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ROLE OF PHOSPHORUS IN EUTROPHICATION AND DIFFUSE SOURCE CONTROL*

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Abstract—Many lakes and some streams and estuaries are showing signs of excessive fertilization due to the input of aquatic plant nutrients from man-associated sources. The key element often found limiting aquatic plant populations is phosphorus. The attempt to control phosphorus input to natural waters as the overall approach for controlling excessive fertilization is technically sound and economically feasible for many natural waters. However, a much better understanding of the relationship between the phosphorus input to a lake and the excessive growths of aquatic plants within the lake must be developed. This development will require a combined biological and chemical approach toward assessing the role of phosphorus in eutrophication for a specific water body. The biological approach will use tissue content, enzymatic and kinetic uptake analysis of phosphorus limitations as well as bioassays of phosphorus availability in order to determine the limiting nutrient for a body of water. The chemical aaproach will utilize amounts of each of the forms of phosphorus present in the lake and the rates of interchange of phosphorus between these various forms.

There will be some waters where control of phosphorus from treatment of domestic waste water input and removal of phosphorus from detergents will not result in significant improvement in water quality. This is because these waters derive their phosphorus from diffuse sources, such as urban and rural stormwater drainage, the atmosphere, and ground waters. In these instances, it may be necessary to initiate in-lake control of phosphorus by the addition of alum or iron salts.

INTRODUCTION

EUTROPHICATION is emerging as one of the most significant causes of water quality deterioration. The two most important questions about these problems are: what is the cause of the excessive fertilization and what can be done to control it? These two questions should be asked together because only through a program designed to limit the "key" aquatic plant nutrient flux to a body of water will a meaningful control program be achieved. The "key" nutrient is that nutrient or nutrients which can be controlled with the current technology and financial resources available. This nutrient may not be the nutrient primarily controlling aquatic plant growth but may be one that, even though not limiting growth, can be made limiting through the control efforts. Of all the elements known to influence aquatic plant growth, phosphorus is the "key" element in most fresh waters where control efforts must be directed. This conclusion is justified from several points of view.

First, phosphorus is one of the elements present in natural waters at concentrations which limit algal growth in many lakes. Secondly, phosphorus is the one element that is often derived primarily from sources related to man's activities. The other elements which may limit aquatic plant growth in some waters, such as nitrogen, carbon and trace elements, are often primarily derived from natural sources which are not readily amenable to control. The third reason for phosphorus control as a means of controlling excessive fertilization is that it appears that a significant phosphate input reduction to many excessively fertilized waters may be affected by removing phosphorus from domestic waste waters.

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While phosphorus is the key element limiting aquatic plant production in some but not all lakes, there are many lakes throughout the world where nitrogen and other elements are limiting algal growth. The concentrations of phosphorus in some of these lakes are such that it does not appear that control efforts directed toward reducing the phosphorus input in accord with current technology and financial resources available, would decrease the phosphorus concentrations in the lake to the point where it would limit algal growth. Therefore what is needed to develop the most meaningful control program for excessive fertilization in natural waters is a method of assessing the role of phosphorus in the eutrophication of a particular lake. A review of the current situation with respect to some of the tests used to assess the role of phosphorus in eutrophication of a body of water is presented in the next section of this paper.

ASSESSMENT OF ROLE OF PHOSPHORUS IN EUTROPHICATION

The recent work on the factors influencing the growth of algae in lakes has demonstrated that the addition of phosphorus will likely stimulate further algal growth. Unfortunately, the techniques available to estimate the amount of reduction in algal growth resulting from a reduced phosphate input are limited; in fact, they are almost non-existent. In order to predict the relationship between a certain phosphate increase or decrease and algal growth with any degree of reliability, a much better understanding is needed of the aqueous environmental chemistry of phosphorus in natural waters. Phosphorus exists in natural waters in a variety of forms, some of which are readily available for algal growth, while others show little or no availability. Various chemical (biochemical) processes tend to convert one form of phosphorus to another. A reasonably detailed mathematical model describing the rates of transformation of the important forms of phosphorus present in natural waters must be developed in order to make quantitative predictions on the relationship between the phosphate input and aquatic plant production in the lake.

Algal bioassay of nutrient status of a lake

In the past few years, the U.S. Environmental Protection Agency, several industrial firms, and universities have been developing an algal nutrient assay procedure. One of the objectives of the Provisional Algal Assay Procedure (PAAP) (E.P.A., 1969) is the assessment of the potentially available phosphorus present in a water sample that would stimulate algal growth. The achievement of this objective may be very difficult to obtain since there may be little relationship between the forms of phosphorus that become available in a few weeks in an algal culture compared to the forms that become available in a lake, stream, or ocean. The physical, chemical and biological environments of the lake and a bottle or flask are markedly different. The algal cultures that are normally used in the PAAP type procedure have much higher densities of algae and bacteria than most lake waters. In addition, the chemical composition of these waters are different. These factors could influence the availability of particulate forms of phosphorus and the transport of the materials from the sediments to the overlying waters. These problems should not be a deterrent to attempting to assess the biologically available phosphorus. On the contrary, considerable effort should be placed in this endeavor especially on lakes that are scheduled for phosphate input reduction in the next few years. Detailed studies should be made of these lakes in order to attempt a prediction on what the effect of this reduction would be on the lake. The predicted effect should be compared to studies of the nutrient levels and aquatic plant populations both before and after phosphate reduction. It is possible that by using this approach, empirical correlations will be developed between the bottle method and what takes place in the lake. In time, sufficient experience will be gained using the PAAP approach to make reasonably accurate predictions of the potential effect of altering a nutrient input and the response of the lake aquatic plant populations.

Some controversy has developed over the interpretation of the algal assay procedure for assessing limiting elements in algal growth. The problem centers around the fact that these measurements determine what may be limiting algae at the particular time of the measurement. The measurements may provide very little information on what could limit algae as a result of some corrective action taken to limit algal nutrients from entering the lake. For example, for Lake Washington, the studies by EDMONDSON (1970) show that the algae present in this lake in 1963 were, in general, nitrogen limited. Subsequently, the diversion of Seattle's waste water effluents from this lake reduced the phosphate input much more than the nitrogen input to the lake with the result that the total productivity of the lake decreased markedly. As of 1970, the algae present in Lake Washington have become on the average phosphorus limited. In this case, sufficient amounts of phosphorus were removed from the lake so that the algal populations switched from nitrogen limitation to phosphorus limitation.

