

Chapter 15

Assessing the Water Quality Impacts of Phosphorus in Runoff from Agricultural Lands

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The excessive fertilization (eutrophication) of waterbodies is recognized as one of the major causes of the impairment of the beneficial uses of waters through the growth of excessive amounts of aquatic plants such as algae and water weeds. Agricultural land use has been found to be an important source of N and P compounds leading to excessive fertilization of some waterbodies. Increasing attention is being given to controlling the water quality impacts of nitrogen and phosphorus compounds in stormwater runoff and irrigation tailwater discharges from agricultural lands. The US EPA is developing numeric chemically based nutrient criteria which will lead to increased efforts to restrict the discharge/release of N and P compounds from agricultural lands. This paper presents a review of issues that should be considered in assessing/managing the impacts of phosphorus derived from agricultural land runoff on eutrophication-related water quality.

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Introduction

Increasing attention is being given to controlling the water quality impacts associated with excessive fertilization (eutrophication) of waterbodies. This effort is leading to increased attention to the role of agricultural stormwater runoff and irrigation return water (tailwater) as a source of aquatic plant nutrients (nitrogen and phosphorus compounds) that cause excessive fertilization of waterbodies. The discussion presented herein is an overview of some of the issues that need to be considered by agricultural interests and those regulating agriculture in evaluating the water quality significance of nitrogen and phosphorus derived from agricultural land runoff/discharges. For a more detailed discussion of many of these issues, consult Jones-Lee and Lee (1), Lee and Jones-Lee (2) and references cited therein.

Water Quality Impacts of Waterbody Excessive Fertilization

The excessive fertilization of waterbodies is a long-standing, well-recognized water quality problem throughout the US and other countries. It is manifested in excessive growths of planktonic (suspended) algae and attached algae, as well as macrophytes (water weeds), which can either be floating, such as water hyacinth or duckweed, or attached-emergent. The impacts of excessive fertilization-eutrophication on a waterbody's water quality were discussed by Lee (3) and Lee and Jones-Lee (2). The impacts include:

- Domestic Water Supplies
Tastes and odors, shortened filter runs, THM precursors, and increased costs
- Violations of Water Quality Standards
pH and dissolved oxygen - photosynthesis
- Toxic Algae
Toxicity to fish and animals
- Impaired Recreation
Impaired swimming, wading, boating, odors and scum
- Impact on Fisheries
Improved fish production, less desirable fish at high levels of fertilization
- Shallow Water Habitat
Loss of attached vegetation and aquatic life habitat

Overall, excessive fertilization is one of the most important causes of water quality impairment of waterbodies. The US EPA (4), in its last National Water

Quality Inventory, has listed nutrients as the leading cause of impaired lakes and reservoirs. Further, the Agency lists agriculture as the primary source of constituents (nutrients and sediments) that impair lakes.

The fertilization of waterbodies is often of benefit to the fisheries-related water quality. Lee and Jones (5) have surveyed the world's literature on the relationship between phosphorus loads to waterbodies and fish production. As expected, there is a strong relationship between the normalized P load to waterbodies and the fish biomass.

Nutrients of Concern

The nutrients of primary concern are nitrogen and phosphorus compounds. While algae, like other forms of aquatic plants, require a wide variety of chemical constituents, light and appropriate temperatures to develop, the primary issue of concern in managing algal populations is the nutrient that is present in the least amount compared to algal needs. Typically, it is nitrogen and algal-available phosphorus compounds that are of concern. With respect to nitrogen, algae can use nitrate, nitrite, ammonia and, after conversion to ammonia, organic nitrogen compounds. All of these forms of nitrogen are nutrients for algal growth. While some blue-green algae at times can fix (utilize) atmospheric nitrogen gas (N_2) that is dissolved in water, and thereby use it as a source of nitrogen for growth, this occurs under restricted conditions, even for those blue-greens which have the potential ability to fix nitrogen gas dissolved in water.

With respect to phosphorus, it is the soluble orthophosphate that is available to support algal growth. There are many forms of phosphorus that do not support algal growth, particularly the particulate forms, as well as some organic phosphorus compounds and oxygen-phosphorus polymer chain and ring compounds (condensed phosphates).

