Eutrophication (Excessive Fertilization)

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Abstract

Excessive fertilization (eutrophication) of lakes and reservoirs is recognized as one of the most important causes of water quality impairment of lakes, reservoirs, and some streams, rivers, and nearshore marine waters. Driven by excessive input of nitrogen and phosphorus, eutrophication is characterized by the presence of sufficient planktonic and attached algae and/or water weeds to impair the use of water for domestic water supply (tastes and odors, shortened filter runs, THM precursors, etc.), recreation, and fisheries (decline in coldwater fisheries, fish kills). The control of excessive fertilization requires an understanding of the loading of nutrients, nutrient availability, and the quantification of the relationship between nutrient load and eutrophication response for the waterbody of concern. Simple concentration-based standards are unreliable for effective eutrophication control. The Vollenweider – OECD eutrophication modeling approach, as amplified by the authors, can be used to develop and evaluate nutrient control options and estimate the change in eutrophication-related water quality that could be achieved for the control program for a given lake or reservoir.

Key Words:
Excessive fertilization, eutrophication, nitrogen, phosphorus, nutrients

Introduction

"Eutrophication" is the process of a waterbody's becoming increasingly rich in aquatic plant life such as algae and aquatic macrophytes (water weeds). It is driven by the increasing input of aquatic plant nutrients, principally nitrogen and phosphorus, from natural and anthropogenic sources. While natural eutrophication takes place over geologic time, activities of people that increase the aquatic plant nutrient inputs to waterbodies can rapidly accelerate this process and cause cultural eutrophication. Thus the term "eutrophication" has become synonymous with "excessive fertilization" or the input of sufficient amounts of aquatic plant nutrients to cause the growth of excessive amounts of algae and/or aquatic macrophytes in a waterbody such that beneficial uses of the waterbody (i.e., water quality) are impaired. Beneficial uses of waterbodies that stand to be impaired by the presence of excessive amounts of aquatic plant life include domestic and industrial water supply, recreation, and fisheries.

Because of the public health and environmental quality significance of these water quality impairments, myriad strategies have been advanced to evaluate and regulate excessive fertilization

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and nutrient input to waterbodies, with varying degrees of technical validity and demonstrated effectiveness. This chapter reviews what should be considered in assessing the impacts of nutrients that are added to a waterbody on the waterbody's eutrophication-related water quality. References are provided to more detailed discussions of the issues covered.

Impacts of Excessive Fertilization on Water Quality

The excessive fertilization of waterbodies is a long-standing, well-recognized water quality problem throughout the US and other countries. It is manifested as excessive growths of planktonic (suspended) algae, attached algae, and aquatic macrophytes (water weeds). Aquatic macrophytes can be floating forms such as water hyacinth or duckweed, or attached-emergent forms. Water quality problems caused by these growths, discussed in detail by Lee (1973), are summarized below.

Domestic Water Supplies. When raw water supplies contain large amounts of algae and some other aquatic plants, the cost of treatment increases and the quality of the product may be diminished. Planktonic algae can shorten filter runs. They can also release organic compounds that cause tastes and odors, and, in some instances, serve as trihalomethane (THM) and haloacetic acid (HAA) precursors. THMs are chloroform and chloroform-like compounds; HAAs are low molecular weight chlorinated organic acids. These compounds are produced when the precursors react with chlorine during the disinfection process and are regulated as human carcinogens.

Violations of Water Quality Standards. Excessively fertile waterbodies can exhibit marked diel (over a 24-hr day) changes in pH and dissolved oxygen concentrations that can result in repeated short-term violations of water quality standards. During daylight, algal photosynthesis removes CO_2 from the water which increases the pH; algal respiration in the night releases CO_2 and lowers the pH. In late afternoons the pH of excessively fertile water can be found to exceed the water quality standard for pH. Similarly, algae produce oxygen during photosynthesis, but consume it during respiration. Just before sunrise, after sufficient nighttime algal, bacterial and other organism respiration, dissolved oxygen concentrations can be below water quality standards for protection of fish and other aquatic life. Excessively fertile waterbodies that thermally stratify (develop a thermocline) often exhibit dissolved oxygen depletion below the thermocline due to bacterial respiration of dead algae. Richards (1965) showed that one phosphorus atom, when converted to an algal cell which subsequently dies, can consume 276 oxygen atoms as part of the decay process.