Rather than assessing what is limiting algae at the time of sampling, a procedure is needed to assess whether or not it is feasible to control an algal nutrient to the point where it will limit the algal populations in the lake. It is suggested that in the case of phosphorus limitation, a PAAP approach could be used in the following manner. A sample of the water to be tested would be used to assess the algal productivity under standard conditions. The water would then be treated with iron or aluminium salts or lime to reduce the phosphate content of the water. Alternately, it would be possible to use ion-exchange resin to remove the phosphorus from solution. The PAAP-like procedure should then be run on the treated water. Since there is no method by which phosphorus alone may be removed from the water, it is necessary to take one additional step in order to be certain that the results obtained indicating decreased growth after phosphorus removal are due to the removal of phosphorus and not some other element. This step involves taking the treated water, adding the same amount of phosphorus as was present prior to treatment and then running standard PAAP-type analyses of the water. If the results are essentially comparable to the analyses of the original untreated water, then one can be reasonably certain that the decreased growth after treatment is due to phosphorus removal. If on the other hand, there is a marked difference between the original water and the water which had been treated with phosphorus, studies should be conducted to determine what element causes the difference.

Another problem with the algal assay procedures is that the nutritional status of algae may change within a few hours during a day. This problem is of particular importance in using short-term assay procedures based on carbon-14 uptake techniques. It is conceivable that samples taken during the middle of the day would show carbon limitation in some lakes during the periods of most active photosynthesis, while from an overall point of view, the algae present in the lake would be nitrogen and/or phosphorus limited. Under these conditions, it is highly unlikely that the carbon limitations shown by algae under massive bloom conditions during late afternoon would be of any significance from a water quality point of view. The numbers of algae present under these conditions is sufficiently high that any small increase resulting from addition of carbon to the system would be insignificant in terms of causing further water quality deterioration.

Simultaneously with the attempt to develop an empirical correlation between algal culture nutrient enrichment and depletion experiments, studies should be initiated on the nature of the chemical–biochemical processes that govern the transformations of phosphorus in natural waters. These studies should be directed specifically toward defining a reasonably sophisticated mathematical model of the aqueous environmental chemistry of phosphorus in natural waters. In a sense, the PAAP approach represents an attempt to crudely model the relationships of phosphorus and other nutrient input and algal growth in natural waters. In time, the mathematical modeling based on detailed studies of chemical processes and the PAAP "biological model" would be refined so that they become one in the same. Probably a combination of the two approaches will yield the greatest results in the foreseeable future.

Limiting-surplus algal nutrients

In recent years, FITZGERALD (1969), FITZGERALD and LEE (1971), of the University of Wisconsin and others have developed enzymatic and tissue assay procedures that enable estimates to be made of whether an aquatic plant has grown in an environment that has excess or limiting nitrogen and phosphorus. These techniques offer a potentially powerful tool for determining the relative roles of nitrogen, phosphorus and other elements in fertilizing natural waters. Information of this type could lead to an assessment of the potential effects of a certain nutrient input or reduction on the growth of aquatic plants in a lake. However, studies by Fitzgerald have shown that some aquatic plant populations have highly variable limiting-surplus phosphate values.

At the present time, it is very difficult if not impossible to translate the results obtained using one or more of the limiting-surplus algal assessment techniques into a general assessment of the type of corrective actions that should be taken to determine which of the nutrients should be limited in a eutrophication control program. The work of Fitzgerald has shown that various algal populations in the same lake show different limiting nutrients. Also, the limiting nutrient may change in a relatively short period of time. For example, studies by Fitzgerald on *Cladophora*, an attached algae along the shore of Lake Mendota have shown that prior to a rain this algae was nitrogen starved. Within a few days after the rain, it had surplus nitrogen. One of the more interesting observations of FITZGERALD (1969) using the limiting-surplus nutrient assay procedure was that the algae in an algal bloom consisting of two dominant planktonic algae did not share the phosphorus available to them. He found that one of the plankters was growing under limiting phosphorus, while the other had surplus phosphorus. This observation raises some questions about the generally held concept that there is rapid exchange (turnover) of phosphate among the reservoirs of phosphorus in natural water.

There is need for detailed studies on the relationship between the chemical composition of waters, organisms–particulate matter, PAAP results from limiting nutrient assays and the limiting-surplus phosphate present in attached and planktonic algae.

Available phosphorus

One of the questions that has been frequently asked in the past is how much of the chemically measured phosphorus, i.e. orthophosphate found in a sample of water is available for algal growth? RIGLER (1968) has reported that in some lakes, substantial amounts of the measurable orthophosphate are not readily available for algal growth. If this is a general case, the interpretation of phosphate analytical data would be extremely difficult.

Recently, however, WALTON and LEE (1971) have conducted a study on the relationship between the amounts of phosphorus available in natural waters based on an algal bioassay procedure similar to the PAAP procedure and the standard molybdate reactive phosphate in a water sample. Samples were taken from a variety of natural waters including phosphorus released from lake sediments, decaying algae, etc. They found that the standard molybdate test for soluble orthophosphate can be used to quantitatively predict the algal populations that will develop in a standardized laboratory bioassay procedure in which all other elements are present in excess except phosphorus. The primary differences between the results of RIGLER (1968) and those of WALTON and LEE (1971) were the levels of orthophosphate present in the samples. Walton and Lee worked with samples of lake waters which had ten or more micrograms per liter of soluble orthophosphate present, while Rigler was working with much lower levels. It is conceivable that both results are correct. Where much higher levels of orthophosphate are found, i.e. 10 $\mu g\ l^{-1}$ or greater, most of the phosphorus that is measured by the molybdate test is orthophosphate which is readily available for algal growth. At the $\mu g\ l^{-1}$ or less levels, a significant part of that measured by the test may not be available for algal growth.

A factor often overlooked in studies on the biological availability of aquatic nutrients such as phosphorus which could cause a discrepancy between bioassay and chemical procedures is the role of biodegradable organics. In some natural waters, especially those receiving partially treated waste waters, the concentration of biodegradable organic matter and bacteria able to utilize the organics is very high. In situations where adequate organics to support bacterial growth and low orthophosphate are present in the water, the bacteria, because of the much shorter generation time, can remove phosphorus from the water and make it unavailable for algal growth during a study of a few weeks duration. In other words, in a situation where algae and bacteria are competing for phosphorus, the bacteria are more efficient competitors. This kind of situation would result in finding that a substantial part of the soluble molybdenum blue reactive phosphorus is not immediately available for algal growth. In time, however, with the depletion of the readily biodegradable organic matter, the bacterial populations will die, releasing the phosphorus for algal growth.

