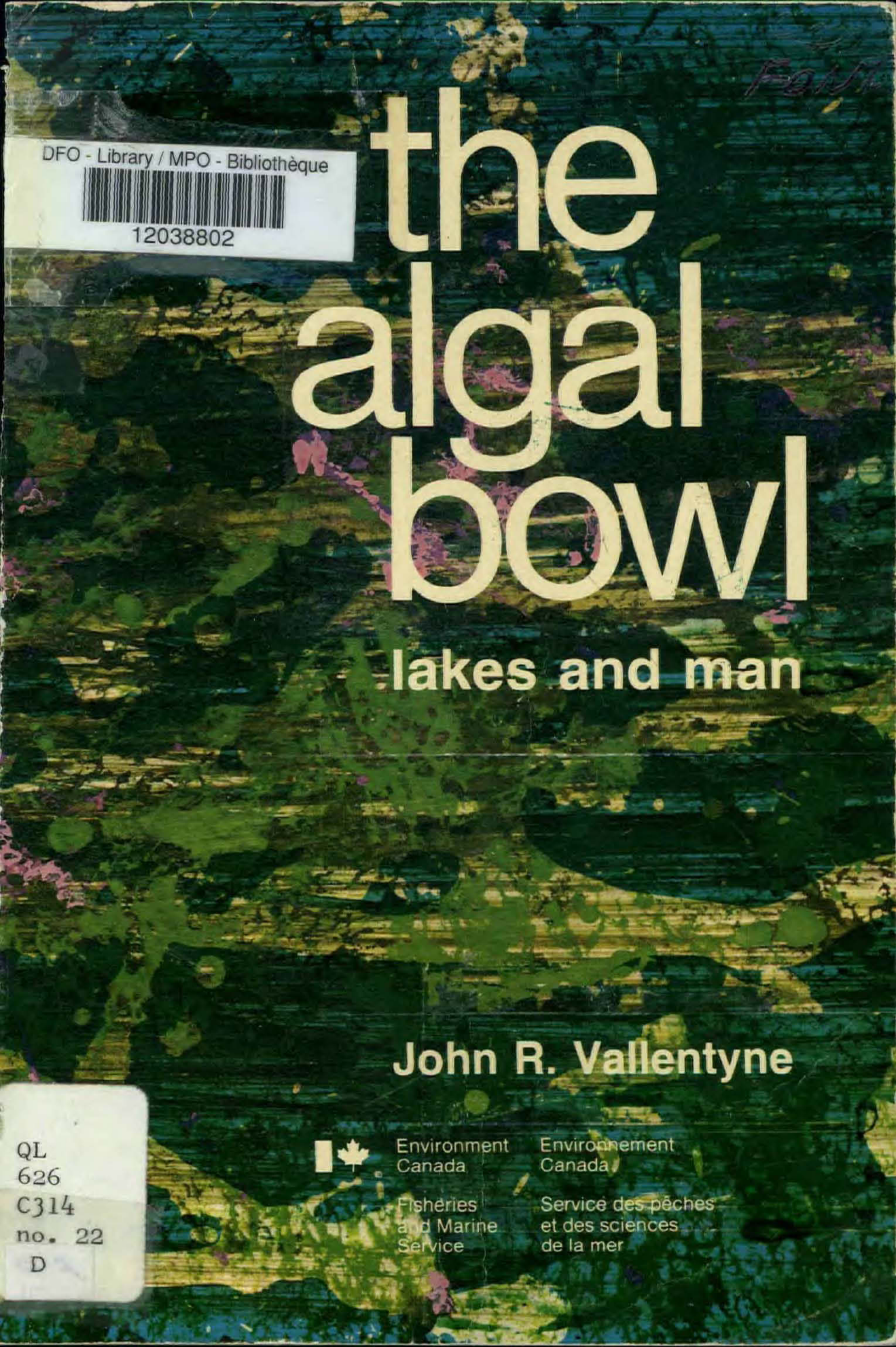

Faith

the algal bowl

lakes and man

John R. Vallentyne

Environment Canada
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THE ALGAL BOWL

Lakes and Man

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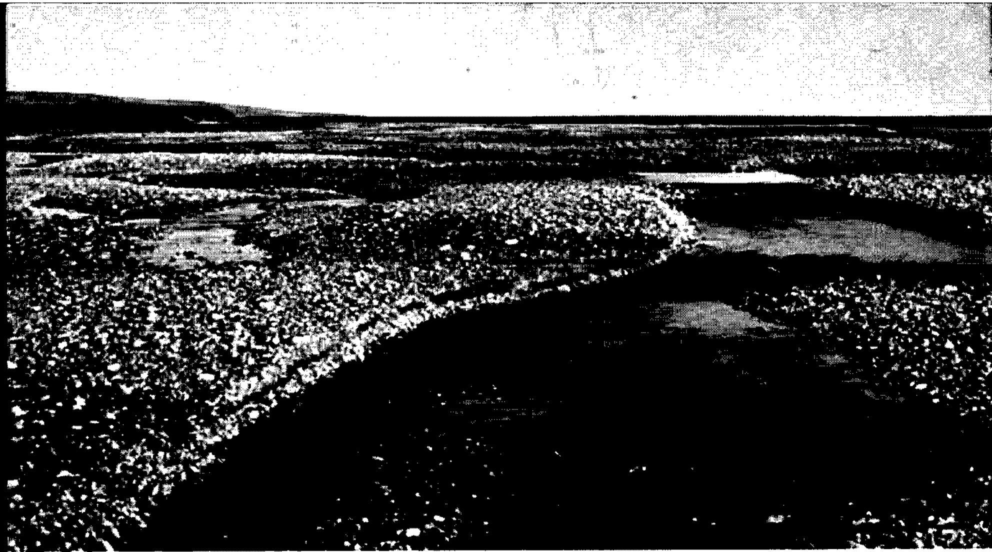
A lake is the landscape's most beautiful and expressive feature. It is the earth's eye; looking into which the beholder measures the depth of his own nature.

from *Walden*
by Henry David Thoreau



Eutrophication in the Canadian Arctic (Aug. 1970). Upper — *unpolluted stream flowing into Meretta Lake, Cornwallis Is. located at 75° N lat.*
Lower — *algal scums in a polluted stream entering the same lake. Pollution is caused by sewage from the community of Resolute (mean annual population about 100). Photographs by Dr D. W. Schindler.*

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MISCELLANEOUS SPECIAL PUBLICATION 22

THE ALGAL BOWL

Lakes and Man

John R. Vallentyne
Winnipeg, Man.

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Ottawa 1974

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To

Ann Vallentyne

About the Author

Dr John R. Vallentyne is Senior Scientist at Canada's Freshwater Institute in Winnipeg, Manitoba. A member of the Editorial Board that assembled the widely discussed 1969 Report to the International Joint Commission on pollution in the lower Great Lakes, Dr Vallentyne was at the center of the controversy over detergent phosphates and lakes from the start. A Canadian by birth, he received his training in limnology at Queen's University, Kingston, Ontario, and at Yale University, New Haven, Connecticut. He lectured in biology and ecology at Queen's from 1952 to 1958 and then at Cornell University from 1958 to 1966. On moving to the Freshwater Institute in 1966, Dr Vallentyne helped assemble a group of limnological experts to increase understanding of the causes of man-made eutrophication. Within two years Winnipeg was recognized as a major international center of limnology.

Recipient of the Journal Fund Silver Pen Award (1955–59) for learned writing, he is the author of over sixty scientific publications on lakes. He was a Visiting Fellow at the Geophysical Laboratory of the Carnegie Institution of Washington in 1956–57 and held a John Simon Guggenheim Fellowship for study in Italy in 1964–65.

CONTENTS

PREFACE

This book might aptly have been subtitled "Nine Essays by a Schizophrenic Author in Search of a Nonexistent Reader." Each chapter was written so it could, in large part, stand on its own; also, I was a split personality in writing the book. I wanted to communicate to nonspecialist readers without sacrificing a scientific approach.

Two events led to the conception of the book. The first was the warm response I received to my article on *The Principles of Limnology* published in *American Scientist* in 1957. It suggested there was a real interest among scientists from other disciplines in lakes and the processes that go on within them. The other event was my participation as scientific advisor to the International Joint Commission in its 1970 hearings on water pollution in the lower Great Lakes. This revealed to me how poorly informed industrial officials and the public were about lakes. As I sat listening to presentations made by housewives, mayors, high school students, bankers, farmers, marina operators, heads of tourist associations, and high ranking officials from industry and government, I realized the full extent of public ignorance about lakes and eutrophication. No one seemed to have the slightest idea of what "limnology" and "eutrophication" meant, let alone what they were all about. I was particularly astounded at the lack of environmental knowledge exhibited by senior representatives of the detergent industry; and also at my own inability to project myself wholeheartedly into their position as detergent manufacturers.

The striking feature of the controversy was not so much a lack of knowledge as the uneven distribution of particular kinds of knowledge among various segments of society. Limnologists had known for 50 years that the addition of two elements alone, phosphorus and nitrogen, generally sufficed to induce increased plant growth and other signs of eutrophication in natural waters. The problem was: nobody else knew it. When phosphate-containing detergents were first introduced on a major scale in 1947, it was impossible to guess that by 1969 use of sodium triphosphate (STP) in the United States alone would amount to over 1000 million kilograms (2200 million pounds) per year.

It was necessary to make a clear distinction between the knowledge needed to understand eutrophication and the knowledge needed to control it. Representatives of the detergent industry repeatedly confused this issue by stressing the complexity of the process of eutrophication, without referring to the comparative simplicity of control. They would not admit detergent phosphates played a role in the cause of man-made eutrophication, and avoided any recognition of the importance of detergent phosphates in the control of eutrophication.

This book is an unusual, but I hope not unpalatable, concoction of matters of both scientific and public interest. If we, as people, are to make judgments, we must understand the reasoning on which those judgments are based. I have, therefore, not sacrificed logic and development of understanding in attempting to make this account readable and interesting; nor have I hesitated to state my opinions on a number of matters I feel need to be brought into the open.

My intended audience is the environmentally interested segment of the public that justly finds scientific treatises too tedious, and picture books on nature study too trivial, for the environmental threats we will soon be facing. I hope to attract as promoters and salesmen some of the international experts in limnology, geochemistry, and freshwater biology who, with their predecessors, established the material on which the book is based. It is also my hope that the book is not too heavy-handed to reach a broad segment of the public, and will be useful to prospective students of limnology and related disciplines.

John R Vallentyne

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ABSTRACT

VALLENTYNE, J. R. 1974. The algal bowl: lakes and man. Fish. Res. Board Can. Misc. Spec. Publ. 22: 186 p.

This is a book for nonspecialists about lakes and how they are affected by nutrients derived from human activities (man-made eutrophication). The nine chapters cover the following topics: (1) the biological classification of lakes and the role of phosphorus and nitrogen compounds in stimulating the growth of algae and aquatic weeds; (2) historical accounts of man-made eutrophication of the Lake of Zürich, Lake Erie, and a chain of four lakes in the vicinity of Madison, Wis.; (3) how the vertical circulation of water in lakes is regulated by the action of sun and wind; (4) interrelationships among carbon dioxide, oxygen, and organic matter in natural waters; (5) phosphorus in the biosphere; (6) methods for control of man-made eutrophication; (7) detergent phosphates in the cause and control of man-made eutrophication; (8) the 1970 controversy over nitrilotriacetate (NTA) as a replacement for sodium triphosphate in detergents; (9) a view that man-made eutrophication is better regarded as a sign of a deeper, Faustian problem than as a problem in itself. While the central theme of the book is that phosphorus is the key to the control of man-made eutrophication, an analysis of ultimate causes shows the need to control demophoric (population × technological) growth. A list of scientific terms and definitions is included, an appendix with an updating of events to 1974, suggestions for additional reading, and a sequence of tables and figures for the scientifically inclined reader.

RÉSUMÉ

VALLENTYNE, J. R. 1974. The algal bowl: lakes and man. Fish. Res. Board Can. Misc. Spec. Publ. 22: 186 p.

Cet ouvrage, préparé à l'intention des non-spécialistes, traite des lacs et de la façon dont ils sont affectés par les apports de matières nutritives découlant des activités humaines (eutrophisation due à l'homme). Ses neuf chapitres traitent des sujets suivants: (1) classification biologique des lacs et influence des composés de phosphore et d'azote sur la croissance des algues et des herbes aquatiques; (2) historique de l'eutrophisation due à l'homme dans le lac de Zürich, le lac Érié, et une chaîne de quatre lacs dans le voisinage de Madison, Wis.; (3) mode d'action du soleil et du vent sur la circulation verticale de l'eau des lacs; (4) interactions de l'acide carbonique, de l'oxygène et de la matière organique dans les eaux naturelles; (5) phosphore dans la biosphère; (6) méthodes de contrôle de l'eutrophisation due à l'homme; (7) phosphates détersifs, et cause et contrôle de l'eutrophisation due à l'homme; (8) la polémique de 1970 sur l'usage du nitrilotriacétate (NTA) comme substitut du triphosphate de sodium dans les détersifs; (9) le point de vue que l'eutrophisation due à l'homme doive être considéré comme le signe d'un grave problème, évocateur de Faust, plutôt qu'un problème en soi. Alors que le thème central de l'ouvrage porte sur le phosphore en tant que clé du contrôle de l'eutrophisation due à l'homme, une analyse des causes ultimes fait ressortir la nécessité de contrôler la croissance démophorique (population × technologie). Nous donnons une liste de termes scientifiques et définitions, une chronologie des événements jusqu'à 1974 en annexe, des références pour lectures supplémentaires et enfin une série de tableaux et de figures pour le lecteur à tournure d'esprit scientifique.

A SUGGESTION TO READERS

If you don't have a strong background in science, I suggest you start this book at page 105, reading chapters in the sequence 7, 8, 1, 2, 5, 6, 9, interspersed with occasional ventures into chapters 3 (Lakes are made of water) and 4 (How a lake breathes), which highlight some major principles of limnology. Approach them as you would two boxes of chocolates, sampling the contents periodically, but never devouring more than can be comfortably digested at one time.

Remember — to keep lakes clean we must all pull together.

Chapter 1

THE ALGAL BOWL

In which the biological classification of lakes is described and an account presented of factors involved in man-made eutrophication.

Some time before the year 2000, unless something is done to avert the situation, we shall find ourselves living in the middle of an Algal Bowl, with effects on water comparable to those on land during the great American Dust Bowl of the 1930s. Caused by overcultivation of marginally productive land in the high plains area west of the Mississippi River, during a period of prolonged drought and depression, the Dust Bowl was initiated by a reduction of plant cover and the erosion of topsoil by wind. "Black blizzards" clouded the sky from view, depositing wind-blown clays and sands over everything in sight — blinding jackrabbits, ruining car engines, and devastating fertile agricultural lands hundreds of kilometers away. In the central part of the Dust Bowl, some barbers refused to shave their customers, for in two strokes a razor could lose all its edge from particles of grit embedded in the skin. Matters became progressively worse until May 12, 1934, in what was probably the greatest dust storm in the recorded history of the earth, over 300 million tons of topsoil were blown eastward across the North American continent, depositing dirt and grit all along the way.

Just as the Dust Bowl arose from misuse of land, so is the Algal Bowl arising from misuse of water. The focal centers are already on the scene in areas of dense population and technology where sewage wastes rich in phosphorus and nitrogen blend with water, sun, and warmth to provide essential ingredients of the recipe for cultural (man-made) eutrophication.

Eutrophication is the term used by scientists who study lakes to describe the complex sequence of changes in aquatic ecosystems caused by an increased rate of supply of plant nutrients to water. The immediate ecosystem response is an increase in photosynthesis and abundance of plants. This gives rise to: increased productivity at all levels of the food chain, up to and including fish; successional changes in the kinds of organisms inhabiting aquatic ecosystems; and reduced levels of dissolved oxygen in bottom waters.

Eutrophication constitutes a problem in well-to-do, technologically developed areas, because waters tend to be valued there more for aesthetics, recreation, and water supply than as a medium for the production of food. In not so well-to-do areas, the situation is just the reverse. Water is highly valued for food production. To understand what has been happening in terms of man-made eutrophication during the 20th century, it is necessary to outline the biological basis of the trophic (nourishment) classification of lakes.

Lakes are classified biologically on the basis of their productivity. Since green plants lie at the bottom of the food chain, converting the energy of sunlight into calories of edible food, it is their abundance and rate of production that primarily determines productivity at all higher levels of the food chain. In waters low in dissolved coloring matter — brown humic materials that color bog lakes — three general lake types are delineated in a continuously rising scale of productivity. These are termed *oligotrophic*, *mesotrophic*, and *eutrophic* lakes.

Oligotrophic lakes have a low nutrient supply in relation to the volume of water they contain. As a general rule they are deep lakes with average depths greater than 15 meters (about 50 feet) and maximum depths greater than 25 meters (about 80 feet). The waters are clear with plant growth occurring at various depths of the water column rather than just near the surface. Oligotrophic lakes have high concentrations of dissolved oxygen in the hypolimnion (the cool, bottom water of thermally stratified lakes). Lake trout, whitefish, walleye, and other species highly prized by fishermen, live happily in the cool, deep, oxygen-laden waters of oligotrophic lakes in summer when most of us sweat in the heat of the sun.

Some of the larger and better known oligotrophic lakes of the world are Great Bear Lake and Great Slave Lake in northwestern Canada, lakes Superior and Huron in the St. Lawrence drainage basin of North America, Lake Tahoe in the United States, Lake Geneva (Léman) in Europe, and Lake Baikal in the USSR.

The most important things to remember about oligotrophic lakes are that they tend to be deep, transparent, and with a low density of plant life in surface waters. A Secchi disc[1] lowered into the water can almost always be seen at depths of 3 meters (10 feet) or more in summer.

Eutrophic lakes lie at the other end of the spectrum. They have a high nutrient supply in relation to the volume of water they contain. As a result of this and other factors, dense growths of planktonic green and blue-green algae occur in surface waters. In extreme cases they have the appearance and consistency of a thick pea soup. Mats of rooted plants and filamentous algae may also carpet the bottom in shallow-water areas, depending on the competition for light between planktonic (open-water) and benthic (bottom-living) plants. The waters of eutrophic lakes typically become so turbid in summer, as a result of plant growth, that a Secchi disc disappears from sight at depths of a meter (3 feet) or less. One plant shades another in the struggle for light.

As a general rule, naturally eutrophic lakes are shallow with average depths less than 10 meters (about 33 feet) and maximum depths less than 15 meters (about 50 feet). Dissolved oxygen tends to be depleted in the bottom waters of eutrophic lakes during periods of restricted circulation — in summer if the lake is thermally stratified

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[1] A white disc 8 inches (20 centimeters) in diameter used as a measure of water transparency. It originated with Commander Cialdi, head of the Papal Navy in 1865. On board the SS *L'Immacolata Concezione* (SS *Immaculate Conception*) he and Professor P. A. Secchi conducted a series of tests that led to the development and standardization of the "Secchi" disc.

and in winter if there is a cover of snow and ice. As a result of low concentrations of dissolved oxygen and other factors, fish such as lake trout cannot survive in eutrophic lakes. The dominant fish tend to be warmwater species, members of the minnow and bass families (carp being one of the more typical representatives in extreme cases).

Examples of large eutrophic bodies of water are the south basin of Lake Winnipeg in central Canada, the western basin of Lake Erie in the St. Lawrence drainage system, Lake Balaton in Hungary, and Lake Victoria in Africa. The most important facts to remember about eutrophic lakes are: high nutrient supply, high production at all levels of the food chain, shallow depth and low transparency due to excessive plant growth in surface waters.

Mesotrophic lakes occupy an intermediate position between these two extremes. They are intermediate in respect to nutrient supply, depth, biological productivity, water clarity, and oxygen depletion in the hypolimnion. Mesotrophy is just a convenient category for lakes that are borderline between oligotrophy and eutrophy. Yellow perch is one of several species of fish that commonly reach maximum abundance in mesotrophic lakes.

When this classification of lakes was first developed, it was largely based on the species of benthic (bottom-living) animals present in deepwater sediments. Some species were found to be more sensitive to low concentrations of oxygen than others. As a result, even today it is common to refer to lake types in terms of the species of midge (insect) larvae. A *Chironomus plumosus* lake, for example, is eutrophic; a *Sergentia coracina* lake, mesotrophic; and a *Tanytarsus lugens* lake, oligotrophic.

Thus, a single sample of invertebrates dredged from the bottom of a lake at almost any time of the year could give a living history of past conditions of oxygen depletion. This could in turn be related to the classification of lakes as oligotrophic, mesotrophic, and eutrophic. It appears now, however, that two factors were confused in assessing the trophic states of lakes. One of these was nutrient supply, which was primarily determined by events on land. The other was concentration of oxygen in bottom waters, which was largely determined by the form of the lake basin and only secondarily by the rate of nutrient supply.

As criteria for the biological classification of lakes were more fully understood in terms of causal events, it became clear that three primary factors regulated productivity and determined the position of a lake on the scale of oligotrophy–eutrophy. These are now recognized as the rate of nutrient supply, form and depth configurations of the lake basin, and climate (primarily light and temperature).

In a given climatic zone, lakes in areas of nutrient-rich soil were found to be more productive than lakes of similar shape and size in areas of igneous rock drainage. In regions of comparable climate and geology, shallow lakes were found to be more productive than deep lakes. And, other things equal, tropical lakes were found to be more productive on an annual basis than lakes at high altitudes or near the poles.

Having now discussed the biological classification of lakes, the next step is to consider what happens to lakes with the passage of time. Lakes are but a temporary feature of the landscape. Their ultimate fate is to become filled with sediment and eventually be supplanted by grassed or forested land. Exceptions occur in areas where the land is sinking, as is the case in the large Rift Valley lakes of Africa. In such cases lakes can have constant or sometimes increasing depths over geologically long periods of time.

