NUTRIENT LOADING ESTIMATES FOR LAKES

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ABSTRACT: The nitrogen and phosphorus loads to a waterbody may be reliably estimated on the basis of the waterbody's watershed land use pattern and the nitrogen and phosphorus export coefficients for each dominant type of land use. Good agreement was found in a comparison between the nitrogen and phosphorus export coefficients developed in this study and the measured amounts of nitrogen and phosphorus transported to 38 U.S. waterbodies. Good agreement was also found between the load estimated by the Vollenweider model relating the mean annual in-lake and inflow phosphorus concentrations of a waterbody, and the measured amounts of phosphorus that actually entered the 38 waterbodies.

INTRODUCTION

Excessive fertilization (eutrophication) is one of the most significant causes of water quality deterioration in lakes and reservoirs in the United States and in many other countries. In recent years, a number of investigators have developed models for quantitatively relating nutrient loads (usually phosphorus) to the eutrophication responses of a waterbody resulting from these loads. The responses reflect a wide range of water quality impairment, including increased algal biomass, fish productivity, total phosphorus concentration, oxygen depletion in the hypolimnion, water clarity, taste and odors, and shortened filter runs for domestic water supplies (1-7,9-13). The effective use of these quantitative nutrient load-eutrophication response models depends not only on the basic structure and predictive capability of the model used, but also on the accuracy of the nutrient load estimates used as input to the models.

The major nutrient inputs to a waterbody generally are wastewater discharges, land runoff, the atmosphere (precipitation and dry fallout), and ground water (principally nitrogen). The inputs from several of these sources, especially the non-point sources, are usually difficult to quantify reliably. The accuracy of the estimate of the nutrient load to a waterbody is dependent upon a number of factors, including the frequency and duration of sampling of the point and non-point sources, analytical methodologies used, percent of tributaries sampled, etc.

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It is the purpose of this paper to present several methodologies for assessing the accuracy of nutrient load estimates. These approaches may also be used to provide estimates of nutrient loads in the event of sparse or nonexistent loading information.

WATERSHED NUTRIENT EXPORT COEFFICIENTS

The use of nutrient export coefficients for estimating phosphorus and nitrogen loads is based on the knowledge that, for a given climatological regime, specific types of land uses (e.g., agricultural, urban, or forest) will yield or export characteristic quantities of these nutrients to a downstream waterbody over an annual cycle. This nutrient export is associated primarily with land runoff resulting from precipitation in the watershed and is usually expressed on an areal basis. Knowing the area of land in a watershed devoted to specific uses and the quantities of nutrients exported per unit area of these uses (i.e., the nutrient export coefficients), it is possible to estimate the annual total phosphorus and nitrogen loads to a waterbody from non-point sources.

Rast and Lee (24) reviewed the literature on nutrient export coefficients for the purpose of developing generalized nutrient export coefficients which would be applicable to large parts of the United States. Based on this review, representative values of major watershed nutrient export coefficients are presented in Table 1. Examination of Table 1 shows that several differ-

TABLE 1.—Typical Values of Watershed Nutrient Export Coefficients

Watershed land usage (1)	Source: Sonzogni and Lee (31) (2)	[a]Source: Uttormark, et al. (34) (3)	Source: U.S. EPA (28) Omernik (22) (4)
(*a*) Total Phosphorus (g P/m^2 · yr)			
Urban	0.1	0.15	0.03
Rural/agriculture	0.07	0.03	0.03 (0.02)[b]
Forest	—	0.02	0.01 (0.02)[c]
Wetlands	[d]	[d]	[d]
Atmosphere:			
Precipitation	0.02	—	—
Dry fallout	0.08	—	—
(*b*) Total Nitrogen (g N/m^2 · yr)			
Urban	0.5	0.5	0.8
Rural/agriculture	0.5	0.5	1.0 (0.6)[b]
Forest	—	0.25	0.4 (0.4)[c]
Wetlands	[d]	[d]	[d]
Atmosphere:			
Precipitation	0.8	—	—
Dry fallout	1.6	—	—

[a]"Average" value indicated by Uttormark, et al. (35).
[b]"Mostly agriculture" (other types present).
[c]"Mostly forest" (other types present).
[d]Net nutrient contribution is considered to be zero.

ent nutrient export coefficients, varying widely in some cases, have been reported for various major land-use activities. From this review, Rast and Lee developed the values presented in Table 2 as generally applicable to many U.S. waterbody systems. The overall approach used in developing the values in Table 2 is reviewed in the following.

Based on their extensive literature review, Uttormark, et al. (34) concluded that when using land-use activities as the basis for estimating non-point source nutrient loads, there is little justification at the present time for the delineation of land usage within drainage basins beyond the four broad categories of urban, agriculture, forest, and wetlands. They indicated that available nutrient export data are too fragmentary and variable to warrant further subdivision of land-use categories. Loehr (21) and Wanielista, et al. (39) have also used these general categories. Vollenweider (personal communication, 1977) has indicated, based on studies of land usage in watersheds in Germany, that a further delineation in the agricultural land-use category into arable land and pasture/meadows may be useful because these two latter classes of land-use activities export distinctly different quantities of phosphorus and nitrogen. Rast and Lee (24), however, found that the nutrient export values re-ported by Vollenweider for these two agricultural land-use sub-categories were considerably higher than the North American agricultural values reported by Uttormark, et al. (34), and were therefore atypical of nutrient export from agricultural lands in the United States.