Another cause of a discrepancy between available phosphorus as measured by the standard molybdenum blue method and that obtained in a bioassay procedure is the presence of small amounts of arsenic in the water. The practice of treating lakes with sodium arsenite for aquatic weed control has in some instances created relatively large concentrations of arsenic dissolved in the water. Studies by S. Kobayashi currently in progress at the University of Wisconsin Water Chemistry Program have found that some of these treated lakes have an excess of 0·5 mg l^{-1} of dissolved arsenic. Many natural waters have a few $\mu g\ l^{-1}$ arsenic present from natural sources. Independent of the source, this arsenic will be measured as dissolved phosphate in most molybdenum blue phosphate procedures. CHAMBERLAIN and SHAPIRO (1969) have reported that significant numbers of Minnesota waters have sufficient amounts of arsenic to cause significant errors in orthophosphate analyses.

CRITICAL NUTRIENT CONCENTRATIONS

Some years ago SAWYER *et al.* (1945) and more recently VOLLENWEIDER (1968) attempted to establish the critical concentrations of nitrogen and phosphorus in natural waters based on a chemical analysis of the water. These investigators have found an empirical correlation between excessive fertilization of a lake and waters that contain in excess of 10 $\mu g\ l^{-1}$ of soluble orthophosphate. They also found that the inorganic nitrogen must be in excess of 0·3 $mg\ l^{-1}$ in order to not limit the aquatic plant population. In a sense, these numbers are crude mathematical models of the chemistry of phosphorus and nitrogen in natural waters as they relate to aquatic plant production. These numbers are used in a yes/no type of relationship where it is expected that excessive growths of algae will occur when these concentrations are exceeded. It is also known that as the concentrations of nutrients increase above the critical levels, there is an increase in frequency and severity of obnoxious algal blooms in a lake. However, little information is available to quantitatively correlate the degree of eutrophication of a lake with the levels of nitrogen and phosphorus present. This topic would be a fruitful area for research. It is possible that results obtained from a chemical analysis of water in predicting algal growth will be as meaningful as those obtained from the bioassay procedure being developed. As previously discussed, the bioassay procedure does not take into account many of the factors that occur or that would influence the availability of phosphorus in the lake. At best, all that could be attained as a result of many years of detailed study is a correlation between the bioassay procedure and what occurs in the lake.

Possibly this same empirical correlation could be developed between relatively simple measurements of the composition of the water and organisms and the results of a test during which a sample of the water under investigation is allowed to stand in the dark for a period of time so that bacterial action can release readily available algal nutrients. This test would give an immediately available crude estimate of the potentially available phosphorus in a sample. The chemical approach is likely to be much less expensive and yield equally valid results. The basic concept of this approach is that there is a certain relatively fixed ratio of nitrogen and phosphorus needed for algal growth. Planktonic algae typically contain about 106 carbon and 16 nitrogen to 1 phosphorus atom. It is well known that these ratios change depending on the environment; however, these ratios are probably constant enough to make reasonable predictions as to what is likely to limit algal growth, i.e. nitrogen or phosphorus in most natural waters. This has been the case for Lake Washington where the examination of Edmondson's data shows this relationship. This was also found for Lake Superior, Lake Tahoe and the lower Madison lakes.

SIGNIFICANCE OF PHOSPHATE EXCHANGE WITH SEDIMENTS

One of the frequently used arguments against large expenditures for phosphate removal from waste waters and detergent formulations is that lake sediments represent a significant source of nutrients for the overlying waters. LEE (1970a) has recently reviewed the factors influencing the exchange of nutrients and other chemicals between sediments and water. The available data shows that sediments serve as a sink for phosphorus with the net flux of phosphorus from lake water to the sediments. Laboratory studies (LEE, 1970b) have shown that under completely mixed conditions, relatively rapid release of phosphate occurs under both anaerobic and aerobic conditions from a variety of lake sediments. Under static conditions, a slow release rate of phosphate is observed. These results point to the importance of mixing processes in determining the relative flux of phosphorus from the sediments. To estimate the role of natural water sediments in supplying phosphate to the overlying waters, a much better understanding of the hydrodynamics of lakes, with emphasis on the sediment-water interface, is needed.

It is possible, though, that intense storms may play a very important role in fertilizing lakes during the critical recreational period of the summer. Under severe conditions of turbulence, large amounts of sediments are mixed into the overlying waters from the near-shore and depending on the lake's morphology, the deeper waters of the lake. Because of the extreme complexity of the hydrodynamics of lakes, it is unlikely that the information needed to better define the relationship between nutrient release under laboratory conditions and field conditions will be available in the near future. Therefore, it is likely that a much more empirical approach will have to be used. It is felt that an approach utilizing the relatively simple techniques of a stirred and unstirred leaching test under oxic and anoxic conditions could potentially be correlated with field results in which large-scale nutrient removal experiments are conducted. Every nutrient removal project being contemplated within the next few years should include some laboratory leaching test on the sediments of the lake. The results of these leaching tests should be compared to the rate of recovery of the lake upon nutrient input reduction. This type of information may eventually lead to empirical correlations which would, in time, enable some predictability on the role of lake sediments in affecting the rate of recovery of lakes after nutrient input reduction. These empirical leaching tests should be accompanied by the empirical phosphorus characterization tests developed for estimating the forms of phosphorus in soils such as the procedures developed by CHANG and JACKSON (1958) and the recent modifications thereof for lake sediments (see WILLIAMS *et al.*, 1971).

