INLAND WATERS BRANCH

DEPARTMENT OF ENERGY, MINES AND RESOURCES

The Control of Eutrophication

Prepared by the Canada Centre for Inland Waters, Burlington, Ont., Fisheries Research Board of Canada, Winnipeg, and Inland Waters Branch, Ottawa.

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Introduction

The controversy over the respective roles of phosphorus, nitrogen and carbon as critical elements in limiting the eutrophication process has recently been renewed. All three of these elements, plus many others, are essential and must be readily available to produce extreme algal growth.

This report, using information provided by scientists of the Department of Energy, Mines and Resources and the Department of Fisheries and Forestry, shows that carbon is rarely a critical growth-limiting element in lakes, that nitrogen is of more importance, and that phosphorus in most cases is the critical and controlling factor in eutrophication. Furthermore, phosphorus can be controlled by regulating its use whereas nitrogen cannot be controlled to the same extent. Control of carbon from natural sources is virtually impossible.

Eutrophication

Eutrophication is the process by which lakes age by gradually becoming choked with vegetation and filled with sediment. This process usually takes many thousands or hundreds of thousands of years but, in the case of a number of the world's lakes, man's activities have rapidly speeded up the process. Where man has drastically shortened the life-span of lakes, the process has been termed *cultural eutrophication.*

The most obvious manifestations of cultural eutrophication are the blooms of algae on lake surfaces and the luxuriant growths of algae and rooted plants on the bottom in shallow near-shore areas. Over-abundance of both these kinds of growth interfere seriously with man's uses of lakes for recreation, water supplies and fishing. When algae die, some wash ashore and decay in stinking masses on beaches and at water intakes. Mid-lake growths tend to sink to the lake bottom and use up oxygen in the bottom waters as they decay. Oxygen depletion results in fish die-offs, and in the replacement of clean-water bottom organisms with organisms characteristic of polluted waters and sediments.

Algal "blooms" are said to occur when there is greater than about 10 cubic centimeters of phytoplankton per cubic meter of water. A normal rate of increase in the number of cells in a major bloom in a lake is 20-30% per day, although some maximum rates of 50-100% per day have been observed in culture experiments. The rate of growth in blooms in lakes is difficult to measure, however, since winds move the surface waters and their algal production very rapidly. In addition the growing phytoplankton are sometimes distributed through fairly deep layers when the waters are well mixed by wind action. In calm periods the algae tend to concentrate near the surface. "Carpets" of blue-green and green algae, characteristic of eutrophic lakes, are especially noted for staying close to the water surface. Failure to distinguish between algal growth on the one hand and algal accumulation near the water surface on the other has led to misunderstanding of the rates with which nutrients must be delivered to a growing algal mass.

CONTROLLING FACTORS

In the past few decades, a great deal of scientific effort has been directed towards finding the causes of and possible cures for cultural eutrophication. Much of this work has involved assessing the factors that stimulate excessive algal growth and the lake characteristics that are most conducive to growth. These studies show that the major factors affecting algal production are plant nutrients, water temperature, availability of light, and turbulent transport of nutrients in the water. Of these controlling factors, the only one that man might reasonably control is the supply of nutrients to aquatic plants.

Nutrients

Many substances are required for algal growth. The major nutrients are carbon (C), nitrogen (N), and phosphorus (P) (in addition to hydrogen and oxygen), and the micro-nutrients required in very small quantities, including manganese, iron, silicon, sulphur, molybdenum, and a number of others. In devising a control program two questions must be answered: (1) which nutrient or nutrients most frequently limit algal growth in lakes, reservoirs and rivers? and (2) which of the key nutrients can be most readily controlled by man?