The urban area phosphorus and nitrogen export coefficients of Sonzogni and Lee (31), presented in Table 1, were derived for the Lake Mendota, Wisconsin, watershed. The Sonzogni and Lee coefficients generally represent reasonable averages of the urban area coefficients reported by Uttormark, et al. (34), the U.S.

TABLE 2.—Watershed Nutrient Export Coefficients

Watershed land use (1)	Watershed export coefficient, in grams per square meter times year (2)
(a) Total Phosphorus	
Urban	0.1
Rural/agriculture	0.05
Forest	0.005–0.01
Atmosphere[a]	0.025[b]
(b) Total Nitrogen	
Urban	0.5 (0.25)[c]
Rural/agriculture	0.5 (0.2)[c]
Forest	0.3 (0.1)[c]
Atmosphere[a]	2.4 (1.0)[b,c]

[a]Atmospheric load consists of precipitation and dry fallout directly onto the surface of the water body.

[b](Grams per square meter of waterbody · yr).

[c]Parenthetical values are export coefficients to be used in calculating nitrogen loads for waterbodies in the western U.S. after Rast and Lee (24).

EPA (28), and Omernik (22). The urban coefficients of the U.S. EPA were based on land-use studies done in 473 sub-drainage areas in the eastern United States. While the Uttormark, et al., urban area export coefficients were also derived primarily from land-use studies in the northeastern and upper midwestern U.S., they also include data from several studies done in the southern and western U.S. and are, therefore, more representative of a "national average" than the values of either Sonzogni and Lee or the U.S. EPA. Consequently, Rast and Lee (24) focused on the values of Uttormark, et al. as more accurate national average values for urban areas in the United States.

A rural/agriculture phosphorus "national average" export coefficient of 0.05 g $P/m^2/yr$, adopted in Table 2 by Rast and Lee (24), was an average of the values presented by Sonzogni and Lee, Uttormark, et al., and the U.S. EPA. Rast and Lee also adopted a rural/agriculture nitrogen export coefficient of 0.5 g $N/m^2/yr$ because it was essentially identical to the value of both Sonzogni and Lee and the U.S. EPA. The rural/agriculture export coefficients for both phosphorus and nitrogen are also about the same as those reported by Dunigan and Dick (7) and Omernik (22,23) for agricultural land.

The phosphorus export coefficient of Uttormark, et al. (34) for forested land was thought by Rast and Lee to be too high for use as an average value, based on their literature review and on the comparison of the value with the export coefficient for "mostly forest" land reported by the U.S. EPA (28) and Omernik (22). Consequently, Rast and Lee selected the forest phosphorus export coefficient of 0.01 g $P/m^2/yr$ derived by the U.S. EPA as a representative average value for forested land. The writers now feel that a range of values 0.005 and 0.01 g $P/m^2/yr$ should be used for forested lands. A forest nitrogen export coefficient 0.3 g $N/m^2/yr$ was chosen as an average of the values reported by Uttormark, et al. and the U.S. EPA.

Wetlands or marshes can act as sinks or sources of nutrients, depending upon the specific season of the year. It has been found, however, that the quantities of phosphorus that enter and leave wetlands over an annual cycle are essentially equal (34,17). On this basis, Rast and Lee (24) concluded that the net contribution of nutrients from wetlands is zero over the annual cycle, as noted in Table 1. A further analysis of nutrient cycling in wetlands is presented elsewhere (34,17,11). It is noted that while an established wetland would be expected to discharge the same amount of phosphorus over the annual cycle as the quantity which entered it, the phosphorus discharged from the wetlands could be in a markedly different chemical form than the phosphorus entering the wetland. Phosphorus leaving wetland areas should generally be less available to aquatic plants than the phosphorus entering the wetland (11,18).

Both an average value and a parenthetical low value are presented for the nitrogen export coefficients in each land-use category in Table 2. The low values were included for use in estimating nitrogen loads for watersheds in the western part of the United States, since the quantities of nitrogen derived from land-use activities in that part of the country are typically lower than in the upper midwest or eastern U.S. This is because the concentrations of ammonia and especially nitrate in atmospheric precipitation appear to be lower in the western part of the country.

The generalized atmospheric values presented in Table 2 for estimat-ing the nutrient contributions to waterbodies from precipitation and dry fallout directly onto a waterbody were taken primarily from studies done in the Great Lakes Region (8,40), rather than from the study of Sonzogni and Lee noted in Table 1. The atmospheric values in Table 2 are essen-tially the same as those reported by Dunigan and Dick (7) and Omernik (22,23), and Rast and Lee (24) concluded they were sufficiently accurate for generalized use in estimating loads from atmospheric deposition.