CONTROL OF PHOSPHORUS

The removal of phosphorus from detergents is expected to reduce the phosphorus concentrations in most municipal waste waters in the U.S. by 50 per cent. The treatment of waste waters by iron, aluminium salts or lime can readily bring about a 90 per cent reduction in phosphorus present in waste waters. It is likely that phosphorus will be removed from heavy-duty household detergents within the next two to three years. Also phosphorus removal from waste waters will become a common practice in 4–6 yr. As a result of these steps, in a few years many natural waters will show a marked improvement in water quality. The greatest improvement will occur where phosphorus is already limiting algal growth and the primary source of phosphorus is domestic waste waters. The rate of improvement will be dependent upon the hydrology of the drainage basin, morphology of the lake and the characteristics of the water and sediments. There will be, however, many instances where this improvement will occur for a relatively short period of time because urbanization of a lake's watershed results in a significant increase in the flux of aquatic plant nutrients from urban drainage. In addition, there are some situations in the United States where surface and ground waters and precipitation naturally contain concentrations of phosphorus above those found by SAWYER *et al.* (1945) which cause excess growth in southern Wisconsin lakes. Recent studies by the University of Wisconsin Water Chemistry Program have found ground waters containing 20–30 $\mu g\, l^{-1}$ of soluble orthophosphate in areas where there are little or no activities of man. This phosphorus is derived from natural sources and is always associated with ground waters contained in aquifers consisting of quartz and other silicate mineral sands. These sands are very low in calcite and dolomite as well as iron and aluminum oxides. The lakes in these areas are naturally eutrophic and receive a substantial part of their nutrients from ground waters.

A review of the current situation on the Great Lakes shows that the open waters of Lakes Michigan, Superior, and Huron have phosphorus limited algae. Lakes Erie and Ontario are probably borderline with respect to the algae having surplus phosphorus, i.e. the algal growth may be limited by other elements. It is likely that 80 per cent removal of phosphorus from waste water sources will cause phosphorus to be limiting for algal growth in the lower Great Lakes. In lower Green Bay, based on the studies conducted by SRIDHARAN and LEE (1972), 80 per cent removal of phosphorus from the waste water sources will not reduce the phosphorus concentrations in the water to the point where it will limit algal growth. The 80 per cent removal of phosphorus from the waste waters in lower Green Bay will probably result in a 50 per cent overall reduction of phosphorus in the lower Bay. Such a reduction will not be sufficient to make phosphorus concentrations in the water sufficiently low to limit algal growth. In situations such as lower Green Bay and other near-shore waters of metropolitan areas of the Great Lakes, it may be necessary to control the diffuse sources of phosphorus.

In addition to urban and natural sources, agricultural activities of various types tend to increase the concentrations of phosphorus above the levels necessary for excessive growth of algae and other aquatic plants. While it may be relatively simple and inexpensive on a per capita basis to treat point sources such as waste waters for phosphorus removal, diffuse phosphorus sources such as urban storm water drainage, agricultural runoff and ground waters may be difficult, prohibitively expensive and almost impossible to control. In these instances, it may be necessary to initiate in-lake treatments such as the addition of iron or aluminum salts directly to the lake water to precipitate or co-precipitate phosphorus, thus carrying it to the lake sediments.

At the present time, there is insufficient information available to predict the results that can be obtained by this technique. The preliminary studies, such as those by WALL *et al.* (1970) show promising results; however, additional studies over longer periods of time will be necessary to begin to evaluate the effectiveness of this method of lake restoration. Some of the more significant questions in this area include an evaluation of the chemicals that may be used, such as iron, aluminum, polyelectrolytes and other coagulant aids; methods of applications in temperate lakes after ice-out, after thermocline is formed, before or after algal blooms develop, to the surface waters only, hypolimnion only, etc.; the amount of mixing and flocculation necessary to achieve the removal, including studies on how best to apply the chemicals, what doses are necessary, etc. A thorough evaluation of the potential effects of iron and aluminum salts on the benthic fauna must be conducted before large-scale testing should be practiced. In addition to evaluating the effectiveness of this technique on the control of planktonic algae, consideration should be given to studies on lakes where the problem is one of excessive growth of macrophytes and attached algae. The results are likely to be markedly different for these two types of problems. While the addition of chemicals to lakes to control the excessive growth of algae must be viewed with caution, it is felt that a sufficient promise of significant benefits is likely to accrue from the addition of alum and/or other salts for phosphate control in lakes to warrant the expenditure of considerable funds in large-scale field testing of this technique. This method should not be viewed as a cure-all for excessive fertilization problems. It should only be used in those lakes where all of the readily controllable sources of nutrients have been curtailed. There will be lakes, though, where the nutrient sources are sufficiently diffuse that the economic feasibility of controlling them is very slight. Under these conditions, the in-lake treatment of nutrient control may be an effective method of controlling excessive fertilization with little or no harm to aquatic ecosystems.

Since in many natural waters phosphorus is derived to a significant extent from a variety of sources (such as urban storm water drainage and agricultural runoff), increased attention should be given to the control of these diffuse sources of phosphorus. Because of their diffuse nature, chemical treatment of these sources will be extremely expensive, quite probably prohibitive. Rather than attempting to collect and treat drainage waters from urban and agricultural areas, a more fruitful approach might be to study in detail specific sources of phosphorus in urban and agricultural areas, and then attempt to control the specific source at its origin. For example, it is known that urban storm water drainage contains large concentrations of phosphorus. At the present time, essentially nothing is known about the specific sources of phosphorus in the urban environment. The mass balance approach needs to be made in a number of urban communities throughout the United States in order to determine the relative significance of lawn fertilization, gasoline combustion, dust fall, terrestrial plants, etc. as sources of phosphorus in urban areas.

KLUESENER (1972) has recently completed a study on the amounts of nitrogen and phosphorus derived from urban stormwater drainage in Madison, Wisconsin. He found that the amounts of phosphorus present in the storm water drainage of Madison were similar to those found by WIEBEL *et al.* (1964) for Cincinnati, Ohio. KLUESENER (1972) noted that the highest concentrations of phosphorus in the urban stormwater drainage were associated with the leaf fall period during the fall. Recently, COWEN and LEE (1971) conducted a study on leaves as a source of phosphorus and found that large amounts of phosphorus are readily leachable from dead leaves. It appears, based on these studies, that more effective leaf pick-up during the fall might minimize the amounts of nutrients derived from this source in urban storm water drainage.

The potential significance of the control of phosphorus from any source can be estimated based on the types and amounts of phosphorus derived from various sources for a body of water. In some instances crude estimates of the land use patterns within a lake's watershed and the amounts of phosphorus derived from each type of use pattern can provide adequate information to potentially assess the significance of a control program designed for minimizing excessive fertilization of a body of water.