Most of the lakes that now exist were formed recently in terms of earth history. They were created by the scouring and depositional action of vast continental mountains of glacial ice that blanketed extensive tracts of land in the northern and southern hemispheres as recently as 10,000–15,000 years ago. Wherever a water-impermeable basin was formed by scouring or damming, a lake came into existence. A cursory comparison of maps showing the former distribution of glacial ice and the present distribution of natural lakes suffices to show the relation between the two.

Average rates at which sediments have been accumulating in these lakes is only a millimeter ($\frac{1}{25}$ inch) or so per year. This sounds small, but accumulated over the 10,000–15,000 years that have elapsed since the recession of the last continental glaciers, it amounts to an average of 10–15 meters (33–50 feet) of sediments — more in some lakes than in others.

The secrets of the past lie locked in these sediments that have been deposited, grain after grain, over long periods of time. The information is there for the asking, if one knows what to ask, how to look for the answers, and how to interpret results. Limnologists (specialists in the scientific study of inland waters) are able to do this from detailed analyses of biological and biochemical remains preserved in sediments. A record is even preserved in the form of pollen of trees, shrubs, and grasses that formerly covered the surrounding land.

From the knowledge that deep lakes tend to be oligotrophic and shallow lakes eutrophic, limnologists inferred that oligotrophic lakes must evolve toward a condition of eutrophy with time. This was, in fact, demonstrated in the 1930s and 1940s by microfossil remains of ecological "indicator" organisms in long cores of sediments taken from the bottoms of lakes. It was shown that several eutrophic lakes evolved into a condition of eutrophy from a condition of oligotrophy. The fossilized remains of midge larvae in the lowermost (oldest) sediments corresponded to forms such as *Tanytarsus*, characteristic of oligotrophic lakes. At higher (more recent) levels these graded into remains of mesotrophic genera such as *Sergentia* and eventually into eutrophic forms such as *Chironomus*. These findings were confirmed and extended through analysis of remains of diatoms, cladocerans (water fleas, a group of zooplankters), and plant pigments. These results indicated that a slow natural process of eutrophication accompanies the aging of lakes and infilling with sediment.

More recently, some limnologists suggested that the importance of this natural process of eutrophication may have been exaggerated by the conscious selection of lakes that are now eutrophic. The effects of oxygen depletion, due to changes in the form of a lake basin as a result of infilling with sediments, were confused with changes in nutrient supply. In natural eutrophication, species changes were primarily caused by form-induced oxygen depletion rather than by changes in nutrient supply. (The hypolimnion disappears when a lake becomes so shallow that wind-driven currents maintain circulation of water to all depths throughout the year.) There is also evidence that some deep lakes have evolved from a eutrophic toward an oligotrophic state. In areas sensitive to climatic change, the trophic state of a lake can be determined by climate alone.

The process of natural eutrophication is thus more complex and perhaps proceeds much more slowly than was earlier thought. The fact that many deep lakes have continuously remained in an oligotrophic state, since the time of the last glaciation, suggests that in deep lakes natural eutrophication is an immeasureably slow process.

In contrast to this slow and sometimes nonexistent process of natural eutrophication, another much more rapid process has been taking place in thousands of lakes in recent decades. This is the process of cultural or man-made eutrophication, caused by enrichment of water with nutrients derived from human activities. The principal nutrients involved are compounds of phosphorus and nitrogen. The primary sources are municipal sewage and, to a lesser extent, agricultural and livestock-holding operations.

As a result of the enrichment of water with nutrients derived from human activities, numerous waters have started to bloom with planktonic algae or growths of aquatic weeds and filamentous attached algae, creating conditions in years or decades that would require thousands of years to come about in the absence of man, or perhaps never take place.

The sequence of biological and chemical events in this succession is a pattern that repeats itself independently of time and location. The history of the Lake of Zürich, the first well-documented case of man-made eutrophication, has since been repeated verbatim in thousands of lakes, reservoirs, and estuaries throughout the world. Man-made eutrophication can just as easily occur in a small body of water neighboring an isolated community in northern Canada — Meretta Lake near Resolute on Cornwallis Island, for example — as it probably did near the sites of ancient civilizations millenia ago. Human attitudes have apparently not changed all that much since the days of the Old Testament: "And I brought you into a plentiful country, to eat the fruit thereof and the goodness thereof; but when ye entered, ye defiled my land, and made mine heritage an abomination." (Jeremiah 2:7).

Man-made eutrophication results in deterioration of water quality. Drinking water that was once clear and pure now tastes "funny" and is turbid during periods of algal blooms. Filters on municipal and industrial water intake lines have to be cleaned much more often. Many bathing areas, once clear and refreshing to swim in, are now coated with algal slimes, or perhaps occasionally piled high with blue-green algae or other aquatic vegetation washed in by storms. As a result of increased production of plant and invertebrate food, fish populations often rise in abundance, but with a shift in species composition. Lake trout and whitefish, if present, decline in favor of species of lesser economic value. Perch may increase for a time, in the succession, to be replaced eventually by coarser fish, such as carp.

Unnoticed by the casual observer, subtle changes in abundance of different aquatic organisms in a lake allow the skilled specialist to extrapolate from the past into the future, to determine both the direction and rate of change. The appearance of certain blue-green algae, such as *Oscillatoria rubescens*, or the shift from a bottom community of bloodworms (midge larvae) to sludgeworms (aquatic oligochaetes), can be sufficient to characterize the past and suggest changes yet to come.

More commonly, it is not the appearance or disappearance of a species that characterizes the process of eutrophication, but complete shifts in species composition of the aquatic ecosystem. Experience, judgment, and intuition are required in interpreting such data. It is not something an untrained person can do any more than a layman can practice medicine.

Naturally productive, eutrophic waters are generally located in regions of naturally productive land. Cases of man-made eutrophication, on the other hand, parallel the distribution and activities of man. However, there are so many similarities between the end results of these two processes that they could easily be confused in origin if the true causes remained unknown. It is, in fact, this confusion of space and time that has led many astray in trying to relate states (oligotrophy, eutrophy, etc.) to a process in time (eutrophication).

In two respects, rate and reversibility, natural and man-made eutrophication are as different as night and day. Natural eutrophication is slow and, for all practical purposes, irreversible under a given set of climatic conditions. It is caused by change in the form and depth of a basin as it gradually fills with sediment. To reverse natural eutrophication in this sense, one would have to scour out the basin again — a rather formidable task in any man's terms.

Man-made eutrophication, on the other hand, is rapid and reversible. It is caused by an increase in the rate of supply of nutrients to an essentially constant volume of water, without any appreciable change in the depth or form of a basin. As a result, man-made eutrophication can be reversed by eliminating man-made sources of supply. *Reversed*, however, should not be interpreted to mean anything other than a return to what was there before the advent of man. A lake that was eutrophic prior to human settlement cannot be made oligotrophic by removal of man-derived nutrients. It can only return to its former level of eutrophy.

In cases where care has been taken to eliminate all man-derived sources of nutrients to nutrient-polluted lakes, signs of recovery toward the presettlement state have appeared within a few years. More often, not all sources of supply are controlled, and results are less than desired. Even when appropriate action is taken, several years may be required before statistical trends of recovery can be distinguished from annual fluctuations caused by weather and other factors.

The most important nutrient elements causing eutrophication are phosphorus and nitrogen. To appreciate their effect in triggering growth of aquatic plants, one need only consider the amounts of phosphorus (P), nitrogen (N), and carbon (C) in typical plant tissues relative to their dry weight and fresh weight. The ratios by weight for an average community of algae are approximately 1P:7N:40C:100 dry weight:500 fresh weight. This means if one of the three elements is growth-limiting in a lake and all other elements are present in excess of physiological needs, phosphorus can theoretically generate 500 times its weight in living algae; nitrogen, 71 (500:7) times, and carbon, 12 (500:40) times.

Phosphorus and nitrogen, the two elements that most commonly limit plant growth in lakes, are 1000 times more concentrated in sewage effluents than in the waters of lakes unaffected by man. It is therefore not surprising that their addition to natural water has an effect like turning up the volume control on an amplifier, in terms of accelerating the growth of plants. A comparatively small input produces a greatly magnified result.

This amplifying effect of phosphorus and nitrogen compounds has been known to those involved in the pond culture of fish as long as it has to farmers on land. In ponds, phosphate and nitrate fertilizers are added to stimulate growth of algae, the result being a transfer of energy to all higher levels in the food chain, including fish.

The triggering effect of phosphorus and nitrogen compounds on plants can also be illustrated by comparing relative amounts of different elements required for plant growth to supplies available in the aquatic environment. This is comparable to a demand:supply ratio as used in economics.

Plants have a certain demand for elements in water in order to be able to reproduce, the magnitudes of demand being in direct proportion to the concentrations of chemical elements in plant cells. When the rates of supply of various elements to plants correspond exactly to the amounts present in the plant community, then the situation resembles a well-managed factory. Stockpiles and availability of raw materials will be in exact proportion to their occurrence in the product.

On the other hand, if one or more of the raw materials are in limited supply relative to the others, then the overall rate of production will be limited by the rates of supply of those materials. The magnitude of the demand:supply ratio can thus reveal the component most likely to limit production. The higher the demand:supply ratio, the greater the extent to which a given element will limit growth.

Demand:supply ratios for the 15–20 odd elements required for growth of various species of freshwater plants are given below, based on a world-average situation. These ratios were calculated by estimating the chemical composition of an average community of freshwater plants, and then dividing by the mean chemical composition of the river waters of the world.[2] Demand:supply ratios for theoretical world-average situations in late winter (prior to the burst of algal growth) and midsummer (at the height of maximum plant abundance) are as follows:

	Demand:supply	
Element	Late winter	Midsummer
Phosphorus	80,000	up to 800,000
Nitrogen	30,000	up to 300,000
Carbon	5,000	up to 6,000
Iron, silicon	Generally low, but variable	
All other elements	Less than 1,000	

The significant point is that phosphorus and nitrogen are the two elements most often limiting plant growth in aquatic ecosystems. Their relative importance may vary from area to area, but in order to bring about increased plant growth, both generally have to be present at the same time. In situations where phosphorus and nitrogen compounds are in rich supply, as in sewage lagoons, carbon can occasionally become limiting to plant growth. But even in these circumstances carbon may not limit growth, for it can be sucked in across the air–water interface from the supply of carbon dioxide in the atmosphere. With regard to other elements required for plant growth, there is no evidence suggestive of roles in any way comparable to those of phosphorus and nitrogen. (Diatoms — algae with siliceous walls — can, however, be limited by the supply of silicon; and iron has been found to be limiting in some waters.)

In 1970, an average U.S. citizen contributed 1.6 kilograms (3.5 pounds) of phosphorus and 4.5 kilograms (9.9 pounds) of nitrogen to water per year in the form of municipal wastes. In

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[2] Data were derived from various sources for the chemical composition of freshwater plants. See Livingstone (1963) and Table A1, p. 166, for a complete list of data.

addition, whether he knew it or not, he contributed about one-tenth of that amount of phosphorus and twice that amount of nitrogen to water through his per capita share of national agricultural and livestock production. Rounding the figures, results look like this:

> *In 1 year one citizen discharges 2 kilograms (4.4 pounds) of phosphorus and 12 kilograms (26 pounds) of nitrogen to water, creating 1 ton of living plants.*

For a city of 1 million inhabitants, the comparable story reads:

> *In 1 year a city of 1 million inhabitants discharges 2 million kilograms (4.4 million pounds) of phosphorus and 12 million kilograms (26 million pounds) of nitrogen to water, creating 1 million tons of living plants.*

Quite apart from the use of fertilizers on land, one of the problems arising from agriculture is the "urbanization" of farm animals in feedlots where they are housed and fattened for market. When one realizes that the physiological wastes produced by farm animals typically exceed those of the human population in most countries by a ratio of 10:1, it isn't too hard to understand how problems from livestock can arise. With the output of physiological wastes from a cow equivalent to that of 16 adult humans, a feedlot with 1000 head of cattle can be equivalent to a small city in waste output.

One might assume, from all that has been said up to now, there is a direct and exact relation between rates at which nitrogen and phosphorus compounds are supplied to lakes and the resulting plant production. Generally this is true, but only in a rough, statistical sense. Many factors modify the extent to which nutrients become amplified into plant growth. In addition to rate of nutrient supply, the following can be of considerable importance in determining the extent to which nutrients become expressed in plant growth:

(1) amount of light available to green plants (controlled by light from the sky and suspended clays or dissolved coloring matter in the water);

(2) concentrations and availability of nutrients (varying with the nature and location of sources of supply);

(3) form and depth of the lake (to be discussed in more detail later);

(4) temperature (regulated by geography and climate, with varied effects on different plant species);

(5) sedimentation of algae and nutrient-coated clays (varying with turbulence and particle size);

(6) removal of nutrients and algae in outflow water (influence of the "flushing time" of a lake);

(7) grazing activities of filter-feeding zooplankton, bottom-living herbivores and fish (removing plant food as it is produced);

(8) parasitism by bacteria, fungi, and other microorganisms (increased death of plants by disease);

(9) regeneration of nutrients from decomposition of plant and animal remains in water and in sediments (reutilization of a former supply);

(10) degree of mixing of lake water by wind (sometimes carrying algae below the photosynthetic zone and also causing upwelling of nutrient-rich bottom water).

It is the interplay of these varied phenomena that attracts the limnologist to his task of constructing simplicity and order from what seems like and truly is a bewildering complexity.

One final question remains to complete this general account of lakes and eutrophication. Is eutrophication *peculiar* to lakes? The answer is that it is not. The phenomena associated with eutrophication are only more fully expressed in standing bodies of water such as lakes, reservoirs, and estuaries than in rivers. The reasons for this are related to light penetration, water motion, and aeration.

Plant production tends to be low in the upper parts of rivers for a number of reasons: banks tend to be heavily wooded, reducing the incident light; nutrients are flushed away before plants have time to utilize them completely; and nutrient concentrations are typically low. In the lower stretches of rivers where nutrient concentrations can be high, suspended silts and clays frequently restrict the penetration of light.

Lakes and reservoirs, on the other hand, are sedimentation basins. Also, because of their expanse they are fully exposed to sunlight. The greater clarity of water and fuller exposure to the sun's radiation permit more effective utilization of the nutrient supply.

The second factor of importance, flushing time, can readily be understood by performing a simple kitchen experiment. First, fill an egg cup or cocktail jigger with milk. Next, place a glass in a large bowl in the kitchen sink. The milk serves as a pollutant to be introduced into the stream of water flowing from the tap; and the glass, when it is full of water, as a lake. The bowl is only there to collect the overflow, so it can subsequently be measured.

Now, start the tap flowing at a medium rate. When the water just fills the glass and begins to overflow, pour the milk evenly into the stream. The stream will be seen to clear itself instantly of the milk; but 8–10 flushings of the glass are required before the liquid within is restored to its original transparency.

The point is that dissolved chemicals in lakes are not flushed out as rapidly or completely as in comparable stretches of rivers. The resultant delay can lead to a buildup of nutrients from increased inputs due to human activities. Then problems start to arise.

This completes the general discussion of the classification of lakes as related to eutrophication. In the next chapter, attention is focused on the detailed histories of three lakes unwittingly fertilized by man, and the significance of the water transport system of waste disposal as related to eutrophication.

Chapter 2

LAKES AND MAN

In which the fertilizing effects of sewage wastes on water are described for three areas, with the suggestion that man-made eutrophication has been caused by the water transport system of waste disposal.

Enrichment of natural waters with nutrients induces a variety of biological and chemical changes in water quality, which can be viewed as beneficial or detrimental depending on the uses. The effects in terms of recreation, drinking water supply, and "aesthetics" are generally unwanted, whereas those on fish production may or may not be desirable, depending on the extent to which fish (such as carp) that thrive under eutrophic conditions are needed as food. The view of eutrophication as a problem or resource is thus, to a large extent, determined by one's pocket book. It is therefore perhaps fitting, in the affluent throw-away society of the technologically enriched world, that waste nutrients should boomerang in the form of unwanted plant growth.

Three examples illustrate the general sequence of events that takes place when nutrients derived from human culture find their way to lakes. The first pertains to the Lake of Zürich in Switzerland, where seemingly trivial events, first recorded in 1896, turned out to be a foreboding of more substantial changes that appeared later. The second concerns four lakes in the vicinity of Madison, Wis., in which massive algal blooms and related events — most unusual to the people living there — appeared between 1914 and 1958. The third refers to the eleventh largest, in surface area, of the world's great lakes, Lake Erie.

The area around the Lake of Zürich has been settled by man for millenia, from prehistoric lake-dwellers through Roman occupation and the Dark and Middle Ages to the present. Looking down on the broad expanse of the long lake basin from the upper part of the old city of Zürich, the colorful panorama, studded with occasional settlements and isolated homes, is impressive. From a distance it is not evident that the lake has been polluted with nutrients for most of the 20th century. Nor would one expect the lower part of the Lake of Zürich to be eutrophic, from its rather great mean depth of 50 meters (163 feet) and maximum depth of 143 meters (466 feet).

So far as has been recorded, nothing unusual happened in the Lake of Zürich until the 1890s, when two species of planktonic algae appeared in bloom proportions. These were the diatom, *Tabellaria fenestrata*, and the blue-green alga, *Oscillatoria rubescens*. This was the signal of later events that, between 1900 and 1970, resulted in massive growths of diatoms and blue-green algae; severalfold increases in concentrations of chloride ions and dissolved organic matter in the water; decreased water transparency in summer; precipitation of calcium carbonate (marl) as a result of increased photosynthesis; growths of filamentous algae, such as *Cladophora* and *Ulothrix*, on bottom areas near the shore; oxygen depletion in the bottom water; disappearance of trout and whitefish populations; and a concomitant rise in the abundance of perch and members of the minnow family.

Dr L. Minder, one of the early Swiss limnologists, documented many chemical changes that took place. While he was engaged in these studies, another Swiss scientist, Dr Fritz Nipkow – pharmacist by profession and limnologist by desire — was examining cores of sediment taken from the deepest part of the lake. Nipkow discovered that the sediments contained delicate, well-preserved layers representing seasonal successions of events year after year from the time of the first algal blooms. Pollen grains and diatom frustules associated with early spring were overlain by late spring and summer forms, and these in turn by species characteristic of late summer and autumn. The same pattern was repeated layer after layer. Due to this fortunate circumstance, it was possible to answer a number of questions pertaining to the lake that would have been difficult to answer otherwise. One of these concerned the abundance of blue-green algae.

Although blue-green algae were known to have bloomed in the Lake of Zürich with increasing frequency since the 1890s, few remains occurred in the sediment. Unlike diatoms, which have strong siliceous cell walls, blue-green algae tend not to preserve very well. However, a Swiss chemist, Hans Züllig, in 1959, reported finding a pigment peculiar to blue-green algae in the sediment. The name of the pigment was myxoxanthophyll. By determining concentrations of myxoxanthophyll at different levels in the sediment, and with the help of Nipkow's bands, Züllig was able to trace the incidence of blue-green algal blooms back to the 1890s.

Studies undertaken after World War II by Dr E. A. Thomas and other Swiss scientists showed that a buildup of growth-limiting nutrients, phosphates and nitrates, had occurred in waters below the photosynthetic zone. Paralleling this buildup, the incidence and duration of algal blooms began to increase with time. When algae reduced the concentrations of critical nutrients in surface waters to almost undetectable levels in summer, blooms persisted because of a continued supply of nutrients from land and atmospheric precipitation.

While all of these changes were taking place in the lower, densely settled part of the Lake of Zürich, the shallow upper basin, separated by a constriction of the lake, was not appreciably affected by man. It remained much as it has always been, forming a control for the experiment man had unwittingly performed in the lower lake.

To combat these changes, a drainage diversion was constructed around part of the shore, carrying nutrient-rich wastes to the Limmat River which, as the outlet to the lake, transported the nutrients to the Rhine River and then to the North Sea. In the mid-1960s after a long controversy on the best means of controlling eutrophication, a program of phosphorus removal from municipal wastes was initiated in an attempt to reduce the problems associated with increased plant growth. Looking at it from the point of view of the organisms living in the lake, this was a sign that humans were finally beginning to do their own work.

By the early 1970s it was clear the Lake of Zürich was recovering from its long history of enrichment with nutrients from municipal and agricultural wastes. Perhaps in another 50 or 100 years some limnologist may find a record of these events in sediment cores taken at a later date, factually demonstrating the success of today's limnologists and sewage treatment engineers.

The next case concerns four lakes in the vicinity of Madison, Wis. Their depths, areas, and volumes are given in order of flow:

	Depth in *meters*			
Lake	Maximum	Mean	Area in km^2	Volume in m^3
Mendota	25.6	12.1	39.4	478,000,000
Monona	22.5	8.4	14.1	119,000,000
Waubesa	11.1	4.9	8.2	40,000,000
Kegonsa	9.6	4.6	12.7	59,000,000

Aside from a passing reference to a bloom on Lake Mendota in 1850, first reports of noxious algal growths in lakes Mendota and Monona occurred in 1882. Whether this was merely a bad year due to unusual climatic conditions, or accentuated by raw sewage discharged into Lake Mendota by 10,000 inhabitants of Madison at that time, is not known. The lakes occur in an area of naturally productive land. With the usual year-to-year fluctuations of climate, occasional natural blooms would not be unexpected.

The first attempt at sewage treatment in Madison was initiated in the latter part of the 19th century. A new treatment plant to handle the growing population was later put into operation in 1914 with the treated effluent discharged into the Yahara River just above Lake Monona. The sewage, as usual, was treated for the removal of fast-settling solids and organic carbon, but not for removal of phosphorus or nitrogen. Within 2 years of installation of the plant it was obvious something quite unexpected (by the local population) was taking place. Blooms of blue-green algae, particularly *Anabaena* and *Aphanizomenon*, were appearing in the lake in frequency and abundance never seen before. By the early 1920s, thick mats of floating blue-green algae, piled up by onshore winds, were so offensive that even on hot and humid nights persons living near the lake bolted their windows, preferring a stifling enclosure to the putrid breeze.

