Model

One useful application of the Vollenweider-OECD models in overall ecosystem functioning assessment is in the management of toxics in aquatic systems. This is an area of particular importance to the U.S. Environmental Protection Agency (EPA) and state water pollution control agencies, which are beginning to implement control programs for toxics in industrial and domestic wastewaters [14]. One of the most important questions that has to be addressed in the cost-effective implementation of these programs is the potential benefits that can be derived from the control of toxicity in a wastewater effluent in terms of overall ecosystem functioning as it relates to designated beneficial uses of the receiving waters. If the toxicity is restricted to an area near the point of discharge, that is, the mixing zone, it may be of little or no significance to the overall ecosystem. However. if the impact is system-wide and directed toward system components of concern to the public, such as the numbers of catchable desirable fish, then much greater emphasis should be given to developing control programs. While ecosystem functioning evaluation approaches that focus on measurement of one aspect of the ecosystem may indicate that an impact has occurred, especially if evaluated near the point of discharge of a toxic effluent, this impact may be of little or no consequence to the functioning of the *overall* ecosystem. The Vollenweider-OECD modeling approach allows evaluation of the overall functioning of a number of integrated aspects of the ecosystem. Lee and Jones [15] have discussed the problems of implementing the U.S. EPA [14] toxics control program as it relates to beneficial uses of receiving waters.

An example of how the Vollenweider-OECD models can be used for overall ecosystem functioning evaluation is seen in work the authors of this paper are doing in the New York; New Jersey coastal waters. Preliminary evaluations of the phosphorus load and chlorophyll response for the Hudson/

Raritan estuary in New York and New Jersey show that less algal biomass is being produced than would be expected based on the normalized phosphorus loading. The authors suspect that this situation may be related to the presence of toxics in these waters. However, what will happen to eutrophication-related water quality as the concentrations of toxics are reduced is of concern to the recreational, commercial, and residential developments in that area. It is believed that as the toxics are reduced, as they will be with increased control, the problems with excessive fertilization will increase; the algae will be able to grow to the levels expected based on the loading of nutrients and the other characteristics of the ecosystem. Therefore, unless phosphorus control programs are initiated along with toxics control programs, the development projects and existing uses, which are tied to the aesthetic character of these waters, may be adversely impacted by toxics control programs. The Vollenweider-OECD modeling approach can be used to determine how much phosphorus control is needed to achieve a given level of planktonic algal production in a particular water [7]. In addition to the concern for eutrophication problems resulting from the toxics control programs, the model also indicates that the toxics present at this time may be in sufficient quantities to limit the ability of the system to support fish, because of decreased amounts of planktonic algae.

It has also been found that, in laboratory toxicity tests, water extracts from sediments of the Hudson/Raritan estuarine system have substantial toxicity to algae and varied (generally low to moderate) toxicity to higher level organisms. The approach discussed herein could be used to assess the overall impact on ecosystem functioning associated with this source of contamination, and to help assess the cost-effectiveness of techniques that may be considered for remediation and future handling of the contaminated sediments.

Sensitivity of Relationships

In assessing the potential utility of the Vollenweider-OECD modeling approach (or any approach) for overall ecosystem functioning evaluation in a particular water, it is important to consider the sensitivity of a potential management decision to the results of the evaluation. Ecosystem functioning and the characteristics used to assess ecosystem functioning may be highly variable within any one system, and may vary considerably with the season, year, or other naturally occurring conditions. The scatter of points about the lines of best fit in the models illustrated attest to the natural variability in ecosystem functioning and to the variability that results from constraints in our ability to define the relationships precisely. It should be noted that a considerable part of the variability about the lines of best fit relates to the accuracy with which measurements of chlorophyll and phosphorus loads can be made.[3] Nonetheless, since chlorophyll and phosphorus determinations are among the more reliable measurements typically made, the reliability of this approach is likely to be at least as good as the reliability of other, less well established methods of assessment of ecosystem functioning.