TABLE 1. AMOUNTS OF PHOSPHORUS CONTRIBUTED FROM VARIOUS SOURCES IN SOUTH CENTRAL WISCONSIN

Source	Amount
Domestic waste water	2 lb capita^{-1} yr^{-1}
Urban storm water runoff	0·8 lb acre^{-1} yr^{-1}
Cropland and pasture runoff	0·04 lb acre^{-1} yr^{-1}
Woodlands	0·003 lb acre^{-1} yr^{-1}
Manured lands (100 cows mile^{-2}) (15 tons manure cows^{-1} yr^{-1})	1 lb acre^{-1} yr^{-1}
Drained marshes	40 lb acre^{-1}
Rainfall	Variable
Groundwater	Variable

After LEE *et al.* (1966), LEE (1970).

TABLE 1 presents the results of the studies by LEE *et al.* (1966) on the amounts of phosphorus derived from various sources in south central Wisconsin. While the loading factors presented in TABLE 1 were derived from one specific area they may be used as very crude estimates of the amounts of phosphorus derived from other areas with a similar topography and climate. It should be noted, however, that a review of the literature on the amount of nutrients derived from various types of land use shows tremendous variability, depending on the investigator, the area studied, and other yet unresolved factors. The data presented in TABLE 1 should be used as a general guideline. It is readily apparent that the urbanization of a lake's watershed results in a tremendous increase in the amount of phosphorus that the lake may receive. If the value of 0·003 lb yr^{-1} is taken as a natural background, then converting the land to croplands results in about a 10-fold increase in the phosphorus flux. A 20-fold increase in flux is noted in the conversion of crop lands to urban areas. The magnitude of this change is much greater if the urban areas were at one time marshes since studies at the University of Wisconsin Water Chemistry Program have shown that drainage of marshes results in a very significant release of nitrogen and phosphorus in the drain water (LEE *et al.*, 1971). This release probably takes place over a period of several years and it is estimated that marshes of the type found in southeastern Wisconsin would release in the order of 40 lb of phosphorus per acre. It should be noted from the data in TABLE 1 that not all conversions of agricultural lands to urban areas result in an increase in nutrient flux since manured lands resulting from dairy herds will actually result in a decrease in nutrient flux when the land is converted to urban areas. This is because the manured lands contribute something on the order of 1 lb acre^{-1} yr^{-1} of phosphorus while the urban storm water drainage yields slightly less than this amount. The inputs from rain fall and ground water should not be overlooked since both of these can contribute large amounts of phosphorus to a body of water.

One of the methods beginning to be used for controlling agricultural and urban storm water drainage is the zoning of land use. In Wisconsin there has been recent legislation which is specifically designed to prevent urban development in Lake Mendota's watershed because of the potential deleterious effects the conversion of farm land to urban areas would have on increasing the nutrient flux to this lake. Further, Illinois is enacting legislation which prevents certain types of fertilizer application on lands with a slope greater than a certain degree. This legislation is designed to minimize the amounts of nutrients derived from certain types of agricultural practices. Another example of this type of development is the current legislation being considered on the Lake Mendota drainage basin. The proposed laws would prevent the winter spreading of manure from dairy operations and the draining of marshland for agricultural or urban use. It is likely that these developments in Wisconsin and Illinois will set the pattern for similar developments throughout North America.

In addition to determining the amounts of nutrients derived from various types of activities of man in urban and agricultural areas, studies must be initiated to determine what part of the phosphorus from these sources is or can be made available for aquatic growth. Some urban and agricultural activities contribute large amounts of total phosphorus; however, most of this phosphorus is in a form, i.e. particulate, organic, etc., that is not immediately available for the growth of algae. A much better understanding must be achieved on the aqueous environmental chemistry of particulate, inorganic, and organic phosphorus in order to ascertain the real significance of the various forms of phosphorus derived from urban and agricultural areas in stimulating the growth of aquatic plants.

About the best that could be done at this time is to state that in most instances the available phosphorus is somewhere between soluble orthophosphate and the total phosphorus. The fraction of organic and particulate phosphorus that becomes available in natural waters is extremely important in designing meaningful eutrophication control programs for diffuse sources of nutrients. There is little point in attempting to control particulate forms of phosphorus when it is known that the phosphorus would not become available for algal growth under the conditions existing in the receiving waters.

CONCLUSIONS

Phosphorus is a key element in causing the excessive fertilization of natural waters. At this time there is insufficient evidence to quantitatively predict the role of phosphorus in the excessive fertilization of a given lake. Research is needed on assessing this role using a variety of chemical and biological techniques. Emphasis should be placed on determining phosphorus sources, forms, rates of transformation, and availability for aquatic plant growth in natural waters. The results of these investigations should be formulated into mathematical models which would enable predictions of the relationships between phosphorus input and the excessive growths of aquatic plants in natural waters. Increased efforts should be devoted to the control of phosphorus from diffuse sources such as urban storm water drainage and agricultural runoff. Phosphorus should be removed from detergents as soon as suitable replacements are found which have been properly evaluated with respect to potential environmental impact and personal safety hazards. Large-scale studies should be conducted on the control of phosphorus in lakes by direct treatment of the lake with phosphorus-precipitating chemicals.

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DISCUSSION

Professor Lee assumes throughout his paper that eutrophication is bad *per se*; but surely eutrophication is a biological term of precise meaning, which means a movement from a low productivity state to a high biological productivity (eutrophic) condition. In fact, one of the aims of the IBP seems to be to encourage biological productivity, to help feed the world population. There is little doubt that eutrophication run wild can cause problems of productivity in the wrong place at the wrong time, such as algal blooms in lakes and reservoirs, leading to anaerobic conditions, fish mortalities and difficulties with water treatment; and unbridled growth of Cladophora, with hyacinth, etc., in open bodies of water. But it seems to me to be thoroughly wrong to control eutrophication on principle; let us stick to defining actual problems, assessing the cause of each one, and then defining and applying the correct cure in the right place at the right time.

Imperial Chemical Industries,
Brixham.