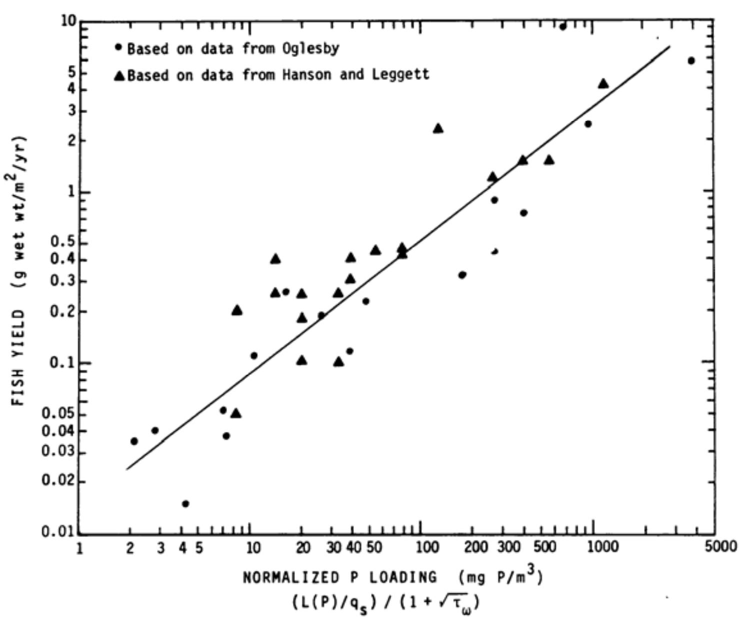
Toxic Algae. One of the major stimuli for the US EPA's recently increased attention to excessive fertilization is the *Pfiesteria* problem in Chesapeake Bay (US EPA, 2000a); fish kills occurred there due to the presence of toxic algae. Fish kills associated with toxic algae have occurred in various waterbodies around the world, including off the west coast of Florida, for many years. In addition, blue-green algae at times excrete toxins that are known to kill livestock and other animals that consume the water.

Impaired Recreation & Aesthetics. Excessive growths of attached algae and aquatic macrophytes can impair swimming, boating and fishing by interfering with water contact. Severe odor problems can also be caused by decaying algae, water weeds, and algal scums.

Water clarity – defined by the depth of the waterbody at which the bottom sediments can be seen from the surface — is an aesthetic quality that is compromised by eutrophication. Waterbodies with high degrees of clarity (i.e., the bottom can be seen at depths of 20 or more feet) have low planktonic algal content; in more eutrophic waterbodies, the sediments can only be seen at a depth of a few feet. The greenness of water, which contributes to diminished water clarity and is caused by the presence of algae, can be quantified by measurement of planktonic algal chlorophyll. Inorganic turbidity also diminishes water clarity and can influence the perception of greenness of a waterbody. Often, quite high levels of planktonic algal chlorophyll can be present in a shallow waterbody or river without the public's perceiving it to be excessively fertile, if the water is brown due to inorganic turbidity.

Impact on Fisheries. As illustrated in Figure 1, fertilization increases total fish production (biomass). However, as Lee and Jones (1991) discussed, it can adversely affect the production of desirable types of fish, especially at high fertilization levels. In stratified waterbodies, algae grow in surface waters, die, and settle to the hypolimnion (bottom layer) where they are decomposed. As noted above, the oxygen demand created by algal decomposition can be sufficient in eutrophic waterbodies to deplete the hypolimnetic oxygen. This means that the desirable coldwater fish (e.g., salmonids, trout) that normally inhabit the cooler hypolimnion cannot survive there because of insufficient oxygen. Thus the higher fish production characteristic of highly eutrophic waterbodies is typically dominated by rough fish, such as carp, which can tolerate lower dissolved oxygen levels.

Figure 1. Relationship between Normalized P Load and Fish Yield
(from Lee and Jones, 1991)



Shallow Water Habitat. Emergent aquatic vegetation in shallow waters provides important habitat for various forms of aquatic life. As discussed by Lee (1973), increased planktonic algal growth reduces light penetration (water clarity) which in turn inhibits the growth of emergent vegetation. This can result in loss of significant aquatic life habitat.