Rast and Lee evaluated the general applicability of the nutrient export coefficients in Table 2 by comparing the measured nutrient loads to a large number of waterbodies with the calculated loads based on wa-tershed land-use distribution and the export coefficients in Table 2. They used approximately 38 U.S. waterbodies as the data base for this com-parison (Figs. 1-2). These waterbodies were studied as part of the In-ternational Cooperative Programme for the Monitoring of Inland Waters (24) of the Organization for Economic Cooperation and Development (OECD). A listing of the U.S. OECD waterbodies, including location, estimated trophic status, and identification number for subsequent fig-ures, is presented by Rast and Lee (24).

The solid line in Figs. 1-2 signifies a perfect agreement between the calculated and reported (mostly measured) nutrient loads for the U.S. OECD waterbodies. The broken lines represent the degree that the re-ported nutrient loads may be over or underestimated relative to the cal-culated loads. The shaded zone represents the range within which the estimated loads are within a factor of ±2 of the reported loads. Thus, for example, the ±3 broken line indicates that the estimated load is three times greater than the reported load. In general, Rast and Lee found that most of the estimated loads were within a factor of ±2 of the measured loads. It should be noted, however, that while the U.S. OECD study included a variety of watersheds across the U.S., it did not include many watersheds in areas receiving less than about 25 cm/yr of precipitation. Caution should be exercised, therefore, in applying the nutrient export coefficients in Table 2 to watersheds in arid climates until studies have been conducted to demonstrate the applicability of these coefficients to that specific climatic regime.

It is noted that Reckhow, et al. (27), and Reckhow and Simpson (26) have recently presented a compilation of land-use export coefficients de-rived from a large number of studies. They use several of these coeffi-cients in demonstrating error analyses associated with the prediction of in-lake phosphorus concentrations from land-use information. While their compilation is a summary of some studies from which nutrient export coefficients have been derived, Reckhow, et al. (27) make the observa-tion, nevertheless, that the selection of phosphorus export coefficients for a given land-use activity is still largely subjective in nature. In light of this observation, a significant weakness of their report is that they offer no practical guidelines or criteria for making an appropriate selec-tion of export coefficients. Rather, the user must rely mainly on "match-ing" their specific land-use characteristics with those presented in the compilation of Reckhow, et al. Another significant deficiency of the

