The North American Experience in Eutrophication Control through Phosphorus Management

G. Fred Lee* PhD, PE and R. Anne Jones* PhD
Distinguished Professor Associate Professor
Department of Civil and Environmental Engineering
New Jersey Institute of Technology
Newark, New Jersey USA

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INTRODUCTION

The theme of this conference is phosphate in water as it impacts the quality of life. Most of this conference is devoted to those water quality problems described as being associated with phosphate, and to the control of phosphate in the environment. However, it is important to emphasize that the water quality or "quality of life" problems that are of concern at this conference are not caused by phosphate per se; phosphate is non-toxic, essential for all life, and widely used by man for many beneficial purposes. Phosphate is, however, one of the major chemicals needed by aquatic plants, and contributes to the growth of algae and other aquatic plants in surface water. The "quality of life" concerns for phosphate are thus largely impairments of beneficial uses of surface waters that are caused by excessive amounts of algal biomass (eutrophication). Excessive fertility may cause impairment of a number of types of beneficial uses such as recreational, water supply, commercial, irrigation, and industrial. The algal-related impairment of water supply water quality through the association of increased algal growth with increased trihalomethane (THM) precursors, is now receiving increasing attention.

Phosphate is only a focal point of this conference because it is one, of many, substances needed for the growth of algae, because reductions in phosphate may result in reductions of algal biomass, and because the input of phosphorus to many waters can be managed. In actuality, the amount of algae that develop in a waterbody depends on the supply of algal-available forms of phosphate, nitrogen, and a multitude of trace nutrients, as well as on the morphology and hydrology of the waterbody.

Phosphate is added to aquatic systems from a variety of sources, both "natural" and associated with the activities of man. In addition, the cultural activities of man increase the inputs of many other chemicals, especially nitrogen, that are also essential for the growth of algae. If any of the nutrients essential for algal growth could be reduced to a sufficient extent in a waterbody, the

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* Presently, President & Vice-President of G. Fred Lee & Associates, El Macero, CA
gfredlee33@gmail.com www.gfredlee.com

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algal growth could be reduced to a sufficient extent in a waterbody, the amount of algal biomass that could develop could also be reduced. In the 1970's it became clear to environmental engineers and scientists and others concerned with management of excessive fertilization of waters that of the wide variety of chemicals that our industrial society adds to surface waters which contribute to the excessive growths of algae and other aquatic plants, phosphate was the element most easily and most inexpensively controlled, and that algal biomass could indeed be reduced by reducing the input of phosphate to a waterbody. It also came to be understood that not all forms of phosphorus could be used by algae for growth; that is, some forms are algal-available forms, others may become available over time, and still others are not available for use by algae. One of the major sources of phosphate associated with man's activities is domestic wastewater which contains phosphate from metabolic and other wastes, as well as household laundry and other detergents.

This paper reviews the development in North America of an understanding of the causes of excessive fertilization of surface waters, and the development of quantitative relationships between the input of planktonic algal nutrients to a waterbody and the resultant algal biomass. It also reviews the approaches to eutrophication management in North America and to the evaluation of their efficacy for water quality, or "quality of life" enhancement.

HISTORICAL PERSPECTIVE

Phosphorus and Wastewaters

Some of the first records of concerns about excessive algal growth in surface waters in the USA were about the chain of five lakes on the Yahara River near the city of Madison, Wisconsin. In a conference devoted to algae and metropolitan wastes held in 1960 (Bartsch, 1961), Sarles (1961) indicated that in the late 1800's there were reports of excessive growths of algae having occurred in these lakes in the early 1880's. Maki et al. (1984) indicated that one of the first investigators to define a relationship between algal growth and the amount of dissolved phosphorus in water was W. Atkins in 1923 (Atkins, 1923). Atkins postulated that high concentrations of phosphorus in a surface water was indicative of contamination from domestic wastewaters.

The early problems of excessive fertilization of the Madison lakes were addressed by a series of diversions of Madison's domestic wastewater discharges from the upper lakes in the chain to the lower lakes. In 1958, these wastewaters were finally diverted completely out of the lakes to Badfish Creek which enters the Yahara River downstream of all of the lakes (Lawton, 1961). The diversion of domestic wastewaters around the waterbody of concern was also the approach adopted by the city of Seattle, Washington for control of the excessive fertilization of Lake Washington, and by the communities on the shore of Lake Tahoe in California and Nevada. While this approach assisted in the remedy of excessive algae problems in the waterbody of focus, it had the potential to simply relocate the site of manifestation of the problem. Wastewater diversion could contribute to excessive fertility problems in the waterbody into which the wastewaters are diverted, or in waterbodies downstream of the discharge. By the mid 1960's it began to be understood that the removal of phosphorus from domestic wastewaters could be an effective method of controlling excessive growth of algae in those waterbodies in which a principal source of phosphate was domestic wastewaters.

Probably the most dramatic example in North America of the relationship between phosphorus load from domestic wastewaters and excessive fertilization of a waterbody was provided by the data on Lake Washington near Seattle, Washington. Anderson (1961) reviewed the information available at that time and found a strong correlation between the P load to Lake Washington from domestic wastewater sources and the planktonic algal chlorophyll, Secchi depth, and hypolimnetic oxygen depletion in the lake. It was the work of W. T. Edmondson of the University of Washington and his associates that caused the city of Seattle to divert its wastewater discharges from Lake Washington to Puget Sound. Data gathered more recently by his associates and him (Edmondson and Lehman, 1981; Edmondson, 1985) have confirmed the very strong correlation between the phosphorus load to, or content of, the lake and the planktonic algal-related water quality of the waterbody both before and after the diversion.

Control of Other Elements

During the late 1960's, considerable controversy developed in the technical community about the relative importance of carbon, nitrogen, and phosphorus in eutrophication and its control. By the early 1970's it was clearly demonstrated in a series of conferences that it would be rare that the inorganic carbon content of a waterbody would limit phytoplankton biomass to a sufficient extent to affect eutrophication-related water quality (NAS, 1969; Likens, 1972; Jenkins, 1973; Middlebrooks et al., 1973).

There was also controversy about the relative merits of nitrogen versus phosphorus control for eutrophication management. In the 1960's, the US EPA-predecessor organization conducted large-scale studies of nitrogen removal at the South Lake Tahoe wastewater treatment plant. These N removal facilities were not operated after the demonstration project was completed because they were judged to be too expensive and to not necessarily be effective in eutrophication management. The efficacy questions arose because certain blue-green algae can, at times, use dissolved nitrogen gas as a source of nitrogen, through nitrogen fixation reactions. Thus, these nitrogen-fixing algae, which tend to cause severe water quality problems, have a limitless source of nitrogen and may be selected-for when other types of nitrogen are in short supply.

As nutrient limitation of algal growth in surface waters came to be better understood, the concept was emphasized that in order for either nutrient to actually limit algal biomass, the concentration of available forms of the nutrient had to be below a level that would limit growth (Lee and Jones, 1988a). Further, Schindler (1977) noted that even in waterbodies in which nitrogen was at limiting levels, effective reduction in algal biomass could be achieved by reducing phosphorus loads. Additional information on nitrogen and phosphorus control in domestic wastewaters is presented in the Water Pollution Control Federation nutrient control manual (Albertson, 1983).

USA/Canadian Great Lakes

The problems of excessive fertilization of the US/Canadian Great Lakes have received international attention since the late 1950's. Particular notoriety was given to Lake Erie by the popular press's description of the "death" of Lake Erie due to excessive growths of algae. In the late 1960's, governmental agencies in the USA and Canada began efforts to control the excessive fertilization of the Great Lakes by reducing the phosphorus inputs to the lakes from domestic wastewaters. In 1972, the USA and Canada signed the Great Lakes Water Quality Agreement (GLWQA) which limited the phosphorus concentration in domestic wastewaters discharged to the international Great Lakes or their tributaries at a rate of 1 mgd (million gallons per day - 0.044 m3/sec) or more, to 1 mg P/L. The application of this P restriction only to those discharges of 1 mgd or more was specified because the costs per capita for smaller wastewater treatment plants were substantially higher than for the larger plants. Total costs for plants discharging more than 1 mgd were less than $0.01/person/day while for smaller plants the costs were tens of cents/person/day. The 1 mgd cut-off limit for P control was thus determined to be the economic limit which could be readily afforded at that time by the communities affected.