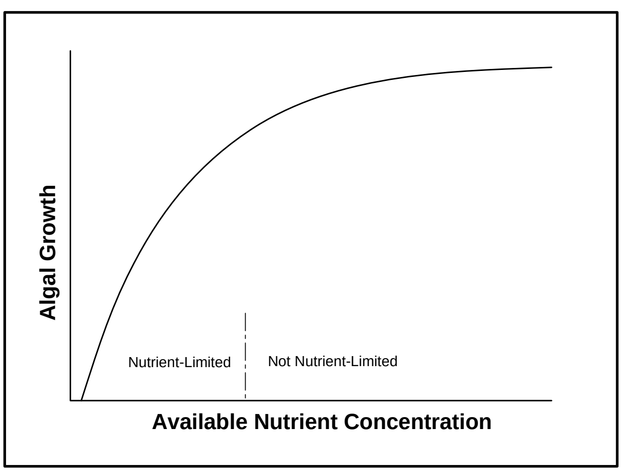
Overall Impacts. Excessive fertilization is one of the most important causes of water quality impairment of waterbodies. In its last National Water Quality Inventory, the US EPA (2000a) listed nutrients as the leading cause of impairment of lakes and reservoirs.

Controlling Excessive Fertilization

Algae and other aquatic plants require a wide variety of chemical constituents, light, and appropriate temperatures to grow. Of those factors, however, only nutrient input is amenable to sufficient control to effect a meaningful decrease in algal and aquatic plant biomass to reduce the adverse impacts of excessive fertilization. The issues of which nutrient(s) should be controlled, sources of the nutrient, what type of and how much control is needed, and the positive impacts of the control must be addressed in an eutrophication management program.

Limiting Nutrient. For managing algal populations, the primary focus should be on control of the nutrient that is present in the least amount compared to algal needs, i.e., the limiting nutrient. Increasing or reducing the amount of that nutrient available to algae will effect an increase or reduction in the algal biomass that can be sustained. This is illustrated in Figure 2 which shows that additional growth occurs in response to additional input of the limiting nutrient up to the point at which it is present in greater amounts than can be used. Nitrogen and phosphorus are the nutrients that typically limit algal growth. Phosphorus is more often the limiting nutrient in freshwater waterbodies, while nitrogen is often the limiting nutrient in marine waters. While the potassium content of some soils can limit the growth of terrestrial plants, potassium is not an element that limits aquatic plant growth.

Figure 2. Relationship between Nutrient Concentration and Algal Biomass (from Lee and Jones-Lee, 2000)



In order to determine which nutrient is limiting algal growth in a particular waterbody, some have relied on the comparison of the concentrations of nitrogen and phosphorus to the "Redfield" stoichiometric ratio of these elements in algae (16:1 atomic basis or 7.5:1 mass basis) shown in Equation 1.

$$106\ CO_2 + 16\ N + 1\ P + \text{trace elements} \Rightarrow \text{algae} + O_2 \qquad (1)$$

It is presumed that if the ratio is smaller than this, N would be limiting, and vice-versa. This can give very misleading results and lead to unreliable nutrient control measures because whatever the "ratio," either or both could be present in ample amounts for algal growth (Lee and Jones-Lee, 1998). Rather, it is the concentration of algal-available forms of nutrients at peak biomass – when the algal growth is being limited – that should be assessed. If the concentration of either has been decreased by its utilization to below growth-rate-limiting concentration, there is reasonable certainty that that nutrient is limiting algal growth.

Typically, growth-rate-limiting concentrations for phosphorus are on the order of 2 to 8 μg/L available P, and for nitrogen, 15 to 20 μg/L available N. It is important to recognize, however, that even growth rate-limiting concentrations can support appreciable algal biomass if there is sufficient time for algal growth to occur. Further, in many highly fertile waterbodies neither nitrogen nor phosphorus is limiting algal growth. Both can be present above growth-rate-limiting concentrations – i.e., on the plateau of the algal growth-nutrient concentration relationship in Figure 2.