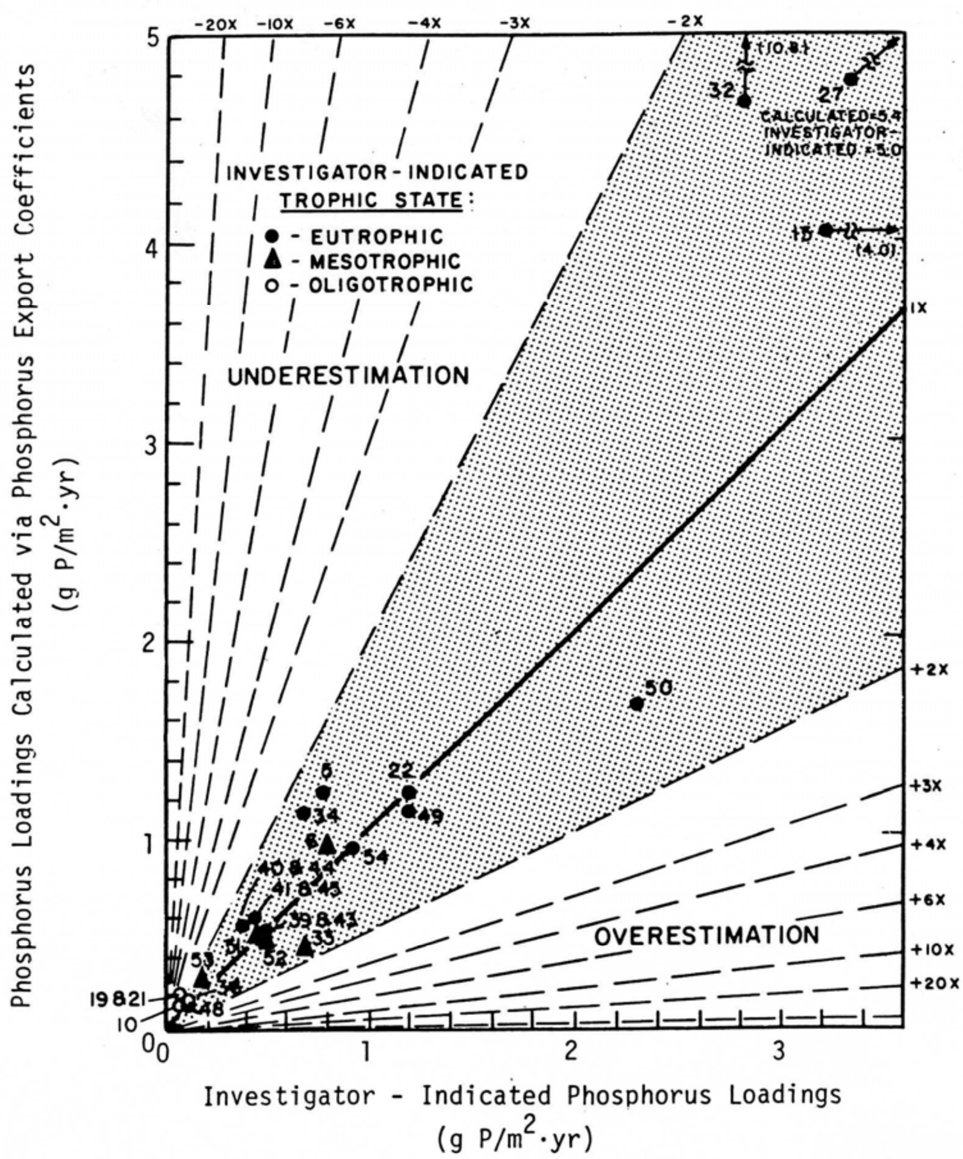

FIG. 1.—Evaluation of Phosphorus Load Estimates Using Phosphorus Export Coefficients

Reckhow report is the failure to review the extensive work done on this topic as part of the U.S. OECD studies that were published as a U.S. EPA report in 1978 (Rast and Lee (24)) and were included as a summary paper covering the U.S. OECD eutrophication studies published by Lee, et al. (20). The U.S. OECD eutrophication studies provide one of the most comprehensive data bases that ever have or will ever likely be developed on the amounts of nitrogen and phosphorus derived from various types of land use in the United States.

An important advantage of the coefficients described in this report is that they represent values which appear to be sufficiently general to be applicable to a wide range of watersheds in the U.S. Thus, the subjective