From 1912 to 1953 copper sulfate, an algal poison, was applied to the surface waters of Lake Monona in an attempt to get rid of the algae. Between 1926 and 1936, 27,000–45,000 kilograms (60,000–100,000 pounds) of copper sulfate were applied annually to reduce algal growth. These additions now lie buried in copper-rich layers of sediment — a useful reminder to future scientists of the futility of trying to solve man-made eutrophication problems without cutting off the supply of nutrient-rich wastes.

In 1928, the city of Madison completed the first stage of a new sewage treatment plant. Effluent from this plant bypassed Lake Monona, entering the Yahara River between Lake Monona and Lake Waubesa. In other words, nothing had really been done other than to shift the effluent to the next lake downstream. Eutrophication problems immediately started to appear in lakes Waubesa and Kegonsa. Copper sulfate was, in turn, applied to these lakes to reduce algal growth. Lake Monona improved, but not as rapidly as expected. Perhaps this was because of continued, though lower, input of sewage (not all was diverted initially) and persistence of wastes from agriculture, storm sewers, and industrial effluents that still entered both Lake Monona and Lake Mendota.

The history of biological events in the Madison lakes is not as completely recorded as for the Lake of Zürich. But enough is known to say with assurance that the causes and responses were similar in both cases. In 1944, Claire N. Sawyer and James B. Lackey showed that the causal factors of eutrophication in the Madison lakes were supplies of phosphorus and nitrogen compounds in the incoming waters.

Later work indicated that the Yahara River below the four lakes was also affected. In 1954, a dense bloom of the blue-green alga, *Aphanizomenon flos-aquae*, caused a complete fish kill below the point of discharge of the sewage effluent. As a result of intense biological consumption of dissolved oxygen at night, at a rate faster than it could be replenished from air, the fish died of asphyxiation. Only a few carp survived in a small pocket above the point of discharge.

In 1952, a brewery that had long been in operation ceased discharging its waste to Lake Monona. A new sewage diversion scheme originally developed in 1942, but delayed 15 years by legal battles over land, was completed in 1958. Since then effluent from the sewage treatment plant, still as rich in nutrients as ever, has flowed around the lakes into Badfish Creek. Badfish Creek, now a mobile sewage lagoon, flows into the Yahara River where the nutrients are someone else's problem.

The lakes have improved immensely. No longer is it necessary to add copper sulfate in high and potentially dangerous quantities. Although by no means devoid of algae, a condition neither possible nor desirable, the lakes are free of the pea-soup blooms that once occurred. Rumor has it, though, that Lake Mendota, uppermost lake of the chain, is becoming enriched with sewage effluents from a community lying upstream.

As interesting as these histories of lakes in Switzerland and Wisconsin may be, they are dwarfed by the geographic immensity of change in Lake Erie, fourth largest in surface area of the chain of five St. Lawrence Great Lakes — a body of water 26,000 square kilometers (almost 10,000 square miles) in area. It is ironic that Lake Erie, the last of the St. Lawrence Great Lakes to be penetrated by the white man, would be the first to fall prey to his machinations.[3]

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[3] Lake Erie was discovered by the white man in 1669 when Louis Jolliet, guided by a friendly Iroquois, entered the lake from the west via Lake St. Clair and the Detroit River. The prime reason for the late discovery was the presence of the warfaring Iroquois. They controlled the portages between Lake Ontario and Lake Erie.

When Louis Jolliet and his successor, La Salle, viewed the shore of Lake Erie from their heavily laden canoes, they found the water as rich in the variety and size of fish as was the lush forest canopy on the shore with woodcock, quail, wild turkey, and deer. When Cadillac penetrated to the present site of Detroit, he had to part wild geese and swans with his canoes in order to land his party on shore. Now extinct, the passenger pigeon seasonally darkened the sky over Lake Erie by sheer immensity of number.

As 18th century exploration and fur trade gave way to settlement and industrialization, man's prostitution of the environment began to spread from harbors and bays into the main body of the lake. Events that set this into motion started with the formation of coal deposits in Pennsylvania, Kentucky, and Ohio 300 million years ago, and with the formation of enormous deposits of iron ore along the southern shore of what is now Lake Superior over 1000 million years ago.

Following the discovery of these deposits by technological man, Lake Erie became the natural center of the U.S. steel industry. The reason was the ease of water transportation and the 4:1 ratio of coal to iron ore then used in the manufacture of steel. The economics of the 4:1 ratio demanded the center of the steel industry be on Lake Erie, rather than Lake Superior. As the gross tonnage of iron ore passing through the locks at Sault Ste. Marie increased, from a few thousand tons in 1855 to hundreds of millions of tons in 1973, so did the pollution of Lake Erie — from industry and human population.[4]

Adequate support for comprehensive limnological studies on the Great Lakes was not made available by the governments of either

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[4] When William Francis Butler passed through the St. Lawrence Great Lakes in 1870, on his way to help quell the Red River Rebellion in western Canada, he remarked, "But this glorious river system, through its many lakes and various names, is ever the same crystal current, flowing pure from the fountainhead of Lake Superior. Great cities stud its shore, but they are powerless to dim the transparency of its waters. Steamships cover the broad bosom of its lakes and estuaries; but they change not the beauty of the water no more than the fleets of the world mark the waves of the oceans." (William Francis Butler. *The Great North Land.* 1872)

the United States or Canada until the 1960s. Prior to that time, Paul R. Burkholder, Charles C. Davis, and David C. Chandler, to name but three of the early limnologists, performed their work in the 1930s and 1940s largely by "rowboat" limnology.

When adequate financial support did come in the 1960s, the hour was late; such profound changes had taken place that it was difficult to determine what the lake had been like before. The available scientific information, collected with inadequate facilities by a handful of dedicated scientists, was extremely limited.

Unprecedented changes had taken place in the fish populations. Between 1930 and 1965 the numbers of cisco, sauger, whitefish, yellow walleye, and blue walleye in the commercial harvest decreased in succession. By 1970 it could be said authoritatively that blue walleye, once a major species, was extinct in the lake. Yellow perch, smelt, and white bass, on the other hand, were on the increase.

It is virtually impossible now to reconstruct the causes of the changes in fish populations because of lack of fishery and limnological information. Overfishing, oxygen depletion in bottom water, changes in abundance of food organisms, introduced species, toxic pollutants, and ruination of spawning beds were probably all involved. The only clearly identifiable cause was *man*.

From old records of algal populations at a municipal water intake plant at Cleveland, Ohio, Dr Charles C. Davis, then at Case Western Reserve University in Cleveland, Ohio, discovered algae had been increasing rapidly since 1930. Typical results in 1927–30 were 100,000–200,000 cells per liter (a liter is approximately 1 quart). By 1946–48 comparable values had risen to 1,200,000 cells per liter; and by 1960–64 had increased to 1,300,000–2,400,000 cells per liter. Diatoms and blue-green algae were recorded in what seemed to be unprecedented numbers at numerous points in the lake.

By the mid-1950s the shallow western basin of Lake Erie, loaded with wastes from Toledo, Detroit, and other major cities on the U.S. side, had become dangerously susceptible to any change that might tip the scales of nature in an unpredictable way. The first event was a period of unusually warm and quiet weather from September 1 to 5, 1953. As a result of water stagnation and consequent oxygen depletion at the mud surface, practically the entire population of a mayfly nymph, *Hexagenia*, was wiped out in the western basin. This mass mortality of an important item in the diet of many Lake Erie fish was caused by the biological richness of the water and sediments — in part due to nature, in part due to man.

After a brief attempt at recovery, *Hexagenia* became extinct in the western basin by 1960 and was drastically reduced throughout the rest of the lake. To those living around the shores of Lake Erie, it was a mixed blessing as they were no longer pestered by swarms of mayfly adults around light bulbs and screens at night. But the fish were not so pleased; nor were the fishermen whose livelihood depended on fish.

In the early 1960s Dr Alfred Beeton of the U.S. Bureau of Commercial Fisheries (now at the University of Wisconsin, Milwaukee) showed that the chemistry of Lake Erie had changed dramatically since the early part of the century. Comparing concentrations of different chemicals reported by various investigators, he showed that concentrations of sodium, chloride, and sulfate in Lake Erie had more than doubled since 1910. Furthermore, these changes were passed on to Lake Ontario downstream. In contrast, concentrations of chemicals in Lake Superior (uppermost, largest, and least densely settled of the St. Lawrence Great Lakes) had not varied during the same period.

In 1961, Drs John Carr and James Hiltunen of the U.S. Bureau of Commercial Fisheries compared the kinds and abundance of bottom invertebrates in the western end of Lake Erie to those reported for 1930. They found the polluted area of the western basin had increased fourfold from 263 square kilometers (101 square miles) in 1930 to 1020 square kilometers (388 square miles) in 1961. In the 1960s United States Coast Guard authorities advised international shippers not to draw nearshore water from the western end of Lake Erie for drinking purposes, because of possible danger to health.

Biological and chemical changes in Lake Erie and Lake Ontario have been more pronounced than in the other Great Lakes. The reason for this in Lake Erie is its relatively shallow depth, small volume (the smallest of all the St. Lawrence Great Lakes), and the

12,000,000 people inhabiting the drainage basin in 1966. Of this total population, 10,400,000 lived on the United States shore of a lake partitioned equally between Canada and the United States. It was not a case of hands across the border that officials often like to cite.

Many people have wrongly referred to Lake Erie as a dead or dying lake. The real problem is that the western and central basins of the lake are teeming with life, in the form of unwanted microorganisms and coarse fish. Dr Andrew L. Hamilton of the Freshwater Institute in Winnipeg has shown, from the analysis of sediment cores, that the western basin of Lake Erie was in a eutrophic state prior to the appearance of technological man on the shore. But he also showed that since the advent of man the degree of eutrophy has markedly increased. The "overload" is all due to man.

Mixed with more than occasional buckets of oil and grease (1000 barrels a day in the Detroit River alone in 1967), organochlorine insecticides, detergent phosphates, mercury, and the wastes of municipalities, industries, and ships, the western two-thirds of the lake was in the process of becoming an enormous sewage lagoon. Open waters in the eastern end of Lake Erie, however, because of their greater volume and depth, maintained a comparative chastity relative to the whoredom to which the rest of the lake had been put. When the Cuyahoga River at Cleveland caught fire in 1969 from oil on its surface, it was painfully obvious that the patient — *man* much more than the lake — was incredibly sick.

To probe more deeply into the underlying causes behind these and similar events now taking place in tens of thousands of lakes, reservoirs, and estuaries throughout the world, there is no better path to follow than the history of methods used by human populations for disposal of fecal and urinary waste.

The earliest method adopted for disposal of physiological waste was by addition to the soil, a time-honored practice still used in many parts of the world today, including the United States and Canada. It was this same practice Moses advised the Israelites to follow when he said, (Deuteronomy 23:13) "And thou shalt have a paddle upon thy weapon; and it shall be, when thou wilt ease thyself abroad, thou shalt dig therewith, and shall turn back and cover that which cometh from thee."

At the same time, man had learned the benefit of adding manures to agricultural soil and fish ponds in order to replenish nutrients depleted by the perpetual removal of crops. Some of the so-called "night-soil" removed from cities during the Middle Ages was destined for use on land as fertilizer.

With the aggregation of populations into cities, intensified by the industrial revolution, terrifying outbreaks of Asiatic cholera, typhoid fever, and other contagious diseases began to spread with a devastating toll of life. Effects of these are matters of impressive historical record, unread and unappreciated today in the disease-free comfort of our communal systems of water supply and waste disposal.

The need for improved systems of water supply and waste disposal was generally accepted only in the middle of the 19th century, following realization that the spread of Asiatic cholera (and, by implication, other diseases) was caused by drinking water from wells infected with sewage from diseased persons. Based on this discovery, major cities in technologically developed countries slowly began to construct one set of pipes to convey water from an upstream site (some were already there) and another to discharge wastes downstream (commonly leading into storm sewers that were already there). In the process, Sir John Harington's invention of the water closet (flush toilet) came into practical use.[5]

Storm sewers, previously used to carry the erosive rush of rain water from city streets, became recipients of a rather dubious inheritance — municipal waste. With this the old adage, "rain to the river, sewage to the soil," went out the proverbial window with more alacrity than an Italian lover on the appearance of a husband. Wells

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[5] Sir John Harington invented the principle of the water closet (as it is called in Europe) or flush toilet (in the American vernacular) in 1596. His invention did not come into extensive use until the early part of the 19th century.

disappeared from cities and the once familiar cry of the water seller in the streets was heard no more.[6]

Greatest concern in terms of waste treatment in the 19th century was with the removal of disease-causing organisms and organic compounds from municipal and industrial wastes. This attack on organisms of disease needs no explanation now although, because of the poor state of medical knowledge, an explanation was needed then. The reason for the accent on organic matter was that organic-rich wastes created unsightly appearances, foul odors, and fish mortality in natural waters because of oxygen depletion. The person who lived downstream and used the water for washing and drinking didn't like it; but only if he happened to be a landowner was any improvement made.

Most of the treatment systems that have been developed for removal of organic matter from water depend upon the ability of microorganisms to break down organic compounds. In this process of biological oxidation, atoms of carbon, hydrogen, and nitrogen in organic compounds are converted into their oxides. Organic carbon is converted to carbon dioxide (CO_2); organic hydrogen to its oxide, water (H_2O); and organic nitrogen to nitrate (NO_3^-).

Biological oxidation is essentially a slow and controlled combustion of organic compounds, similar in principle to the more rapid process that takes place in the combustion of hydrocarbons in an internal combustion engine. Organisms are able to accomplish this controlled oxidation at low temperatures because of catalysts called enzymes. One can legitimately say the basis of life depends on the trick of creating fire in water, combusting organic compounds at low temperatures and utilizing the energy released for growth and maintenance. Microorganisms in soils and water perform this service of oxidizing our wastes free of charge. Without this service we could not survive.

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[6] Water was once sold on the streets of Europe and North America, as it still is in the older sections of many Asian and African cities. A modern form of the water seller has been reappearing in most of the world's larger cities. Stocks of companies engaged in bottled-water distribution in urban centers are on the highly recommended lists of stockbrokers for active growth and development.

The first systems designed for microbial oxidation of organic matter in municipal wastes were sewage farms, in which the oxidizing ability of microorganisms in soil was used to advantage in agriculture. Lagoons, self-purifying sewage oxidation ponds, evolved somewhat later.

In the latter half of the 19th century "trickling filters" came into use. These are actually not filters, but thick beds of loose gravel designed for good aeration, through which sewage is flushed. Microbial "slimes," rich in bacteria, protozoans, and invertebrates, coat the gravel and carry out the oxidation.

The activated sludge system of sewage treatment, still referred to as "modern" sewage treatment, was first described in 1913. It is a controlled engineering system in which microbially rich ("activated") sludge, that develops during treatment, is returned to the intake line so that organisms of decomposition can start to work immediately on incoming sewage. Methane produced from fermentation of the sludge is used to help heat the treatment plant.

Ninety percent of the organic matter entering one of these continuous-flow systems is oxidized within 4–12 hours. In spite of their utility, systems of this sort in 1972 still served less than 15% of municipal waste generated in the United States and Canada. The typical "waste treatment plants" used by most communities in 1972 differed little from what was available in 1872 — screens to remove coarse materials and a sewage lagoon to permit organic decomposition to take place before wastes were discharged to streams.

Eutrophication happened in spite of sewage treatment for removal of organic compounds, because phosphorus and nitrogen are not appreciably removed during sewage treatment. As atoms, phosphorus and nitrogen are susceptible to recombination and rearrangement in molecules, but not to destruction. Oxidation of organic matter during sewage treatment can even enhance the growth-stimulating effects of phosphates and nitrates by removing substances that inhibit plant growth.

It has taken the better part of half a century for most sewage treatment engineers to learn that liberation of nutrients to water results in a "resynthesis" of organic matter in lakes and streams, negating much of the work performed in sewage treatment works. The only blessing is that in synthesizing new organic compounds, photosynthetic plants evolve oxygen. It has also taken limnologists half a century to realize they have an interest and a role to play in determining what goes on in sewage treatment plants. Fortunately, engineers and limnologists are now working more closely together.

The causes and consequences of man-made eutrophication have now been exposed in general detail, tracing the course of history from the middle of the 19th century to the present. If one had to identify one single factor that, above all others, has determined the course of events, it would be the conversion of wells and out-houses into water mains, flush toilets, and sewage drains. In one fell swoop this helped pave the way for almost everything that followed: (1) increased water pollution from physiological wastes because of the bypassage of soil; (2) increased production of fertilizers to replace nutrients removed from the soil as crops; (3) increased cost of treating wastes composed of more than 99.99% water; and (4) man-made eutrophication.

The overall design of the system to which we have fallen heir (no one would contest the advantage in terms of public health) is a one-way movement of nutrients from land to water. Nutrients are being usurped from soil in the form of agricultural crops and livestock production, passed through intestines and kidneys of man and then delivered to streams, lakes, sediments, and the sea.

As the need for greater production of food for the expanding human population continues to rise, nutrient disruption of aquatic ecosystems is bound to increase. Culture of new, high protein varieties of grain, for example, will result in a greater flow of nitrogenous fertilizers from land to sediments and the sea.

The analysis of eutrophication has now been extended to a point beyond which little more can be said without a more detailed understanding of the biological, chemical, and physical processes that take place in lakes. To lack this understanding is to be like the citizens of Madison, Wis., who saw things happening around them that they could call by name but not truly understand. The beginnings of such a foundation are developed in the next chapter on the circulation of water in lakes.

Chapter 3

LAKES ARE MADE OF WATER

In which the vertical circulation of water in lakes is deduced from a knowledge of temperature, density, and the influence of sun and wind.

Water is such a common substance that, like the air drawn into our lungs 30,000 times every day of our lives, we take it for granted. Pause for a moment to consider its significance.

Vented upwards from deep within the earth through volcanoes, geysers, and fumaroles during 5000 million years of geologic history, water has accumulated at the earth's surface to such an extent that it now covers 70% of the surface to a mean depth of 3.8 kilometers, a little over 2 miles. Forests and deserts have been created at will in response to past alterations in the distribution and abundance of water precipitated from the atmosphere as rain. On four separate occasions during the past 2 million years vast expanses of water in the form of glacial ice overrode continents — depressing the land, sculpturing valleys, depositing long mounds of gravel, damming lakes, recharting river courses, and lowering the level of the world's oceans by more than 100 meters (330 feet).

As a medium of transport requiring neither roads nor rails, water has been a major factor in the development of trade and cultural exchange among diverse peoples of the earth. On land, water means food and survival when it comes at the right times and places;

famine, when it does not. It provides electrical power for many technological conveniences in our homes and is the basis of our recreational pleasure in swimming, fishing, and boating. The thrill of cascading down a mountain slope on skis and the wild excitement of a hockey game also depend on water.

But it is in the human body that water serves us best. Its high specific heat and circulation as the major component of blood permit the even distribution of temperature on which our lives depend. In summer, we are cooled by the high evaporative heat loss of water pumped outward to the body surface by a thousand infinitesimal factories of sweat glands in the skin. We could not survive without drinking it. It comprises two-thirds of our weight. It is the undisputed solvent for transport of food substances in the body and removal of wastes by the kidneys and lungs. As a cleansing agent it prevents the spread of infections and disease.

In short, water is the chemical basis of life — according to many, perhaps a universal requirement for the origin and persistence of life. Our dependence on water has not been alleviated, but has markedly increased with the advent of modern technology. This is illustrated by the high consumption of water in an average U.S. home, 380 liters (100 U.S. gallons) per person per day, equivalent in weight to 380 kilograms (836 pounds) per person per day. No other substance is used to such an extent by man.

Water is unevenly distributed in nature. Percentage distribution of the major forms of water on earth that participate in the hydrologic cycle is as follows:

	Percentage
Oceans	97.1–97.6
Polar ice and glaciers	2.1
Groundwater	0.3–0.8
Freshwater lakes	0.009
Saline lakes	0.008
Soil and subsoil moisture	0.005
Atmospheric water vapor	0.0009
Rivers	0.00009

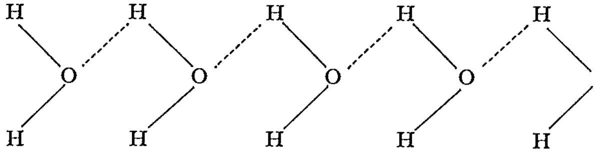
Expressed in terms of volume the fraction of water that occurs in the form of lakes and streams is minute. Yet in spite of this, inland waters play disproportionately large roles in our lives, for we do not live within a volume of water but rather in proximity to water surfaces. Rivers have always been the avenues of commerce — at one time for produce, now more for waste. Lakes, on the other hand, are valued for the peace and tranquility they confer on the mind. It is in the contrast of a lake that landscape achieves its fullest measure of beauty.

But beneath the mirrored surface lies another design, more intricate in pattern — the wild mosaic of a folk dance performed in molecular dimensions by an infinity of water molecules. Invisible forces holding the molecules together in this fluid architecture also act on a larger scale to endow lakes and even oceans with idiosyncracies of their own, features so significant that no account of limnology (the science that deals with inland waters) would be complete without them. For this reason it is important to understand how the chemical properties of water determine many aspects of the behavior of water in lakes.

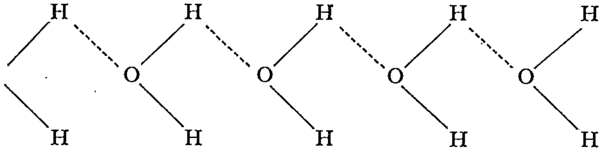
Water, a compound in which hydrogen and oxygen atoms are joined together in the ratio of 2:1, is not a simple substance. In fact, it was only as detailed knowledge of other chemicals accumulated over the centuries that the uniqueness of water came to be fully appreciated. If one had to predict its properties without ever having seen it, much as Mendeleyev in the 19th century accurately predicted the properties of chemical elements not known at the time, the expectation would be that water should exist as a gas at ordinary temperatures.