C. R. PEARSON

Reply

I agree that there seems to be the paradox today of some individuals wanting to fertilize natural waters in order to increase the productivity of these waters as a food resource for man while others, particularly in the more well-developed countries, are spending large amounts of money in order to limit the nutrient flux to a particular body of water in order to try to maintain what is thought at this time to be the most desirable water quality. In general, there is a conflict between increased productivity of water bodies and high water quality maintenance. It is a rare aquatic environment where high quality water is maintained in the presence of high productivity. Normally, increased productivity results in a significant deterioration of water quality with increased frequency and severity of water treatment problems, decreased recreational values and other deleterious effects. It is conceivable that some time in the future we may be deliberately fertilizing many of our natural waters in order to increase food production; however, at this time in most of the more well-developed countries of the world food production is adequate and the major emphasis today is directed toward maintaining high water quality, which in general means a minimum of algal growth in a body of water.

G. F. LEE

During the past 8 yr I have been studying the impact of new reservoirs on the River Nile and one of the most striking features has been the development of dense plankton blooms, equivalent to those experienced in eutrophic reservoirs in Britain, despite the complete absence of pollution in the Nile and phosphorus levels less than one-tenth of those in Britain. An important conclusion of this work is that tropical waters are far more sensitive to eutrophication because temperature and illumination are rarely limiting. Very small increases in phosphorus and nitrate in the Nile could have far more serious consequences than in temperature waters.

Clyde River Purification Board,
Glasgow.

D. HAMMERTON

Reply

I agree with your general conclusion that both temperature and illumination can play important roles in controlling phytoplankton growth in impoundments and lakes. Many of the impoundments on U.S. rivers are relatively turbid due to the large amounts of suspended sediment carried by the river. Under these conditions, the algal populations are often light-limited. Based on my observation on phosphorus levels in many English streams and reservoirs, particularly in the southern part of the country, I find that phosphorous is rarely limiting algal growth. It is not surprising, then, that you would note that you could still have excessive growths of algae in reservoirs on the Nile at one-tenth the level of phosphorous present in many English reservoirs. I know from discussions with John Ridley of the London Metropolitan Water Board that often the phosphorous content of London drinking water is in the order of mg l^{-1} levels of phosphorus. In the U.S., we frequently find that values of 100-fold less than this are sufficient to grow excessive amounts of algae in our surface waters.

G. F. LEE

I have reached exactly the opposite conclusion to the author's, that is, we will never be able to control excessive algal growth by attempting to control phosphorus *input* to a lake because (1) algal require so very little phosphorus for growth (and this very small amount can be recycled many times) and (2) there are such large uncontrollable natural sources that we will never be able to decrease phosphorus input to a sufficiently low level to inhibit or limit algal growth. Have you calculated how little phosphorus is required to support an algal bloom and have you calculated how many times greater the natural, uncontrollable phosphorus input is to a lake. The author's attention is directed to the fact that in Lake Erie, just 1 per cent of the phosphorus entering each year is sufficient to support an algal bloom over the entire 9980 square mile surface of the lake—provided all other nutrients were present in their respective required amounts, and that over 33 per cent of the phosphorus input to Lake Erie is attributable to natural, and therefore mostly uncontrollable, sources.

FMC Corp.
Princeton,
N.J.
U.S.A.
P. F. DERR

Reply

I support your conclusion that very small amounts of phosphorus are needed to develop a rather substantial algal bloom. However, I disagree with your conclusion that it will not be possible to limit algal blooms in lakes by controlling phosphate. The available evidence is overwhelmingly against your conclusion. The work during the past few years has shown that there are large numbers of lakes in which the addition of phosphate will stimulate algal growth. The data can be best interpreted as showing that the algal populations present in these lakes are limited by phosphate. It is reasonable to expect that reducing the phosphate input to these lakes would result in even a greater limitation being placed on the algal population, and therefore a decrease in the frequency and severity of excessive algal blooms. It should be noted that there are lakes and streams where phosphate is not currently limiting algal growth, and where removal of 50 per cent of the phosphorus from domestic waste waters by removal of phosphate from detergents, and/or removal of 80 per cent of the phosphorus by advance waste treatment, will not make phosphate limiting for the algal populations. This is the situation that developed on the lower Madison, Wisconsin lakes some years ago, when the City of Madison diverted its waste waters around the lower lake. Because of the relatively large amounts of phosphorus derived from other sources, such as agricultural drainage and urban drainage from the streets, it was found that the phosphorus in the lower lakes did decrease significantly. However, not to the point where it was limiting. Even here, there was a significant improvement in water quality because of a change of species diversity. Prior to diversion, the lakes were almost pure cultures of certain blue-green algae. After diversion, they had a much more diverse population of algae; since many of these algae do not affect water quality to the same degree as blue-green algae, there was a significant improvement in water quality as a result of diversion.

G. F. LEE

In the United States many waters contain sufficient calcium ion (equivalent to 100 ppm or greater $CaCO_3$ hardness) so that chemical precipitation alone can account for the low algal growth-limiting phosphate concentrations found in many lakes. In Lake Minnetouka, near Minniapolis, Minnesota, Dr. Robert Megard (Univ. of Minn.) has reported that less than 7 per cent of the phosphate added each year remains dissolved in the water—over 93 per cent is deposited in the lake sediments. Does this not mean that over 93 per cent of the *total* input of phosphorus must be stopped before we could even begin to decrease the concentration in the water and after phosphorus input to a lake is decreased to some low level, how will we prevent re-solubilization from the sediments?

FMC Corp.
Princeton,
N.J.
U.S.A.
P. F. DERR

Reply

First, I wish to comment that based on our studies on the chemistry of phosphorus in natural waters, we find virtually no relationship between the hardness of the water, i.e. calcium content, and the amounts of phosphate present. While, from theoretical grounds, phosphate should be precipitated as a calcium species in many lakes, from a practical point of view, it has been found that this precipitation does not occur at a significant rate. The problem may be one of very slow rate of nucleation, and such precipitation may only occur as a result of diagenetic processes in the lake sediments. With regard to your question on the recycling of phosphorus from lake sediments, I wish to point out that there is ample evidence today that lake sediments, in general, tend to act as phosphate sinks. There is a small amount of recycling of phosphate from the sediments, however, based on our recent work, this appears to be primarily associated with mineralization processes, and does not represent a significant release of phosphate from the inorganic species which tend to bind phosphate to the sediments. I feel that it is important to note that there are degrees of eutrophication. As we add more and more nutrients to the lakes, we tend to increase the frequency and severity of abnoxious algal blooms. Mildly eutrophic lakes with small amounts of nitrogen and phosphorus, may have one or two obnoxious blooms each summer. Under the conditions such as occurred in the lower Madison lakes, before diversion of sewage effluent some years ago, there was a continuing blooming process in which the algal scum would accumulate along the shore to the point where the ducks and turtles would walk on the surface of the scum. Therefore, to say that we must remove 90 or more per cent of all the phosphorus going into the lake to have any improvement in water quality is incorrect. There is ample evidence that while we may not be able to make pristine water out of highly eutrophic lakes by removal of phosphate, such removal will tend to cut down the frequency and severity of excessive algal blooms, with the result that there will be an overall improvement in water quality.