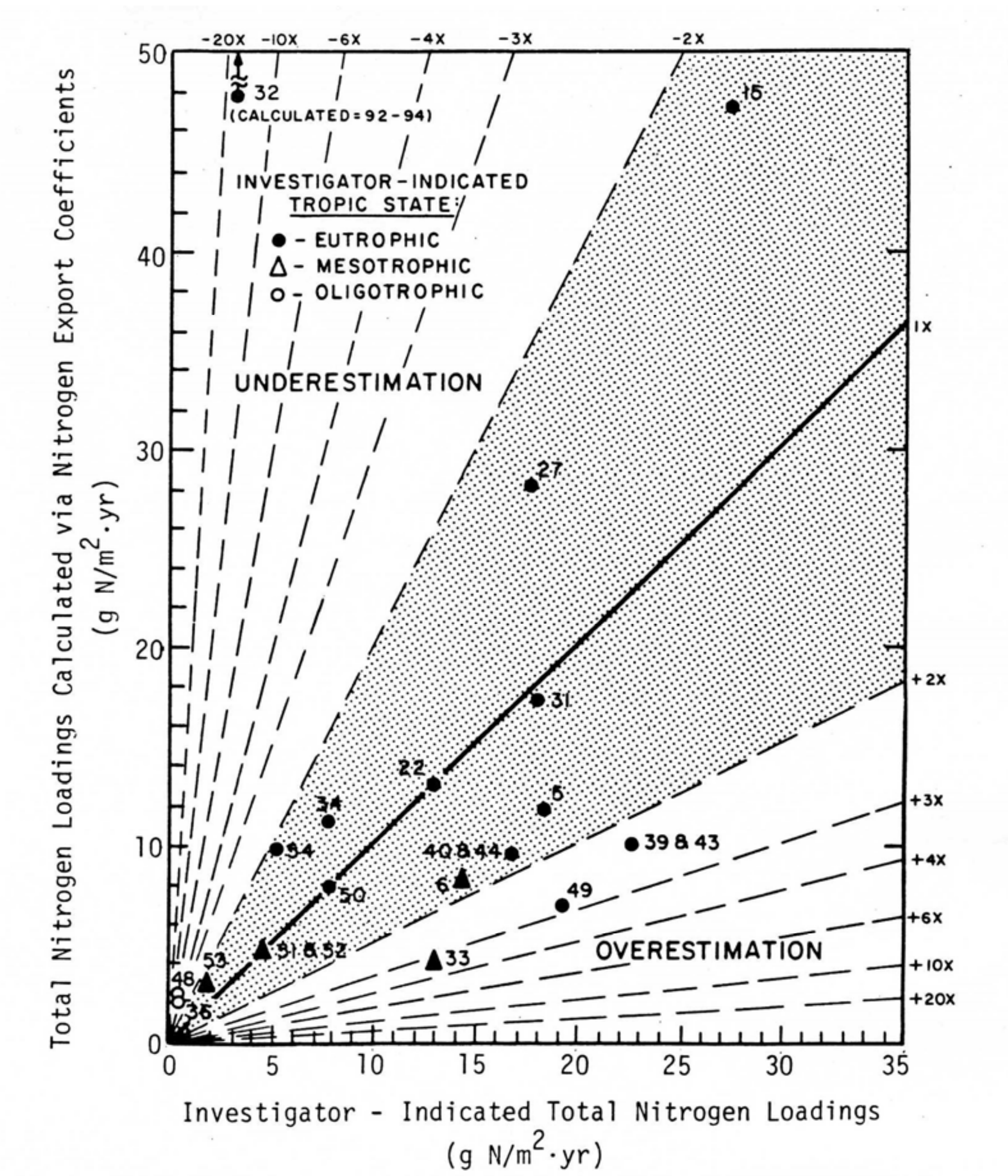

FIG. 2.—Evaluation of Nitrogen Load Estimates Using Nitrogen Export Coefficients

nature of the selection process inherent in the approach of Reckhow, et al. (27) is largely avoided. Furthermore, water quality managers may not be familiar with how the information on land use, precipitation, and water runoff factors described in the report of Reckhow, et al. should be used in selecting the most appropriate value in any given situation. This does not mean that the export coefficients described in this report are necessarily better than those of Reckhow, et al., but rather that they can be used on a more generalized basis (and require less information on specific land-use factors) than those in the compilation provided by Reckhow, et al.

Estimation of Nutrient Inputs from Non-Point Sources.—In order to estimate non-point source nutrient loads using nutrient export coeffi-cients, the watershed of the particular waterbody should be defined from topographic maps. Land usage can be determined with the use of aerial photography. If aerial photographs of the watershed are more than five years old, the watershed should be flown again and aerial photographs with sufficient resolution to define the dominant types of land use should be obtained. Another approach with potential usefulness for identifying land usage within a watershed is satellite imagery, such as that provided by LANDSAT, although this technology is still evolving.

The delineation of land use for most U.S. watersheds can be restricted to urban, rural/agricultural (including cropland and pasture), forest, and wetland categories. As analyzed previously, more detailed definition of land usage at this time does not appear to be justified at the present time since the quantities of nutrients derived from further subdivisions of these major categories are generally not well known, and since the more general categorization appears to be suitable for the purposes intended.

The areal extent of each of these major types of land use is then multiplied by the appropriate nutrient export coefficient listed in Table 2 to obtain the annual load of phosphorus and nitrogen from these non-point sources. The nutrient export coefficients should be used only for estimating annual nutrient loads, since they are based on the annual export of nutrients from watersheds.

It should be recognized that the quantity of phosphorus and nitrogen derived from the land is highly dependent on rainfall frequency, duration, and intensity in the watershed. The average nutrient export coefficients presented in Table 2 would be most applicable during years with "average" quantities of rainfall and other climatic conditions. The estimated loadings may not be accurate if the climatic conditions for the current year, or for the previous year, were atypical. An example of such an occurrence was noted in a study by Lee, et al. (16) of Lake Ray Hubbard, a water supply impoundment located in Dallas, Texas. Prior to the study period, there had been several years of limited rainfall in some parts of the watershed. As a result, some of the farm ponds on various tributaries in these parts of the watershed did not completely fill with water during the dry period. Thus, the phosphorus which did enter the tributaries from the land in these areas was retained in these partially filled upstream ponds. During the study (16) in the spring of 1977, sufficiently heavy rainfall occurred to fill the ponds for the first time in several years, resulting in water and associated nutrients entering tributaries to Lake Ray Hubbard for the first time in several years. During a period of several days of this rainfall period, approximately 8054 of the normal annual total phosphorus load entered Lake Ray Hubbard. This period of heavy rainfall, following several relatively dry years, also resulted in abnormally high phosphorus export coefficients being calculated for the watershed of the affected tributaries.

Studies conducted by the U.S. EPA, in the same general region during the National Eutrophication Survey (29,30), several years prior to the Lake Ray Hubbard study (16), produced phosphorus export coefficients more characteristic of the values found in many other parts of the country. In contrast to the total phosphorus export per unit area of wa-tershed, the total nitrogen export reported by Lee, et al. (16) for Lake Ray Hubbard was not significantly higher than the values reported by

Rast and Lee (24) or the U.S. EPA (29,30). The similar nitrogen values may have been due to the fact that, under normal conditions, ammonia derived from the land is readily oxidized to nitrate, which can be transported via ground water to the lake. Nitrate is not normally retained on the soil surface to the same extent as phosphorus during dry periods. Since the nitrate is not retained on the surface following a heavy rainfall, it is not present in runoff to the same degree as phosphorus.