In 1978, the Great Lakes Water Quality Agreement was revised to require further reductions in the phosphorus loads from some domestic wastewater treatment plants. The revisions specified that the P concentration in the effluents of those wastewater treatment plants discharging more than 1 mgd to Lakes Erie and Ontario could be no more than 0.5 mg P/L. There is considerable controversy about the cost-effectiveness of this revised discharge requirement since in general, its implementation will be achieved through filtration of the effluent (Lee et al., 1979a). As discussed by Lee et al. (1980) and Lee and Jones (1985), a substantial portion of the particulate P in domestic wastewater effluents treated with alum for P removal is in forms unavailable to support algal growth. Therefore, removing particulate phosphate under these conditions greatly increases the cost of P removal without significantly impacting the water quality of the receiving water. Subsequent to the 1978 Great Lakes Water Quality Agreement, there has been a series of modifications in the approach to P load limitations to the lower Great Lakes. These modifications have resulted in the deferment of the implementation of the 0.5 mg P/L effluent limitation, and a broadening of the focus of P control to include non-point source control. Further information on the control of phosphorus and excessive fertilization in the Great Lakes is presented in publications by DePinto et al. (1986) and the International Joint Commission (IJC, 1987).

It was realized when the GLWQA was developed, that some of the algal-available P in domestic wastewater effluents discharged to rivers at considerable distances from a lake would be converted to unavailable forms before it reached the lake. However, because the characteristics and rate of this conversion were largely unknown and because of the desire for the agreement to be conservative for eutrophication control, the regulatory agencies opted for controlling P both from direct and tributary discharges. On the other hand, in its efforts to control the excessive fertilization of Lake Champlain in the 1970's, the State of Vermont adopted a policy requiring that only those wastewater treatment plants discharging directly to the lake achieve P removal to 1 mg P/L. As part of their work on behalf of the State of Vermont evaluating the appropriateness of this policy for P control for Lake Champlain, Lee and Jones (1985) discussed the approaches that should be used to evaluate the potential significance of the conversion of domestic wastewater-derived P in rivers during its transport to downstream waterbodies.

While there are eutrophication-related water quality problems throughout the USA, the major thrust of eutrophication control has been concentrated in the Great Lakes basin and in some parts of New England. It is in these most-recently glaciated regions of the country that the greatest numbers of natural lakes occur, and thus that the public has the greatest opportunity to observe the differences in eutrophication-related water quality. In other parts of the US where there are few natural lakes and the waterbodies present are primarily impoundments, the public has not, in general, been as sensitive about eutrophication-related water quality problems. It is the experience of the authors that planktonic algal chlorophyll concentrations that are considered to be excessive in the Great Lakes region, are accepted as being satisfactory in much of the rest of the country, especially in the lower mid-western, southern, and western parts of the US. For example, it is interesting to note that in one of the Great Lakes for which eutrophication was notorious, Lake Erie, the open-water planktonic algal chlorophyll concentrations rarely exceeded 10 ug/L. This level would be readily accepted as good water quality in many other settings. Thus, the control objectives and approaches that have been adopted in the Great Lakes basin may not be supported or appropriate in other parts of the USA or in other countries.

Estuarine and Coastal Marine Systems

Most of the eutrophication management efforts were begun in the 1960's in fresh waters, and are being carried out through the 1980's. Since the late 1970's, the eutrophication of estuarine and coastal marine waters has received increasing attention. A summary of the eutrophication of estuarine and marine waters was presented at an international conference held in 1979 (Neilson and Cronin, 1981). Jaworski (1981) discussed the eutrophication of the Potomac Estuary near Washington, D.C., as one of the tidal freshwater, estuarine, and marine waters for which excessive fertilization has become a problem. Efforts were made in the late 1970's to control excessive fertilization of the Potomac Estuary by controlling phosphorus from the Washington, D.C. wastewater treatment plant which discharges to the estuary.

There has also been concern about the excessive fertilization of the overall Chesapeake Bay system of which the Potomac Estuary is part. Governmental agencies in the Chesapeake Bay region have adopted a policy requiring that domestic wastewater treatment plants discharging to the Bay reduce the total P in their effluents. In some areas, the effluent total P limitations were established as low as 0.1 mg P/L. Also, in some areas, restrictions have been applied to the nitrogen concentrations in domestic wastewater effluents discharged to the Bay (ERM, 1987). Such restrictions were established because algal growth in some parts of Chesapeake Bay is believed to be limited by the nitrogen concentration in the waters.

It has thus been concluded that the most effective eutrophication management program for the Chesapeake Bay system is the control of both phosphorus and nitrogen. In 1987, an agreement was reached between the US Environmental Protection Agency (US EPA) and the States of Maryland, Pennsylvania, and Virginia, and the District of Columbia to achieve an overall 40% reduction of the phosphorus and nitrogen loads to the main stem of the Chesapeake Bay (US EPA et al., 1987). Considerable efforts are thus being made to control these elements from non-point sources such as urban and agricultural runoff as well as from domestic wastewater. Randall and Krome (1987) reviewed the technology available for the control of nutrient inputs to this system.

Some of the most recent developments in estuarine and marine eutrophication management have occurred in the New York City--northern New Jersey area of the USA. Excessive fertilization of New Jersey's coastal waters has been of concern for many years. In 1976, there was widespread deoxygenation of hypolimnetic waters along the coast arising from the oxygen demand of planktonic algae. This deoxygenation resulted in the large-scale die-off of shellfish, benthic fish, and other organisms, and is estimated to have caused the loss of more than $500,000,000 in commercial and recreational fisheries and shellfisheries in this area. Deoxygenation occurs nearly every year in some of these coastal areas. Further, excessive algal biomass interferes with the recreational use of the highly valued northern New Jersey beach areas. The Hudson/Raritan Estuary (the New York Harbor area) receives the domestic wastewaters from more than 10 million people. Lee and Jones (1987) have shown that if 90% of the P from these wastewaters were removed, as can readily be done, there would be a significant improvement in eutrophication-related water quality for some of the northern New Jersey coastal beaches.

Detergent Phosphate

One of the approaches that has been adopted in several parts of the USA and Canada in an attempt to control excessive fertilization is the banning of household laundry detergent formulations which contain phosphate as a builder.

Since the late 1940's, phosphate in the forms of pyrophosphate and tripolyphosphate has been added to many laundry detergent formulations as a builder to complex calcium and magnesium. By the early 1970's, phosphorus accounted for about 12% by weight of detergent formulations; approximately 50 to 60% of the phosphate in US domestic wastewaters was from household laundry detergents. This substantial percentage of P from detergents prompted a number of political entities to adopt bans on the use of household laundry detergents that contained more than a trace (0.5% by weight) of phosphate. Some of the first bans were adopted in the early 1970's by the States of Indiana and New York. Some local political entities, such as Dade County, Florida, also adopted detergent P bans. At about the same time, the Canadian Province of Ontario adopted a limitation for P in detergent formulations of 2.2% P by weight. Since that time, a number of other states, including Minnesota, Michigan, Vermont, Wisconsin, and recently North Carolina, Virginia, Maryland, and the District of Columbia have adopted detergent P bans. It is estimated that at this time, approximately 50 to 60 million people in the USA (approximately 25% of the USA population) use laundry detergents which do not contain more than trace amounts of phosphate.

Since the initiation of these bans, questions have been raised about their effectiveness in reducing the phosphorus loads to waterbodies to a sufficient extent to cause improvements in eutrophication-related water quality. During the mid-1970's, the detergent manufacturers in the USA voluntarily significantly reduced the phosphorus content of their formulations sold throughout the US, from about 12% P by weight to about 6%. Berthouex et al. (1983, 1985) reported that today the detergent P content in domestic wastewaters in non-bans areas of the USA is variable, but is generally on the order of 20 to 25% of the total P. Greek (1988) reviewed the current composition of detergent formulations.

Booman and Sedlak (1986) reviewed the detergent P situation in the US with particular reference to Chesapeake Bay. They pointed out that the detergent P bans in Maryland, the District of Columbia, and Virginia could not be expected to result in any improvements in eutrophication-related water quality in Chesapeake Bay. Similar conclusions have been drawn by Maki et al. (1984) for detergent P bans in other parts of the USA and Canada. As discussed below, their conclusions were to be expected based on the fact that household laundry detergent-derived P typically represents a small part of the P loads to waterbodies. To date, there have been no documented cases in which a detergent phosphate ban has resulted in an improvement in eutrophication-related water quality in either the USA or Canada. Lee and Jones (1986a, b) developed an approach for evaluating whether a detergent P ban in a particular region could be expected to result in an improvement in eutrophication-related water quality in a particular waterbody. This approach is discussed in a subsequent section of this paper.