By analogy with hydrogen sulfide and other substances, the expected freezing point of water should lie at –100° Centigrade (–148° Fahrenheit) and the boiling point at temperatures below the true freezing point (0° C, 32° F). None of the unique attributes of water could be anticipated, such as the supremacy of its solvent power, its large heat capacity, and high surface tension. This contrast between expectation and fact signifies that, concealed within the structure of the liquid, there must be subtle forces binding water molecules together. How else could one explain the unexpectedly high amount of energy required to transfer molecules from the liquid state into vapor?

These hidden forces that operate on an infinitesimal scale within the magic liquid are called hydrogen bonds. Shifting about with more rapidity than flies before a swatter, they create flickering associations between one water molecule and another. This incessant "hand shaking" of molecules endows the liquid with a continuity and permanence in change. If our eyes could see the ballet of molecules in action, a quartet of dancers linked by hydrogen bonds (broken lines) might look like this:



and an instant later like this:



As Albert Szent-Gyorgyi once put it, "Water is the only molecule that can turn around without turning itself around."

Among the several aspects of water that have fascinated chemists is one that, above all others, determines the pattern of the vertical circulation of water in lakes. This is the strange way in which the density of water changes with temperature. Of all liquids studied to date, only two have been found to exhibit maximum density at a temperature above, rather than at, the freezing point. One of these is water. The other is cesium chloride, a rare laboratory chemical that occurs as a liquid only at very high temperatures.

This peculiarity is matched by another unusual feature. Water differs from practically all other substances in being more dense as a liquid than as a solid. As might be suspected, these two unusual features are related. They stem from a common cause.

Consider what an unusual place the world would be if ice were denser than water. Glaciers would sink to the bottom of the oceans, and ponds would freeze "under" instead of over. Oceans would perhaps be reduced to a thin film of supersaline water on top of a sedimentary rock that we would recognize as ice. Pressure of the atmosphere would be many times greater, laden with gases that would otherwise have passed to the sea. Probably life would never have evolved.

Ice has a density of only 0.92 gram per cubic centimeter as compared to approximately 1.0 gram per cubic centimeter for water in the liquid state. The low density of ice is a consequence of the way water molecules are arranged in the crystalline structure. Spaces are repeated at regular intervals as a result of fixed positions in which molecules are held in the solid. The more flexible arrangement of molecules in the liquid permits a denser packing.

Water in the liquid state exhibits its maximum density at a temperature of 4° C (39° F), just a few degrees above the freezing point. Two opposing forces are responsible for this unusual feature. One is the common property among all liquids and gases for the distances between molecules to increase with rising temperature. Considering this process alone, one would expect water to exhibit its maximum density at the freezing point, successively decreasing in density with rising temperature. The other force is the tendency for water molecules to group together in ice-like arrangements as the temperature of the liquid approaches the freezing point. Considering this second process alone, one would expect water to exhibit its minimum density at the freezing point, successively increasing in density with rising temperature. The combined operation of the two processes results in the closest overall packing of molecules at 4° C (39° F).

The most significant feature of the relationship between temperature and density of water is that it is not a straightline relationship. The extent of density change per degree of temperature change depends on the actual temperature. For example, the difference in density between samples of water at 10 and 11° C is 12 times greater than between samples of water at 4 and 5° C — 0.000095 gram per cubic centimeter vs. 0.000008 gram per cubic centimeter. The difference in density between samples of water at 20 and 21° C is 26 times that of water at 4 and 5° C — 0.000211 gram per cubic centimeter vs. 0.000008 gram per cubic centimeter.

The general rule is: *the change in the density of water per degree change in temperature increases as the temperature departs from 4° C, both above and below.*

This is an important rule, well worth the time that it may take to commit it to memory. It is useful because it permits a number of characteristics common to all large water bodies to be interrelated and explained in simple, fundamental terms. Knowing the rule, it is easy to understand why dissolved oxygen tends to become depleted in the bottom waters of eutrophic (productive) lakes during summer, why lake trout disappear from lakes affected by man-made eutrophication, and how vertical circulation of water in tropical lakes can be restricted as a result of small gradients in temperature. Without the rule, these phenomena could only be interpreted as interesting, but isolated and unconnected events.

The principal utility of the temperature–density rule is that it permits inferences to be made about whether the waters of a given lake are in complete circulation from measurements of temperature. *Thermal stratification implies incomplete vertical mixing of waters.* The logic is simple. Where there is a vertical gradient of temperature there must also be a vertical gradient of density; and a vertical gradient of density is prima facie evidence of incomplete circulation.

You may have noted, on diving into a lake early in the season, or on a particularly still and sunny day in summer, that water near the surface is often considerably warmer than the water below. The sun has warmed the surface waters more rapidly than the wind has mixed them with the underlying water. Layering persists because warm water is lighter (less dense) than cold water at temperatures above 4° C. Later in the season, or after a good wind when the sun-warmed waters have been mixed to greater depths, one can dive deeply without detecting any marked change in temperature. If you have experienced such things you may know a good deal more about lakes than you suspect.

Temperatures at various depths in lakes during midsummer, when thermal stratification is most marked, generally follow one of two common patterns. In shallow lakes, well exposed to the wind, temperatures will be found to be practically constant from top to bottom — typically varying less than 2° C (3.6° F). This uniformity of temperature indicates that the waters are well mixed throughout.

The other common pattern occurs in water bodies with maximum depths in excess of 5–10 meters (16–33 feet). In this case three characteristic layers are present: (1) an upper zone of warm water in which temperature is more-or-less uniform throughout; (2) an intermediate zone in which temperature declines rapidly with depth; and (3) a lower zone of cold water in which temperature is again more-or-less uniform throughout. These three layers are termed *epilimnion*, *metalimnion*, and *hypolimnion*, respectively. They are depicted schematically in Fig. 1.

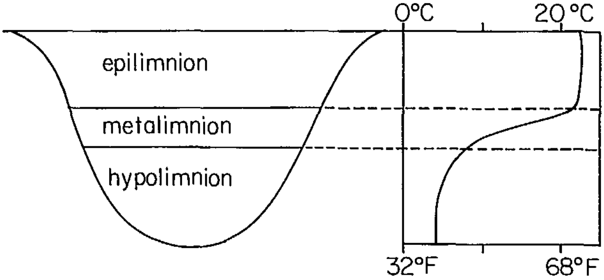


FIG. 1. *Typical thermal structure of a lake in temperate latitudes in summer.*

The technical names for the three layers can easily be remembered from the meaning of the Greek roots from which they are derived. *Epi* — on or upon; *meta* — among; *hypo* — under; and *-limnion* from *limnos* — pond or lake.

The metalimnion is also commonly referred to as the *thermocline*, literally meaning *thermal gradient*. Although many limnologists use the terms metalimnion and thermocline interchangeably, the former is really the water mass and the latter the thermal gradient by which it is most readily characterized.

The gradient of density in a thermally stratified body of water can be calculated from a knowledge of lake temperatures, using a conversion table listing the density of pure water for various temperatures.[7] This procedure is tantamount to assuming the only factor regulating density in lakes is temperature. This is a reasonable assumption for most lakes. Exceptions are meromictic (partially circulating) lakes with salt-laden bottom waters that rarely, if ever, mix with the waters above.

The result of such calculations can easily be guessed. The gradient in density per unit depth in the epilimnion will be small or nil because of the uniformity of temperature. Exactly the same will be true of the hypolimnion. But in the metalimnion the gradient in density will rise to reach a maximum slightly above the point at which the rate of change of temperature with depth is maximal.

The density gradient in the metalimnion forms a barrier that prevents the mixing of epilimnetic and hypolimnetic waters. Just as physical work must be performed in mixing cream and milk, or oil and vinegar, so must physical work be performed in mixing layered water masses of different density. The only difference is that in lakes the mixed waters cannot separate again as do mixtures of aqueous and oily fluids. Other things equal, the amount of work required to mix layered water masses of different density is proportional to the difference in density and the sharpness of the gradient.

Strange as it may seem from the minute changes in density associated with temperature changes in the thermocline, they are sufficient to prevent wind from completely mixing epilimnetic and hypolimnetic waters in lakes. Because of the marked reduction of turbulence and current velocities with depth, there is always some limit to the depth of the epilimnion created by even the strongest winds. A well-developed thermocline can be just as effective a barrier to downward moving currents as the shore or bottom of a lake. The

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[7] See Table A3 (p. 168).

characteristic change of temperature in the thermocline is thus a secondary reflection of the density barrier to mixing rather than a primary factor in itself.

Since temperatures in lakes can be measured more easily than density, limnologists typically infer the presence of a density barrier to mixing from temperature data alone. This practice is so common that students beginning the study of limnology find it difficult to understand why limnologists seem so preoccupied with the study of temperature. Of course, they aren't. It is the physical barrier to mixing that interests them. So, when a limnologist speaks of the physical "barrier" of the thermocline, remember — it is a barrier in density rather than temperature.

But the thermocline is not only a physical barrier in the sense of restricting water movements; it also acts via temperature as a biological barrier affecting dispersal and growth of diverse aquatic organisms. Green plants and many forms of animal life — mayflies, caddisflies, molluscs, sunfish, and bass — reside in the warm, well-illuminated waters of the epilimnion in summer. Cold-water fishes such as trout, ciscoes, whitefish, and the small crustacean, *Pontoporeia*, on the other hand, rarely stray from the cool hypolimnion. Other plants and animals find their requirements best satisfied in the metalimnion. Adopting a completely different way of life, some deep-water organisms make daily vertical migrations in the water column, coming to the surface at night and remaining at depth during the day. Thus the potential for growth and survival in different layers varies with the life-style of each species.

To understand how thermal characteristics of lakes change during the year, it is necessary to disentangle the separate influences of the sun and wind. This is a rather artificial procedure as the two always act together in nature; however, in combination the principles and ultimate causes involved are obscured. The procedure will be first to examine the characteristics of pure water in relation to the wavelengths of light emitted by the sun, later extending the logic to interpret events taking place in lakes.

Only three parts of the sun's spectrum are of direct significance in the structure and metabolism of aquatic ecosystems. These are:

(1) ultraviolet radiation, consisting of wavelengths[8] shorter than those visible to the human eye; (2) visible radiation; and (3) infrared radiation, composed of wavelengths longer than those visible to the human eye. Properties of the radiation in each of these three regions are briefly described below.

Ultraviolet radiation — Some insects, aquatic crustaceans, and other organisms can see ultraviolet light and have evolved complex behavioral patterns that are dependent on the ultraviolet radiation produced by the sun. Humans, on the other hand, are blind to ultraviolet light. We detect it only from tanning or sunburn reactions produced in our skin. Most of the ultraviolet radiation emitted by the sun is absorbed by the ozone layer in the upper atmosphere. The small amount reaching the earth's surface is important in the production of vitamin D and in the behavior of some organisms, but otherwise it is not known to be of major significance in lakes.

Visible radiation — The visible radiation emitted by the sun passes through the atmosphere with very little reduction in intensity except when the sky is covered with clouds. The colors we can discern within the visible spectrum are: violet, blue, green, yellow, orange, and red in order of increasing wavelength. Some violet and blue light at short wavelengths is scattered, during passage through the atmosphere, in a plane at right angles to the direction of light from the sun. That is why the sky looks blue — because of blue light scattered by small molecules and dust particles in the atmosphere. For the same reason, sunsets look red. Since much of the blue light is scattered in other directions, red wavelengths are accentuated in the light that passes directly from the sun to our eyes.

Infrared radiation — Also known as heat radiation, cannot be detected by the human eye. Owls, on the other hand, are able to detect infrared radiation visually, a characteristic that enables them to locate mice, in the dark, from the heat radiated by their bodies. We sense infrared radiation only by heat-sensitive nerve endings

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[8] The electromagnetic spectrum is commonly subdivided into wavelength or frequency bands in much the same way that radio frequencies are subdivided into commercial, police, and citizen bands.

located in the skin. Infrared radiation is emitted by all hot bodies, of which the sun and an electric heater are two examples.

Of the total radiation emitted by the sun that reaches the earth's surface, approximately half occurs as infrared radiation and half as visible radiation. Although a person with sunburn might justly claim otherwise, the amount of ultraviolet radiation is insignificant. The case is different on the moon. Lacking an atmosphere, the moon is constantly bombarded with ultraviolet radiation from the sun. For this reason the suits and visors worn by astronauts have to be impermeable to ultraviolet radiation. Without such protection the eyes and bodies of the astronauts would be burned.

When radiation from the sun strikes a water surface, some is reflected, some is absorbed and in the process converted into heat energy, and some is transmitted through the water column depending on its thickness and the wavelengths of light involved.

Water selectively absorbs some wavelengths of light more than others. Infrared radiation, for example, is absorbed more strongly by water than visible radiation.[9] Likewise, the percentage absorption of visible light in a given water column decreases continuously from the red part of the spectrum down to the blue part of the spectrum. At still shorter wavelengths the situation reverses — ultraviolet light, violet light, and blue light at shorter wavelength are absorbed to a greater extent than blue light at longer wavelength. Although it might at first be thought that water often looks blue because of its transparency to blue light, the more common reason is because of reflected blue light from the sky.

In lakes, other factors in addition to water modify penetration of the sun's radiation. Suspended silts and clays, dissolved humic material, and microscopic plant life can all exert a pronounced effect. They will be neglected for the moment to accent the significance of water.

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[9] People who do not realize water is more transparent to ultraviolet radiation at long wavelengths than it is to infrared (heat) radiation may develop intense sunburn on days when a light mist pervades the sky. Not feeling the direct heat of the sun's rays, they assume, erroneously, that the sun's radiation is evenly reduced over all wavelengths of the spectrum.

A useful rule concerning the absorption of light by homogeneous liquids and solids was formulated by J. H. Lambert in the 18th century. Lambert found when light of a given wavelength passed through a homogeneous solid or liquid, the percentage of light absorbed by each successive unit of distance was constant. In the case of infrared light, if 90% is absorbed by a column of water 1 meter in length, a column of water 2 meters in length will absorb 99% of the incident light. (Ninety percent of the original 100 units of light is absorbed by the first meter and 90% of the 10 units remaining is absorbed by the second meter. This leaves only one unit of light to pass through the entire 2-meter column.)

A similar relationship holds for light at other wavelengths, the actual amount of absorption depending on the absorption characteristics of water at each particular wavelength. Thus, if 2% of incident light in the green part of the spectrum is absorbed by a column of water 1 meter long, somewhat less than 4% will be absorbed by a column 2 meters long. (Two percent of 100 units is absorbed by the first meter, and 2% of 98 units by the second meter.) Since water does not evenly absorb light at different wavelengths, the color of the sun in clear lakes changes with depth from yellowish orange at the surface to blue below.

Knowing (1) that light energy is converted into heat energy on absorption, and (2) that the greatest amount of absorption must occur closest to the light source, a simple prediction can be made for lakes. Lakes should be most intensively heated by the sun in the uppermost layers where greatest absorption occurs. If a lake could be kept under completely quiescent conditions in continuous sunlight, temperatures would be highest at the surface and decline rapidly with depth. The most dramatic changes in temperature would occur immediately below the water surface.

This prediction can easily be tested in a simple home experiment.[10] An infrared lamp or high-intensity light bulb, corresponding to the sun, is positioned over an aquarium filled with cold water from the tap. After an hour or so an ordinary outdoor thermometer

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[10] For a description of this and other home experiments see Vallentyne (1967).

can be used to show, as predicted, that the depth distribution of temperature is exactly as described above. Temperatures will be highest at the surface and decline rapidly with depth.

The situation in natural lakes is entirely different, as has already been described. Waters of the epilimnion are uniform in temperature to considerable depths, not uncommonly 3–20 meters (10–65 feet), depending on the size of the water body. The difference between the results obtained in the aquarium experiment and those observed in natural lakes is principally due to the action of the wind. Wind, rather than the sun, is the primary agent responsible for distributing heat to deeper parts of lakes. The transfer is achieved by means of waves and water currents. The major work of the sun is confined to the uppermost few meters of water where practically all the infrared and red radiation of the sun is converted into heat.

In the case of very turbid waters, rich in suspended clays, all the sun's radiation may be screened out in the uppermost few centimeters (inches). On the other hand, in extremely clear waters such as Lake Tahoe on the California–Nevada boundary, blue light from the sun may penetrate to depths in excess of 100 meters (330 feet).

A strange situation occurs in a class of lakes known as partially circulating or *meromictic* lakes. Water temperatures in the deepest parts of these lakes are often *higher* than in the immediately overlying water. The circumstance that permits this is the occurrence of high concentrations of dissolved chemicals in the deepest waters.[11] The high density caused by these dissolved substances creates a year-round barrier to mixing that is just as effective as the barrier of the thermocline in summer. Depending on the depth and transparency of the overlying water, the salt-laden bottom water tends to accumulate heat like a closed car parked in the sun. The heat is easily gained through absorption, but lost only with difficulty. The most extreme case known is Hot Lake, in the State of Washington, USA. Because of its shallowness — the lake is only 3 meters (10 feet) deep — the

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[11] The two most common causes of this condition are: (1) subsurface influx of salt-laden groundwater; and (2) extreme protection from the wind. Typically, both requirements have to occur simultaneously.

temperature of the salt-rich bottom water rises to 50° C (122° F) in summer and can be as high as 30° C (86° F) in winter under a cover of ice.

The temperatures of bottom waters in tropical lakes generally lie in the range of 15–25° C (59–77° F). Surface temperatures are typically 5–10° C (9–18° F) higher. This differs very little in terms of density stratification from the situation in temperate lakes, even though the temperature differences in tropical waters are smaller. This is because of the large density differences per degree of temperature change at high temperatures. A good general rule to remember is: bottom temperatures of lakes are rarely, if ever, lower than the mean temperature for the coolest month of the year. This stands to reason because air temperatures have to be low for a long time in order to cool what usually amounts to a large volume of water.

Although the thermocline retains its structure throughout spring and summer, it is often tilted from a horizontal position when a prolonged wind piles up epilimnetic water at the downwind end of a lake. In extreme cases the angle of tilt can be such that the thermocline rises to the surface at the upwind shore. When the wind ceases the situation is unstable with respect to gravity. The thermocline then begins to ponderously oscillate back and forth in teeter-totter fashion until dampened out by opposing wind stresses or frictional losses. These motions, known as internal seiches, induce turbulence into the hypolimnion and are important for a number of other reasons.[12] You may have noticed, as have the citizens of Toronto on occasion, peculiar relations between temperatures of air and water at bathing beaches. Sometimes the water is unseasonably cold when the sun is shining and the air is hot. At other times the reverse is true. When such things happen they are usually the consequence of an internal seiche from a previous wind.

A simple and yet effective model of an internal seiche can be made by reversing the normal procedure for mixing ice, whiskey, and

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[12] *Seiche* is pronounced as in "saysh." The origin is probably from the Swiss–French word, *seiche*, meaning "sinking" (of water). This refers to the lowering of water level on the downwind end of a lake after a prolonged wind. The term is also said to have originated from the French word *sèche*, meaning dry.

water in a glass. Fill a wide glass about $\frac{1}{3}$ with water. Tilting the glass at an angle, slowly add whiskey to taste, layering it carefully on top of the water. The upper layer of whiskey corresponds to the epilimnion and the lower layer of water to the hypolimnion. There is a gradient of density between them corresponding to the density gradient associated with the thermocline. Tilt the glass back and forth two or three times attempting to move in unison with the motion of the whiskey. Then hold the glass steady in a horizontal position to observe internal seiches. Finally, add ice as desired and enjoy the drink. (For non-drinkers, a similar experiment can be performed by layering water over sugary tea.)

Seasonal changes of temperature and density in lakes are best described using as an example a temperate lake that freezes over in winter. When ice coats the surface of a lake it is said to be "inversely" stratified with respect to temperature. Cold water at 0° C lies in contact with ice, above warmer and denser water between 0 and 4° C.

With the coming of spring, ice melts and the waters are mixed by wind. Shortly, the lake is in full circulation and temperatures are approximately uniform throughout (close to 4° C). With further heating from the sun and mixing by the wind, the typical pattern of summer stratification develops, dividing the lake in epilimnion, metalimnion, and hypolimnion.

In late summer and early autumn, as the lake cools in sympathy with its surroundings, convection currents of cold water formed at night sink to find their appropriate density level, mixing with warmer water on their way down. With further cooling, and turbulence created by the wind, the thermocline moves deeper and deeper. The temperature of the epilimnion gradually approaches that of the hypolimnion. Finally the density gradient associated with the thermocline becomes so weak that it ceases to be an effective barrier to downward moving currents. The lake then becomes uniform in temperature indicating it is again in full circulation. With still further cooling, ice forms at the surface to complete the annual cycle.

With this, the brief interlude with water comes to an end. In relating the infinitesimal forces within the magic liquid to the properties of lakes, some of the mystery of water has been both revealed and lost. Events perhaps unrealized by the casual observer have been explored in principle and detail, permitting an appreciation of how sun and wind, acting in unison, determine many of the thermal characteristics of lakes. But looking at the matter in another way, perhaps one could equally well say that these great powers are merely acting out their parts in a play that has been written within the confines of a single water molecule.

Chapter 4

HOW A LAKE BREATHES

In which an account is given of factors that regulate the balance of carbon dioxide, oxygen, and organic matter in lakes.

The circular movement of hands on the face of a clock, the migration of air in and out of the lungs, the transition from morning stillness into an afternoon breeze, the up and down motion of pistons in a car engine, the evaporation and precipitation of water on earth, the succession of life in the biosphere — all of these cyclic processes "run," only because they are driven by energy from the sun. Travelling at a velocity of 300,000 kilometers (186,000 miles) per second, this perpetual flow of radiation from the sun consumes only 8⅓ minutes in its passage to earth. On arrival, most is converted directly into heat. Only a minor fraction is transformed into stored forms of energy that persist for varying lengths of time, eventually decaying into uniformly distributed heat.