Estimation of Nutrient Inputs from Point Sources.—In order to estimate the total phosphorus and nitrogen loads to a waterbody, it is also necessary to have an estimate of the point source nutrient loads, as well as the non-point source loads. As reviewed by Rast and Lee (24), the most significant point sources for nutrient loads to waterbodies are gen-erally domestic wastewater treatment plant effluents discharged directly to the waterbody, or, more commonly, to a tributary of the waterbody. Measurements of the flow and the chemical content of such effluents are normally made routinely by plant personnel. The phosphorus and nitrogen can he calculated, therefore, as the product of the average dis-charge multiplied by the average phosphorus and nitrogen concentra-tions. An alternative method is to estimate the nutrient input on the basis of the number of people served by the facility and the type of wastewater treatment provided (24). For the U.S., the per capita total phosphorus load after conventional secondary treatment is approxi-mately 1.1 kg P/person/yr. For nitrogen, the load is on the order of 2.7 kg N/person/yr. Those wishing to use per capita contributions to estimate the point source nutrient loads in other countries are cautioned, however, to evaluate the applicability of these values to other countries since these values are somewhat different from those observed by the writers for municipal wastewaters in Spain and Japan, possibly reflect-ing differences in basic food stuffs and eating habits, usage of phosphate detergents, presence of significant numbers of garbage grinders, etc., in these and other countries.

It should also be determined if there are any other potentially significant nutrient sources in the watershed, such as animal feedlots. If other potentially significant nutrient sources were found, it would then be necessary to quantify the nutrients derived from these sources as well. Export coefficients for sources such as feedlots have been reported in the literature (e.g., see Vollenweider (38) and Loehr (21)).

Applicability of Nutrient Export Coefficients.—The application of nutrient export coefficients to specific watershed land-use activities as a method of estimating nutrient loads is a useful tool in directing the field monitoring programs, so that such programs can focus on those nutrient sources likely to be of major significance to a waterbody. This approach can also be used to evaluate the reliability of nutrient load estimates based on field studies. It is usually always preferable that nutrient loads be measured wherever possible. In the absence of any field studies, however, this approach can provide an estimate, usually accurate within a factor of two, of the amounts of nutrients expected to enter a waterbody on the basis of specific land-use activities. Horstman, et al. (9) provide an example of how this approach can be used to assist in making water quality management decisions in cases where loading data are limited.

VOLLENWEIDER IN-LAKE PHOSPHORUS/INFLOW PHOSPHORUS RELATIONSHIP

The empirical phosphorus loading-lake response models developed by Vollenweider (36-39) during the OECD study, and those developed by Rast and Lee (24) on the basis of the U.S. portion of the OECD study, are statistical correlations between factors which generally exert primary control over the eutrophication process in waterbodies (24,20,12). Based on the initial work of Vollenweider (35-38), Rast and Lee (24) and Jones and Lee (12) have developed statistical correlations between the annual phosphorus load on an areal basis (normalized by mean depth and hydraulic residence time), and the water quality response parameters of chlorophyll concentration (water "greenness"), Secchi depth (water clarity), and hypolimnetic oxygen depletion rate, as well as other parameters. These three relationships, in particular, have been found basically applicable to a large number of waterbodies located in several parts of the world.

These relationships have their conceptual origin in the work of Vollenweider who derived an input-output mass balance equation for total phosphorus in waterbodies. Rast and Lee (24) have provided an analysis of these relationships.

Vollenweider (35) has shown that the ratio of a waterbody's mean in-lake phosphorus concentration to its inflow phosphorus concentration $(P)_\lambda/(\bar{P})_i$, is theoretically equivalent to the value of the hydraulic residence time expression, $1/(1 + \sqrt{\tau_\omega})$. This theoretical relationship can be used to check the reliability of phosphorus load estimates to a waterbody, since the inflow phosphorus concentration is a function of the phosphorus load, i.e., $(\bar{P})_i = L(P)/q_s$. Any major deviations of the value of $(P)_\lambda/(\bar{P})_i$ from the value of $1/(1 + \sqrt{\tau_\omega})$ would make the reported phosphorus loading data suspect. Vollenweider (personal communication, 1977) has found this relationship useful in tracing loading errors in the estimated phosphorus budgets for Lakes Constance and Lunzer See. Rast and Lee (24) have also found this relationship valuable in evaluating the reported phosphorus loadings for the U.S. OECD waterbodies. It should be noted that no equivalent relationship has been derived for checking the accuracy of nitrogen loading estimates, although a similar approach would likely be applicable. Two factors complicating the formulation of such a relationship are nitrification and denitrification reactions.

In applying the phosphorus relationship to the approximately 38 U.S. OECD waterbodies, Rast and Lee (24) found that the estimated load for most of these waterbodies was within a factor of ±2 of that determined by the U.S. OECD investigator who had extensively studied the water-body (Fig. 3). Furthermore, using this relationship and the U.S. OECD data base, Vollenweider (personal communication, 1977) calculated the standard deviation of the relative error, considering $1/(1 + \sqrt{\tau_\omega})$ as the reference value. He found that 65% of the data points were within a factor of ±2 of the reference value, which is very close to the theoretical 67% statistical value of one standard deviation. Considering the multitude of methods used by the U.S. OECD investigators in determining the annual phosphorus loads (see Rast and Lee (24) for a summary of these