Summary

From an overall point of view, excessive fertilization of surface waters is one of the most important water quality problems in the USA and Canada. In many parts of the USA and Canada, these problems are related to the discharge of domestic wastewaters which enter, directly or indirectly, lakes, reservoirs, estuaries, or coastal marine waters. The focal point of eutrophication control in the USA and Canada has been the control of P from domestic wastewater sources. Today, increasing attention is also being given to the control of N from domestic wastewater sources, as well as to the control of both N and P from urban and agricultural land runoff. Many parts of the US have adopted detergent P bans in an attempt to control, to some extent, excessive fertilization of surface waters. However, the effectiveness of that approach can be seriously questioned.

Some of the most significant advances in eutrophication management in recent years have been made in the quantification of relationships between the input of phosphorus and the amount of algal biomass that will develop in a lake, reservoir, estuary, or coastal marine system. These advances, which are described below, allow determinations to be made of the changes in eutrophication-related water quality that will be expected to occur in essentially any waterbody as a result of any phosphorus control strategy.

EVALUATION OF IMPACT OF PHOSPHORUS LOAD REDUCTIONS ON WATER QUALITY

One of the first comprehensive reviews of the role of phosphorus in contributing to excessive fertilization was published as an OECD (Organization for Economic Cooperation and Development) report by Vollenweider (1968). In that report, Vollenweider provided the first summary of the amounts of nitrogen and phosphorus derived from various activities of man, such as animal cultivation. He also began to describe relationships between the phosphorus loads to waterbodies and the degree of planktonic algal fertility of the waterbodies.

In the early 1970's, through the OECD, Vollenweider organized a study program involving approximately 200 waterbodies in North America, Japan, Australia, and 18 countries in Western

Europe designed to evaluate the relationships that he had developed and continued to develop [referred to herein as the Vollenweider-OECD eutrophication study]. In a series of publications (including Vollenweider, 1975, 1976) Vollenweider described quantitative relationships between the phosphorus loads to waterbodies and the planktonic algal chlorophyll that develops in the waterbodies. Using as a data base the characteristics of a group of primarily European waterbodies, he found an empirical correlation between average planktonic algal chlorophyll concentration and phosphorus load normalized by waterbody area, mean depth and hydraulic residence time (filling time).

Using the data from the US portion of the Vollenweider-OECD eutrophication study, Rast and Lee (1978) and Lee et al. (1978) found that Vollenweider's normalized P load--planktonic algal chlorophyll correlation (model) also described the load--response relationship for the approximately 34 US OECD waterbodies evaluated. Rast and Lee (1978) and Lee et al. (1978) expanded the concept of Vollenweider's relationship and developed analogous relationships between normalized P load and Secchi depth, and hypolimnetic oxygen depletion rate based on the US OECD data. They also showed how these relationships could be used as a basis for estimating the potential benefits to planktonic algal-related water quality that would be associated with reducing the phosphorus loads to a waterbody.

In 1982, the results of the international Vollenweider-OECD eutrophication study were summarized in an OECD publication (OECD, 1982). That publication, however, did not include a discussion of the use of the results for water quality management. The authors (Jones and Lee, 1982a, 1986) have continued to expand the data base for the Vollenweider P load--planktonic algal response models so that at this time data on more than 500 waterbodies located in most parts of the world define the empirical relationship. Figure 1 presents the models as defined by the US OECD and US-post-OECD data that had been assembled as of the early 1980's for normalized phosphorus load, chlorophyll, Secchi depth, and oxygen depletion rates. Figure 2 presents the phosphorus load--chlorophyll relationships for all waterbodies for which the authors had obtained data as of the mid-1980's. In addition, more recent work of the authors has shown that these relationships also describe the coupling of normalized P load and planktonic algae in waterbodies in the USSR (Volga River Basin) as well as many other parts of the world. It is now clear that the relationship developed by Vollenweider relating the normalized phosphorus load to a waterbody and the planktonic algal chlorophyll in the waterbody is universal and has applicability to waterbodies throughout the world.

Rast et al. (1983) have shown that the relationships presented in Figures 1 and 2 can be used to reliably predict the impact of altering the phosphorus load to a waterbody on the waterbody's planktonic algal-related water quality. This means that water quality managers now have a reliable tool that, if properly applied, can provide an assessment of the impact of altering the phosphorus load from a particular source or sources on the planktonic algal-related water quality. It is important to emphasize that while eutrophication is most commonly manifested as planktonic algae, there are waterbodies in which the excessive fertilization is manifested as attached algae or rooted or floating aquatic macrophytes. The Vollenweider-OECD relationships, as well as those developed by the authors and their associates, are not directly applicable to those types of waterbodies. Jones and Lee (1982a, 1986) describe the appropriate use and limitations of these models.

Figure 1.
Relationships between Normalized P Load and Planktonic Algal-Related Response for US OECD Waterbodies (After Jones and Lee, 1982a)