Modern technology could never have advanced to its present state without this stored energy of the sun. The calories in our daily bread are derived from the sun. Electric lights are powered by the sun's energy that, days or weeks before, was consumed in evaporating water from a neighboring sea, transporting it to a higher elevation on land. With a greater time lag, the combustion of coal, natural gas, and petroleum releases energy that fell on the earth as sunshine tens to hundreds of millions of years ago. No modern technologist would ever think to question why our ancestors worshipped the sun; yet, somehow in the luxury of modern technology we have lost all consciousness of our dependence on the sun. Only in a child's instinctive bedtime plea for the hall light to be left on and the door ajar do we recall our deep inborn fear of being alone in the dark.

The sun is the source of virtually all utilizable energy at the earth's surface. One hundred and fifty million kilometers (93 million miles) away, less than 1/2,000,000,000th of its radiation is intercepted by the earth. Of this, only a small proportion, perhaps about 1/1000th on the average, is annually converted photosynthetically into new plant growth.

In the course of photosynthesis, green plants use the sun's energy to manufacture energy-rich organic compounds from carbon dioxide and water. Oxygen is evolved as a by-product. In the reverse process of cellular respiration, plants and animals use oxygen to convert organic carbon compounds back into carbon dioxide and water, releasing the chemically stored energy of the sun for metabolism and growth.[13] The unified action of life as a whole depends on a favorable relationship between these two major processes of photosynthesis and respiration. Upsets of this balance in natural waters affect every form of aquatic life from the smallest bacteria and algae to insect larvae and fish. So it is that a lake, and even the biosphere, can truly be said to breathe.

Chemical and biological transformations involved in the regulation of this "breathing" are exceedingly complex. Fortunately, the principles and general phenomena can be outlined without becoming entangled in detail. But there is danger in avoiding this detail. We are living at a time in history when man's ability to change the biosphere is both immense and real. If we should err environmentally in our societal actions it will probably be because we do not fully understand how complex ecosystems operate in nature — how a seemingly

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[13] Respiration in this book refers to the metabolic breakdown of organic substances in the cells of living organisms. Exchange of gases via the lungs is referred to as breathing.

minor change on our part could perhaps induce events beyond our control. When such things happen, and they are happening on local and increasingly larger scales each day, it is perhaps time to pause and reflect on what we do not know.

In the continual interplay and adjustment between living and nonliving components of the biosphere, changes in one part of the system have induced reciprocal changes in the other. Ecosystems have not remained static in time; like most other things in nature they have evolved. To cite one past example of this evolutionary interplay, it is generally accepted that the entire supply of oxygen in the earth's atmosphere has been derived from the activities of photosynthetic plants. As a consequence of this single event, the world is now a vastly different place than it would have been otherwise. The rate of geological erosion, the chemical composition of natural waters, and the final products of rock weathering have all changed dramatically as a result of the addition of oxygen to the atmosphere. More significantly, neither man nor any animal on earth today could breathe were it not for this inheritance from organisms that we often refer to as the "lower forms of life." A discussion of how the biosphere began to "breathe" may therefore form a fitting prelude to the description of the breathing that takes place in lakes.

To the ancients, life consisted of ordinary matter endowed with "vital spirits." In their ignorance of events that take place in microscopic dimensions they were convinced that worms and maggots were generated "spontaneously" in concoctions such as cow dung and soil. Did they not see it happen with their own eyes? Even in the 17th century, van Helmont, one of the more respected scientists of his time, believed a recipe of wheat grains and a dirty shirt would, if incubated for 21 days, spontaneously generate mice. He was only surprised by their exact resemblance to mice of natural birth.

With the improved vision following the invention of the microscope and the experiments of Redi, Spallanzani, and Pasteur, it eventually came to be recognized that all life originated from preexisting life — as some put it, all eggs from an egg. With that general recognition the scientific question of the primordial origin of life came into being.

Little progress has been made in answering the question beyond the demonstration that a "soup" of organic chemicals was probably present on earth prior to the appearance of life. This "soup" is thought to have existed at a time when the atmosphere was devoid of oxygen, and ultraviolet light penetrated to the surface of the earth. Experiments have shown that many chemical building blocks of life are created when some of the simple gases presumed to have been present in the earth's primitive atmosphere are irradiated with ultraviolet light.

It is believed that through a slow process of chemical evolution, molecules aggregated into primitive living things that fed on the chemical energy of this preformed "soup." Only as the "soup" became depleted in constituents essential for growth, did some aberrant forms develop the ability to synthesize the missing molecules, as these disappeared from the environment, one by one. Eventually photosynthetic plants appeared that could make their own "soup" in a cell. Organisms unable to do this either died out or became dependent on photosynthetic plants.

The development of plant photosynthesis was perhaps the most profound event in the biological history of the earth. In one fell swoop it permitted the utilization of abundant substances in nature as raw materials for photosynthesis; it created a supply of oxygen as a "fuel," which in turn permitted the later development of higher forms of plant and animal life; and ozone was produced from oxygen in the upper atmosphere, shielding the surface of the earth from biologically harmful ultraviolet light. Was this an accident or some part of a more intricate ecosystem design? Regardless of the answer, it is fascinating to consider that the events paving the way for our existence today started with primitive photosynthetic cells several thousand million years ago.

Oxygen is a waste product of photosynthesis. Its accumulation in the atmosphere and utilization by nonphotosynthetic forms of life is a striking illustration of how the biosphere, unlike man, recycles waste products using them to advantage. Oxygen accumulated as a result of a biospheric imbalance in the relationship between photosynthesis and respiration. This is illustrated in the equation below:

$$\underset{\text{energy}}{E} + \underset{\substack{\text{carbon}\\ \text{dioxide}}}{CO_2} + \underset{\text{water}}{H_2O} \underset{\text{respiration}}{\overset{\text{photosynthesis}}{\rightleftarrows}} \underset{\substack{\text{organic}\\ \text{matter}}}{(CH_2O)\downarrow} + \underset{\text{oxygen}}{O_2\uparrow}$$

If there had been a perfect balance between photosynthesis and respiration during the history of the earth, oxygen could never have accumulated in the atmosphere. It accumulated because not all organic matter formed by photosynthesis was oxidized back to carbon dioxide and water. Some was deposited in sediments, forming the fossil organic carbon compounds now occurring in black shales, coal, petroleum, and natural gas. For every atom of carbon fossilized, a molecule of oxygen passed into the atmosphere.

Some scientists have claimed that man may now be in danger of depleting the supply of oxygen in the atmosphere as a result of oxygen consumed in the combustion of fossil fuels. It has been suggested that we may be disturbing a balance that it has taken nature several thousand million years to create. But the balance is not likely to be disturbed, for most fossil organic carbon does not occur in a form economical to mine or burn.

Other scientists have more realistically contended that increased levels of carbon dioxide in air, brought about by the combustion of fossil fuels, could raise the temperature of the earth. This suggestion is based on the "greenhouse" effect wherein carbon dioxide absorbs some of the infrared energy the earth radiates to space. But the immense buffering systems of oceans and photosynthetic plants are likely to handle this matter with ease, particularly photosynthetic plants, since, for every molecule of carbon dioxide assimilated a molecule of oxygen is released. If these natural control mechanisms do operate in the manner suggested, there is no cause for alarm. The trouble is that we do not know enough about the biosphere to determine the extent to which they serve as controls.

Although the exact times of the origin of life and photosynthesis on earth are imperfectly known, it is certain from well-preserved remains of algae in ancient deposits on the north shore of Lake Superior that both events must have occurred more than 2500 million years ago. More problematic biological remains are known from South African rocks, 3300 million years old. Lack of deposits of greater antiquity leaves a question mark between then and the time the earth was formed, 5000 million years ago.

Turning now to the question of how lakes "breathe," carbon dioxide deserves first attention because of its importance in photosynthesis. Among the 15–20 chemical elements required for the growth of different species of aquatic plants, carbon is of prime significance as it comprises approximately half the weight of organic material in living cells. All living organisms have a high demand for carbon; but, as discussed in connection with eutrophication, carbon only rarely limits the growth of aquatic plants in inland waters. In practically all cases (excluding some enriched with sewage wastes) the environmental supply of carbon is more than adequate to meet the demands of photosynthetic plants.

Practically all chemical elements known to occur on earth can be detected at one concentration or another in most inland waters. For some elements, such as uranium and gold, the concentrations are so minute that special methods and precautions are necessary in conducting analyses. Calcium and carbon, on the other hand, usually occur in sufficiently high concentrations to permit detection by routine chemical analysis. In fact, if one had to describe the composition of the substance in inland waters with the formula of a single chemical, it would be that of calcium bicarbonate.

Within their drainage basins, river courses act as collecting ducts for precipitation from the atmosphere, the products of rock weathering and vegetational synthesis on land, and the wastes of man and other animals. In granitic areas with thin soil, such as the vast Precambrian Shield areas of northern Canada, Scandinavia, and the USSR, the amount of inorganic material leached from the land is low. Lakes and streams in these areas accordingly have low concentrations of dissolved inorganic salts and are said to contain "soft" water. In contrast, lakes and streams in regions of sedimentary rock drainage typically have high concentrations of dissolved inorganic salts. They are referred to as "hard" waters when they contain appreciable concentrations of calcium and magnesium salts. Water hardness is mainly due to high concentrations of calcium, magnesium, and other doubly and triply charged ions that form precipitates with soaps.

Atmospheric gases also occur in a dissolved form in natural waters. Surface waters in intimate contact with air typically contain 15–25 parts per million of nitrogen by weight and 8–14 parts per million of oxygen by weight. (Nitrogen is actually less soluble than oxygen in water under conditions of equal gaseous pressure. The higher concentration of nitrogen in natural waters is due to the fact that its partial pressure in the atmosphere is more than three times that of oxygen.) When these gases dissolve in water they do not change in chemical structure. In contrast, when carbon dioxide dissolves in water it reacts chemically with water to form a new compound called carbonic acid. Carbonic acid, in turn, exists in equilibrium with three other forms of inorganic carbon—bicarbonate, carbonate, and calcium carbonate.

In all, five different forms of inorganic carbon occur in natural waters: carbon dioxide, carbonic acid, bicarbonate, carbonate, and calcium carbonate. They are all readily interconvertible depending on environmental conditions. Addition of acid to a sample of natural water causes a shift in the forms of inorganic carbon toward carbon dioxide. Addition of base causes a shift of inorganic carbon toward carbonate and calcium carbonate. (Caustic soda and lyes are bases. Acids and bases neutralize each other.)

Conversion of inorganic carbon from one form to another is very much like exchanging the currencies of different countries. The only major point of difference is that in the chemical system the exchange has to be performed in a defined sequence. Thus, if the series *carbon dioxide–carbonic acid–bicarbonate–carbonate–calcium carbonate* is equated to *Denmark–Germany–Switzerland–Austria–Italy,* in the chemical system Danish kroner cannot be exchanged directly into Italian lire. The transaction has to proceed from kroner to marks, marks to francs, francs to schillings and schillings to lire.

Although this sounds very laborious it is actually of little consequence. Except for interconversions between carbon dioxide and carbonic acid, transactions take place with lightning rapidity. There are no long lineups and nature does not impose a charge for making the exchange. Under normal environmental conditions 90% of the theoretical interconversion between carbon dioxide and carbonic acid, the one slow reaction in the series, occurs in minutes.

The situation is entirely different with respect to the interconversion of inorganic and organic forms of carbon. Nature imposes a heavy charge for converting carbon dioxide into organic carbon compounds — the fee, in the case of photosynthesis, being paid by the sun. Part of the fee is returned in respiration when organic compounds are broken down into carbon dioxide and water.

The futility of studying carbon dioxide without reference to the other forms of carbon in aquatic ecosystems should be apparent. When one form of inorganic carbon is removed from or added to the system, the others automatically readjust themselves to minimize the effect of the change. Photosynthesis and respiration also affect the forms and abundance of inorganic carbon in natural waters. In summary, the entire system of carbon compounds in nature has to be examined in the context of the cycle of carbon.

Three concepts are necessary as a prelude to understanding how the carbon cycle operates in nature. These are:

> *Ion* — An ion is an electrically charged atom or molecule. A variety of different kinds of ions occur in natural waters. Many of these enter into the composition of our bodies and are essential for health and survival. Some ions carry a positive charge, such as calcium ions (Ca^{++}) and hydrogen ions (H^+). Other ions carry a negative charge — bicarbonate ions (HCO_3^-), carbonate ions ($CO_3^=$), and hydroxyl ions (OH^-). Hydrogen ions and hydroxyl ions unite to form water ($H^+ + OH^- = H_2O$).
>
> *p*H — The term *p*H refers to the concentration of hydrogen ions on a logarithmic scale extending from 0 (acidic) to 14 (basic). The lower the *p*H the higher the concentra-

> tion of hydrogen ions and the more acidic the solution. A decrease of one unit in *p*H corresponds to a 10-fold increase in the concentration of hydrogen ions.
>
> *Buffers and buffering capacity* — Buffers stabilize *p*H by neutralizing hydrogen ions and hydroxyl ions. Bicarbonate is the principal buffer in natural waters, in the blood of animals, and in the fizzy drinks people often take "the morning after." Soft waters tend to be poorly buffered; hard waters, well buffered. Water, by itself, has no buffering capacity.

Two "kitchen" experiments may help to cement these concepts together and relate them to the carbon cycle. For the first experiment, dissolve a teaspoonful of baking soda (sodium bicarbonate) in a half glass of water. Next, add some vinegar (acetic acid) in small amounts. The baking soda solution fizzes vigorously on addition of vinegar.

The explanation of this experiment is as follows. The solution of baking soda in water contains sodium ions and bicarbonate ions. Vinegar acts as a source of hydrogen ions that convert bicarbonate ions into carbonic acid and carbon dioxide. Carbon dioxide, coming out of solution, causes the effervescence. A determination of *p*H before and after the addition of vingear would show no appreciable change. The solution was buffered by the bicarbonate present in baking soda.

The second home experiment will have already been performed if you live in an area with moderately hard water. Locate a kettle that has been in use for some time. You will probably find that it is coated on the inside with a deposit of calcium carbonate, also known as "boiler scale." It forms as a result of the removal of carbon dioxide from water on heating.

The explanation is as follows. The solubility of all gases in water decreases with increasing temperature. The feature peculiar to carbon dioxide in natural waters is that for each molecule removed a hydrogen ion and a bicarbonate ion react to form carbonic acid; and a hydroxyl ion and bicarbonate ion react to form a carbonate ion and a water molecule. The net result is the formation of a carbonate ion for each molecule of CO_2 removed. In waters containing high concentrations of calcium ions (hard waters) excess carbonate ions may precipitate out as calcium carbonate.

A phenomenon similar to the formation of "boiler scale" occurs naturally in some hard-water lakes as a result of photosynthesis and the warming of water in summer. A light milkiness appears in the water due to the formation of small crystals of calcium carbonate. Calcium carbonate is also precipitated on surfaces of pondweeds and filamentous algae growing on rocks near the shore as a result of the removal of carbon dioxide in photosynthesis.

The various factors affecting the forms and abundance of inorganic carbon in lakes can be summarized by means of the mechanical bird shown in Fig. 2. The chemical equations show how the several forms of inorganic carbon are interrelated, the dots indicating relative abundance of carbon atoms in different forms. For a given environmental change, the flow of carbon atoms in the system follows the law of gravity and is determined by the angle of tilt on the bird's wings. Escape of carbon atoms from the wings indicates passage of carbon dioxide from water into air or precipitation of calcium carbonate from solution.

The *left turn* position of the mechanical bird shows what happens when acid industrial wastes enter natural waters; the *p*H drops, carbon atoms flow in the direction of carbon dioxide, and part of the carbon dioxide is expelled to air. The *right turn* position shows what happens when basic industrial wastes enter natural waters; the *p*H rises, carbon atoms flow in the direction of carbonate and, if the waters are sufficiently hard, some of the carbonate ions are precipitated out of solution as calcium carbonate.

The *wings down* position of the mechanical bird corresponds to removal of carbon dioxide from water due to warming or photosynthesis. The flow of carbon atoms is toward the wing tips. In hard waters, calcium carbonate often precipitates simultaneously with removal of carbon dioxide. The *wings up* position corresponds to the opposite situation — the addition of carbon dioxide to water as a

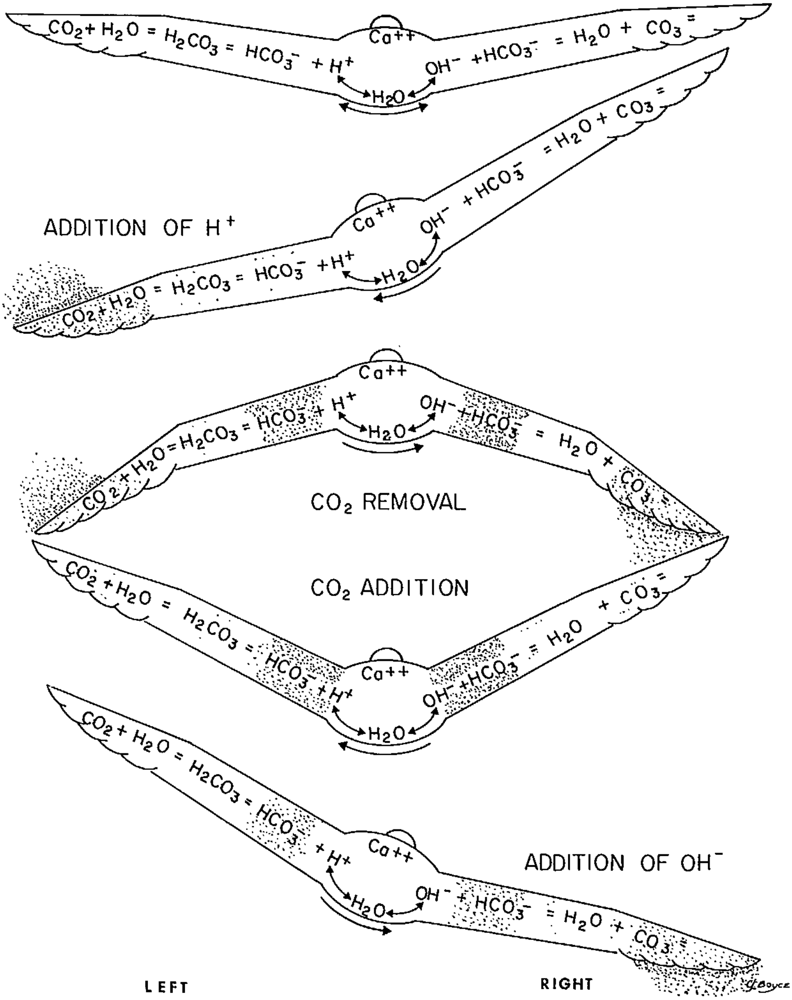

FIG. 2. *A mechanical bird, showing the relationship between various forms of inorganic carbon in water under various conditions. Dots indicate the approximate relative abundance of different forms of carbon, with molecules flowing "downhill," depending on the wing angle with respect to the vertical. Removal of dots (molecules) from the wingtips corresponds to passage of CO_2 from water to air* (left wing) *or formation of calcium carbonate* (right wing). *Arrows under the body of the bird indicate the tendency of water (H_2O) to generate hydrogen ions (H^+) or hydroxyl ions (OH^-). See p. 62–64 for further explanation.*

result of the cooling of water in autumn or due to the respiratory activity of living organisms at night. The flow of carbon atoms is from the wing tips to the body and bicarbonate increases at the expense of carbon dioxide and carbonate ions. If calcium carbonate is present it tends to be dissolved, though only slowly. Precipitates always dissolve much more slowly than they form.

The mechanical bird can now be put to good use in explaining what would otherwise be an unusual aspect of man-made eutrophication — why soft-water lakes respond to nutrient enrichment with dramatic increases in *p*H, whereas in hard-water lakes, calcium carbonate precipitates with no major change in *p*H.

The first response to nutrient enrichment in all natural waters is an increase in the rate of photosynthesis and abundance of green plants. In hard waters this leads to a precipitation of calcium carbonate because of the uptake of carbon dioxide by photosynthetic plants, as already described. In soft waters the concentration of bicarbonate is so low it cannot act effectively as a buffer for hydroxyl ions released by the photosynthetic uptake of carbon dioxide. As a result, hydroxyl ions accumulate, accounting for the dramatic rise in *p*H.

These responses are not just theoretical predictions from armchair scientists. They have been thoroughly analyzed and described in a number of lakes. One of the more interesting cases on record is that of Lake 227, one of 46 small lakes[14] set aside for experimental studies on water pollution. Lake 227 is a soft-water lake. As a result of the increased abundance and photosynthesis of plants,

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[14] By a 1968 agreement between the governments of Canada and Ontario, 46 small headwater lakes and their land drainage basins were set aside for a period of 20 years for research on man-made eutrophication and related pollution problems in fresh water. The lakes are located in an isolated area in northwestern Ontario, just to the east of Lake of the Woods. This imaginative plan was developed in 1965 by Dr W. E. Johnson of the Fisheries Research Board of Canada (now Fisheries and Marine Service, Department of the Environment) and has been executed by staff from Canada's Freshwater Institute, in collaboration with other agencies and universities, under the direction of Dr D. W. Schindler. For a general description of the Experimental Lakes Area see the *Journal of the Fisheries Research Board of Canada*, 1971, 28: 121–301 and 1973, 30: 1409–1552.

brought about by controlled additions of phosphate and nitrate salts over a period of 2 years, the *p*H rose from 6 to 10, representing a 10,000-fold increase in the concentration of hydroxyl ions. The precipitation of calcium carbonate as a result of man-made eutrophication in a hard-water lake has already been described for the Lake of Zürich in Switzerland. Precipitation of calcium carbonate there was merely one of a sequence of well-documented events, later found to be characteristic of nutrient-enriched lakes all over the world.