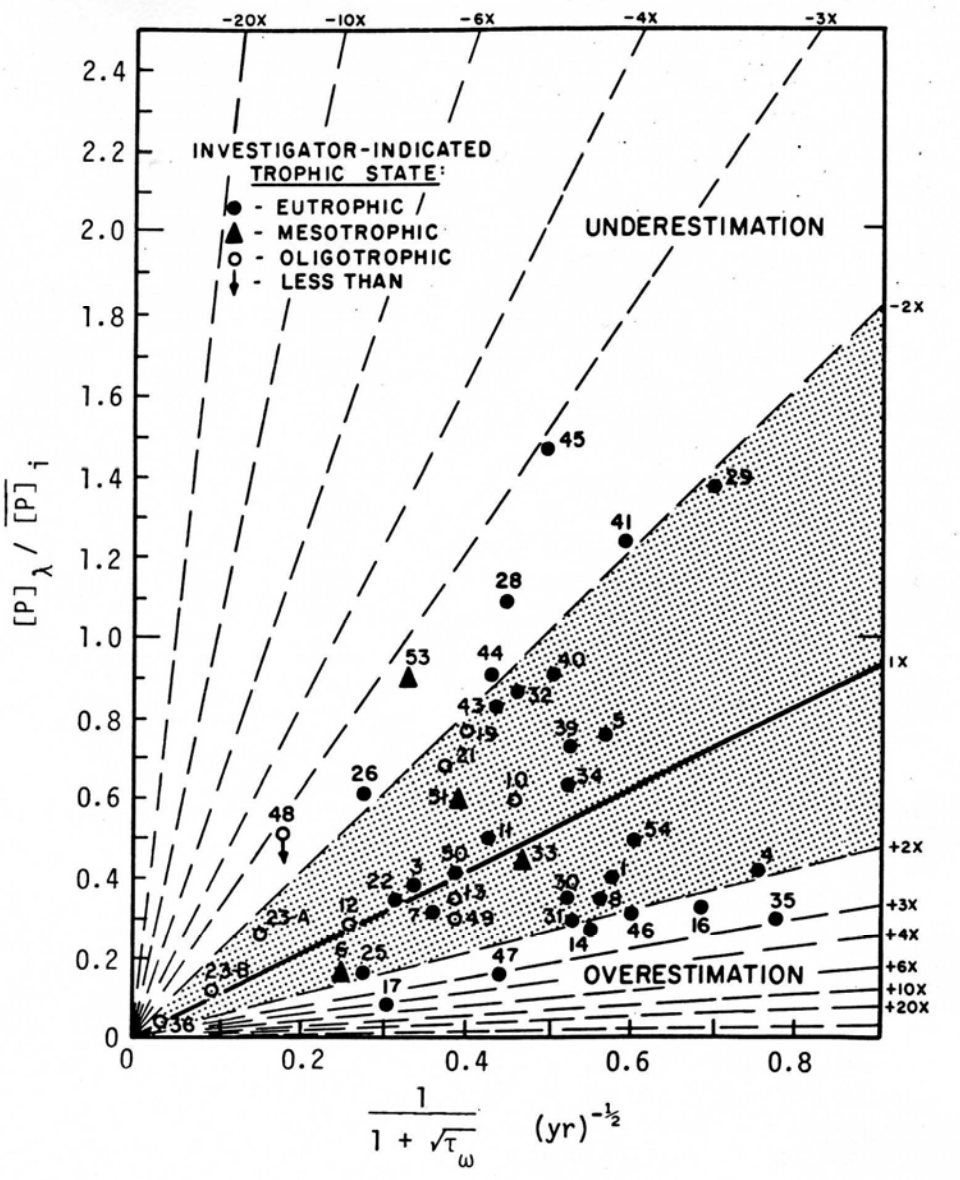

FIG. 3.—Evaluation of Nutrient Load Estimates Using Vollenweider Relationship

methodologies), there is remarkably good agreement between the phosphorus loading estimates made with the Vollenweider relationship and the loads reported by the individual investigators of the U.S. OECD waterbodies.

Once the phosphorus load to a waterbody has been estimated, and assuming that accurate information is available on the average in-lake phosphorus concentration, the Vollenweider relationship can be used to check on the reliability of the estimated load. It should be emphasized that a major disagreement between the values derived from these two approaches for estimating nutrient loads does not necessarily mean that a significant error in the nutrient load estimate has been made. It could mean instead that there may be errors in the values of the other parameters in the model or that the way in which a particular waterbody uti-lizes phosphorus in the production of planktonic algae may be different from similar waterbodies located in many other parts of the U.S. and the world. If the latter situation has occurred, this may necessitate mod-ifying the approach taken to assess the degree of eutrophication in that particular waterbody.

NUTRIENT LIMITATION AND TOTAL VERSUS AVAILABLE FORMS OF NUTRIENTS

The coupling of nutrient loads and eutrophication responses is complicated by several factors, one of which is the nutrient which limits planktonic algal growth in the waterbody of concern. Rast and Lee (24) and Lee, et al. (18) consider the fact that the production of planktonic algae in a majority of waterbodies tends to be limited by phosphorus inputs, or, alternatively, the waterbody can be made phosphorus-limited by sufficient reduction in the phosphorus loads. This places major emphasis in most eutrophication control efforts on the reduction of phosphorus loads (rather than nitrogen) to a waterbody as the major approach on a practical scale for attempting to alleviate the water quality deterioration associated with eutrophication.