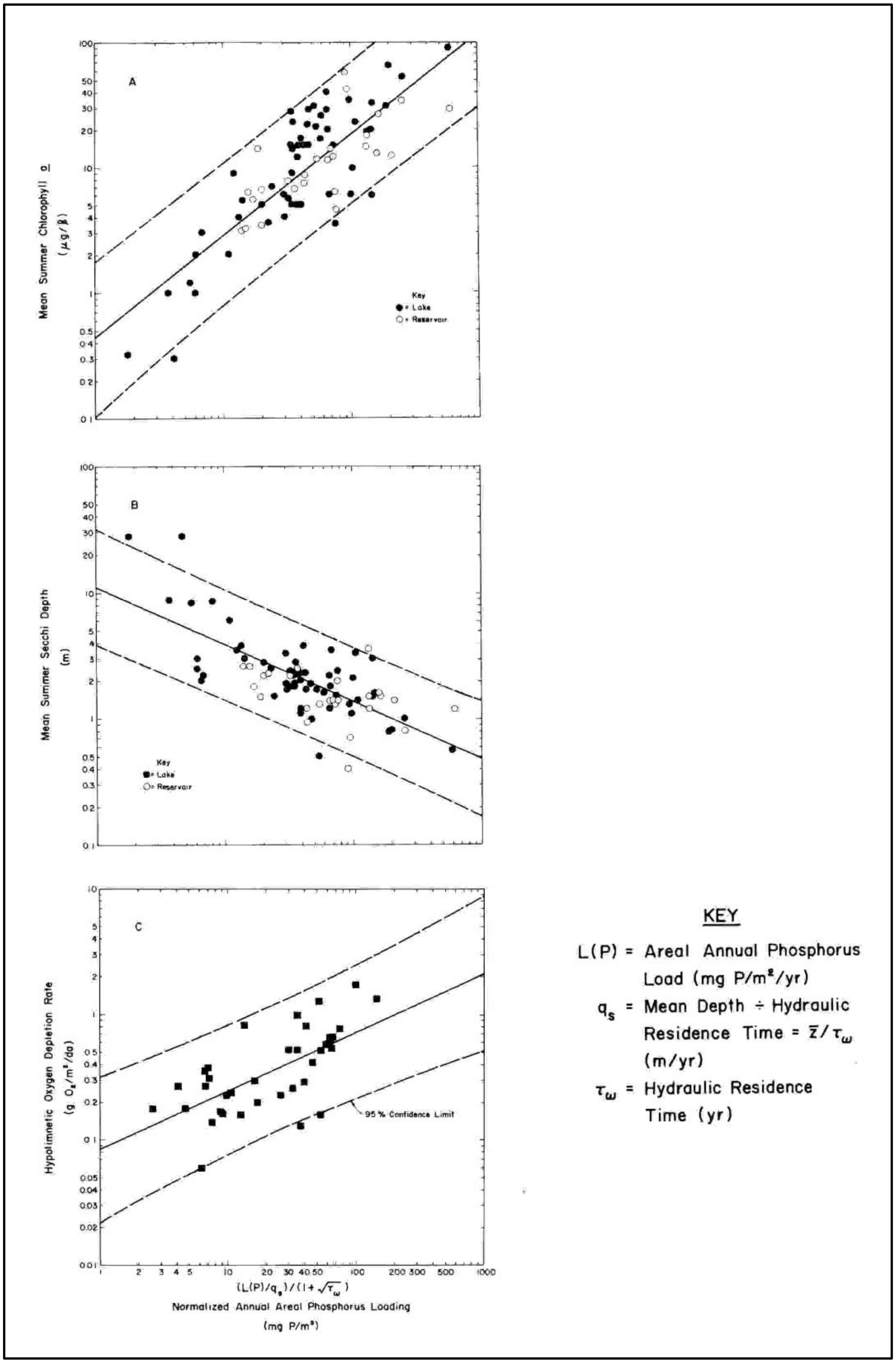
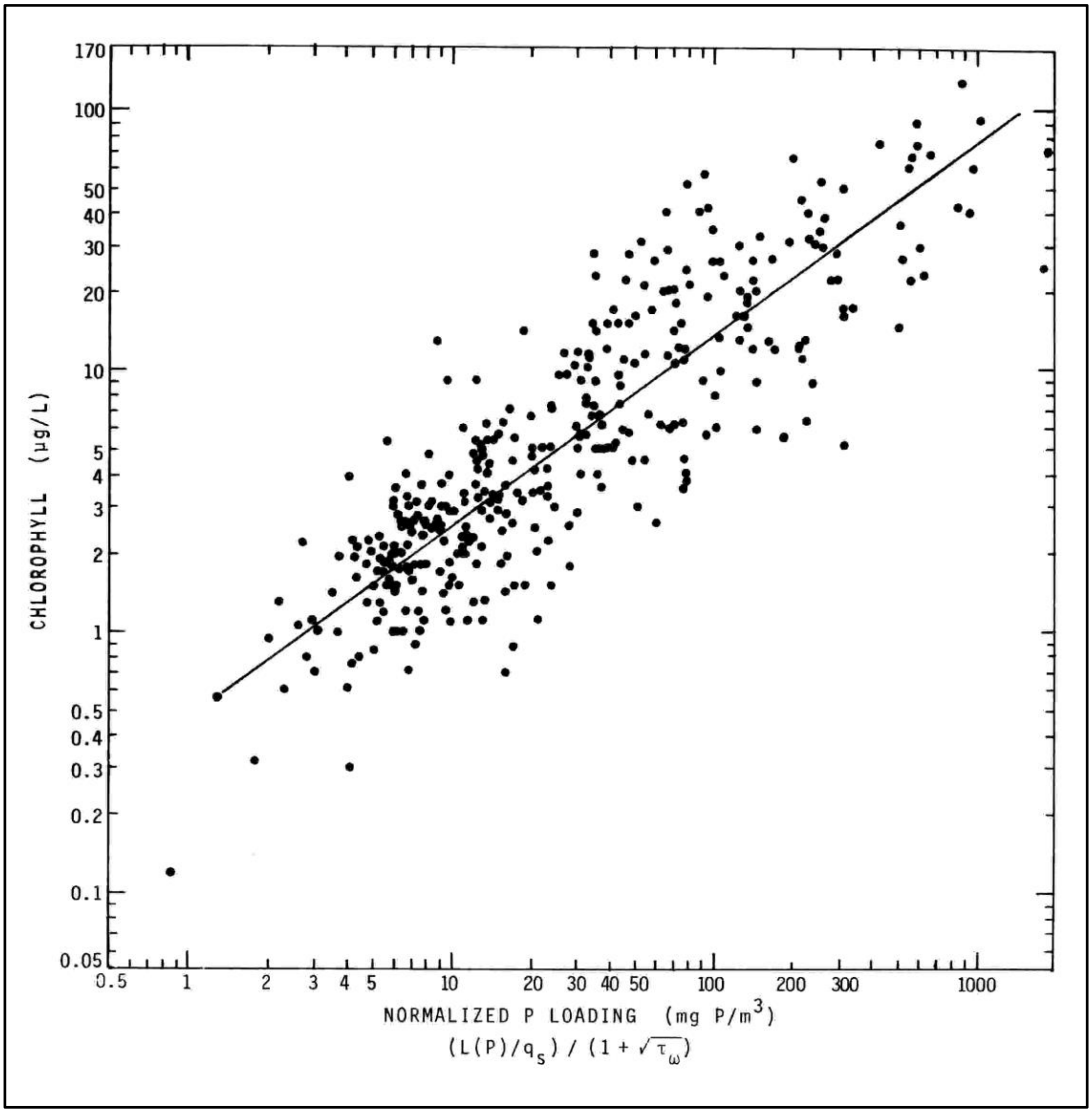


Figure 2.
Updated Relationship between Normalized P Load and Planktonic Algal Chlorophyll
for World-Wide Data Base (After Jones and Lee, 1986)



There is a wide variety of other models which are claimed by some to relate P load or in-lake P concentration to planktonic algal chlorophyll. Some of these models were derived from the Vollenweider model; some are dynamic models. The principal difference between the Vollenweider-OECD models and the others is that the Vollenweider models are based on a world-wide data base of more than 500 waterbodies; the other models are based on much smaller data bases, usually of a regional nature. The Vollenweider-OECD models have been demonstrated to have a high degree of predictive capability for water quality management purposes; none of the others have been demonstrated to have any significant universal capability to predict the impact of altering P loads on eutrophication-related water quality. These aspects are critical for obtaining reliable results from a model.

The authors have used the relationships shown in Figures 1 and 2, coupled with their experience in working on eutrophication management on a wide variety of waterbodies in various parts of the world, to develop an assessment of the degree of phosphorus control necessary to achieve a perceptible change in planktonic algae-caused eutrophication-related water quality. They have found that, independent of the trophic state of the waterbody, the algal-available P load to a waterbody must be changed by at least 20% in order for the public to perceive a change in water quality. It is important to emphasize that the 20% change in phosphorus load will cause a just-perceptible change in eutrophication-related water quality. A readily discernible change would require at least a 25 to 30% change in the algal-available phosphorus load to the waterbody. Even with this information, there is still the attitude among some, notably environmental activists, that "every little bit" of phosphorus control helps manage excessive fertilization. However, it can be readily documented that appreciable phosphorus load reduction must be achieved in order to bring about an improvement in eutrophication-related water quality. Therefore, as discussed below, before a P management option is adopted, it is important that the amount of P load reduction that can be achieved be evaluated through the Vollenweider-OECD eutrophication modeling approach, as described by Jones and Lee (1982a, 1986), to determine whether or not it will result in a meaningful improvement in eutrophication-related water quality.

PHOSPHORUS CONTROL FOR EUTROPHICATION MANAGEMENT

Some of the most important aspects that need to be considered in the selection of any phosphorus control strategy for eutrophication-related water quality management are: (a) the control of forms of phosphorus which are or become available for algal growth (algal-available forms), (b) the removal of sufficient amounts of available phosphorus to result in a perceivable impact on water quality, and (c) the proper evaluation of the expected improvement in planktonic algal-related water quality that can be achieved through the management option under consideration. This section presents a discussion of the most commonly used or considered strategies for phosphorus control for eutrophication management. Special attention is given to the first two aspects identified above. A subsequent section provides a discussion of the evaluation of expected improvement in water quality through P load control.

P Removal from Domestic Wastewater

One of the major sources of available phosphorus for many surface waters is domestic wastewater; every person contributes about 1 kg P/year in sewage (Rast and Lee, 1983). About 0.7 kg P/person/year is from human metabolic waste; between 0 and 0.7 kg P/person/year is from household laundry and other detergents. As discussed above, beginning in the early 1960's it became apparent that for some waterbodies the most cost-effective approach for managing excessive fertilization is the treatment of domestic wastewaters for removal of phosphorus. This is accomplished through co-precipitation with iron or aluminum salts, precipitation with lime, or, more recently, enhanced biological treatment. Other papers at this conference discuss the details of these approaches. Using precipitation or co-precipitation techniques, the total P concentration in domestic wastewater effluents can be readily reduced by 90% at a modest cost.

In the USA today, essentially all urban populations are sewered; the wastewaters collected receive at least primary treatment (settling), and with few exceptions, secondary (biological) treatment before discharge to surface waters. Parts of some municipalities and rural areas use septic tank wastewater disposal systems; the household wastewaters are discharged to a septic tank where a portion of the solids is settled within the tank, and the somewhat-clarified effluent is discharged to a leach field. If the system is working properly, the water and associated contaminants do not become part of the surface waters but rather become part of the groundwater system. Canter and Knox (1985) estimated that approximately 70 million of the 240 million people (approximately 30%) in the USA discharge their wastewaters to septic tank systems.