The equation chemists use to describe the mutual reciprocity treaty that nature has imposed upon the realms of photosynthesis and respiration, shows water and carbon dioxide on one side of the equation, and organic matter and oxygen on the other. Water and carbon dioxide have already been dealt with. It remains now to consider organic matter and oxygen.

Just as various types of natural plant communities develop on land in response to local conditions of climate, topography, and soil, so are there natural communities of aquatic organisms that flourish under particular conditions within lakes. With two major exceptions, the important physiological factors in the aquatic environment are the same as those on land — light, temperature, water currents (instead of wind), and the chemical and textural nature of the environment. The two major differences are: water, which is omnipresent in lakes but in variable abundance on land; and oxygen, which is constant in the air above land but in variable concentrations in the deep waters of lakes.

Three primary life styles have been adopted by organisms in aquatic ecosystems, two associated with open-water conditions and one with bottom deposits. *Plankton* is the community of organisms with limited powers of locomotion inhabiting the open-water environment and mostly living independently of the bottom. The distribution of planktonic species is in large part regulated by water currents. The other group of organisms, inhabiting open-water regions of lakes, consists of fish and other vertebrates that move about "under their own steam." Organisms living in association with bottom deposits are collectively referred to as *benthos*.

Most planktonic species are smaller in size than an average grain of beach sand. But some, such as the larva of the phantom midge, *Chaoborus*, the crustacean *Mysis relicta*, and the widely distributed but rarely seen freshwater jellyfish, *Craspedacusta* — reach 1 centimeter (½ inch) or more in length. Benthic organisms are larger on the average than planktonic forms; they consist of filamentous algae that grow attached to rocks near the shore, pondweeds, and a variety of aquatic insects and other invertebrate animals.

In the daily drama of life in inland waters, planktonic forms move restlessly about in the water in search of food or a mate, using their primitive instincts to avoid being trapped in unfavorable environments. Prey species must be constantly on the lookout for predators ready to pounce on an unsuspecting individual at a moment's notice. The tragedy of death is present as a fact of life — many species laying hundreds or thousands of fertilized eggs, even though in nature only two on the average will survive.

The total number of species of plants and animals in freshwater ecosystems is greater than one might initially think. It ranges well into the thousands for any single lake and into the tens of thousands for inland waters as a whole. New species are still being discovered and described at a rate of several hundred per year. The detailed life histories and interactions of these forms are so complex that an encyclopedia could not fully encompass even the little that is known. But in the complexity of this pattern there lies a common thread that serves to simplify and unite. This is the story of the eater and the eaten, in which similarities of feeding relationships permit organisms to be grouped into a limited number of *trophic* or feeding levels in a food chain.

The utility of this *trophic* approach to ecology is that it permits a dynamic understanding of how energy from the sun flows through successive levels of the food chain — from the sun to green plants; from green plants to herbivores; and from herbivores to carnivores and decomposers. It also serves as a reminder of how organisms in different trophic levels depend on each other. In short, it permits the economics of ecosystems to be assessed.

The trophic level at the base of the food chain consists of green plants. They use the sun's energy to synthesize organic compounds, used as food by organisms at the next trophic level. Expressed on an annual basis, the net efficiency of this energy conversion is rather low in most freshwater ecosystems. It generally ranges from 0.01 to 1.0% when expressed as calories of radiant energy converted into organic material by green plants in the course of a year. This means that 99.0–99.99% of the sun's energy is not utilized in photosynthesis. The principal reasons for these low efficiencies are: (1) light is absorbed by nonliving things (water, suspended clays, dissolved coloring matter) before it reaches the cells of green plants; (2) nutrient deficiencies can limit photosynthesis when light is abundant. These efficiency values seem very low in relation to efficiencies for man-directed syntheses. The latter are deceivingly high as they take no account of the expenditure of human energy involved in gathering, refining, and transporting materials to the site, and other hidden energy costs.

Although these low efficiencies may be unwelcome news to anglers who value lakes for fish, engineers and citizens may find some consolation in them. For, if aquatic ecosystems were more efficient photosynthetically than they are, the increased plant abundance would be noted with distaste in every sip of water or swim at the beach. Sometimes even fishermen's interests can be adversely affected, as in the case of lake trout, where an increased plant abundance can mean more fish, but less trout.

The trophic level at the next position in the food chain consists of herbivores — animals that feed on green plants. In the planktonic community these consist of small forms that strain algae through hairy appendages specifically designed for filter feeding. To appreciate the fantastic anatomical design that evolution has created one should travel with a modern Gulliver into the miniature world of nature as seen through a microscope. Benthic herbivores feed by scraping algae from the surfaces of rocks and pondweeds or by munching on leafy vegetation. They also feed on detritus — minute remains of dead plant and animal tissues.

The net annual efficiency for conversion of plant material into herbivore growth varies, but is typically about 10% in many lakes. This efficiency is much higher than for conversion of the sun's energy into new plant growth. This is because the plant energy that herbivores consume is in a readily assimilable chemical form.

Carnivores, animals that prey on herbivores, occupy the next level of the trophic chain. Many predacious insects, crustaceans, and fish occupy this trophic level. As the mouths of carnivores get larger, carnivores that prey on carnivores come into play, exemplified by pike and lake trout. The net annual conversion of herbivore energy into carnivore growth lies in the same range as conversion of plant energy into herbivore growth — about 10% in many lakes.

As a result of high energy losses associated with the passage of energy through each level of the food chain, the amount of plant material required to produce a given weight of carnivorous fish can be immense. In order to add one unit of weight to a lake trout, for example, the energy equivalent to several hundred comparable units of weight of plant material has to pass through the food chain. The situation is similar in the food chain from grass to cattle, via beefsteak to man.

Organic matter produced by plants and not eaten by herbivores is acted on at another level of the food chain by decomposers such as bacteria, fungi, and protozoans. These microorganisms perform an essential ecosystem service, somewhat like the role a vacuum cleaner plays in respect to dust and dirt in an office or house. In the normal course of our daily lives we are rarely aware of the existence of these microorganisms of decomposition; but we soon would be if they ceased to function. The decomposable wastes we throw out as garbage or flush down the drain would accumulate in the natural environment to a most unpleasant degree.

When we "size up" material objects, as the saying goes, we tend to attribute importance to them in direct proportion to how big they are without ever thinking too much about what they do. It is a surprise to learn that minute, and sometimes almost invisible, populations of algae in lakes can produce as much or more organic matter in a year than trees in an equivalent area of neighboring forest. They accomplish this by "turning over" their populations at a rapid rate.

As a general rule, the smaller the organism or growth stage, the higher the rate of growth is per unit weight. Thus, under favorable conditions, bacteria can reproduce their original weight in a matter of minutes or hours; unicellular algae, in hours or days; but an insect larva takes days to weeks and a large fish or rooted plant, months to years. The same is true of respiratory processes. As one passes from the small to the large in the living world, the rate of metabolism per unit weight declines logarithmically as the weight of the individual increases. For these reasons one can look to microscopic species as the predominant organisms regulating the "breathing" of lakes. Algae are commonly the most important primary producers of organic matter and oxygen. Bacteria, fungi, and other small organisms are the most important agents of decomposition, consuming oxygen in the breakdown of organic matter and producing carbon dioxide. The minuteness of their size is deceiving in terms of the important ecosystem functions they perform.

The depth range over which photosynthetic oxygen production occurs in lakes depends on the transparency of the water. It can be as little as a few centimeters (inches) in very turbid waters, to as much as 30 meters (100 feet) or more in extremely clear lakes such as Lake Baikal in the USSR or Crater Lake, Ore. But in most lakes, the bulk of all photosynthesis occurs in the epilimnion. The hypolimnion is a region of net decomposition.[15]

Since the boundary between the zones of net photosynthesis and decomposition frequently coincides with the thermocline, one can readily appreciate the problem that not uncommonly arises. Cut off from contact with the atmosphere by the barrier of the thermocline and with too little light for active photosynthesis, the

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[15] Most of the decomposition of organic matter that takes place in lakes occurs in the epilimnion where life is abundant and active at higher temperatures than exist in the hypolimnion. The significant feature about the hypolimnion is the *very high ratio of decomposition to photosynthesis*.

hypolimnion is a zone where oxygen is consumed but cannot effectively be regenerated. As a result, the supply of dissolved oxygen tends to become progressively depleted in the hypolimnion with time.

The extent of oxygen depletion in the hypolimnion varies with a number of factors. The two most important of these are: (1) the rate at which organic material falls into the hypolimnion; and (2) the volume of the hypolimnion relative to the dimensions and shape of the lake basin. The first factor is primarily determined by the rate of photosynthetic production of organic matter in the epilimnion; and the second by the extent to which the lake basin acts as a funnel in concentrating the "rain" of dead and dying plankton from above. The situation is comparable to making a pot of tea. The more tea leaves (= dead or dying phytoplankton) and the smaller the volume of water used in making the tea (= volume of the hypolimnion), the darker the final product (= the higher the concentration of organic matter and the greater the consumption of oxygen in the hypolimnion). In very large and deep lakes, oxygen depletion in bottom waters is not extensive because of the large volume of the hypolimnion and large initial supply of oxygen.

The extent of oxygen depletion and carbon dioxide formation in bottom waters of eutrophic lakes intensifies with the progression of summer. Because bacteria and organic matter are concentrated at the sediment surface, oxygen depletion typically proceeds "from the bottom up." When the concentration of dissolved oxygen falls to less than 1 part per million just above the sediment surface, an entirely new sequence of chemical reactions comes into play, first elaborated by Wilhelm Einsele in Austria and Clifford Mortimer in England. Insoluble iron hydroxide in the sediment changes from a ferric (Fe^{+++}) to a ferrous (Fe^{++}) form, inducing a change of sediment color from brown to black.[16] At the same time various chemi-

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[16] The Latin name for iron is *ferrum*. Iron in ionic form can reversibly change from a ferric (Fe^{+++}) to a ferrous (Fe^{++}) state depending on *p*H and concentration of dissolved oxygen. In the presence of high concentrations of dissolved oxygen, iron occurs as rust-colored ferric oxides; in reduced (ferrous) form in sediments it often interacts with hydrogen sulfide to form a black precipitate of ferrous sulfide (FeS). It is often possible to guess the form in which iron occurs in sediments from color alone.

cals are released from the sediment into the water, moving upward and laterally as a result of turbulence induced by internal seiches. Under such conditions, organisms that depend on oxygen disappear from the sediment surface by migration, encystment, or death. If the zone of oxygen depletion extends upward to the thermocline, a heavy mortality of deepwater fish can occur.

With the breakdown of the thermocline in autumn, a reverse process takes place. As the waters of the lake are mixed and reoxygenated, iron hydroxide precipitates. Most other constituents released from sediments decline in concentration, through dilution induced by mixing with surface waters in some cases and by precipitation in others. Some nutrients liberated from the sediment remain in the water to provide nourishment for later algal growth. The importance of nutrient regeneration from sediments in promoting plant growth is debated by limnologists. Some claim it is of wide and general importance; others, that it is only significant in shallow lakes. Additional knowledge is needed to resolve the issue.

Most changes described above for the bottom waters of eutrophic lakes in summer also occur under the cover of ice and snow in temperate and polar lakes. In shallow, eutrophic waters this can lead to a "winter-kill" of fish because of oxygen depletion in the entire body of water. An account of the culture of rainbow trout in "winter-kill" lakes will illustrate how lakes "caught short of breath" due to lack of oxygen can be utilized and developed by man.

In the prairies of western Canada there are innumerable shallow, naturally productive ponds and lakes. Because of their limited depth, rich nutrient supply, and high rates of biological production, they typically become depleted in dissolved oxygen under ice and snow. They are known as "winter-kill" lakes because concentrations of oxygen at the end of the long prairie winters are frequently so low fish do not survive. Fishery workers naturally avoid such lakes when planting young hatchery-reared fish.

The absence of predators in winter-kill lakes and the favorable growing conditions of prairie summers permit some bottom-living invertebrates to become unusually large and very abundant. This is particularly true of *Gammarus*, a shrimplike crustacean that can survive the low oxygen conditions of winter. The waters teem with algae because of the high nutrient supply, and are rich in "overgrown" invertebrates because of the abundant supply of plant food and lack of predators.

With the genius it takes to recognize the obvious, a group of Canadian scientists decided to see if winter-kill lakes could be put to use in rearing marketable fish. The logic was simple — introduce fast-growing fish as fingerlings in the spring and harvest them at marketable size in the autumn. The species selected was rainbow trout. Some trout were planted as 5–7-centimeter (2–3-inch) fingerlings in the spring of 1968 and harvested as 22–35-centimeter (9–14-inch) fish in the autumn. They ranged in weight from 0.3 to 0.45 kilogram ($\frac{3}{4}$–1 pound).

From this small beginning an industry is now in the making, with yields per unit area competitive with prairie wheat. With genetic improvements in brood stock comparable to those for hybrid corn, the Canadian prairies may one day become famous for naturally reared rainbow trout.

This terminates the discussion on regulation of carbon dioxide, oxygen, and organic matter in aquatic ecosystems, and also the diversion into limnology that began with an account of the importance of water in lakes. The story turns next to phosphorus in the biosphere, as a prelude to a systematic analysis of how man-made eutrophication can be brought under control.

Chapter 5

PHOSPHORUS, THE MORNING STAR

In which the role of phosphorus in the economies of nature, life, and man is described.

Like most alchemists of the 17th century, Hennig Brand of Hamburg was possessed with a desire to discover the secret principle of the philosopher's stone, the mythical material reputed to have the power to transform base metals into gold. Although unsuccessful in this quest, Brand brewed a concoction in 1669 that yielded a no less mysterious product; one that, unlike any other substance known at the time, glowed in the dark by its own power and ignited spontaneously when exposed to air. He called it phosphorus, meaning light-bearing, from the name given by ancient Greek and Roman astronomers to the planet Venus when it appeared in the sky as the morning star.

One can easily imagine the stir Brand's discovery must have created at the time, kindling each alchemist's hidden belief that surely, with such a momentous finding as this, the discovery of the philosopher's stone and the chemical elixir of life could not be far away. But chemistry at the time was more of an art than a science. None of its modern foundations had been laid. One hundred years would elapse before the nature of water would be understood as a compound of hydrogen and oxygen, rather than the element for which it was then mistaken. A century and a half would pass before the first chemical synthesis of a biological compound. In 1669 the periodic table of chemical elements had yet to be conceived, the structure of atoms and molecules remained unknown, and acids and bases were described as male and female. Even air was looked upon as a single substance, as in Aristotle's time 2000 years before.

It is significant to man-made eutrophication that Brand used urine as the starting material for his synthesis of elemental phosphorus. By evaporating a large volume of urine to dryness and heating the residue in the presence of fine white sand, he watched mysterious vapors rise into a second vessel where yellow-white crystals of elemental phosphorus formed under a protective layer of water. Little did Brand know, that in his failure to resolve the riddle of the philosopher's stone, he had accidentally discovered a chemical element that 300 years later would be regarded as the essence of life and one of the keys to the regulation of plant growth in nature. Viewing the situation now from the vantage point of later time, let us turn back the clock to retrace some of the events that led slowly, yet inevitably, to the recognition of the central role of phosphorus in life.

After the initial burst of activity that followed Brand's discovery of elemental phosphorus, progress in unravelling the biochemistry of its compounds was slow. The first demonstration of the presence of phosphorus in organisms was made in 1771, by the Swedish chemist, Karl Wilhelm Scheele, who identified it as a major constituent of bone.

The next important event was in 1840, when Justus von Liebig, the founder of organic chemistry, showed that the fertilizing effect of humus on plant growth was due to inorganic salts of phosphorus and nitrogen rather than to organic matter, as previously assumed. This discovery opened the path for studies on soil chemistry in relation to plant nutrition that eventually led to modern methods of crop production.

The 19th century was a time of deep intellectual ferment in regard to the nature and significance of life. Toward the close of the previous century a momentous discovery had been made by Antoine

Lavoisier, father of modern chemistry, whose unjust reward for a life of service to France was the loss of his head on a guillotine.[17]

Lavoisier and Pierre Laplace showed that the amount of heat produced by animals from the consumption of a given amount of food was similar to that produced by chemical oxidation of the same weight of material in the laboratory. This demonstration was of such monumental importance that over 150 years were required for full documentation of the intermediary biochemical events.

Isolation and characterization of organic compounds from living organisms was also proceeding slowly, yet persistently, in the 19th century. Interest accelerated following the synthesis of urea by Friedrich Wöhler in 1828. This was the first widely recognized chemical synthesis of a biological compound. Profound biological generalizations and discoveries were being made. Cells were recognized as the fundamental units of life. New species and morphological structures in plants and animals were being categorized systematically. It was gradually becoming apparent that behind all the architectural complexity of life there was a design, and that this design, at least in some instances, had a mechanistic basis.

Foundations for this belief were greatly strengthened with the publication of Darwin's *Origin of Species* in 1859. Darwin drew attention to the immense changes created by man in domesticated species of plants and animals. If human selection could produce such pronounced differences over a relatively short time, as seen in the

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[17] Antoine Lavoisier served the government of France on various commissions concerned with agriculture, saltpeter and gunpowder, conditions in prisons and hospitals, education, and weights and measures. (The last-named led to the development of the metric system.) He was also an elected member of the Provincial Assembly at Orléans.

Lavoisier's arrest during the French Revolution arose through previous financial association with the Ferme Générale, a tax collection agency. After 5 months of imprisonment, during which time no charges were laid, Lavoisier and 27 other members or former members of the Ferme Générale were — within the short span of 24 hours — charged with conspiracy, tried, found guilty by a Revolutionary Tribunal, and on May 8, 1794, guillotined. An associate remarked the next day, "It required only a moment to sever that head, and perhaps a century will not suffice to produce another like it." Lavoisier's effects, confiscated by the French government at the time of his death, were returned 2 years later addressed to "The widow of the unjustly condemned Lavoisier."

various breeds of horses, pigeons, dogs, cats, and cultivated plants, how much more infinite would be the variety that natural selection could produce over longer periods of geologic time?

With the appearance of *The Origin of Species*, those who previously accepted man as unique and divine in origin suddenly found themselves in the embarrassing position of having to reevaluate their interpretations of man and life. If man had evolved from an apelike form, as was implicit in *The Origin of Species*, then what was the significance of man? At the close of the 15th century, Galileo had tormented the conceit of man with his proposition that the earth was not the center of the solar system. Giordano Bruno was burned at the stake by the Catholic Church in 1608 for this and the even more far-reaching belief that life might not be peculiar to earth. Then, in the middle of the 19th century, Darwin had thrown the very soul of man onto a bed of evolutionary thorns by proposing that *Homo sapiens* originated by purely natural laws from a continuous line that led back to the lowest forms of life.

The Origin of Species revived an age-old scientific discussion about the significance of life. Vitalists claimed special forces were present in living cells; forces that could not be explained in terms of the laws of physics and chemistry. Mechanists, on the other hand, were inclined to regard living organisms as highly complex self-regulating machines, whose inner workings would one day be explained in purely mechanical terms.

The discovery that provided the factual basis for the resolution of these widely divergent claims was made by Edouard Büchner in 1897. Büchner obtained a cell-free extract of yeast, capable of carrying out the process of alcoholic fermentation. With this demonstration of enzymes (specialized proteins that accelerate chemical reactions in living cells) the science of biochemistry arose.

In the years following Büchner's discovery, enzymes were isolated from various tissues and organisms, and studied to determine the mechanisms of catalytic action. As knowledge developed, it became clear that similar enzymes and biochemical cycles were present in organisms as diverse as yeasts and man. With this came the recognition that life had certain common and fundamental biochemical characteristics, on which the immense anatomical diversity was based.

As these pieces successively began to fit into place, it became more and more evident with each new discovery that compounds of phosphorus played unique and essential roles in all the fundamental biochemical reactions of life — photosynthesis, respiration, fermentation, muscular contraction, cell division, and heredity. Eventually phosphorus was recognized along with hydrogen, oxygen, carbon, nitrogen, and sulfur as one of six principal elements that form the backbone of life.

Of several hundred phosphorus compounds isolated from living cells, three deserve particular mention. Two of these, DNA (deoxyribonucleic acid) and RNA (ribonucleic acid), are actually not compounds, but general classes of polymers. The third is a small molecule, ATP (adenosine triphosphate), that functions as a fuel that drives energy-requiring synthetic reactions in cells.

DNA is located in chromosomes within the nuclei of cells, where it constitutes the ultimate units of heredity, genes. Although both DNA and genes were under study in the latter part of the 19th century, it was only in the 1950s that the identity of genes as DNA molecules was firmly established.

DNA is perhaps the most remarkable of all compounds man has yet discovered. Without it no cell, individual, or species could reproduce its internal complexity. Not even Johann Sebastian Bach in a million lifetimes could invent as many variations for the keyboard as natural selection has already produced in the DNA of the chromosomes in living species. One set of those delicate filaments, enclosed within a space a million times more microscopic than a grain of sand, stores the complete information necessary to create an adult organism from a single cell. When, for a given species, the thread of DNA is terminated by the death of the last breeding pair — as has happened to the passenger pigeon, Tasmanian wolf, and several hundred other species that have vanished during the past 200 years — nothing can recall into existence what was there before.

In contrast to DNA, RNA occurs mostly in the cytoplasmic (nonnuclear) parts of cells. Several different kinds of RNA molecules occur in living cells. Some transfer the chemically coded information from DNA to sites of protein synthesis. Others are involved in specifying and assisting in construction of cellular proteins. Different types of RNA molecules operate like managers in a factory, controlling the location and manufacture of parts in such a way that new cells are produced. From knowledge contained in the chromosomal books of instruction, peculiar to each individual and species, they supervise and control the synthesis and operation of enzymatic machines.

To enumerate other phosphorus compounds in living cells without reference to ATP (adenosine triphosphate) would be like listing all of the forms of energy that can be converted into electricity. Long before human societies evolved, organisms discovered the utility of utilizing one form of energy to run a variety of machines. In cells this energy is chemical. It is called ATP.