G. F. Lee

The author's remarks are inconsistent. How does he reconcile his statement that each lake should be examined individually to determine nutrient limitation and his opposition to "banning"—e.g. NTA, with his recommendations of getting rid of phosphorus from detergents.

University of California,
Berkeley,
U.S.A.

D. Jenkins

Reply

I can possibly understand how you feel there might be an inconsistency in my position with respect to the need for control of phosphate. Possibly this apparent inconsistency can readily be explained when we consider the situation that those of us frequently face in trying to control excessive fertilization of natural waters. First, we do have the tools today to begin to examine in some detail whether phosphorus is limiting or can be made limiting in a given body of water for controlling excessive algal growth. I maintain that this is the approach that should be followed. However, I also realise that often we do not necessarily follow the most technically sound approach toward control of our environmental quality problems. Often the public, politicians, conservation activists and others, press for immediate solutions. They have had enough studies. Under these conditions, sometimes a scientist or engineer is placed in a position of having to make recommendations based on very limited knowledge of the system. Under these circumstances, one is faced with trying to draw analogies between behavior of other lakes and streams where phosphate had been controlled, and what might happen in a given lake or stream without additional study. I feel that since, in general, it has been shown time after time that phosphorus is primarily derived from the activities of man, while other nutrients are often derived from natural sources to a major extent, and since phosphorus is often found to be one of the key elements limiting algal growth, that if it is impossible to gain the necessary funds to do a reasonable study on the individual body of water using the tools available, the best "guess" on what should be done to control excessive fertilization is that of controlling excessive phosphate input. Therefore, the apparent inconsistency is only in terms of the financial resources of those responsible for making decisions on control of excessive fertilization. If the resources are available, and if the public will wait several years during which a study will ascertain whether a reduction in phosphate input would likely be of benefit, then conduct the study. If not, because of the overwhelming evidence mounting today that phosphorus is the key element in many situations, then proceed with phosphate removal even though it might not be possible to predict with any degree of reliability the magnitude of the benefit that would be derived from such action.

G. F. Lee

With regard to the situation at Milwaukee where the author believes there is a case for removal of P from detergents because of overloading and by-passing of sewage, why allow untreated raw sewage to by-pass a works without improving that works and instead seek to improve the situation by removing detergent phosphates? Could the author enlarge on his statement that eutrophication is *the most* important water pollution problem in the U.S. when only around 15 per cent of the U.S. population is affected directly by eutrophication, whereas it is understood that around 70 per cent of the population is without basic sewage treatment facilities?

Albright & Wilson Ltd.
Whitehaven.

E. J. Hudson

Reply

I do not wish to give the impression that the City of Milwaukee is not doing a good job in treating its domestic wastewaters. Milwaukee Metropolitan Sewage District is known throughout the U.S. as being one of the few waste treatment facilities in the U.S. that naturally achieves a relatively high phosphate removal. The problem in Milwaukee is one of a combined sewer system which allows storn water drainage to enter domestic sewers. Whenever the flow becomes sufficiently high, then part of the wastewaters are diverted to the Milwaukee River. This is a common problem throughout many of the larger cities in the U.S. Significant steps are being taken to eliminate this type of problem, however, because of the tremendous expense involved of developing a separate sewer system for storm drainage and wastewaters, it will take a number of years to bring this about. During this period, I feel that a significant reduction in phosphate input to Lake Michigan can be made by removal of phosphate from detergents just as soon as a suitable safe replacement has been found. As far as the comment on the statement that only 15 per cent of the U.S. population was affected by eutrophication, I feel that this statement grossly underestimates the significance of this problem in the U.S. This statement rules out all people living in rural areas, in cities which discharge wastewaters to rivers, and on the coast or estuary system. There are significant eutrophication problems in each of these areas, for example in rivers. There are few rivers in the U.S. that have not been impounded. Impounded waters have many of the same problems as lakes with respect to excessive fertilization. Some estuaries, such as the Potomac estuary in Washington, D.C. has a very serious algal problem each summer. Even within rural areas, especially those with sand aquifers and a ground-water table near the surface, there is ample evidence that phosphate will be transported via the groundwater to nearby lakes and streams, and thereby, contribute to the excessive fertilization of these waters.

G. F. LEE

How much *excess* alum was used in your treatment of Horseshoe Lake? Dr. Burns stated that anoxic conditions in Lake Erie greatly increase solubilization of phosphorus. This is assignable to *organic* pollution. Phosphorus is an indicator or tracer of organic pollution, according to Professor Pomeroy, and Drs. Ryther and Dunstan of Woods Hole Oceanographic Institution. The non-algae organic matter added from just one city on Lake Erie, Detroit, is equivalent to raw sewage from over 2,000,000 people!

FMC Corporation, P. F. DERR
Princeton,
N.J.
U.S.A.

Reply

Horseshoe Lake, in Wisconsin, was treated with approximately 200 ppm of alum to the upper 6 ft of the lake. I wish to comment on the potential significance of the sources concerning the problems of deoxygenation of lakes due to their fertility. In the case of Lake Erie, it has been clearly demonstrated that the deoxygenation of the hypolimnion of Lake Erie is not related to the discharge of treated or partially treated wastewaters containing a significant BOD. The deoxygenation process is directly related to the fact that aquatic plant nutrients, such as phosphate, in Lake Erie, stimulate algal growth which results in a significant BOD—being created upon the death of the algae and their settling to the bottom.

What will be the effect of NTA on releasing P from sediments where they are held by heavy metals? NTA has not been shown to readily degrade in all conditions. Work in Sweden, Germany and the U.K., including in the latter case at W.P.R.L. and by Dr. Harkness of the Upper Tame Main Drainage Authority, have shown that NTA removal is unsatisfactory when (1) sewage plants are overloaded, (2) at low temperatures, (3) if complexed with heavy metals.