Availability of Nutrients

Nitrogen and phosphorus exist in aquatic systems in many different forms, only some of which can be used by algae and aquatic plants. Therefore, in assessing the limiting nutrient in a waterbody or evaluating the control of nutrient input to a waterbody, it is essential to consider the forms in which the N and P exist in the loading sources and waterbody. Algal available forms of nitrogen are nitrate, nitrite, ammonia and, after conversion to ammonia, some of the organic nitrogen. The fraction of the organic nitrogen that is available is site-specific and depends on its source and age. Under limited circumstances some blue-green algae can fix (utilize) atmospheric nitrogen gas (N_2) that is dissolved in water and use it as a source of nitrogen for growth. Soluble orthophosphate is the form of phosphorus that is available to support algal growth. Most particulate phosphorus and organophosphorus compounds, and oxygen-phosphorus polymer chain and ring compounds (condensed phosphates) do not support algal growth.

In developing nutrient criteria, US EPA (1998, 1999) has been focusing on total phosphorus rather than algal-available forms. This approach can misdirect control programs to sources whose control will not result in cost-effective improvements in eutrophication-related water quality. For example, it was well-established many years ago that most of the particulate phosphorus in agricultural and urban stormwater runoff is not available to support algal growth. Lee *et al.* (1980) reported on their extensive research as well as the findings of others on this topic in a review of these issues for the International Joint Commission for the Great Lakes. From both short-term and long-term (one-year) tests, they found that the algal available P in agricultural and urban runoff can be estimated as the sum of soluble ortho-P and about 20 percent of the particulate P. Thus, most of the particulate P in agriculture and urban stormwater runoff from a variety of sources is not available for algal growth.

The lack of availability of much of the phosphorus in soils is well-known to the agricultural community which finds that total P in soils is not a reliable measure of plant-available P. As discussed by Lee and Jones-Lee (2002) nutrient criteria for regulating agricultural and urban stormwater runoff should be based on soluble orthophosphate and nitrate plus ammonia plus about

20 percent of the particulate P and N. However, if the source of the P and N is algae then most of the total N and total P will be mineralized and in time will become available to support algal growth.

Sources and Control of Algal Nutrients

Domestic Wastewater Discharges. Lee and Jones (1988) reviewed the North American experience in controlling the excessive fertilization of waterbodies. They reported that domestic wastewater discharges are one of the most significant and controllable sources of available nutrients contributing to eutrophication. To control phosphorus from this source, tertiary treatment of the wastewaters is commonly practiced. Chemical treatment using alum (aluminum sulfate) typically costs a few cents per person per day for the population served by the treatment plant. Enhanced biological treatment of domestic wastewaters may also significantly reduce the phosphorus content of domestic wastewaters. Typically, either chemical or enhanced biological treatment can reduce the phosphorus concentration in domestic wastewater effluent by 90% to 95%. The authors estimate that the domestic wastewaters of more than 100 million people in the world are treated for phosphorus removal in order to reduce the excessive fertilization of the waterbodies receiving the wastewater discharges.

Nitrogen can also be removed from domestic wastewaters although not as readily as phosphorus. Nitrogen removal generally involves nitrification of the ammonia and organic nitrogen to nitrate, followed by denitrification. The cost is typically five to 10 times greater than for phosphorus removal. While phosphorus control in domestic wastewaters is widely practiced, nitrogen control has only been implemented to a limited extent because of the higher cost and the fact that, for most freshwater waterbodies, phosphorus control is the more effective way to control excessive fertilization.

Land Runoff. Another source of nutrients for waterbodies is runoff from land. Based on US OECD (Organization for Economic Cooperation and Development) Eutrophication Study data for about 100 waterbodies' watersheds located across the US, Rast and Lee (1983) determined nutrient export coefficients for main categories of land use. Shown in Table 1, these coefficients define the mass of N and P that runs off a unit area of watershed land annually.

While the export coefficients for a given watershed depend on the particular setting, the values in Table 1 have shown reliability in several areas for estimating the potential significance of various types of land use in contributing nitrogen and phosphorus from a watershed. More specific nutrient export coefficients for agricultural lands should be evaluated based on soil characteristics, types of crops grown and other factors that tend to influence the amount of nitrogen and phosphorus exported from the land. While these coefficients are for total N and total P, when used in the Vollenweider-OECD eutrophication modeling approach discussed subsequently, the availability of the loading is taken into account.