Barth (1985) discussed phosphorus control in municipal wastewaters in the USA, and pointed out that in 1982 approximately 14% of the domestic wastewaters collected in sewerage systems are receiving specific treatment for phosphorus removal. He estimated that by the year 2000, 20% will be treated for P removal. Therefore in the USA, the wastewaters from about 25 million to 30 million people are being treated for phosphorus removal. Based on discussions with Schmidtke (1988), the domestic wastewaters from approximately 9.5 million people in Canada are now being treated for phosphorus removal. Therefore today the wastewaters from on the order of 40 million to 50 million people in North America are receiving treatment for phosphorus removal. This number is likely to increase significantly in the near future with the adoption of domestic wastewater P removal in a number of other areas such as the Chesapeake Bay and eventually the New York City--New Jersey area. According to Kubo (1988) there are approximately 0.5 million people in Japan whose domestic wastewaters are treated for P removal. Based on their discussions with conference participants and others, the authors estimate that the domestic wastewaters from about 50 million to 60 million people around the world are being treated for P removal.

Lee and Jones (1987) reported that in the New York City--New Jersey area, P can be removed from domestic wastewaters at a cost of about $0.04/person/day for the population served by the sewage collection system. This cost estimate is based on the assumption that the treatment plant serves at least 10,000 people, i.e., has a flow of at least 1 mgd (0.044 m3/sec); it covers all aspects of cost for P removal including amortization of the capital investment over a 20-year period. It was interesting to find at the conference that the cost of phosphorus removal in several European countries, including Sweden, West Germany, and France, was approximately the same as is found in the USA when compared on a per capita per day basis. It is therefore concluded that phosphorus removal from domestic wastewaters receiving at least primary treatment is relatively inexpensive, can be readily practiced, and should be used wherever domestic wastewater-derived P represents a potentially significant source of phosphorus for a waterbody experiencing excessive fertilization.

There are numerous examples of improvements in eutrophication-related water quality in surface waters that have resulted from the removal of domestic wastewater P. As discussed above, for any given situation the degree of improvement in planktonic algal-related water quality expected can be determined prior to enactment of P removal, using the Vollenweider-OECD eutrophication modeling approach (Jones and Lee, 1982a, 1986).

It is important to note that domestic wastewater P reduction has been shown to be effective in controlling eutrophication even for waterbodies in which phosphorus is not the element limiting algal biomass during the summer. In a number of the waterbodies that make up the Vollenweider-OECD load--response relationships shown in Figures 1 and 2, P is not limiting planktonic algal biomass. Those waterbodies had the same general relationships between P load and eutrophication response as those in which P was the element limiting phytoplankton biomass. As discussed by Jones and Lee (1986) and by Schindler (1977) even in waterbodies containing significant excesses of P compared to what phytoplankton need for their growth, planktonic algal biomass responds to reductions in P load. It may be concluded, therefore, that the removal of P from domestic wastewaters can be a highly cost-effective method for controlling excessive fertilization in those surface waters in which domestic wastewaters represent a significant source of algal-available phosphorus. Further, the Vollenweider-OECD eutrophication study relationships can be used to predict, on a site-specific basis, whether removal of P from domestic wastewater sources will result in a significant improvement in eutrophication-related water quality in the waterbody receiving the domestic wastewaters.

Septic Tank Waste Disposal Systems

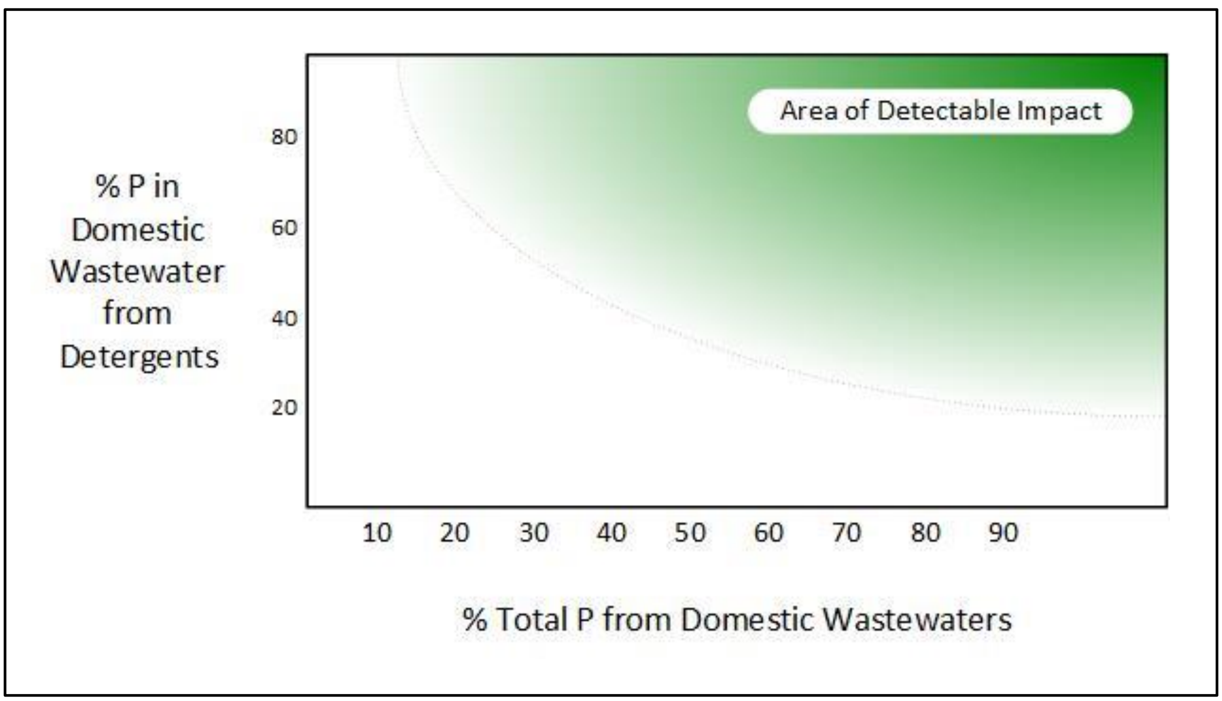
Jones and Lee (1979) discussed the fate of phosphorus associated with domestic wastewaters discharged to septic tank wastewater disposal systems. Through a review of the literature and field studies, they found that under most conditions, the phosphorus from properly operating septic tank systems does not contribute to the eutrophication problems of surface waters. Phosphates tend to be sorbed by aquifer solids, especially in calcareous systems, and therefore are not transported to any significant extent in groundwaters. The exception to this is in aquifers consisting of relatively pure quartz sand such as those which are frequently found in recently glaciated areas. Quartz has limited sorption capacity for phosphate. Therefore, phosphorus associated with septic tank wastewaters discharged to quartz sand systems can be readily transported in groundwaters. If these groundwaters enter nearby surface waters, the wastewater-derived P can contribute to algal growth in those surface waters. In areas where such groundwater transport is of importance, it is possible to significantly reduce the amount of phosphate transported from the septic tank to surface water via the groundwater system by forcing the contaminated groundwater to pass through a crushed limestone bed. The phosphate would be precipitated as a hydroxyapatite on the surface of the limestone particles.

Detergent Phosphate Bans

While detergent P bans have been adopted in North America and in some other countries in an attempt to improve eutrophication-related water quality, none of them have been shown to have had a impact on eutrophication-related water quality. Indeed, based on technical information, it would be an unusual case in which such an improvement would be realized. As discussed above, in order for a readily perceptible improvement in planktonic algal-related water quality to occur, the load of algal-available phosphate to the waterbody in question must be reduced by more than 20%. Reductions in the P content in household laundry detergent formulations used in North America have substantially reduced the portion of domestic wastewater P derived from detergents. In non-ban areas of the US today, detergent P makes up about 20 to 25% of the P in domestic wastewaters. Thus, even for a waterbody in which the total load of available P was from domestic wastewaters, a new detergent P ban would not likely result in even a noticeable change in eutrophication-related water quality.

Figure 3 expresses the relationships among the percent of the phosphorus load to a waterbody that is from domestic wastewaters, the percent of the domestic wastewater-derived P that is from detergents, and the ability of the public to detect a change in eutrophication-related water quality as a result of the adoption of a detergent phosphate ban in the watershed for the waterbody of concern (Lee and Jones, 1986a, b). It is evident from this relationship that today in the USA, where 20 to 25% of the phosphorus in domestic wastewaters is derived from phosphate in household laundry detergents, the adoption of a detergent phosphate ban will not produce a discernible change in eutrophication-related water quality. This relationship explains why Maki et al. (1984) and others have not found a single demonstrated case where detergent phosphate bans have had any impact on eutrophication-related water quality in the USA or Canada. It also strongly supports the position of Booman and Sedlak (1986) that the recently-adopted bans in the Chesapeake Bay region of the USA will have no impact on eutrophication-related water quality in Chesapeake Bay.