Variability may also be associated with the differences in manifestations of primary production in any given water body. The response parameters used in these models are associated with planktonic algal growth. The extent to which unusual proportions of the primary production are in nonplanktonic algal forms may contribute to some of the scatter. These characteristics, however, may vary over an annual cycle or from year to year. Even with whatever variation exists in the accuracy of chlorophyll and phosphorus load measurements, and with variations in the conditions of the water bodies, the predictive capability of this approach has been clearly demonstrated [11], with the predicted values of planktonic algal chlorophyll found to be within 50% of the measured values in real-world situations. This type of verification is not available for most types of environmental quality models when applied to systems other than those for which they developed and tuned. It illustrates the solidity of the

[3]Vollenweider, R. A., Canada Centre for Inland Waters, Burlington, Ontario, Canada, personal communication, 1983.

models and their applicability despite normally expected variations in planktonic algal chlorophyll and other measurements.

As an example of the sensitivity of the model, examination of Fig. 1 shows that a water body with a normalized phosphorus loading of 100 mg phosphorus/m^3 would be expected to have an average chlorophyll concentration of between 4 and 60 µg/L. For a water body on which minimal data were available, if the average chlorophyll concentration were substantially out of that range, one could consider the system to behave differently from other systems evaluated. This may seem to be a rather insensitive indicator, with more than an order of magnitude in a "normal" characteristic range. However, several things must be considered before that assessment can be deemed to be appropriate. First, based on a considerable body of data, the range of the "norm" for the variety and number of water bodies included is consistent throughout the three orders of magnitude of normalized phosphorus loading for which data are available. It thus appears that the family of points describing the norm is, indeed, an appropriate assessment of the degree of variability that can be expected in the chlorophyll response—or overall ecosystem functioning—to normalized phosphorus loading. The data base for the models is extensive and expansive and, for most of the water bodies included, is based on a substantial monitoring program. Second, the sensitivity of this overall ecosystem functioning evaluation approach must be viewed in relation to the sensitivity of other ecosystem functioning evaluation approaches available when extrapolated to overall ecosystem functioning. The authors are not aware of any other ecosystem functioning modeling approach that has been evaluated for the variety and number of water bodies that the Vollenweider-OECD modeling approach has.

Third, and most important, if a monitoring program is established on the water body in question, in which load and response are measured over a several-year period, the location of the couplings for the water body from year to year can be more closely defined. As discussed by Jones and Lee [7], having this data base can reduce the range of the norm for the particular water body in question considerably. However. the behavior of the water body in its phosphorus load-response relationship in the model, the external perturbations, and the recovery time for perturbations must be well understood before load-response couplings that fall within the family of points shown in Fig. 1 are judged to represent substantial effects on overall ecosystem functioning.

Summary and Conclusions

The Vollenweider-OECD models provide a synthesis indication of overall ecosystem functioning. They can describe whether as many algae grow as would be expected based on the normalized phosphorus loading or whether something is causing fewer algae to grow. They also describe whether as much fish biomass is supported by the algal biomass measured or expected as would be expected. In addition, they provide insight into the effects of perturbations on the functioning of the ecosystems assessed, such as nutrient load reductions or increases, or changes in the morphological or hydrological characteristics of the water body. These relationships have demonstrated capability to predict the impact of such perturbations on the aspects of the overall ecosystems evaluated. The models are based on the actual load-response relationships found in a wide variety of aquatic ecosystems throughout the world.

While some ecosystem function tests are of limited scope in that they only assess a small portion or aspect of the system, or rely on a laboratory model ecosystem, the Vollenweider-OECD modeling approach can assess a variety of functions and, indeed, integrates them into an overall system assessment. In the use of any ecosystem functioning test or evaluation approach for environmental management purposes, this integration needs to be made. Only in the context of how a perturbation has affected the overall integrity of an ecosystem—a much broader context than one aspect of the system—can effective management programs be developed. This is the focus of the Vollenweider-OECD models.

Acknowledgment

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