Nutrient Runoff Control BMPs. Controlling nitrogen and phosphorus in runoff from rural land has not been highly successful. Sharpley (2000) reviewed the experience in trying to achieve a 40% reduction in nitrogen and phosphorus loads from agricultural lands in the Chesapeake Bay watershed. He indicated that limited progress has been made toward achieving that goal after about

15 years of effort. Similarly, Logan (2000) reported that little progress has been made in effectively controlling phosphorus from agricultural runoff in the Lake Erie watershed.

Table 1. Watershed Nutrient Export Coefficients (from Rast and Lee, 1983)

Land Use	**Export Coefficients ($g/m^2/y$)**		
	Total Phosphorus	**Total Nitrogen**	
Urban	0.1	0.5	0.25*
Rural/Agriculture	0.05	0.5	0.2*
Forest	0.01	0.3	0.1*
Other:			
Rainfall	0.02	0.8	
Dry Fallout	0.08	1.6	

* Describe nitrogen loadings for waterbodies in Western US.

Sprague *et al*. (2000) reviewed factors affecting nutrient trends in major rivers of the Chesapeake Bay watershed. They noted the difficulty discerning major changes in the contribution of nutrients from agricultural lands in the watershed due to year-to-year variability in nutrient export. This variability is related to a number of factors, including climate. They indicated that one of the principal methods for nutrient reduction from agricultural lands has been land retirement – i.e., termination of agricultural activities on the land.

Various "best management practices" (BMPs) have been implemented to control nutrient export from agricultural activities including grassy strips, buffer lands, altering fertilizer applications, etc. The US EPA (2000b) discussed the current information on BMPs to control potential pollutants derived from agricultural lands. While claims are made as to their effectiveness, it is evident from the US EPA review and the authors' experience that there is a lack of quantitative understanding of the cost-effectiveness of BMPs for control of nutrients from agricultural activities (Lee and Jones-Lee, 2004). Quantitative studies are urgently needed to determine how various BMPs influence phosphorus and nitrogen export from the land, efficacy for controlling eutrophication, as well as costs associated with controlling phosphorus export to various degrees (e.g., 25, 50 and 75%). This information then needs to be viewed in the context of what agricultural interests of various types can afford relative to market prices, including issues of foreign competition. Maintaining agriculture through subsidies is a long-standing tradition in the US. The control of nutrients from agricultural lands for the benefit of downstream waterbody users may also become one of the subsidy issues that will need to be considered in order to keep agriculture viable (although subsidized) in many parts of the US.

Importance of Light Penetration. Algal growth in almost all waterbodies is light-limited to some extent. Turbidity and natural color diminish the penetrability of light into a waterbody which affects the extent to which algae can use available nutrients. In fertile waterbodies, where the presence of abundant planktonic algae reduces the penetration of light further by self-shading, algae can photosynthesize only in the upper few feet of water. It is important to understand the influence of inorganic turbidity and natural color on the coupling between nutrient loads and eutrophication-related water quality. While erosion from a waterbody's watershed may increase the nutrient load, it also increases the turbidity in the waterbody, which in turn decreases light penetration and thereby slows algal growth. Thus, control of erosion in a waterbody's watershed can result in greater algal growth for the same nutrient concentration than would occur if the waters were still turbid from erosion in the watershed.

Issues That Need to Be Considered in Developing Appropriate Nutrient Control Programs

There are several key issues that need to be considered and evaluated in formulating nutrient control programs, the most important of which is the relationship between nutrient load and eutrophication-related water quality in the waterbody of concern. Each waterbody has its own water quality-related load—response relationship that needs to be defined.

First, the nature of the water quality impairment needs to be defined. This includes defining what the problem is (e.g., recreation impairment, aesthetics, tastes & odors), when the water quality problems occur (e.g., summer, fall, winter, spring), how eutrophication is manifested (planktonic algae, attached algae, macrophytes), and the desired eutrophication-related water quality characteristics. Next, the limiting nutrient during the period of concern and the primary sources of that nutrient should be determined. Each source should be evaluated for the availability of nutrients, the controllability of the available nutrients, and the cost of implementing and maintaining the control strategy. Finally a reliable modeling approach needs to be applied to estimate the improvement in eutrophication-related water quality that would be effected by the estimated expenditures for the potentially viable control options.