For most freshwater waterbodies, it is the algal-available phosphorus in the water that limits algal growth. For marine waters, there is often surplus algal-available phosphorus compared to nitrogen. This can result in nitrogen becoming the limiting nutrient controlling the stimulation of algal growth. While the potassium content of some soils can limit the growth of terrestrial plants, potassium is not an element that limits aquatic plant growth.

There are frequently significant problems with the approaches used by some investigators in determining whether nitrogen or phosphorus is limiting algal growth in a waterbody. As discussed by Lee and Jones-Lee (6), the approach that should be used to determine the limiting nutrient is to examine the concentrations of available forms of nutrients at peak biomass, and then, if the

concentrations present are below growth-rate-limiting concentrations, there is reasonable certainty that the nutrient that occurs under these conditions is potentially limiting algal growth. Typically, growth-rate-limiting concentrations for phosphorus are on the order of 2 to 8 $\mu\text{g/L}$ available-P, and for nitrogen are on the order of 15 to 30 $\mu\text{g/L}$ available-N (in the form of nitrate, nitrite and ammonia). It is important to understand that, even at growth-rate-limiting concentrations, appreciable algal biomass can develop if there is sufficient time for algal growth to occur.

In many highly fertile waterbodies, neither nitrogen nor phosphorus is limiting algal growth. Both are present above growth-rate-limiting concentrations -- i.e., they occur up on the plateau of the algal growth-nutrient concentration relationship.

Total Phosphorus Versus Algal-Available Phosphorus

The US EPA (7), as part of developing nutrient criteria, is focusing on total phosphorus. However, 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.* (8) conducted extensive research on this topic, and also published a review of these issues for the International Joint Commission for the Great Lakes. They found, based on their work as well as the work of others, that the algal available P can be estimated as the soluble ortho-P, plus about 20 percent of the particulate P in agricultural and urban runoff. Algal-available nitrogen can be estimated as the nitrate plus nitrite plus ammonia, and some site-specific fraction of the organic nitrogen. The fraction of the organic nitrogen that is available depends on its source and age.

Algal growth experiments in which all nutrients needed for algal growth are available in surplus of algal needs except for the P in the water sample being tested, showed that most of the particulate P in agricultural and urban stormwater runoff from a variety of sources is not available for algal growth. These results are based on both short-term and long-term (one year) incubation. As discussed below, the lack of availability of particulate P in agricultural and urban stormwater runoff has important implications for development of BMPs and their evaluation.

Phosphorus Index

The US Department of Agriculture, the Natural Resources Conservation Service (9) and others have been developing a qualitative approach to estimating phosphorus fertilizer runoff from various types of agricultural lands. This effort

is leading to what is called the "phosphorus index" (PI). As currently developed, the PI is composed of a number of weighting factors. The stated objective of the PI is to provide guidance to the agricultural community on the relative potential for phosphorus applied in a fertilizer to be exported from the agricultural lands. The PI approach needs to be expanded from a qualitative discussion of phosphorus export issues to a quantitative assessment of how these various factors that lead to phosphorus export impact the phosphorus export coefficient for a particular type of soil, crop, fertilizer application rate and other dominant factors controlling phosphorus export.

Nutrient Criteria

In the 1990s the US EPA began to develop numeric chemically based nutrient (nitrogen and phosphorus) criteria which could be used to regulate nutrient runoff from agricultural and urban areas, as well as from domestic and industrial wastewater sources. Agriculture and other nutrient dischargers now face the use of nutrient (N and P) criteria to regulate nutrient releases from land. The US EPA's (10, 11) current approach for developing nutrient criteria will likely lead to many waterbodies' becoming listed as Clean Water Act 303(d) "impaired" waterbodies due to nutrient concentrations above the criterion values. The 303(d) listing will lead to the need to develop TMDLs to control nutrient runoff from agricultural lands and other sources.

The US EPA (12) has proposed two approaches for developing nutrient criteria. The national chemical-concentration-based default values are based on nutrient concentrations in the water, which are estimated based on pre-cultural activities (no agricultural or urban activities) in the waterbody's watershed. This relationship is shown in Figures 1 and 2. The US EPA default nutrient criteria are based on the nutrient concentration at the intersection of the "reference" stream 75th percentile nutrient concentration with the 25th percentile concentration for all streams as the criterion value. If there are no reference streams in an area then the 25th percentile of the nutrient data for a stream becomes the nutrient criterion. This approach is arbitrary and has nothing to do with regulating the impact of the nutrients.