LIMITING NUTRIENTS

The answer to the first question is a complex one. Growth-limiting supplies of phosphorus, nitrogen and silicon (diatoms, i.e. silica-containing algae) have been demonstrated in many lakes; similar growth-limitation has been reported less frequently for nutrients such as iron, molybdenum, manganese, carbon and other elements. For every ton of phosphorus in the algal biomass, 40 tons of carbon and 7 tons of nitrogen on the average are present, although these ratios vary with the species and with growing conditions. The ratios can be used, however, as a rough guide to the relative supply of each nutrient required in lake waters to sustain extensive algal growths, assuming other nutrients to be present in excess.

Carbon

Carbon is available in lakes from a number of sources. Through exchanges with the atmosphere, surface waters are usually saturated with dissolved carbon dioxide (CO_2). CO_2 may be either gained from the atmosphere or lost to it when liberated by biochemical processes. Bicarbonates and carbonates are present in abundance in most lakes due to natural geochemical processes, and are readily converted to CO_2 by well-known chemical reactions. During their growth period, algae assimilate bicarbonate ions as shown by a sharply increased pH from 9 to over 10 in water which surrounds algal blooms. The supply of ions in the near-surface growing zone can be continually replenished from the main water body by turbulence, and in most lakes this source alone is sufficient to support the observed biomass.

A further source of carbon is the natural organic matter supplied to lakes from land vegetation and from wastes (sewage) dumped into lakes. The strength of such wastes is usually measured as BOD_5 (Biochemical Oxygen

Demand), a measure of the active constituents decomposable in 5 days under controlled laboratory conditions. BOD is primarily a measure of the carbonaceous matter attacked by bacteria with consumption of oxygen.

To obtain some idea of the relative magnitude of these sources of carbon in a natural lake system, consider Lake Erie. The annual loading of BOD to the whole lake is estimated at 200,000 tons (Report to IJC, 1969) and the carbon equivalent is 75,000 tons. In contrast the amount of bicarbonates in the lake (20-25 parts per million carbon) is *10 to 12.5 million tons* of carbon, which is approximately *150 times* as much as the carbon from sewage wastes *in an entire year*. It has been estimated (Harlow, 1968) that at the height of the growing season the biomass weighs 4.9 million tons and this contains about 1.8 million tons of carbon. That is, there is *24 times as much carbon* in the biomass as could come from the BOD waste discharge loading *in a whole year*.

Experimental work suggests that carbon can be a limiting substance in very soft water, i.e., in water with inorganic carbon less than 6 mg/ℓ (ppm). Even in such lakes, however, the introduction of inorganic fertilizers high in phosphorus and nitrogen has been found to stimulate excessive algal growths. Prof. R.R. Langford of the University of Toronto undertook fertilization experiments on three relatively untouched lakes in Algonquin Park in the late 1940's and early 50's to attempt to increase trout production. The addition of a commercial fertilizer containing 12% N, 24% P and 12% potassium resulted in very substantial algal growths and other symptoms of eutrophication. Similar experiments at the Fisheries Research Board's experimental lakes program near Kenora, Ontario in 1969 produced algal blooms by introducing inorganic fertilizers (phosphates and nitrates only) into lakes with less than 1 mg/ℓ (ppm) of carbon.

Although carbon can be growth-limiting in some environments heavily polluted with sewage treatment plant effluents (due to the high supply of phosphorus and nitrogen), it does not normally limit algal growth in lakes.

Nitrogen

Nitrogen concentrations in lakes may limit, at times, the extent of algal growth. Sawyer's work of 1947 on Wisconsin lakes suggests that, in late winter, inorganic nitrogen concentrations of about 200-300 μg/ℓ (ppb) are needed, along with inorganic phosphorus concentrations of at least 10-20 μg/ℓ (ppb), to stimulate blooms of algae in summer. As a result of Thomas' (1953) study of Swiss lakes, he concluded that there is no reason to suppose that anything other than nitrogen and phosphorus need be taken into account as limiting nutrients. He concluded also that, if phosphorus is available in the water before growth starts, in sufficient quantities to cause substantial blooms, nitrogen can become limiting later in the summer.