Another complicating factor is the fact that while phosphorus (as well as nitrogen) enters, and exists in, waterbodies in a number of different chemical forms, only some of these forms can be readily used by algae, i.e., only some forms of phosphorus are immediately biologically available or potentially available over time. Lee, et al. (18) provide a detailed analysis of the biological availability of phosphorus in natural waters and its implications for phosphorus management strategies. Lee, et al. concluded, based on the work of Cowen and Lee (3) and Cowen, et al. (4), that the available phosphorus input from diffuse sources in the Lake Ontario basin can be approximated generally as the sum of the tributary soluble orthophosphate content plus 20% of the particulate phosphorus content. DePinto, et al, (5) have reported that approximately 50% of the particulate phosphorus present in domestic wastewater treatment plant effluents is readily available to support algal growth. They also reported that about 80% of the total soluble phosphate in domestic wastewater treatment plant effluents is readily available. Cowen, et al. (4) reported that the available nitrogen input from diffuse sources in the Lake On-tario basin can be approximated as the sum of the tributary total am-monia and nitrate content, plus 80% of the organic nitrogen content. While not reviewed by Cowen, et al. (4), the tributary nitrite content should also be added to this list, since nitrite is or will likely become an available nitrogen form for uptake by algae. While nitrite is generally thought to be highly reactive in natural water, one of the writers (Lee), in studies of Colorado Front Range rivers, is finding nitrite concentra-tions, in both the summer and winter, in the mg N/L range below some domestic wastewater treatment plants.

The locations of point source inputs relative to the waterbody itself can also impact the biological availability of nutrients. The available fraction of the nutrient load to a waterbody from a point source can be markedly different, if the point source discharge is into a tributary several kilometers or more upstream of its entrance into the waterbody, than if the point source discharge is directly into the waterbody or into a tributary near the point at which the tributary enters the waterbody. Furthermore, as analyzed by Rast and Lee (24), Lee, et al. (16), and others, if a waterbody has arms or bay areas with hydraulic residence times greater than about two weeks during the summer months (which is sufficient time for substantial algal growth to occur), large amounts of the nutrients entering the arm or bay can be rendered unavailable by retention in the sediments, such that the nutrient load to the main body of the lake can be considerably less than the load entering the arm or bay. For example, Lee, et al. (16) found that an arm of Lake Ray Hubbard retained as much as 90% of the phosphorus load entering it. Furthermore, if the waterbody is long and narrow, considerable amounts of nutrients can be retained in its upper end. These points have been considered by Rast and Lee (24) and Jones and Lee (12).

The statistical eutrophication modeling approach used in this evaluation is based on total phosphorus loads. In its formulation, however, internal nutrient cycling and the biological availability of phosphorus are accounted for to some degree. It would be expected that waterbodies which receive disproportionate amounts of particulate phosphorus (compared to the U.S. OECD waterbodies) would not show the same degree of planktonic algal growth for a given total phosphorus load than if more of the phosphorus load were in biologically available forms. Furthermore, if a phosphorus load reduction program incorporates the removal of mostly particulate phosphorus, a smaller improvement in phytoplankton-related water quality would be expected than if a greater proportion of the available phosphorus load were removed. In the practical application of these OECD phosphorus loading models for water quality management, these writers have observed that, to the present time, the biological availability of the phosphorus inputs have not presented a major problem in their use in assessing the expected water quality responses of lakes to phosphorus load reductions. Differences in the biological availability of the total phosphorus loads likely account for some of the variance observed thus far in the phosphorus loading models developed in the U.S. OECD study (24,35,20,12). However, in the practical use of these models for assessing the water quality impact of changes in phosphorus loads, each waterbody is considered individually and its position relative to the regression line of best fit does not change, i.e., the same relative confidence intervals are maintained in assessing the lake response to a reduced phosphorus load. The effect is to move the data point for an individual waterbody essentially parallel to the regression line corresponding to the reduction in its phosphorus load. Further analysis of this approach is provided by Rast and Lee (24), Jones and Lee (12), and Rast, et al. who consider the practical application of these phosphorus loading models, and Rast, et al. (25) who consider the predictive capability of these empirical models in assessing the water quality responses of waterbodies to changes in their phosphorus loads.

Recently, the Quality Control in Reservoirs Committee of the American Water Works Association has developed three reports designed to provide guidelines for the use of the U.S. OECD eutrophication modeling approach in developing phosphorus management programs for waterbodies. These reports provide information on the minimum monitoring program needed to apply the U.S. OECD eutrophication modeling approach to a waterbody (15), methods for estimating nutrient loads to a waterbody (19), and methods for estimating the limiting nutrient in a waterbody (14). These reports should be consulted for further information on the use of the U.S. OECD eutrophication modeling approach for managing excessive fertilization in a lake or impoundment.

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