Desired Nutrient-Related Water Quality. The first step in developing appropriate nutrient load criteria is to identify the eutrophication-related water quality problem as well as the desired outcome of management for the waterbody. Types of problem/solution goals that may be identified include, as discussed above, preventing violations of average or worst-case-diel DO or pH standards, controlling algae-caused domestic water supply raw water quality problems (e.g., controlling tastes and odors, lengthening filter runs, reducing THMs, etc.), or increasing water clarity (Secchi depth). This evaluation should be done through a public process conducted by the regulatory agency because the public's perception of eutrophication-related water quality can be site-specific. In those areas where there are numerous waterbodies with marked differences in lake water clarity, for example, the public has the opportunity to compare waterbodies that are green with those that are clearer. There, the public's perception of high water quality is quite different from that in areas where all the waters have the same general greenness due to planktonic algae.

Nutrient control must be undertaken with appropriate consideration of factors that govern how the nutrient loading is used within the specific waterbody. Eutrophication modeling is used to integrate these factors to relate nutrient load to eutrophication-related water quality response. There are basically two types of eutrophication models:

- an empirical, statistical model, such as the Vollenweider-OECD eutrophication model discussed subsequently herein, developed from a large database quantifying how nutrient concentrations or loads relate to the nutrient-related water quality characteristics of the waterbody, and
- deterministic models, in which differential equations are used to describe the primary rate processes that relate nutrient concentrations/loads to algal biomass.

Deterministic models have a number of drawbacks for use in eutrophication management. Because of the number of equations incorporated into a deterministic model, there is no unique solution to the model. "Tuning" the model to match the nutrient loads and eutrophication condition in the waterbody of interest at the outset may not properly represent the conditions and response after nutrient load alteration. Thus its ability to reliably meet the goal of management evaluation – i.e., predicting the benefit to be gained by management options – is limited.

If the water quality problem is related to planktonic algae, the Vollenweider-OECD Eutrophication modeling approach is the recommended approach for determining the reduction in nutrient loads/concentrations necessary to achieve the desired nutrient-related water quality in many lakes and reservoirs. Described by Rast and Lee (1978) and amplified by Jones and Lee (1982, 1986), this model empirically relates normalized phosphorus loading to eutrophication-related water quality parameters of chlorophyll, water clarity, and hypolimnetic oxygen depletion rate through relationships formulated by Vollenweider (1976). These relationships take into account the influence of the key factors of the waterbody's mean depth, hydraulic residence time, and surface area on the utilization of phosphorus by algae within a waterbody. These models, based on the OECD (1982) and post-OECD Eutrophication Study data, are shown in Figure 3. Each point in each figure represents a lake, reservoir or estuary for which the nutrient load and eutrophication response had been measured for at least a year to generate the model point. Jones and Lee (1986) updated this model with data for more than 750 waterbodies in various parts of the world (Figure 4). The use of this modeling approach and its reliability for predicting the changes in response parameters after a change in nutrient loading has been described by Rast *et al.* (1983).

Rate of Recovery. One of the issues of particular concern in eutrophication management is the rate of recovery of a waterbody following reduction in the nutrient/phosphorus loads. Because large amounts of phosphorus are stored in lake sediments, some have incorrectly concluded that reducing the phosphorus load from the watershed would result in little improvement in water quality, especially in a waterbody with a long hydraulic residence time. However, Sonzogni *et al.* (1976) demonstrated that the rate of response in eutrophication-related water quality to reduction in phosphorus loading is governed by the phosphorus residence time in the waterbody. The P residence time in years is the total mass of phosphorus in the waterbody water column divided by the annual load. This is typically much shorter than the hydraulic residence time.