Figure 3.
Conditions under Which Detergent P Ban May Result in
Perceptible Improvement in Eutrophication-Related Water Quality
(After Lee and Jones, 1986a, b)



In the USA today, many of those working with water quality control agencies readily admit that detergent P bans that have been and are being adopted will have no impact on eutrophication-related water quality. They are adopted primarily to placate environmental activist groups or others who want to demonstrate that they are working to "improve" environmental quality. This, unfortunately, is misdirected effort that would be better focused on addressing the implementation of eutrophication control programs that will have an impact on water quality. The decisions to adopt detergent P bans in the USA are not being made on the basis of available technical information.

It is important to note that the relationships shown in Figure 3 do not indicate that there is no place in the world where detergent phosphate bans could improve water quality. There are differences in the phosphate content of household laundry detergents in various parts of the world, and in approaches for handling and treating domestic wastewater. What is typical of the USA and Canada is not necessarily typical world-wide. However Figure 3 does illustrate that in order for detergent phosphate bans to be effective in influencing eutrophication-related water quality, the waterbody must have essentially 100% of its algal-available phosphorus derived from domestic wastewater sources. In addition, about 40% or more of the P in those domestic wastewaters must be derived from laundry detergents. Where both of these conditions are not met and yet detergent phosphate bans are adopted, the motives are likely political or something other than water quality related. If the domestic wastewaters are collected and at least primary treatment is provided, a far more cost-effective way to control eutrophication is the treatment of the wastewaters for phosphorus removal. As discussed above, this is a readily achievable, widely practiced, inexpensive method of eutrophication control that is highly effective in those areas where domestic wastewaters represent the dominant source of algal-available phosphorus for the waterbody.

There are situations, especially in undeveloped or less-developed countries, where large amounts of untreated domestic wastewaters are discharged directly to surface waters. Under these conditions, the adoption of detergent phosphate bans until such time as proper domestic wastewater treatment can be developed, may be a way to achieve some interim improvement in eutrophication-related water quality for a particular waterbody.

There may be situations in which even if there is collection and treatment of domestic wastewaters, detergent P bans could have some impact on the phosphate load to a waterbody; these are associated with combined sewer overflows (CSO's). In many parts of Europe and in some parts of North America and other countries, the sewerage systems carry both domestic wastewaters and urban stormwater runoff. Such systems carry both of these types of wastewaters to the treatment plant for treatment. However, during periods of intense rainfall or runoff, the volume of water exceeds the capacity of the treatment works, and some of the wastewater-stormwater is deliberately diverted to nearby surface waters. When that occurs, untreated domestic wastewater is being discharged directly to surface waters. According to de Oude (1988), many European countries design their treatment systems to allow a maximum of 5 to 10 combined sewer overflows per year. This results in the direct discharge of P to surface waters equivalent to about 10% of the treatment plant's P load. In the USA today, some cities are developing approaches to eliminate the discharge of combined sewer overflow to surface water without treatment. This is usually accomplished by developing sufficient storage facilities to hold the excess flows during high runoff, and treating the stored water before discharge. The potential significance of detergent P in CSO's can, in most instances, be readily assessed using the Vollenweider-OECD modeling approach. As discussed below, it is important to determine the availability of the phosphorus in the CSO's as part of the management option evaluation.

Another aspect of detergent P control that needs to be considered in making the decision whether or not to adopt bans is the availability of the phosphate derived from detergents. Some assume that all of the pyrophosphate and tripolyphosphate (condensed P) in detergent formulations is available for algal growth. Indeed, in the development of Figure 3 it was assumed that detergent-derived P is completely available. As reported by Lee and Jones (1985), it has been found by several investigators that hydrolysis reactions convert part of such condensed P to algal-un-available forms. Clesceri and Lee (1965) found that on the order of 50% of the condensed P of the type used in detergent formulations was not available to support algal growth in the culture systems used. The work of Villessot et al. (1985) (Villessot, formerly of the Fondation de l'Eau, Limoges, France) showed similar results. Lee and Jones (1985) discussed the need for further work on this topic to define whether the algal-un-available forms can be converted over extended periods of time to algal-available forms. If this conversion does not occur, detergent-derived P is even less of a potential problem than is being assessed today since a significant part of that P would not be available to support algal growth.

In assessing the potential benefits of detergent phosphate bans for the improvement of eutrophication-related water quality in France or any other country, it is important to consider the amount of algal-available P that can be controlled during the period of the year when excessive fertilization problems are of greatest significance in impacting water quality. If the detergent P ban will not reduce the algal-available P by at least 25% of the total algal-available P load during the time when excessive fertilization is of greatest concern, no discernible improvement in water quality will be expected through the adoption of the detergent P ban.

Essentially whatever the particular characteristics of the waterbody in question and the amounts of domestic wastewater input and detergent P content of them, the improvement in planktonic algal-related water quality that can be achieved by a detergent P ban can be reliably estimated before enactment of such a measure, using the Vollenweider-OECD modeling approach. As discussed below, the Vollenweider-OECD studies and subsequent studies have developed a reliable basis upon which to predict the improvement in eutrophication-related water quality that can be achieved at a particular location as a result of adopting a detergent phosphate ban, or for that matter, the implementation of any phosphate control program.

Control of P from Diffuse (Non-Point) Sources

For many waterbodies of the world, the primary source of phosphorus and other chemicals that support planktonic algal growth is runoff from forest, agricultural, and urban lands in the watershed. The US EPA held a conference in 1985 to air a variety of perspectives on the pollution of waters from non-point sources (US EPA, 1985). The authors and their associates have done a considerable amount of work in this area, much of which has been devoted to nutrients. Rast and Lee (1978), Lee et al. (1978), and Rast and Lee (1983) have quantified the amounts of nitrogen and phosphorus that are typically derived per unit area of forest, agricultural, and urban land in the USA. The nutrient export coefficients developed by them are presented in Table 1. While these numbers have applicability to the conditions generally found in most areas of the USA, they need to be evaluated before they are used in other countries, to be certain that some cultural, industrial, geological, or other conditions do not significantly affect the nutrient export from these types of land.

An important consideration in evaluating the potential benefit to eutrophication-related water quality that can be attained by control of non-point sources of phosphorus is the algal-availability of the P from these sources. Lee et al. (1980) conducted a comprehensive review of the literature on this subject and reported that much of the P derived from diffuse sources, such as urban and agricultural runoff, is not available to support planktonic algal growth. Much of the P that is derived from agricultural land runoff, for example, is associated with particulate matter in soil particles eroded from the fields. Other non-point sources of P may also contain substantial particulate loads. As reported by Lee et al. (1980), a number of investigators have found in the USA that only about 20% of the P in the particulate matter in land runoff is available to support algal growth. For many situations in the USA and Canada only about 50% of the total P derived from land runoff is available to support algal growth.

Because of the potentially high fraction of forms of P in non-point sources that are unavailable for algal growth, it is inappropriate to use the total phosphate load as a basis for evaluating the potential benefits to algal-related water quality of reducing agriculturally derived P to a certain degree. The proper basis for making such an assessment is the reduction in algal-available P. In the Great Lakes region of the USA and Canada, it has been found that the algal-available P can be estimated as the sum of the soluble orthophosphate (as measured by the ascorbic acid/molybdate procedure (APHA et al., 1985) after the sample has been filtered through a 0.45 u pore-size filter) and about 20% of the difference between total P and soluble orthophosphate. For most systems, the difference between total and soluble ortho P is equivalent to the particulate phosphorus. As discussed by Lee et al. (1980), while this approach for estimating algal-available P has been found to have widespread applicability, before it is used in other areas algal bioassays should be conducted to determine the fraction of the particulate phosphorus from the particular source that is available to support algal growth. Lee et al. (1980) provided information on the use of algal bioassays for such an evaluation.