The Organization for Economic Co-operation and Development (OECD) has published an extensive survey on eutrophication by Dr. R.A. Vollenweider (1968) in which 20 lakes in Europe and North America were classified according to their degree of eutrophication. Vollenweider found that the degree of eutrophication was closely related to the annual loading of nitrogen and phosphorus to the lake, and to the depth and volume of the lake. For example, a lake with a mean depth of 50 metres was found to be eutrophic when it received nitrogen loadings of greater than 8 gm/m^2 of water surface per year and phosphorus in excess of 0.5 gm/m^2/year. For shallower lakes, lesser amounts are required and for deeper lakes greater loadings are needed to produce eutrophic conditions.

Nitrogen enters lakes primarily in the form of nitrates, ammonia and organic nitrogen compounds from a variety of sources, including natural drainage from soils from farm fertilizers, manure and organic wastes and from the atmosphere by precipitation. Some species of blue-green algae use nitrogen directly from the air.

Phosphorus

Phosphorus does not occur as abundantly in nature as does either carbon or nitrogen, and even though it is required by algae in smaller quantities it is generally recognized as being most frequently the triggering factor in eutrophication and the substance limiting the overall extent of algal growth. An analysis of data published by Thomas (1953) on 46 Swiss Lakes was carried out by Vollenweider (CCIW - FRB, 1970) to relate the decrease in C, N and P in the lakes during the growing season to the initial concentrations of these same elements in the spring. The lakes ranged widely from clear, oligotrophic waters to highly-enriched eutrophic waters. The seasonal decreases in C, N and P are due largely to uptake of the nutrients; the highest were found for initial concentrations of P, with N falling between. This illustrates the dominant function of the initial P concentrations on lake metabolism. Phosphates thus appear to be the key substance governing the production of algae in these 46 Swiss lakes.

In Lake Erie the ratio of carbon in bicarbonates to total phosphorus in the waters is 400 to 1 in the western basin and 800 to 1 in the lake as a whole. If the average C:P ratio in algal cells is taken as 40:1, then there is *10 times more bicarbonate-carbon available in the western basin and 20 times more in the lake as a whole than would be required for algal growth to completely deplete the water of phosphorus.* It is very clear then that carbon, even that from the bicarbonate sources alone, is not generally a limiting element in Lake Erie.

Vallentyne (FRB-1970) has pointed out that the concentration of bicarbonate in the lower Great Lakes has not changed appreciably in the last 100 years, whereas algal growths have increased immensely, thus showing that carbon has not been an important factor. Additional surplus carbon is generated from decay of the biomass itself plus the relatively small amounts of BOD from waste loadings and from atmospheric exchanges. These sources would provide an additional 2 to 2.5 million tons of carbon per year and hence a disparity in the C:P ratio even greater than that normally required for luxuriant algal growth. To put this another way, if all of the annual phosphorus loading to Lakes Erie and Ontario is assumed to be taken up by the biota (an exaggeration), the amount of C required for the same mass of biota (assuming P:C = 1/40) is only about 25% of the annual carbon loading to Lake Erie and about 15% of that to Lake Ontario. The carbon loading estimate assumes that water flowing into each lake has the same alkalinity as lake water. Similar calculations show that *in the western basin 4 times more nitrogen is present than that needed for the maximum biomass that could be generated by available phosphorus.* In the whole lake there is a six-fold surplus of nitrogen, assuming an average N/P ratio in the biomass of 7:1. The calculations show that in Lake Erie waters phosphorus is the generally limiting growth element.

Controllable Factors

In decreasing order of importance in triggering the growth of aquatic plants, therefore, are phosphorus, nitrogen and carbon, if these three elements only are considered. But which of the three can be most readily controlled by man so as to arrest and reverse the accelerating eutrophication of our lakes?