Figure 3. Relationships between Normalized P Load and Eutrophication-Related Water Quality Response – US OECD Eutrophication Study Results (after Rast and Lee, 1978)

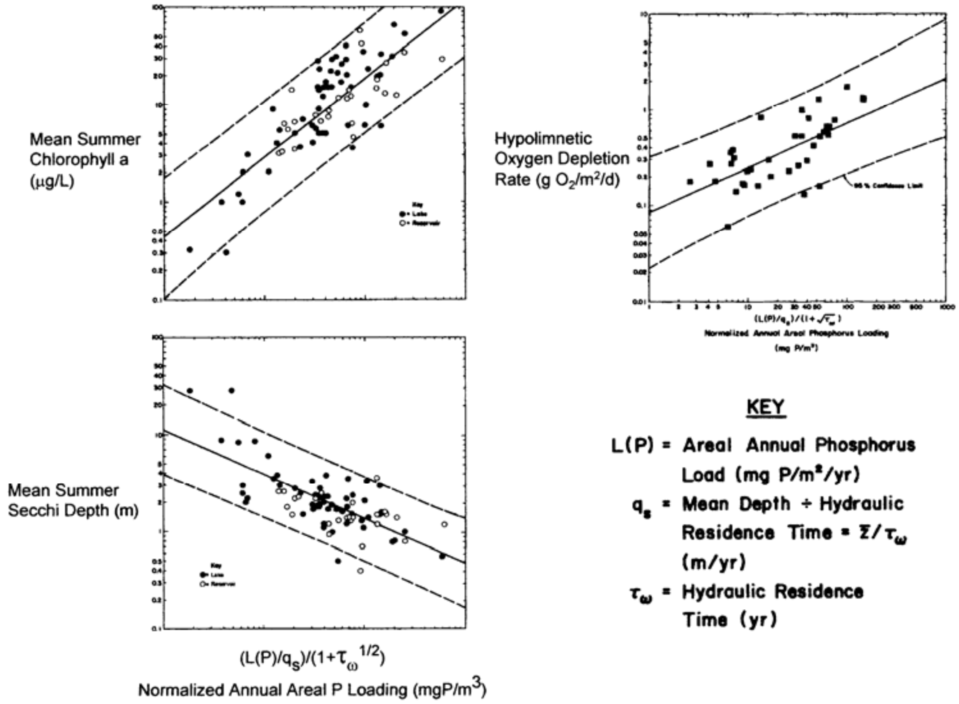
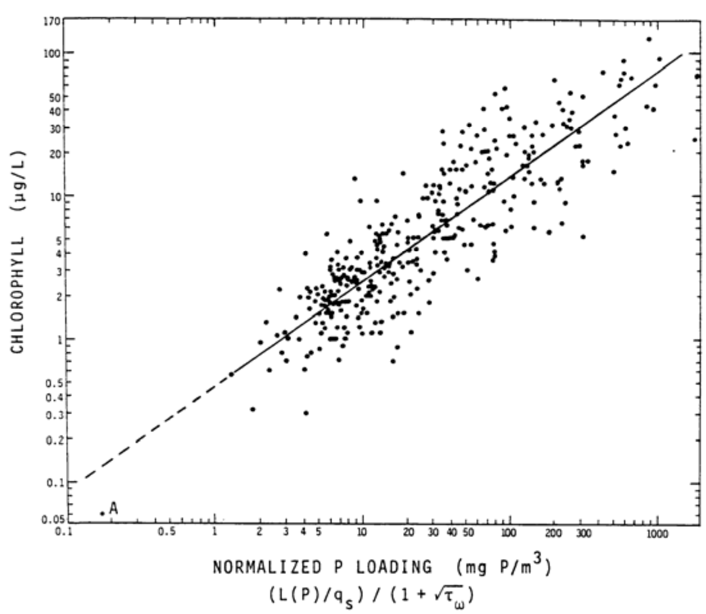


Figure 4. Updated Relationship between Normalized P Load and Planktonic Algal Chlorophyll Response (after Jones and Lee, 1986)



Conclusions and Recommendations

Excessive fertilization – eutrophication – is a major cause of water quality impairment. Domestic wastewaters, urban stormwater runoff and agricultural runoff/discharges are significant sources of nutrients that contribute to excessive fertilization of some waterbodies. Site-specific investigations are needed to determine the contribution of algal available nutrients from these sources and the extent to which they can be controlled. Using the Vollenweider-OECD eutrophication modeling approach, the expected improvement in beneficial uses that could be achieved in many lakes or reservoirs by effecting a given load reduction, and the expected recovery time can be estimated.

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