Unilever Research, J. A. G. TAYLOR
Port Sunlight,
Cheshire.

Reply

All of the data that I have seen, including our own work, indicate that NTA does in fact rapidly degrade in natural waters. I do not foresee, based on the available evidence, that the use of NTA in household detergents will result in a general problem of increased solubilization of metals in natural waters. There is still some need for research in this area, however, the research conducted thus far seems to how that based on both laboratory and field results, NTA does not appear to have a significant effect on metals present in natural water sediments.

G. F. LEE

The water from a drained marsh contained 40 lb of phosphorus per acre per year according to the author which concerned the speaker. In Northern Ireland "basin" bogs are drained to produce agricultural improvements and "blanket" bogs for afforestation. These have a large water holding capacity. Was the drained marsh referred to by the author acid or alkaline? The bogs in Northern Ireland are acid, sometimes as low as pH 5·2.

Water Quality Branch,
Dept. of Industrial and Forensic Science,
Ministry of Commerce,
Belfast.

JAMES F. MORGAN

Reply

The marshes that we have studied are all alkaline marshes, occurring in limestone areas. I would expect that marshes draining non-limestone areas would have a low pH, and might behave somewhat differently with respect to phosphate release, than the alkaline marshes of southern Wisconsin. There is need for additional study on this matter, in order to define whether in fact there is a significant difference between the two types of marsh systems.

G. F. LEE

M. N. Burns was invited to comment on the opinion expressed by one discussor that a reduction of P input to Lake Erie would effect little change. Dr. Burns stated that there has been developed a correlation between increased P loadings to Lake Erie and increased deoxygenation of the bottom waters. This correlation has not yet been proved to be causal. This increased deoxygenation has caused anoxic conditions which have increased the P release rate from the sediments by 11 times the toxic rate, causing further growth. This work is described in "Project Hypo" Paper 6, Canada Center for Inland Waters, Burlington, Ontario.

Are the author's statements in his paper consistent with the following statement he made in 1970. "The current state of knowledge of algal ecology is such that it is impossible to relate the frequency of severity of algal blooms to specific phosphate levels in the water. It is also impossible to predict the phosphate levels that will be present in a water for a given phosphate flux to the water. Present available technical information does not appear to be sufficient to predict water quality that will result from 80 per cent phosphorus removal."

FMC Corp.,
Princeton,
N.J.
U.S.A.

P. F. DERR

Reply

I still support the statement that you quoted concerning the current degree of information on the relationships between specific phosphate levels of algal blooms in lakes, and the relationship between a given phosphate flux and algal growths. Further, I maintain that no one at the present time is in the position to accurately predict the amount of reduced algal growth that would occur in a given body of water as a result of reducing the phosphate input by 80 per cent. While it might appear on the surface that there might be a contradiction between statements made then, and now, concerning the need for removal of phosphate from waste waters, and the statements that you quoted, it should be noted that in fact there is no contradiction. While we cannot make accurate predictions about the change in frequency and severity of algal blooms, as a result of reducing phosphate input, there is overwhelming evidence that the only steps that can be taken at this time to control excessive fertilization of some bodies of water, is to reduce the phosphate input as much as possible. At this time, it appears economically and technically feasible to remove phosphorus from domestic waste waters at relatively small cost. Therefore, I maintain that we must proceed with all vigor to removal of phosphorus in any situation where phosphorus is either currently limiting, or is likely to become limiting in a body of water that is experiencing or could be expected to experience excessive growths of algae. Hopefully, within a few years, based on the current research that is underway in many parts of the world, we would be able to make a much more accurate prediction of the benefits that will be derived from such corrective action. We cannot wait until all of the answers are in before we proceed. In this case, we must take the necessary steps now, in order to protect water quality to the maximum extent; and the necessary step in many instances is the step of removal of phosphorus from waste waters. It should be noted, as mentioned in my discussion, that we may have to remove phosphorus from urban storm-water drainage and agricultural drainage in order to in some cases, only slow down the rate of deterioration of water quality due to excessive fertilization.

G. F. LEE

This brief comment is submitted in response to several questions raised by conference participants concerning the possible (or probable) extent to which waters in the United States are actually or potentially threatened by eutrophication. I will not attempt to discuss whether or not eutrophication is "good" or "bad". Furthermore, industrial wastes, raw municipal wastewater, agricultural or urban runoff, etc., are not considered in this note, nor are vessel discharges or distributed sources of nutrients. Only actual or potential eutrophication of lakes and impoundments resulting from discharge of treated (primary, secondary, tertiary) unicipal effluents will be discussed here.

There are approximately 12,500 municipal sewage treatment plants with over 25,000 individual outfalls in the U.S. as of 1970. In an effort to determine the extent to which these outfall discharges could effect receiving water quality, the U.S. Environmental Protection Agency has completed the first part of a larger, national eutrophication survey program. The objective of this first part of the survey was to determine how many of the 12,500 sewage treatment plants were discharging either directly to lakes or impoundments, or were discharging, within a distance of 25 miles from a lake or impoundment, into tributary rivers.

The results of this relatively simple task are that, of the total of 12,500 sewage treatment plants, over 3000 are discharging io lakes, impoundments, or to streams tributary to the latter. The total number of lakes and impoundments receiving these discharges is approximately 1200, for an average of 2–3 sewage treatment plants per receiving water body.

Simple arithmetic on this most conservative of estimates suggests that Dr. Okun's guess (that only 15 per cent of the U.S. populace lives in areas affected by eutrophication problems) is wrong. The figure of 25 per cent (3000/12,500) I am suggesting assumes that the sample of sewage treatment plants included in the survey is statistically similar (in terms of persons served per treatment plant) to all treatment plants, and that the size frequency distribution (in MGD) of the 3000 waste treatment plants is similar to that of all treatment plants. The 25 per cent figure may be an overestimate of the magnitude of this one part of the eutrophication problem since both actually and potentially affected lakes and impoundments are included in the enumeration. However, the figure represents an under-estimation of the extent of eutrophication since all other sources of nutrients attributable to human activities (road building, agriculture, other soil disturbances, industrial effluents, etc.) were excluded, as were the eutrophication problems of waters other than lakes or impoundments such as free flowing rivers, bays, and estuaries.

NORMAN R. GLASS

Office of Research and Monitoring
U.S. Environmental Protection Agency,
Washington D.C. 20460,
U.S.A.