By far the largest source of carbon in Canadian lakes, except those in Precambrian areas, is the carbonic acid solution of calcium in the atmosphere and the magnesium carbonate sediments in the drainage basins. The resulting bicarbonate ions, which arise from natural geochemical processes, appear to be present in quantities more than adequate to meet the demands of biomass production. The quantity of carbon in this form is not controllable by man, nor for the most part is it created by man's activities. In most lakes (e.g. Lakes Erie and Ontario) the organic carbon input from sewage is a small fraction of the total carbon loading. On a number of lakes on granitic rocks in the Canadian Shield, however, bicarbonate concentrations are very low ($\lesssim$6 ppm as carbon) and in these cases control of the input of organic carbon from sewage might help control eutrophication. Experiments on lakes in Algonquin Park and near Kenora, however, indicate that control of inorganic fertilizer substances, especially phosphorus, is essential to the control of eutrophication, even in these lakes.

Nitrogen enters lakes from rain, snow and dustfall (16,000 tons/year to Lake Erie and 12,000 tons/year to Lake Ontario). Leaching from natural soils and from soils that are artificially fertilized is another source. On Lakes Erie and Ontario, 60-70% of the nitrogen comes from diffuse sources including agriculture, not readily controlled. By contrast 70% of the phosphates entering Lake Erie and nearly 60% entering Lake Ontario are from directly controllable "point" sources, municipalities and industries.

Phosphates are more tightly bound to soil-clay particles (and to lake sediments) than is the case with nitrogen compounds. Throughout Europe and North America it is generally found that more phosphorus inputs to lakes come from point sources of municipal and industrial wastes than is the case for nitrogen.

Thus not only is phosphorus a key element in algal growth, but it is the most *controllable* of the elements essential for such growth.

A Phosphate Control Program

The main sources of phosphorus in 1967 to Lakes Erie and Ontario are summarized in Table 1. Of the municipal discharges of phosphorus to the lakes, it is estimated that about 60% comes from detergents. This means that detergent phosphorus accounts for about 40% of the total P loading to Lake Erie and to Lake Ontario. Human wastes account for most of the balance of the municipal discharge of phosphorus or about 25% of the total input.

From a national point of view, Canada contributes very little of the phosphate input to Lake Erie (less than 20%) and only 2-3% of the total input can be attributed to Canadian detergent sources. On the other hand, in Lake Ontario, excluding the inputs from Lake Erie, Canadian P loading is about equal to that from the United States. Canadian detergent use accounts for about 19% of the total phosphorus loading and about 43% of the Canadian input.

TABLE 1

LAKE ERIE				LAKE ONTARIO			
	From U.S.	From Canada	Total		From U.S.	From Canada	Total
Municipal	59%	5%	64%		29%	26%	55%
Industrial	3%	4%	7%		1%	2%	3%
Land Drainage	15%	6%	21%		4%	4%	8%
Input to St. Clair R. from L. Huron			8%	Input to Niagara R. from L. Erie			34%

About 30,000 tons of phosphorus entered Lake Erie in 1967 and this is projected to increase to about 45,000 tons per year by 1986 if no remedial measures are taken. Based on the empirical evidence of the state of eutrophication of lakes with various loadings (Vollenweider, 1968) the report to the IJC (1969) recommends that the P inputs to Lake Erie be reduced to 10,000 tons per year. To achieve such a drastic reduction, a 3-step program is essential:

(1) reduction and eventual removal of phosphates from detergents,

(2) phosphate removal to the highest degree practicable at sewage treatment plants and

(3) a program to reduce agricultural contributions through erosion control, improved fertilization practices and control of farm animal wastes.

Phosphate replacement in detergents would achieve a reduction of about 12,000 tons (1967) on Lake Erie and, while this would not be sufficient in itself to achieve the goal, it would bring about an improvement in the condition of the lake. It should be noted here that the success of any control program on Lake Erie depends almost entirely on the willingness of the United States to act.