When the terminal phosphate group is removed from ATP, energy is released that can be used for muscular contraction, the synthesis of energy-rich compounds, or growth. In the process ATP is converted to ADP (adenosine diphosphate) and a phosphate ion. The circle is complete when various carbohydrates, fats, and proteins are broken down to carbon dioxide and water in cellular respiration. Energy released in the breakdown is used to resynthesize ATP from ADP and phosphate. In this way countless different organic fuels are converted into a single form that serves various energy-requiring processes in cells. As is the case in most biological systems, reactions of ATP and ADP are cyclic — the products of one reaction serving as the starting material for another that in turn regenerates the first.

The cycle of phosphorus in the biosphere is primarily regulated by three factors: biological uptake, precipitation reactions with certain positively charged ions, and a one-way flow to sediments and the sea. In most natural occurrences, phosphorus atoms are fully complexed with oxygen atoms to form phosphate ions.[18]

Phosphoric acid (H_3PO_4) dissociates into hydrogen ions and several different kinds of phosphate ions to an extent that depends on concentration and the *p*H of the medium. Since all the different phosphate ions are interconvertible depending on *p*H, there is no need to bother with their names.

In general, phosphate compounds tend to be soluble in water except in the case of minerals formed by interaction with calcium, iron, aluminum, and some other ions. These react with phosphate ions at neutral or high *p*H to form precipitates that have a low solubility in water. The reactions are as follows:

$$\text{calcium ion} + \text{phosphate ion} \rightleftharpoons \text{calcium phosphate} \downarrow$$
$$\text{ferric ion} + \text{phosphate ion} \rightleftharpoons \text{ferric phosphate} \downarrow$$
$$\text{aluminum ion} + \text{phosphate ion} \rightleftharpoons \text{aluminum phosphate} \downarrow$$

The first reaction predominates in calcareous soils (soils that are rich in lime). The reaction is more complicated than one might first think, since it leads to the formation of apatite minerals, complex crystals that also contain other ions.[19] In lime-deficient soils, phosphate ions principally react with iron and aluminum ions to form salts of low solubility. In summary, the chemical behavior of phosphorus is governed by geochemically abundant ions, principally those of calcium, iron, and aluminum, that react with phosphate ions to form precipitates.

Living organisms also play a major role in regulating concentrations of phosphorus in nature. Phosphates are rapidly metabolized

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[18] Some organic compounds with phosphorus–carbon linkages are known. It has been suggested that phosphine (PH_3), a gas that spontaneously ignites in air, may be the cause of the flickering glow of the will-o'-the-wisp or *ignis fatuus* sometimes claimed to be seen on surfaces of marshes on pitch black nights. Although this is pure conjecture, it is not without the thread of possibility. Some bacteria can transform phosphate into phosphine under laboratory conditions.

[19] Apatites occur as skeletal materials in vertebrates (as bone and in the enamel of teeth), in shells of marine phosphatic brachiopods, and in a few other groups.

in the soil by microorganisms and are taken up with other nutrients by the "root hair" cells of terrestrial plants. Along with nitrogen and potassium, phosphorus is one of the elements most commonly depleted in cultivated soils by the removal of crops. This is why it is a major component of fertilizers.

In the surface water of lakes in temperate latitudes, dissolved phosphate tends to pass through seasonal cycles of concentration. These cycles are largely controlled by seasonal changes in sunlight and temperature, and activities of green plants. Dissolved phosphate accumulates in winter when photosynthetic activity is low. Later, in spring and summer, dissolved phosphate in the epilimnion typically becomes almost undetectable due to removal by photosynthetic plants.

Sometimes people not familiar with lakes are surprised to hear that the concentration of dissolved phosphate is often low, prior to the appearance of algal blooms. Their first thought is that phosphorus must be present in an adequate supply since the blooms occur in spite of the low concentrations. What they forget, or perhaps do not know, is that plants store phosphate in excess of their immediate needs, utilizing the excess under conditions of phosphorus deficiency at a later time. Like the empty dish after a good meal, the concentration of dissolved phosphate in water is low just prior to the appearance of algal blooms because the phosphate is in the algae.

The rapid rate at which dissolved phosphate ions are removed from surface waters is indicative of the active role they play in lakes. When radioactive phosphate is added to the surface waters of lakes it is taken up by algae within a matter of minutes. Later, the death and sedimentation of algae results in a slow transport of phosphorus from water to sediments. In contrast to the rapid uptake of dissolved phosphate ions from water by plants, a few weeks or months may be required for sedimentation.

The overall cycle of phosphorus in nature is essentially a one-way drainage to the sea. No volatile compounds exist that can be returned to land through atmospheric transport and precipitation as is the case for carbon and nitrogen. The little recycling that does occur is brought about by the slow geologic upheaval of marine sediments and, on a shorter time scale, the removal of fish from the sea by man and fish-eating birds.

The world's supply of high-grade phosphate rocks is currently estimated to be about 50 billion tons, mostly in the form of apatites — complex calcium phosphate minerals that also contain hydroxyl and fluoride ions. There are three principal areas of supply: Morocco and adjacent regions, an area in the USSR west of the Ural Mountains, and in the northwestern and southeastern parts of the United States. Some of these deposits were formed by igneous processes that took place deep within the earth. In other cases they consist of marine sedimentary rocks. No counterpart to processes that in former times caused sedimentary phosphate deposits has been discovered in modern oceans.

The world's reserves of phosphate rocks are sufficient to fulfill current demands for what some estimate as hundreds, and others an indeterminate number, of years to come. The significance of this time, whatever it may be, hinges on technology and how one views a nonrenewable resource in terms of time.

Phosphates enter into the economy of man in many different ways. Their principal uses in the United States in 1967 were: 70% in fertilizers, 13% in detergents, 8% in animal feeds, and the remaining 9% distributed among a variety of applications such as leavening agents in baking powders and cake mixes; anticorrosion agents for car bodies; fireproofing materials; chemical agents in some types of water softeners; smoke bombs and incendiaries; insecticides; rodent poisons and lethal nerve gases; and as additives to gasoline, "muds" used in oil drilling operations, bottled "pops" and tonics, toothpastes, dental cements, matches, and plasticizers. Note how the uses range from life-promoting fertilizers to deadly poisons intended for rodents, insects, and man. One drop of sarin, a lethal nerve gas containing phosphorus, if not immediately washed from the skin, can kill a man as rapidly as a bullet through the brain.

In closing this discussion of phosphorus in the economies of life, nature and man, the hands of the clock turn back to where the account began — to Hennig Brand's synthesis of elemental phosphorus in 1669. A modern industrial process, based on the reaction he discovered, gave rise in 1969 to a horror story of industrial pollution — one that contrasts the design of nature and the magic of life with the behavioral attributes of man. Much of this industrially produced elemental phosphorus was destined for use in detergents.

The story begins in the 1960s in Long Harbour on the eastern shore of Placentia Bay, Newfoundland, where a Canadian company established an industrial plant to produce elemental phosphorus from phosphatic rocks imported from Florida. The company located the plant in Newfoundland because of the guarantee of cheap electric power from a province wanting to diversify its economic base.

Much to their dismay, the fishermen of Placentia Bay awoke on the morning of December 12, 1968, to find marine herring floating belly-upward in Long Harbour with extensive hemorrhaging of blood vessels about the gills and fins. Because of this redness about the head and fins the fish became known as "red herring." Fishery inspectors were notified, but since they hadn't encountered a case of "red herring" before, they didn't quite know what to do, except to explore the area in the vicinity of the plant. Samples were frozen and sent to biological experts for study, but even the experts were puzzled. None of the usual factors involved in fish mortality seemed to be present.

The water in which the dying fish were found (at Long Harbour, adjacent to the industrial plant) was saturated with oxygen and did not contain excessive amounts of organic wastes. Pathogens and parasites were also lacking in the fish. The only symptoms were the hemorrhaging about the gills and fins, and the watery nature of the blood in dying fish. Although nothing like it had been heard of before, one significant fact was established by divers on January 27, 1969. The entire bottom of Long Harbour, to a depth of 4.5 meters (15 feet), was devoid of animal life. On the suspicion that something very serious was wrong, the area was closed to fishing, and fishermen advised to destroy any catches that contained "red herring."

No further reports of "red herring" occurred until February 1969, when they were observed off the mouth of Long Harbour. Then, with surprising rapidity, occurrences started to spread to distant locations. All up and down the coast large numbers of "red herring" were seen wandering blindly in surface waters. Fishermen were afraid to eat their own fish and rumors began to circulate of poisonous gases said to have been dumped into the bay after the close of World War II. Though nothing was certain, public suspicion was directed at the industrial plant.

Suspicions of scientists involved in the investigations were also directed at the plant. The number of coincidences was too high to be accidental. In the first place, the mortality on December 12, 1968, included a variety of animal life in addition to herring. Secondly, it occurred in Long Harbour in direct proximity to the industrial plant. Thirdly, the date December 12 (as it later turned out) coincided with the first period during which the plant operated — from December 10 to 16. Finally, further occurrences followed the reopening of the plant on January 10, 1969. (The one-month delay in the appearance of the next mortality was probably associated with diffusion of the causal toxin from the harbour out into the open waters of the bay.) The problem was not so much establishing the source of the trouble, as it was documenting a foolproof case that included a direct demonstration of the cause. To close down a multi-million dollar operation because of the possibility that it might be the cause of a fish kill is not something that a government, or, for that matter, any organization could do lightly, without fear of being subsequently sued, particularly when the actual cause of death remained unknown.

Research scientists established that effluent from the plant was toxic to animal life. Three potentially toxic principles were identified: acidity, cyanides, and elemental phosphorus. Experimental tests showed only elemental phosphorus was capable of producing the "red herring."

The next step was to show elemental phosphorus was actually present at the time of death of the fish in sufficient concentrations to cause mortality. This necessitated the development of a new method to analyze trace amounts of elemental phosphorus in fish tissues. After the method had been perfected, it was applied to normal and frozen specimens of fish collected at the time of the previous kills, and also to fish reared in the laboratory in the presence of known concentrations of elemental phosphorus. The results showed the livers of affected fish contained extremely high concentrations of elemental phosphorus, with lesser amounts in fatty tissues and still less in muscle. With this demonstration, it was obvious to the industry that a firm legal case was on hand and ready to be used. Disclaiming any responsibility, the management voluntarily decided to close down the plant on May 2, 1969, for the installation of pollution control facilities.

It is estimated that the total cost to the company due to closure of the plant, reimbursements to fishermen for their losses, removal costs for "vacuum-cleaning" the bottom of Long Harbour, and other factors, was $5,000,000. The plant is in operation again. The 450 kilograms (1000 pounds) of elemental phosphorus formerly discharged to the waters of Long Harbour each day are now recovered in plant operations or detoxified by oxidation prior to discharge.

Although industrial cases of human poisoning from elemental phosphorus were known from the early part of the 19th century, this was the first documented case of environmental effects. The Canadian investigating team unearthed only one previously published experimental study of the toxicity of elemental phosphorus to fish. It was subsequently learned, however, that a comparable case of environmental pollution with elemental phosphorus occurred in Sweden, and had been documented in government reports (in Swedish), but not widely publicized.

Government inspectors who originally approved the design of the factory at Placentia Bay were, unfortunately, ignorant of the harmful environmental effects that would ensue. The industry, well aware of the toxicity of yellow phosphorus to man, assumed it would be rapidly oxidized in the natural environment and thereby rendered harmless.

But it turned out that elemental phosphorus in colloidal form is not readily oxidized in water, a fact that could easily have been established by prior experiment. It was the death of fish that gave the warning signal to man.

Were it not for the fish, and the alertness of fishermen, fishery inspectors, and the research team that ultimately traced the cause, irreparable human damage could have been done. As little as 0.6 milligram (0.00002 ounce in weight) of elemental phosphorus, an amount equivalent to a few grains of salt, can induce hepatitis in man. A dose of 100 milligrams (0.003 ounce) results in death.

With this, the chapter on "Phosphorus, The Morning Star" ends. Attention is focused next on phosphorus and the control of man-made eutrophication.

Chapter 6

THE ENVIRONMENTAL PHYSICIAN

In which methods are described for the control of man-made eutrophication.

In the chapter, "Lakes and Man," it was suggested the water transport system of waste disposal should be regarded as the cause of eutrophication problems that have appeared during the 20th century. The present situation is really just a roundabout way of dumping plant fertilizers into water. The process starts with the application of fertilizers rich in phosphorus and nitrogen to soil, replacing the quantities removed in the harvest of crops. Crops in turn serve as food for humans, leaving the body in the form of urine, feces, and the carbon dioxide of exhaled air.[20] Nutrients in urine and feces then flow via sewage ducts into rivers, lakes, and estuaries where they act as fertilizers, amplifying the growth of aquatic plants. Introduction of phosphate-based detergents after World War II added another technological component to the one-way flow of nutrients to sediments and the sea.

In this chapter, attention is focused on methods for control of man-made eutrophication. Some of these, such as the use of toxic chemicals to kill plants, merely remove the signs of eutrophication without attempting to treat the cause. Others "solve" the problem

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[20] Lungs are organs of excretion, like the kidneys. An average adult exhales 0.25 liter (about ½ pint) of breath containing 5% carbon dioxide 20 times per minute. In 24 hours this amounts to 0.67 kilogram (1½ pounds) of carbon dioxide.

by displacing it to another area, as in sewage diversion schemes. In localities where property values are high and land is at a premium, the most reasonable approach may be to remove phosphate from sewage by chemical precipitation, using the phosphate-rich sludge as fertilizer on land. The most efficient solution in an ecosystem sense is the totally cyclic one, the use of sewage treatment plant effluents as fertilizers to increase the yield of some harvestable crop. In this case, however, care must be taken to prevent spread of disease and contamination of the cyclic food chain with industrial toxins.

Costs associated with these treatments vary depending on the treatment, the population served (per capita costs declining with increasing population), and various economic factors. The cheapest method in a short-term sense is to poison unwanted plants with some aquatic herbicide; however, this is also the most dangerous method in terms of possible side effects and the most expensive in the long run, since it does nothing to remove the cause. Diversion schemes become undesirably expensive even for large metropolitan centers when distances begin to increase beyond 25 kilometers (15 miles). Although construction costs may be high, depending on the local terrain, once a diversion has been completed maintenance and operational costs are low. Operational costs for nutrient removal, based on recycling or chemical precipitation of phosphate, typically range from 0.1¢ to 1¢ per person per day (roughly 50¢ to $5 per person per year) depending on the population served, local prices of chemicals, sludge removal costs, and other factors. "A penny a day keeps man-made eutrophication away" was a reasonable slogan for most citizens of the United States and Canada in the early 1970s.

Most of us would prefer not to have to pay for sewage treatment, thinking matters will always take care of themselves "some other way." When it comes right down to it, sewage treatment is not a terribly exciting business.

This tendency to view sewage treatment only in terms of costs is somewhat like going to a restaurant for dinner and then ordering solely on the basis of lowest price. When sewage treatment is examined in the broader context of benefits accrued and expenditures that would otherwise have to be made, it turns out to be surprisingly cheap. On a per capita basis, the cost of nutrient removal is equivalent to the purchase of 1 liter (1 quart) of bottled water a month or a glass of mineral water (club soda is perhaps the closest North American equivalent) a week.

There is a close functional similarity between the human body and man-dominated parts of the biosphere. Both are ecosystems in their own way, one controlled (in part) by the will of an individual and the other controlled (also, in part) by the will of a community. In both cases, within limits imposed by nature, it is human will that determines the behavior and health of the system. When the human body is injured or some part of the system goes out of control, the mind of the individual directs the body to a medical physician for help. In a like manner, when an ecosystem is injured or some part of it (a pest species, for example) goes out of control, the collective mind of the community calls an environmental physician for help — that is, an experienced ecologist. In each case the physician does the best he can with the tools available, writing out a prescription, giving general advice, or perhaps suggesting the need for hospitalization. But he cannot force the patient to do anything, even if the patient is dying. The patient has to will himself to be brought back to health.

This comparison of an ecosystem to the human body is exact and appropriate. However, one qualification must be clearly understood. Expressed in terms of medical practice, our knowledge of ecosystems today is equivalent to that of the human body in the latter part of the 18th century. At that time the internal anatomy of the body was only known in gross detail; and physiology, except for William Harvey's demonstration of the circulation of the blood, was hardly understood at all. Bacteria had been seen, but were not recognized as agents of disease; knowledge of vitamins, hormones, and antibiotics did not exist; and the need for aseptic procedures in surgical practice was not realized.

Based on this analogy, we should not be too surprised if, in the latter part of the 20th century, we are inflicted with environmental ills equivalent to epidemics of typhoid fever, cholera, and bubonic plague that characterized earlier times. In our ignorance we will attribute such environmental catastrophes, when they happen, to forces beyond our control, as disease was regarded in the 18th century.

But, to environmental physicians who will look back on us from the vantage point of the 23rd century, there may be another way of describing this attitude. They will rightly attribute our misstatements and misunderstandings to ignorance of the causes of environmental problems. They will say we lived at a time when forces of the environment were not understood.

The environmental physician may advise his patient to stop smoking (abate air pollution), go on a diet (control population), slow down in activity (reduce the pace of technology), or drink in moderation (avoid excessive consumption of hydrocarbons); but he cannot force the patient to conform. Whether the patient conforms is up to the patient, not the physician. If the patient follows the physician's advice it is probable, though by no means automatic, that improved health will result. On the other hand, if the mind controlling the body behaves like an alcoholic, there is little the environmental physician can do other than assist through education.

On this note of realism, some prescriptions used in the treatment of man-made eutrophication may now be examined. They are given in approximate order of first historical use (except for recycling which is the oldest of all). The first prescriptions deal with some "quack" medicines for "Treatment in Lakes" (headache tablets for appendicitis might be an appropriate medical analogy). Attention then shifts to "Diversion of Sewage Wastes" (how to pass your schizophrenia downstream). Then, following a general account of the significance of nutrients in the control of eutrophication, responsible remedies (ones that deal with causes) are discussed under the following headings: Removal of Nutrients from Sewage; Nature (Recycling) for Nutrient Removal; and Control of Agricultural Wastes. The sequence ends with a history of Lake Washington, USA, which shows the critical role of phosphorus in a sewage effluent diversion scheme.

Treatment in Lakes

One of the earliest and still commonly used methods to control algae and aquatic weeds in ponds and lakes is adding chemicals that inhibit growth. This approach makes no attempt to come to grips with the causes involved. It is like the man who solves the problem of a leaky roof by placing a pan underneath to catch the drip.

Chemical treatment of natural waters is potentially dangerous since uncontrolled addition of toxic compounds can result in deleterious side effects. In some areas, permits are required and the dosages and conditions of application carefully controlled by governmental regulations. The more usual practice, however, is a policy of environmental "laissez-faire" (do-as-you-please). In view of present ignorance of long-term effects of these chemicals, this lack of policy is not likely to persist. Good advice is that if laissez-faire exists in your community, get rid of it.

One of the more common treatments to reduce the incidence of blue-green algal blooms is the application of copper sulfate to surface waters. Copper in ionic (Cu^{++}) form is a general biological poison; however, by judicious application in relatively low concentrations it can bring about the death of algae without detriment to fish or aquatic invertebrates. This was the method used between 1912 and 1958 to reduce the incidence of blue-green algal blooms in the chain of lakes at Madison, Wis., as discussed in the chapter "Lakes and Man." Thousands of tons of copper sulfate were used over a 46-year period in what eventually was recognized as a futile effort to create clear-water conditions in lakes still polluted with nutrients.

Most of the copper added to the Madison lakes precipitated almost immediately on contact with water in the form of insoluble compounds, produced by reaction with carbonate and bicarbonate ions naturally present in the water. The copper now lies locked in the bottom sediments of the affected lakes. For a time it served its purpose, as it does in many other waters similarly treated today. But, by no stretch of the imagination could the use of copper sulfate to reduce algal growth be considered as anything other than a temporary control. Effect of a single application in terms of preventing algal blooms seldom lasts for more than a few weeks.

Another chemical used for the temporary treatment of both natural and man-made eutrophic bodies of water is alum (potassium aluminum sulfate). Unlike copper, alum does not act as a toxicant, but rather as a chemical coagulant. It forms a flocculent precipitate of aluminum hydroxide that acts as a trap for phosphate ions and organic materials. These are removed from lake water with the settling of the precipitate. The presence of aluminum hydroxide at the sediment surface may also help keep phosphate in the sediments of shallow ponds and lakes. Since alum acts as a coagulant for materials in water (rather than as a poison) it is of no use in streams where a fresh supply of nutrient-rich water enters every second.

Other chemicals used to control the growth of algae and aquatic weeds include compounds of arsenic and mercury, 2,4-D, and a variety of organic compounds with suspiciously short abbreviations for long technical names. Some of these are known to be dangerous nonspecific toxins; and none has been adequately tested in terms of overall ecosystem effects. Pollution control agencies and public health officials should be asked to approve in writing any proposed additions of toxic chemicals to the environment.

One pollutant-free method recently purported to reduce blue-green algal blooms in lakes is controlled circulation and aeration of water by introducing a stream of air bubbles below the thermocline. This is an extension of a much older application, aeration of surface waters to increase biological rates of oxidation of waste organic matter in natural streams. One of the possible mechanisms may be in preventing localized areas of high nutrient concentrations from which algae can "seed" other areas of a lake. Also, since algae tend to be localized in zones favoring optimal reproduction, the randomizing effect of mixing may reduce photosynthesis and growth. The principal virtue of the method is that it does not involve the addition of foreign chemicals, but its effectiveness is debated.

Mechanical weed cutters, the aquatic equivalents of combine harvesters, have been used for control of rooted aquatic plants. For maximal effect the harvest should be deposited on land under circumstances that favor absorption and retention of nutrients by soil. Merely burning the dried remains at the lakeshore is insufficient to solve the problem, since phosphorus and nitrogen salts are concentrated in the ash. The wet harvest should be deposited on flat terrain that drains away from the lake in order to achieve the desired result.