The US EPA default nutrient criteria development approach is made even more unreliable as the result of the Agency using total P and TKN among the "nutrients" that are used in selecting the default criterion value. As discussed herein, for many waterbodies, especially in streams and rivers during elevated flows, large amounts of the total P and TKN are not in and do not convert to algal available forms. The US EPA's approach for developing ecoregion-based default nutrient criteria is obviously technically flawed and can readily lead to inappropriate regulation of nutrient runoff. Ditoro and Thuman (13) have commented that the US EPA's default nutrient criteria approach has neglected the link between nutrient concentrations and water quality impacts and implies that 75 percent of the waterbodies in an ecoregion will not meet nutrient criteria.

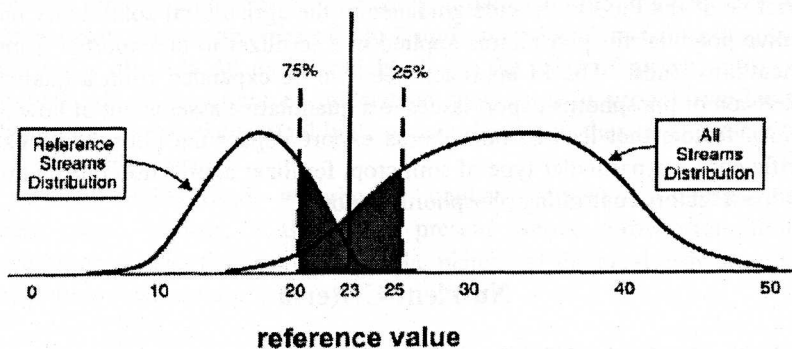


Figure 1. Source: US EPA, *Nutrient Criteria Technical Guidance Manual, Rivers and Streams* (12).

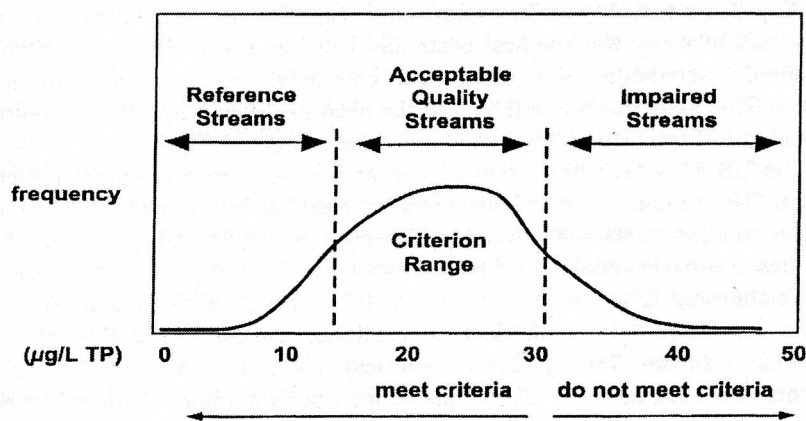


Figure 2. Source: US EPA, *Nutrient Criteria Technical Guidance Manual, Rivers and Streams* (12).

The Agency states that if states do not develop “scientifically defensible” nutrient criteria by the 2004 deadline, the default nutrient criteria will be imposed on the states as the state nutrient water quality standard. While recent information from the Bush administration (11) indicates that the 2004 deadline may be slipping, the Agency staff is still claiming that the states must have well-developed nutrient criteria by that date.

In developing appropriate nutrient criteria, it is suggested that the TMDL development approach is an appropriate approach to follow. This approach involves the following steps:

- Developing a problem statement – define impaired waterbody(ies).
- Establishing the goal of nutrient control (i.e., the desired water quality).
- Determining nutrient sources, focusing on available forms.
- Establishing linkage between nutrient loads and eutrophication response (modeling).
- Initiating a Phase I nutrient control implementation plan to control the nutrients to the level needed to achieve the desired water quality.
- Monitoring the waterbody for three to five years after nutrient control is implemented to determine whether the desired water quality is being achieved.
- If not, initiating a Phase II where, through the monitoring results, the load-response model is improved and thereby able to more reliably predict the nutrient loads that are appropriate for the desired water quality.