On Lake Ontario, the situation is somewhat different. This lake could have oligotrophic-clear lake conditions if suitable controls are instituted now. The 1967 P loading was $\sim$ 13,700 tons/year and this is projected to rise to 27,000 tons/year by 1986 if no control measures are instituted. Of the 1967 P loading of 13,700 tons, about 7,400 tons came from municipal sources, 60% of which or about 4,400 tons from detergents. A reduction in loading of the 4,400 tons would be highly significant in keeping Lake Ontario in a mesotrophic state until nutrient removal facilities can be built. Detergents used in Canada contribute 19% of the total direct P loading to Lake Ontario. Of the Canadian portion of the total P load, 43% is from detergents used in Canada.

NUTRIENT REMOVAL

Technology for phosphorus removal at sewage treatment plants is developing rapidly. Removal of phosphates in the treatment plants has been attempted by addition of lime, alum or of iron compounds at some stage of the treatment process. Although enthusiasm for lime treatment was greatly increased by the results of experiments at Richmond Hill announced in 1969 by the Ontario Water Resources Commission, further evaluations suggest that sludge removal and other costs may be quite high. For example, a recent report by J.F. MacLaren Ltd., and J.L. Richards and Assoc. Ltd. entitled, "Report and Technical Discussions on Master Plan of Water Works and Waste Water Treatment for Regional Municipality of Ottawa-Carleton" estimates that the introduction of phosphate removal by lime treatment will approximately double both capital and operating costs of primary plant expansion.

Sludges from both alum and iron precipitation processes can be treated in anaerobic digesters but the high pH of lime sludges would likely adversely interfere with the anaerobic digestion process. At any rate, definitive all-inclusive cost figures for lime treatment are difficult to obtain. Chemical costs for the lime process should not change with concentration of phosphates in the inflow to plants, but other operating costs of sludge removal, etc. would decrease if phosphates in detergents were reduced. Estimates of savings in treatment operation costs by removing phosphates from detergents are difficult to obtain except for the alum treatment process in which chemical costs go up as phosphate content goes up. These estimates are contained in the Report to the IJC and indicate that, in the Lake Erie and Lake Ontario basins alone, savings of the order of $5 million/year in Canada and $17 million/year in U.S. would result from elimination of phosphates in detergents, if all major municipalities were equipped for phosphate removal at waste treatment plants by the alum precipitation process.

REFORMULATION OF DETERGENTS

Detergents sold in Canada have a very wide range of phosphate content. Laundry detergent powders contain from 28 percent to 66 percent phosphate, expressed as STP (sodium tripolyphosphate) or 16 to 38 percent phosphate expressed as P_2O_5 (phosphorus pentoxide) while liquid detergents have generally less than one percent STP. Phosphates serve a number of useful functions in detergents and it has proven difficult to find a suitable substitute which can serve all these functions. The search for possible replacements has yielded only a few which show promise. The most widely used is NTA (sodium nitrilotriacetate), which has seen several years use as a partial replacement for phosphates in detergents in Sweden and in a few U.S. products. No environmental ill effects have been reported from this use of NTA, and the amount of nutrient nitrogen from this source would increase nitrogen levels in municipal wastes by only a few percent. Other possible alternatives being actively experimented with in various parts of the world include sodium citrate and organic polyelectrolytes. In addition to the possibility of substitutes for phosphates, other modifications of washing procedures are possible including the use of soap and detergent combinations.

The conclusion of the U.S. Congressional Committee examining "Phosphates in Detergents and the Eutrophication of America's Waters" (Union Calendar #469, April 14, 1970) is as follows:

> "The Committee concludes that replacements soon will be widely available for the polyphosphate builders in detergents. Detergents made without phosphates may not clean as well as present-day products under all conditions. Under some conditions, they may clean better. But they will reduce the phosphate pollution of our waters from municipal and industrial sewage by as much as 70 percent."