The importance of focusing on algal-available P in using the Vollenweider-OECD eutrophication study results has been found in a number of instances to be the key to the successful application of these results to a particular waterbody. For example, in their study of Salto Grande Reservoir on the Parana River in Argentina, Beron and Lee (1984) found that the total P load to this reservoir was a poor predictor of the planktonic algal chlorophyll in the reservoir. However, most of the P entering that reservoir was associated with erosional material. When the total P load was corrected to algal-available P, assuming that about 20% of the particulate P was available for algal growth, a good correlation was found between algal-available P load and planktonic algal chlorophyll in this reservoir. A similar situation was found by Lee and Jones (1981) for the Bighorn Reservoir in Wyoming, USA. In order to properly correlate the phosphorus load to planktonic algal chlorophyll in a waterbody receiving large amounts of particulate P from erosion, the P load must be adjusted to account for the algal-unavailable P included in the total P. Failure to make such adjustments will result in erroneous results from the Vollenweider-OECD eutrophication models in predicting the impact of altering P loads on eutrophication-related water quality.

In a number of parts of the USA and Canada, agricultural practices are being altered to minimize the amount of total P entering surface waters from land runoff. One altered practice is "no-till (plowing)" or limited-till farming. Rather than plowing the land at the end of the growing season or early the following spring before sowing seed, the farmer plants seeds in the next growing season without plowing or with minimal plowing, and uses herbicides to minimize weed growth. Such practices have been found to significantly reduce the amount of total P derived from the land. However, according to Randall and Krome (1987) and Reutter et al. (undated) such practices may actually increase the amount of soluble orthophosphate (algal-available P) from the land. Further, they appear to decrease crop productivity and increase the potential for environmental hazards associated with increased pesticide-herbicide use. It is therefore very important to critically examine the efficacy of altering agricultural practices, such as using no-till or limited-till farming, for eutrophication management. If this is not done, substantial effort could be expended by farmers in the name of water pollution control that would have little or no impact on eutrophication-related water quality, and in fact could make the situation worse than if they had continued their original farming practices.

The control of phosphorus in urban stormwater collected in independent-separate collection systems is often difficult to achieve. These systems frequently collect stormwaters from a limited area and discharge them to a nearby watercourse such as an urban lake or river. The typical approach used in the USA to attempt to minimize the impact of contaminants in urban stormwater runoff is to establish short-term detention basins to remove larger particles. However, Lee and Jones (1980) reported that this approach is usually ineffective for removing available forms of contaminants such as heavy metals, nitrogen, and phosphate that can have an adverse effect on lake or river water quality. This is because most of the contaminants available to affect water quality are either soluble or associated with finely divided particles, neither of which are removed in detention basins. It is important in the development of contaminant control programs for urban stormwater runoff, as with other non-point sources, to properly define the availability of the contaminants to affect water quality and develop programs designed to control those forms of the contaminants that can affect water quality.

Overall, in considering P removal from non-point sources for eutrophication management it is important to assess the availability of the P that may be removed through the management option. In addition, it should be recognized that it is difficult to achieve control of P from non-point sources because of economic, political, and technological factors and limitations.

SUGGESTED APPROACH FOR DEVELOPING EUTROPHICATION MANAGEMENT PROGRAMS

It has been clearly established that if the input of algal-available phosphorus to a waterbody can be reduced by a sufficient amount, there will be an associated reduction in the planktonic algal biomass. The most reliable and only verified approach available today for assessing the potential improvement in planktonic algal-related water quality that can be achieved by phosphorus management options is the Vollenweider-OECD eutrophication modeling approach. Based on their experience in developing and evaluating approaches for managing eutrophication-related problems in various parts of the world, the authors have found that the development of a eutrophication management program for a particular waterbody or group of waterbodies should include the components described in this section.

Definition of Water Quality Problems

The first step in the development of any eutrophication management program should be the definition of the water quality problem or problems that are of concern. Lee (1973) reviewed many of the types of water quality problems associated with excessive fertilization of waters, and pointed out that waters that are excessively fertile for one use may have desirable quality for another. In addition to the problems listed by Lee, the development of trihalomethane precursors, of concern for water supplies, appears in some waterbodies to be associated to some extent with algal biomass. Randtke et al. (1987) reviewed the sources of trihalomethane precursors for water supply waterbodies. If the use impairments are caused by aquatic macrophyte development, management approaches would likely be different from those applied to problems associated with planktonic algae.

The locations within a waterbody in which the problems occur and time of year in which they occur should be delineated. The approaches to management and the degree of management needed may be different depending not only on the beneficial use impairments caused by excessive growths of algae, but also on the location of the problem area relative to the sites of input of P, the morphology and hydrology of the waterbody, and the time of year in which the problems occur. For example, planktonic algal-related water quality problems for many water supply waterbodies occur during the late summer when the blue-green algae tend to develop to the greatest extent. This is also the time when the public perceives the greatest deterioration of the water quality for recreation. Also, if the location of the problem is restricted to an arm or a bay of a reservoir, more localized control options may provide satisfactory results.

Definition of Nutrient Sources

The amounts of phosphorus and nitrogen derived from each of the principal components of the watershed should be determined. This assessment includes the determination of the amounts of N and P from municipal, industrial, and agricultural wastewaters, and runoff from urban, agricultural, and forested land. In many instances, these nutrient loads can be estimated with sufficient reliability without substantial monitoring. The N and P loads from domestic wastewaters can often be estimated based on the number of people discharging wastewaters to the surface waters in the watershed and the population equivalent loads of P and N (see Table 1). Also, in many instances the nutrient loads from the land within the watershed can be estimated with a sufficient degree of reliability based on land use and nutrient export coefficients (see Table 1). In studies of eutrophication management in several parts of the world, the authors have found that aerial photographs or satellite imagery of a waterbody's watershed are useful in delineating and quantifying the land areas devoted to the dominant uses. Consideration must also be given to industrial discharges which contribute large amounts of P, especially animal husbandry involving large populations of cattle, pigs, ducks, chickens, etc., as potential sources of P within a waterbody's watershed.

While it may be possible to obtain most of the information needed to make a preliminary application of the Vollenweider-OECD model to a particular waterbody with limited additional data collection, should there be need for additional data, the approaches described by the authors (Lee and Jones, 1988b) should be considered as a framework for conducting such studies.

Once the dominant nutrient sources have been identified, they should be evaluated for the potential availability of the nutrients. As discussed above, this is especially important for non-point sources of P. In addition, the pattern of input from each of the sources should be evaluated to identify seasonality of the input of available P relative to periods of algal-related water quality concern, and relative to the hydrology and morphology of the waterbody.

Define Hydrological and Morphological Characteristics

Information must be collected on the hydrologic and morphologic characteristics of the waterbody. Specifically, the mean depth, waterbody surface area, and waterbody volume need to be determined. For situations in which these characteristics vary with time over a year, see the discussion in Jones and Lee (1986). If hypolimnetic oxygen depletion rate is of concern, the surface area and volume of the hypolimnion, as well as the characteristics of stratification need to be defined. The Vollenweider-OECD eutrophication models should not be applied directly to waterbodies in which the hydraulic residence time (volume/annual inflow) is less than about two weeks.

For lakes and reservoirs with hydraulic residence times greater than one year, and in which there is essentially complete mixing of incoming waters within the waterbody within a few days, the annual P load is typically the appropriate load to consider. However, for many other systems, especially some of the French rivers, the excessive fertilization problems of the summer months are controlled by the P discharged a few weeks prior to the time of concern. For such systems, annual P loads are inappropriate bases for estimating the impact of altering the P loads on eutrophication-related water quality. The authors have found that the Vollenweider-OECD eutrophication study results can be applied to slow-flowing rivers such as are found in some parts of France by considering the relationship between the algal-available P loads that occur within a particular reach of the river, and the planktonic algal biomass that develops a week's to two weeks' travel time downstream of this reach. This lag period is applicable to summer conditions and reflects the time that it takes algae to develop to their maximum biomass based on the nutrients available to them. Eutrophication of rivers is discussed in a subsequent section.

Vollenweider-OECD Load--Response Modeling

In accordance with the Vollenweider-OECD eutrophication modeling approach, the P load determined for the waterbody must be normalized by waterbody surface area, mean depth and hydraulic residence time (see Figures 1 and 2). The mean planktonic algal chlorophyll should then be plotted as a function of the phosphorus load as normalized according to the model. If the waterbody plots within the family of points shown in Figure 2, it may be concluded that this modeling approach can be used to predict the impact of altering the P load to a certain degree on the planktonic algal chlorophyll in the waterbody. While some domestic water supply water quality problems are related to a considerable extent to the amounts of particular types of algae, planktonic algal chlorophyll is usually a satisfactory surrogate that can be correlated with the severity of these problems. As discussed by Jones and Lee (1982b), each domestic water utility should develop a relationship between planktonic algal chlorophyll and specific algal-related water quality problems in its water supply waterbody. With this information it should be possible to develop correlations between the cost of remedying the problems, such as for taste and odor removal, and planktonic algal chlorophyll.