This approach is an iterative approach, where, over a period of at least five to possibly 15 years, through two or more consecutive phases, it will be possible to achieve the desired water quality and thereby establish the nutrient loads which can be translated to in-waterbody concentrations and, therefore, the nutrient criteria for the waterbody. Information on several of these components is discussed below and by Lee and Jones-Lee (2).

Issues that Need to be Considered in Developing Appropriate Nutrient Control Programs

There are a number of key issues that need to be considered/evaluated in formulating nutrient control programs, the most important of which is the nutrient load eutrophication response relationship for the waterbody(ies) of concern. Each waterbody has its own water quality-related load-response

relationship that needs to be evaluated. The notion that this evaluation should be restricted to just the US EPA's "ecoregion" approach, where waterbodies of a particular type, such as a lake, river, stream, etc., in an ecoregion can all have the same nutrient criteria, is fundamentally flawed since it ignores the vast amount of work that was done in the 1960s and 1970s in developing technically valid nutrient control programs for various types of waterbodies.

The primary issue of concern is the identification of the nutrient loads to a particular waterbody that cause or contribute to excessive fertilization of the waterbody -- i.e., cause water quality use impairment. Associated with this are the issues of when the water quality problems occur (in the summer, fall, winter, etc.), how they are manifested (planktonic algae, attached algae, macrophytes), what the desired eutrophication-related water quality is for the waterbody, what the hydraulic residence time (filling time) of the waterbody is and when the nutrients enter the waterbody that cause the water quality problems. The relationship among these various factors has recently been reviewed by Jones-Lee and Lee (1) and Lee and Jones-Lee (2). The ultimate goal of managing eutrophication-related water quality is to assess how the magnitude of the nutrient-caused water quality problem changes with a change in nutrient loads. This requires that an assessment of the cost of nutrient control to achieve desired water quality be developed.

The US EPA's nutrient chemical-concentration-based default criteria development approach does not adequately consider the variety of factors that influence how nutrients impact water quality beneficial uses of waterbodies. Not all nutrients above pre-cultural conditions are adverse to water quality. For many waterbodies, nutrients above "background" are beneficial to aquatic life resources (see Lee and Jones, 5). The development of appropriate nutrient criteria requires a balancing of the desired water quality in waterbodies with the cost of controlling nutrients from various sources.

The site-specific nutrient criteria development approach advocated herein is potentially supportable by the US EPA. The Agency staff have indicated that a site-specific approach to development of nutrient criteria for a waterbody or group of waterbodies could be accepted by the Agency, provided that it is based on a "scientifically defensible" approach. Thus far, the Agency has not defined what it means by "scientifically defensible," especially as it relates to situations where a waterbody would have high nutrient concentrations from agricultural runoff, where the nutrients are stimulating algal growth as measured by planktonic algal chlorophyll, well above those that, in many waterbodies, would cause significant water quality deterioration.

Control of Phosphorus and Nitrogen

The control of excessive fertilization of waterbodies has largely focused on controlling the phosphorus in domestic wastewaters. At this time there are about 100 million people in the world whose domestic wastewaters are treated for P removal. This is accomplished through tertiary treatment, which consists of either treatment by chemical additions (e.g., aluminum sulfate – alum), or enhanced biological treatment. Lee and Jones (14) have reviewed the North American experience in controlling the excessive fertilization of waterbodies. In general, it has been found that the approach that has been used is to control phosphorus added to the waterbody from domestic wastewater sources through tertiary treatment of the wastewaters.

Development of Appropriate Agricultural Nutrient Runoff Control BMPs

The experience in controlling nitrogen and/or phosphorus in rural land runoff has not been highly successful. Sharpley (15) has reviewed the experience in achieving a 40-percent nitrogen and phosphorus control in the Chesapeake Bay watershed. He has indicated that, after 15 years or so of control efforts, limited progress is being made in achieving the 40-percent reduction goal for phosphorus and nitrogen control from agricultural lands. Similarly, Logan (16), in a review of the experience of phosphorus control in the Lake Erie watershed, has indicated that little progress has been made in achieving effective phosphorus control in agricultural runoff.

Sprague, *et al.* (17) have presented a review of factors affecting nutrient trends in major rivers of the Chesapeake Bay watershed. They point out that it is difficult to discern 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 note that one of the principal methods for nutrient export reduction from agricultural lands has been land retirement -- i.e., termination of agricultural activities on the land.