Detergent phosphate controls are an essential part of any sewage treatment nutrient removal program for three main reasons:

(1) timing - to get an initial reduction in P loading before nutrient removal facilities can be financed and built. The report to the IJC suggests 1975 for completion of treatment plant facilities on Lake Erie and 1978 on Lake Ontario.

(2) cost - reduction in phosphate removal costs at nutrient removal plants will likely be substantial.

(3) need to reduce P inputs from uncontrolled sources unaffected by sewage treatment plants, such as:

(a) combined storm and sanitary sewers

(b) small municipalities without treatment facilities

(c) cottage areas without septic tank facilities.

Likely Effects of Phosphate Control

Concern has been expressed that the sediments of some lakes, especially Lake Erie, are already heavily loaded with phosphates which may be released from the sediments in quantities large enough to negate a phosphate control program. To examine this possibility, Kemp and Mudrochova (CCIW-DEMR, 1970), by an extensive sampling program, determined the amounts of phosphates in the upper centimetre of sediments in Lakes Erie and Ontario. They also undertook experiments to determine how much of the phosphates could be extracted from these sediments. Under conditions for extraction much more effective than natural conditions, they found that all the phosphates extractable from the sediments would increase phosphorus in Lake Erie by only 13% and in Lake Ontario by 4%. Actual amounts in real lake conditions would likely be one to two orders of magnitude less. In addition, recently acquired information on sedimentation rates in the Lakes suggests that in most areas clean sediments would rapidly cover up the polluted ones, if major control measures are introduced. For example, in eastern Lake Erie average sediment accumulation rates are 2.6 mm per year. In short, it is highly unlikely that regeneration of phosphates from the sediments would negate the effects of a control program.

It should also be noted that in Erie about 84% of the phosphate loading each year goes into the sediments. This means that a large percentage of the phosphates is taken out of the system each year, suggesting that control of current inputs should result in a fairly rapid decrease in the phosphorus present in lake waters at the beginning of the growing season. Thus a fairly rapid response in terms of reduced algal blooms could be expected.

Perhaps the most difficult question to answer is whether or not eutrophication can be controlled by the reduction of phosphorus alone. Most evidence suggests that it can. Phosphorus reduction is the only economically feasible solution at the present time, and it is the logical place to start. If population and technological growth continue unchecked in the Lakes Erie and Ontario basins and elsewhere, it may be necessary to introduce a series of accessory remedial measures as well (treatment for the removal of nitrogen compounds may have to be instituted in the future), but the keystone of any eutrophication control program must be phosphorus control. It is not claimed that phosphorus removal will control all the problems of the future, only that it is the best known remedial measure at present and one that must be accepted as the basis for all future controls.

In other parts of the world, phosphorus removal as a remedial measure is now being undertaken at the very eutrophic Swiss lake, Zurichsee, where 55 percent of the phosphorus loading comes from controllable sources. The total diversion of sewage from Lake Washington in 1964-65 resulted in a marked improvement in lake conditions to the point where by 1969 conditions were said to be as good as they had been in 1950. W.T. Edmondson in a forthcoming article shows that algal abundance in Lake Washington is apparently unrelated to changes in nitrate, bicarbonate and CO_2 concentrations. On the other hand, changes in late winter concentration of phosphates and in summer algal growth were very closely correlated. Control of phosphates, therefore, appears to be the most significant factor in the sewage diversion scheme.

Summary

Cultural eutrophication is a problem afflicting all too many Canadian lakes. It has been shown that the most controllable of the essential elements for algal growth, and the key element in the most important lakes in Canada, is phosphorus. On the basis of present scientific knowledge, a phosphate control program is the most practical way of combatting eutrophication problems in lakes presently affected and preventing the deterioration of lakes where the problem is not yet acute.

To be effective, a phosphate control program requires the reduction and eventual removal of phosphates from detergents, a nutrient control program at waste treatment plants and a program to control agricultural inputs of phosphorus.

There is strong evidence that if our lakes are to be saved such a control program must be instituted now.

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