In applying the Vollenweider-OECD modeling approach, it is important that proper attention be given to the characteristics of the waterbody and its nutrient load (Jones and Lee, 1986). If it is found that the waterbody does not appear to behave in the same manner as the more than 500 waterbodies that make up the model data base, the evaluation approaches described by Jones and Lee (1986) should be followed, beginning with reviewing the integrity of the data. If this is done and the load--response relationship for the waterbody still does not fall within the family of points shown in Figure 2, special studies need to be conducted to determine why the waterbody behaves differently from the multitude of waterbodies comprising the model in its utilization of phosphorus in the production of planktonic algae. Once this understanding is achieved, it may be possible to correct the model input so that the model can be applied appropriately (Jones and Lee, 1986).

It is important to use the Vollenweider-OECD eutrophication study results properly in evaluating the potential benefits of controlling P to a certain degree, on the eutrophication-related water quality. In their 1986 review (Jones and Lee, 1986) and in numerous other papers and reports, the authors have discussed the proper use of these relationships. Despite this, they have found that a number of individuals who have attempted to use these relationships and have reported that they did not work, have not adequately considered the characteristics of the nutrient sources or of the waterbodies that govern the development of phytoplankton within them. Failure to make this evaluation properly can lead to erroneous conclusions regarding the potential benefits of controlling P to a certain degree on eutrophication-related water quality in a particular waterbody of concern.

Development of Management Scenarios

Once it becomes clear that the Vollenweider-OECD load--response models can be used for the waterbody under consideration, various nutrient control scenarios can be evaluated to determine their potential impact on the eutrophication-related water quality. Estimates should be made of the reductions in algal-available P that can be achieved with each of the management options under consideration. As noted above, at least a 25% reduction in the algal-available P load must be achieved in order for a discernible improvement in planktonic algal-related water quality to be anticipated.

The revised P load for each of the load reduction scenarios being considered should be normalized by waterbody morphology and hydrology in accordance with the Vollenweider-OECD model. A line should be drawn on the initial load--response plot for the existing conditions in the waterbody, parallel to the line of best fit in Figure 2. The intersection of that line with a vertical line drawn through the revised normalized P load represents the load--response coupling that would be expected to result from the adoption of the management scenario. That coupling shows the expected chlorophyll concentration, Secchi depth, and/or hypolimnetic oxygen depletion rate expected. An evaluation then must be made as to how well the expected response will be meet the management objectives for the waterbody. The authors have provided examples of the use of the Vollenweider-OECD eutrophication modeling approach for the development and evaluation of eutrophication management scenarios. These are summarized in Jones and Lee (1982a, 1986).

An important aspect of eutrophication control programs is the amount of time that it will take for the waterbody to respond to the management program. The amount of time needed for a waterbody's planktonic algal biomass to respond to reductions in available P load to the degree anticipated based on the Vollenweider-OECD models can be estimated as three times the phosphorus residence time of the waterbody (Sonzogni et al., 1976). The P residence time is equivalent to the average in-lake P mass divided by the annual P input. For many waterbodies, the P residence time is on the order of one year. Therefore, in general, a waterbody would be expected to come to equilibrium with its altered P load within about 3 years.

There will be some waterbodies in which the dominant phosphorus sources cannot be readily controlled. Under these conditions, various in-lake eutrophication management options should be considered. These types of options were reviewed by Lee (1973), and more recently by Cooke et al. (1986).

The evaluation of eutrophication management options must include an assessment of the costs of the control option relative to the improvements expected to result. It is the experience of the authors that in evaluating the cost-effectiveness of various P control scenarios it is most appropriate to examine these costs on a per capita per day basis, in which all components of the cost, including amortization, are included. Only through this approach is it possible to begin to put into perspective the real cost of eutrophication control per person in terms of increased sewer bills, taxes, or the cost of goods produced from industrial or agricultural sources.

EUTROPHICATION OF RIVERS

The Vollenweider-OECD eutrophication modeling approach has been applied by-and-large to lentic systems (i.e., lakes, reservoirs, estuaries). Since excessive fertilization is also a problem in some riverine systems, and since algae in rivers use nutrients in the same way they use them in lakes, it is appropriate to discuss evaluation of eutrophication management strategies for rivers. It should be noted that the Vollenweider-OECD models have also been applied to a number of run-of-the-river reservoirs which may be viewed in some respects as slow-moving rivers. Thus it would be anticipated that the principles of the models should also be applicable to eutrophication of rivers.

It has been known for many years that lotic (flowing water) systems can have higher concentrations of nutrients than lakes, reservoirs, estuaries, etc. without the same degree of water quality problems (e.g., Palmer, 1961). Many river systems do in fact develop large populations of planktonic algae; it is rare, however, that these algae significantly adversely affect recreational uses of these waters. Often their presence is overshadowed by inorganic turbidity which dominates water clarity. Planktonic algae in rivers can, however, have a significant adverse effect on the use of a river for water supply, especially as they contribute to taste and odor problems. Planktonic algae in rivers may also contribute to the concentrations of trihalomethane (THM) precursors in water supplies; this topic is in need of additional investigation.

Some rivers in the USA, especially in the South (e.g., Florida), tend to develop large populations of floating macrophytes, especially water hyacinth. In addition to developing planktonic algae, shallow rivers and streams frequently develop significant populations of attached, filamentous algae and benthic algae. In rivers in which the total depth of the water is less than about twice the Secchi depth, benthic algae may be dominant. At this time, nutrient load--eutrophication response relationships for floating macrophytes, attached algae, or benthic algae have not been developed. It is expected that they will be different in some respects from those described by Vollenweider for planktonic algae.

The US EPA (1987) has continued to perpetuate inappropriate guidance on critical concentrations of P in rivers by repeating invalid information it presented in the "Red Book" water quality criteria (US EPA, 1976). As discussed by Lee et al. (1979b) in the American Fisheries Society Water Quality Committee's critique of the US EPA (1976) section on Phosphate, the approach advocated by the US EPA is technically invalid. Contrary to the US EPA's guidance, there is no general relationship between the total P content of a river and the planktonic algal biomass within the river or within downstream lakes, reservoirs, estuaries, or marine waters. As discussed above, the hydrology and morphology of the waterbody and the availability of the phosphorus must be considered in making this evaluation for water mass. A variety of other factors also influences the amount of planktonic algae at a particular location in a river, the most important of which is the available P loading and characteristics for the two weeks prior to the water's reaching the particular location. It appears that for slow-moving rivers (with velocities less than about 0.1 m/s) a modified version of the Vollenweider-OECD eutrophication models can be used to estimate the planktonic algal biomass that would be expected to develop in a water mass, a week's to two weeks' river travel time downstream.

CONCLUSIONS

Eutrophication is one of the most significant causes of water quality deterioration throughout the world. Its impacts range from nuisance conditions for recreation to contributing to fish kills (via hypolimnetic oxygen depletion) and contributing trihalomethane precursors to water supplies. While the input of a variety of nutrient contaminants from natural and cultural sources contribute to the growth of algae, it has been found in many parts of the world that excessive fertilization may in general be most readily controlled by reducing the inputs of available P to the waterbodies. In some areas, it may be necessary to control both P and N inputs, especially in coastal marine systems.

The Vollenweider-OECD eutrophication study results provide a framework through which reliable predictions can be made of the impact of altering the P from any particular source on planktonic algal-related water quality. It is important to focus eutrophication control on sources that contribute algal-available P. It has been found that at least a 25% reduction in the total load of algal-available P must be achieved in order to bring about a readily discernible improvement in eutrophication-related water quality.

Domestic wastewaters are a potentially significant source of P for many excessively fertile waterbodies that have shown changes in fertility in the past 50 or so years. The most cost-effective way of controlling P in domestic wastewaters is through treatment of the wastewaters for P removal using alum, iron, or enhanced biological treatment. This can be accomplished for a few cents per person per day for the population served by the treatment plant. In the USA and a number of other countries, detergent P bans have been found to be ineffective in reducing eutrophication-related water quality problems because the amount of P contributed from household laundry detergents is usually a small part of the total phosphorus load to the waterbodies. It would be rare that detergent P bans would be effective in controlling the excessive fertilization of waterbodies. The Vollenweider-OECD eutrophication modeling approach can be used to predict those situations in which detergent P bans could be effective for improving eutrophication-related water quality.

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