The US EPA (18) has developed a discussion of the current information on BMPs to control potential pollutants derived from agricultural lands. Based on this review and the authors' experience, there is a lack of quantitative knowledge on the cost-effectiveness of agricultural nutrient control best management practices (BMPs). There are a variety of BMPs that are often indicated as being of potential value, such as grassy strips, buffer lands, etc.;

however, these so-called BMPs are largely effective only under low flow conditions and for particulate P. There is an urgent need to conduct quantitative studies on a variety of similar land and crop/fertilizer application situations to determine how these various BMPs influence algal-available phosphorus and nitrogen export from the land. These studies should be conducted in such a way as to provide for reliable cost estimates for controlling phosphorus export to 25, 50 and 75 percent of the uncontrolled (normal) conditions.

This information is essential to developing assessments of what can be done in the way of phosphorus control for various types of agricultural land use at various expenditures. This information will need to be presented in the context of what agricultural interests of various types can afford, relative to foreign competition, etc., that is establishing the market prices for agriculturally produced goods. There is a long-standing tradition in the US of wanting to maintain agriculture through subsidies. 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 a viable (although subsidized) agriculture in many parts of the US.

High-Tech Farming and Nutrient Runoff Management

Based on a recent review of information on high-tech crop production, it appears to be possible to significantly increase the yields of certain crops by what is being called "precision farming" approaches. Basically, this approach involves detailed soil mapping of the nutrient characteristics of the soil to provide for nutrient addition to specific areas where there is a deficiency, proportional to the deficiency. This approach maximizes the crop yield for the fertilizer applied. It apparently can at the same time result in reduced nutrient losses from the land to surface and ground waters. For further information on precision farming that was developed by North Carolina State University Water Quality Group for the US EPA, consult US EPA (18).

As part of developing nutrient control programs from agricultural lands, precision farming should be examined for selected areas in the watershed and for selected crops and soil types to determine if increased crop yield can result in increased profit to pay for the precision farming data requirements and, at the same time, reduce the amount of nutrient runoff from the precision-farmed area, compared to conventional farming techniques. Adopting this approach should lead to a better understanding of factors controlling nutrient export from various areas and crops.

Evaluating Allowable Nutrient Load to Waterbodies

To establish the allowable nutrient load for a waterbody, it is necessary to model the nutrient load eutrophication response relationships for the waterbody. There are basically two types of models:

- An empirical, statistical model, such as the Vollenweider-OECD Eutrophication model discussed by Jones-Lee and Lee (1) and Lee and Jones-Lee (2), which involves a large database on how nutrient concentrations or loads relate to the nutrient-related water quality characteristics of the waterbody.
- A deterministic model, in which differential equations are used to describe the primary rate processes that relate nutrient concentrations/loads to algal biomass.

The deterministic modeling approach, while able to be tuned to relate nutrient loads to eutrophication response, may have limited predictive capability. Because of the number of equations used, there is no unique solution to the model, and therefore, tuning the model may not properly represent the conditions that would be important in predicting eutrophication response (such as planktonic algae) under altered nutrient loads.

Desired Nutrient-Related Water Quality

The first step in developing appropriate nutrient water quality criteria is to establish the desired nutrient-related water quality for the waterbody(ies). This should be done through a public process conducted by the regulatory agency. Lee and Jones-Lee (2) have discussed an approach to evaluate the desired water quality in a waterbody.

Conclusions and Recommendations

Excessive fertilization of waterbodies is a major cause of water quality impairment. Agricultural runoff/discharges are significant sources of nutrients which contribute to excessive fertilization of some waterbodies. There is need for site-specific investigations to determine the amount that agricultural nutrient discharges/releases contribute to the excessive fertilization of some waterbodies. Managing excessive fertilization of waterbodies using technically valid, cost-

effective approaches requires understanding of nutrient load eutrophication response relationships for the waterbody.

There is need for information on nutrient export coefficients for various types of agricultural situations such as soil, crops, fertilizer application rates and approach, etc. BMPs need to be evaluated based on how they impact agricultural land algal-available nutrient export coefficients and the cost of treatment to achieve a 25-, 50- and 75-percent reduction in nutrient export. This information can then be used to formulate appropriate nutrient management programs for agriculture and other sources of nitrogen and phosphorus compounds that are causing excessive fertilization of waterbodies.

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