Diversion of Sewage Wastes

Sewage diversion ducts and channels have been constructed in some areas to prevent nutrient-rich effluents of sewage treatment plants from entering bodies of waters used for recreation or water supply. Lac d'Annecy in France, the Lake of Zürich in Switzerland, Schliersee and Tegnersee in Germany, Lake Washington and the Madison lakes in the United States are lakes that have been protected in this way.

Diversion, of course, is not treatment. It merely passes the problem downstream. Provided no one is living there, and nutrients are not transported to another utilized site, it can constitute an advantageous solution. Often, however, it is only a momentary solution in terms of population expansion and land development.

Seas and oceans are prime areas for waste disposal from an engineering point of view because of their immense volume and absence of human inhabitants. Also, in many areas of the oceans an increase in productivity would be beneficial. But even marine waters can be adversely affected by nutrient enrichment, particularly areas with restricted circulation such as estuaries and embayments. The Baltic Sea is already showing signs of eutrophication as a result of the addition of nutrients and organic wastes from countries surrounding its shore. Entire continental shelf areas of the oceans may soon be affected.

The history of sewage treatment and the location of effluent pipes in Madison, Wis., outlined in the chapter on "Lakes and Man," is the best commentary on diversion schemes. The first diversion merely shifted problems from the uppermost lake to the lake below.

The second diversion transferred the problems to the two lowermost lakes in the chain. The third diversion transported sewage effluent around all four lakes via Badfish Creek to the Yahara River. The "trade-off" has resulted in an overall benefit. However, it took the citizens a long time to understand the difference between diversion and cure. There may still be more to learn.

One interesting case combines diversion with reuse of both the water and nutrients in sewage. It shows what can be done when a little human ingenuity is applied to a suitable geographic terrain. The case pertains to Mexico City, a community of 7,000,000 people that chose not to treat its sewage at all, except for the removal of coarse materials with screens.

Wastes from the city are pumped through an underground pipe, 7 meters (23 feet) in diameter and 70 kilometers (43 miles) long, into a reservoir in another basin that drains by the long course of the Montezuma River to the sea. The reservoir is used both for storage and to allow time for the death of human pathogens that might otherwise spread disease. In the arid and sparsely populated receiving basin, the inhabitants want both the water and nutrients (the "black water," as they say) to make the most of unfavorable agricultural land. The only cost of sewage treatment is the cost to pump it to an area where it is used as a resource — the concept of recycling at its best.

Significance of Nutrients in the Control of Eutrophication

Methods for control of eutrophication discussed up to this point make no attempt to reduce the delivery of nutrients derived from human culture to water. As attention now shifts to methods involving nutrient removal and recycling through soil, a preliminary account of the relative importance of phosphorus to other nutrients in the control of eutrophication may be helpful.

In the chapter on "The Algal Bowl," phosphorus and nitrogen were identified as the two most important nutrients involved in the triggering of plant growth in lakes. Other things equal, it would seem likely that one or the other would best serve as a means of control.

The primary reason for attaching more importance to phosphorus than nitrogen (or for that matter, any other plant nutrient) is that of all chemical elements required by plants, phosphorus is the most controllable (by man) and the most growth-controlling in terms of plants. The relationship is not accidental. It results from the use of the same controls by nature and man. Both are due to the geochemical abundance of calcium, iron, and aluminum ions and their tendency to form water-insoluble precipitates with phosphate ions.

The rationale for phosphate removal to control man-made eutrophication is as follows:

(1) Laboratory and field experiments have shown that the chemical treatment to remove phosphate eliminates most of the fertilizing effect of effluents from sewage treatment plants on natural waters. The demonstration that this effect can be reversed on the readdition of phosphate alone shows that it is due to removal of phosphate, rather than some other factor.

(2) Technology for removing phosphate from sewage is readily available and economically feasible. Technology for removing other nutrients, including nitrogen, has not been developed to the same extent.

(3) In most lakes not polluted by man, phosphorus tends to limit plant growth more than any other element. Thus, by restricting the supply of phosphorus to lakes, natural controls are utilized to the fullest extent.

(4) In sewage-polluted lakes the proportion of the total supply of phosphorus directly attributable to man is typically higher than for any other growth-limiting element. In other words, phosphorus is more controllable because more of it originates from man.

(5) Phosphorus is retained by soil to a greater degree than nitrogen. By accentuating this natural control process with the removal of phosphorus from sewage a maximum return on the investment is almost automatically assured.

(6) When the supplies of readily available phosphate in water are depleted to the point that they limit further growth of plants, no accessory supplies are available from the atmosphere. Nitrogen, on the other hand, can be transported across the air–water boundary both as elemental nitrogen (N_2), a major constituent of air, and as ammonia (NH_3). Most organisms are unable to use elemental nitrogen; however, certain blue-green algae and bacteria can. They convert elemental nitrogen into ammonia and organic nitrogen compounds, which then become available as nutrients in aquatic ecosystems.

These six points form the central basis of the rationale for the removal of phosphate from municipal and industrial wastes as a means of controlling man-made eutrophication. Supplies of phosphorus from agricultural sources must also be reduced in areas where there is an appreciable transfer from land to water. It is, in fact, always wise to determine the relative quantities of phosphorus arising from various natural and human sources. If the major source is from agriculture, treatment of sewage for phosphate removal may have little effect in curing eutrophication.

The first question often arising in the minds of those unfamiliar with aquatic ecosystems is whether a reduction in the supply of a single nutrient, such as phosphorus, can control accelerated plant growth in the aquatic environment. Some people believe eutrophication is so complicated and poorly understood that it is naive to think control via any single element, such as phosphorus, could work in all cases. Sunlight, nitrogen, carbon, and a variety of other factors are known to limit growth of aquatic plants under natural conditions. Proponents of such arguments, however, show by the very questions they raise that they do not understand the distinction between causes and mechanisms of control.

Two examples will reduce the distinction to its utmost simplicity. The first is that it is always easier to destroy than it is to build — the means of destruction having little to do with the complexity and means of construction. The second concerns Asiatic cholera, a disease now largely restricted to India, which was rampant throughout the world prior to the 20th century. The discovery of an effective control mechanism for cholera was made 30 years prior to the discovery of the causal organism by Robert Koch in 1883. The mechanism of control was deduced without knowing anything about the cause of the disease or the manner in which cholera bacillus affects the human body. The secret was to separate sewage from the drinking water supply.

One of the principal reasons limnologists are confident man-made eutrophication can be reversed is the fact that individual applications of phosphate-rich fertilizers to lakes produce only short-lived effects. The situation is similar to the effects of alcohol on the human body at a cocktail party; the system is disturbed for a time, but soon returns to its previous state. Carrying the analogy further, man-made eutrophication is like alcoholism, as it is the continued supply of the disturbing influence that creates and perpetuates the disturbed state. If the will to cure exists, it can be cured.

In summary of the information presented above, it can be said authoritatively that attempts to control eutrophication without restricting the supply of phosphorus to water are likely to be without major effect.

Removal of Nutrients from Sewage

Three principal methods are available for removing phosphate from sewage by chemical precipitation. These are based on reaction with lime (calcium oxide), iron (in various forms), or aluminum (usually as alum — potassium aluminum sulfate). All of these methods have the added advantage of removing organic substances and often some nitrogen as well as phosphate.

Relative costs of the different treatments vary with local prices of chemicals, the particular engineering treatment used, the need for capital outlays, and so on. Sometimes a waste can become a resource, as in the case of waste "pickle liquor" from the steel industry. This liquid waste, rich in acid and iron, can be combined with sewage to remove phosphate, acid, and iron. In the process, a waste is transformed into a resource.

One factor that can be of concern is sludge disposal. This is particularly true in the case of the lime method because of the large amount of sludge caused by precipitation of calcium carbonate. It is a reminder that precipitation methods depend on the addition of chemicals to sewage. Following Barry Commoner's rule that "everything has to go somewhere," the added calcium, iron, or aluminum ions end up in sewage sludge, and the sulfate ions that typically form the other part of iron and aluminum salts pass into water. Although this procedure appears to be adding to pollution, it is really trading off a problem for a nonproblem.

Drs G. V. Levin and Joseph Shapiro have developed a method for the removal of phosphate from sewage that does not depend on the addition of chemicals. The method is based on the knowledge that microorganisms associated with sewage sludge take up excess phosphate under well-oxygenated conditions and release it in the absence of oxygen.

In terms of control of eutrophication, nothing further is gained by treating sewage for removal of nitrogen compounds if phosphate has already been removed. It takes only one growth-controlling element to curtail plant growth. Nitrogen, however, may constitute a problem in its own right in contributing to high nitrate levels in water or in consuming dissolved oxygen, as in the oxidation of ammonia to nitrate.[21]

Various processes are available for removing nitrogen, based on distillation of ammonia at high *p*H, biological denitrification (conversion to elemental nitrogen that then passes to air), or removal by ion exchange resins similar to the zeolites used in water softening. Methods that involve "stripping" of ammonia from water into air only redistribute the problem, unless the ammonia is removed and concentrated prior to liberation of the stripped gases to the atmosphere.

Nature (Recycling) for Nutrient Removal

Nutrient removal by addition of sewage or treated sewage effluents to soil, the most ancient method of waste disposal, is still used

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[21] The principal form of inorganic nitrogen in sewage is ammonia.

in many parts of the world (though rather rarely compared to more modern forms of sewage treatment). Nevertheless, it is the best illustration of a total ecosystem approach and, as such, is being rediscovered in some parts of the United States and Canada today. The community of South Tahoe (bordering Lake Tahoe in the southwestern USA) pumps the effluent from its $19,000,000 sewage treatment plant over a drainage divide into a reservoir where it is fed out for irrigation. In some parts of Pennsylvania and Michigan, nutrient-rich effluents from sewage treatment plants are used to promote forest growth. In the dry Okanagan Valley of British Columbia, they are being used on an experimental basis to accelerate production of grain. In principle, these practices do not differ from the use of animal manures for fertilization of agricultural land.

Wastes of society can be put to good use in accelerating the growth of agricultural or forest crops, if human pathogens are not redistributed in the process. This approach finds its best application in tropical or semitropical areas, where plant growth occurs throughout the year. In latitudes lying closer to the poles, its application is more limited because of frozen soil in winter.

Under some circumstances, standing bodies of water can also be used for nutrient removal, when sites are available for the purpose and climate permits year-round growth of aquatic plants. In warm climates, sewage lagoons and carp ponds often become one and the same thing, with carp transported to clean water several weeks before harvest. In some parts of southeast Asia it is not uncommon to find outhouses and poultry pens located directly over carp ponds. Wastes from one "industry" become directly available as a resource for the next. In a series of specially constructed ponds, the city of Munich, Germany, puts its wastes to use in the production of fish.

In temperate latitudes, sewage lagoons do not function well in terms of nutrient removal. They are too shallow and typically flushed out so rapidly that they behave more like rivers than lakes. Short flushing times and inadequate depths do not permit burial and retention of nutrients in sediments. They are also completely ineffective in terms of nutrient removal during winter when the reduction of sunshine limits algal growth. They can even serve as a source of further nutrient supply by releasing nutrients previously deposited in the sediments.

Although these instances, in which nature is utilized for removal of waste and the production of some utilizable crop, are not highly efficient in terms of modern technology, they can nevertheless result in overall economic benefit. The major value is not the resource produced, but elimination of a pollution problem with an added side benefit. In terms of recycling, high efficiency in the usual economic sense should not be regarded as a major goal. Part of the definition of a waste is that the means of recovery do not justify the expense (in a human, though not an ecosystem sense). It is interesting to reflect that nature's largest factory, the machinery of photosynthetic plants, operates with a net annual efficiency that seldom exceeds a few percent of the utilizable energy of the sun.

Control of Agricultural Wastes

In most countries physiological wastes produced by farm animals outweigh those produced by man by a factor of 10:1. Were it not for the fact that most animal wastes are delivered directly to soil, eutrophication problems in agricultural areas would be many times worse than problems from municipal sewage.

Deleterious ecosystem effects arising from agriculture mostly stem from two practices. One is associated with feedlots, areas where turkeys, chickens, cattle, and other domesticated animals are reared in dense populations without effective utilization or treatment of the wastes produced. The situation is equivalent to a city without a sewage treatment plant.

The other problem inherited from agriculture arises from economically wasteful fertilization practices. In some areas, manures and artificial fertilizers are applied to soils in late autumn or even in winter on top of frozen ground. Depending on the rate of melting of snow in spring and the slope of the terrain, major fractions of nutrients can be carried away in solution or in suspension. The circumstances differ little from the runoff of water over cement.

Inputs of nutrients to water from agricultural and livestock-rearing operations are usually not major except under conditions of intense land use as in feedlots. The primary needs in such cases are largely educational, based on the economics of ecosystems rather than individuals. The primary need is to return to principles accepted centuries ago — the recycling of animal wastes as fertilizers for crop production and ploughing of fertilizers into soil. In the technological revolution of agricultural practice, these and other simple principles have fallen prey to the same fate as the art of shoeing a horse. The principles need to be revived.

History of Lake Washington

One case of sewage diversion has been of considerable importance in interpreting the role of phosphorus in the control of eutrophication. This is the limnologically well-documented history of Lake Washington, a body of water 128 square kilometers (50 square miles) in surface area with a maximum depth of 59 meters (194 feet) and a mean depth of 18 meters (59 feet). It lies within the boundaries of metropolitan Seattle, Washington, USA.

Most of the problems of Lake Washington have been associated with population increase and associated changes in the flow of sewage effluents. The population of metropolitan Seattle was about 300 in 1865, and rapidly increased to over 1,200,000 by 1965. The first growth of the city occurred between Lake Washington and Puget Sound, the latter an arm of the Pacific Ocean. In 1922, pollution problems created by 30 outfalls of raw sewage to the lake were so bad that a diversion was created to carry sewage to the Sound. The lake soon reverted to a healthy state.

In 1930, sewage effluents began entering the lake from treatment plants in outlying communities. By 1962 the discharge of these effluents had risen to a level of 76,000,000 liters (20,000,000 U.S. gallons) per day. In all cases the sewage was given normal treatment for removal of organic substances, but not for removal of inorganic plant nutrients.

By the mid-1950s it was obvious to Dr W. T. Edmondson, noted limnologist at the University of Washington, that the lake was beginning to repeat the history of eutrophication in the Lake of Zürich, Switzerland. *Oscillatoria rubescens* and other blue-green algae started to bloom. Transparency of the water in midsummer, as measured by the visibility of a Secchi disc, decreased from a value of 3–4 meters (10–14 feet) in 1950 to less than 2 meters (6 feet) in 1957. In the 1950s Dr Edmondson began alerting city officials of other changes that would take place. The officials were concerned.

In 1958, citizens of metropolitan Seattle decided by a special vote to do something to save the lake. A diversion scheme to carry the nutrient-rich effluents to the sea was initiated in 1961. By the end of 1963 effluents discharged to the lake had decreased from 20,000,000 to 14,500,000 gallons per day. The values were reduced further to 11,000,000 gallons per day in 1965, to 200,000 gallons per day in 1967, and to zero in 1968.

As these changes were taking place Dr Edmondson and his students were on the lake measuring concentrations of various chemicals and kinds and abundance of algae and other microorganisms. Even before the diversion was half completed evidence that the lake was improving began to accumulate. Year-to-year trends in the concentration of dissolved phosphate during late winter were beginning to show a decline, with a parallel decrease in the abundance of planktonic algae in midsummer. Transparency of the lake in summer was beginning to increase.

By 1970, Lake Washington was back to where it had been in 1950 in terms of plant growth and other signs of eutrophication. A rapid and remarkable recovery had taken place. Citizens and officials of the city were delighted with the result. By acting in time they averted what would otherwise have been an embarrassing and undesirable situation, if not community disaster.[22]

The most significant finding, obtained by Edmondson and his associates at the University of Washington, was a direct correlation

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[22] Dr W. T. Edmondson's work was supported by the U.S. National Science Foundation, a federal organization devoted to the support of science for cultural, rather than economic, purposes.

between concentration of dissolved phosphate in late winter and the abundance of planktonic algae in midsummer. None of the other nutrients measured showed a change comparable to the change in algal abundance.

The implications were clear. The primary effect brought about by diversion of wastes was the decreased supply of phosphorus to the lake. This, in turn, caused the reduction in plant growth. No other explanation fitted so well with the facts. The question still remains, however: Will lakes Erie and Ontario respond to removal of phosphate from sewage as rapidly and effectively as Lake Washington responded to effluent diversion?

Dr Richard A. Vollenweider, noted Swiss-born limnologist at the Canada Centre for Inland Waters in Ontario, developed a predictive theory of eutrophication based on the annual supplies of phosphorus and nitrogen delivered to lakes. His summary shows that many of the world's lakes have been seriously affected by overloading of nutrients in recent decades.[23] But, more important than this, he created the scientific basis now in use throughout the world for the control of eutrophication. Knowing the rates at which phosphorus from natural and man-made sources enter a lake, it is possible to predict the response to control measures. His work has been put to good use in lakes Erie and Ontario.

Nothing has been said in this chapter of the significance of detergent phosphates in eutrophication, yet, in 1970, 50% or more of the phosphorus in municipal sewage in Canada and the United States arose from this source.[24] The next chapter discusses the controversy in 1969–70 over the significance of detergent phosphates in the cause and control of man-made eutrophication.

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[23] See Vollenweider (1968).

[24] It is unlikely that household wastes from isolated homes and small communities will be treated for removal of phosphates because of poor control and high cost of treatment on a small scale. In this respect there is a pronounced difference beween the average summer cottage situation in North America and Europe. In North America, summer cottages tend to be equipped with all the luxuries of the city, including automatic dish washing and clothes washing machines, their ducts commonly proceeding directly to water rather than passing through septic tanks and soil. In Europe, summer cottages are valued more for the contrast that they offer to city life; nutrient pollution is much less on a per capita basis.

FIG. 3. *Detergent foam from a fountain in front of the U.S. National Gallery of Art, Washington, D.C., in 1959, when nonbiodegradable detergents were in common use. Under governmental pressure, the detergent industry developed biodegradable surfactants in 1965. Scenes such as this no longer exist in the United States and Canada. See p. 117–118 for further explanation.*

Chapter 7

DETERGENTS AND LAKES

In which the history of the 1969–70 detergent phosphate controversy is described, with an account of the role of phosphates in cleansing, and how their use can be reduced.

On October 7, 1964, the Governments of the United States and Canada requested, under the Boundary Waters Treaty of 1909, that the International Joint Commission inquire into and report as soon as practicable upon three questions pertaining to pollution in the lower St. Lawrence Great Lakes. The Commission, a permanent body of three representatives from Canada and three from the United States, was created in 1911 as an outgrowth of the Boundary Waters Treaty. Since that time, its members have resolved a number of important problems along the 8763 kilometer (5443 mile) border to the mutual benefit of inhabitants on both sides.

Avoiding any word or phrase that could possibly be construed as bias, the two governments asked the Commission:

(1) Are the waters of Lake Erie, Lake Ontario, and the international section of the St. Lawrence River being polluted on either side of the boundary to an extent which is causing or is likely to cause injury to health and property on either side of the boundary?

(2) If the foregoing question is answered in the affirmative, to what extent, by what causes, and in what localities is such pollution taking place?

(3) If the Commission should find that pollution of the character just referred to is taking place, what remedial measures would, in its judgment, be most practicable from the economic, sanitary and other points of view, and what would be the probable costs thereof?

Early in 1965, the Commission established two Advisory Boards to supervise the necessary investigations, one for Lake Erie and the other for Lake Ontario and the international section of the St. Lawrence River. The Boards were composed of officials from the state, provincial, and federal governments involved, who in turn drew upon their various resources to carry out the long and tedious investigations. The Boards' assessment was completed with the publication of a report containing a summary of findings and recommendations in November 1969, followed by two thicker and more detailed volumes of data in the spring of 1970.[25]

Among the 19 specific recommendations pertaining to various aspects of pollution in the lower Great Lakes, one created more discussion than all the others combined. That recommendation was for a program of phosphorus control to halt the growing trends of cultural eutrophication.

The Boards recommended that:

(a) phosphates in detergents be immediately reduced to minimum practical levels, with total replacement by environmentally less harmful compounds by 1972;

(b) the remaining phosphate in municipal sewage effluents be reduced by not less than 80% prior to specific dates from 1972 to 1978 for different parts of the basins, with continued

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[25] Report to the International Joint Commission on the Pollution of Lake Erie, Lake Ontario, and the International Section of the St. Lawrence River. Vol. I, Summary (1969); Vol. 2, Lake Erie (1970); Vol. 3, Lake Ontario and the International Section of the St. Lawrence River (1970). Ottawa and Washington.

reduction thereafter to the maximum extent economically feasible;

(c) programs be developed for the reduction of phosphorus inputs to water from agricultural sources;

(d) any new and significant changes in the addition of phosphorus to waters in the basins be regulated.

Part (a) of this recommendation created all the controversy, primarily because of the initially hostile reaction from the detergent industry. The recommendation was made because detergents, in 1969, accounted for more than half the phosphate in municipal sewage, a state of affairs that had come about since 1947. Manufacturers had been aware that governmental pressure was mounting for the removal of phosphates from detergents, but the timing and source of this recommendation came as a complete surprise.

There were good reasons for approaching the detergent question separately from the sewage treatment issue, as the International Joint Commission subsequently recognized in its final report. First, the removal of phosphates from detergents would result in a relatively rapid and permanent removal of at least 50% of phosphorus in municipal wastes. Secondly, it would result in a substantial reduction of treatment costs for phosphate removal at sewage treatment plants. (In the technical report to the Commission, annual savings in chemical costs associated with treatment in the lower Great Lakes basin were estimated to be $22,000,000 per year.) Thirdly, removal of phosphates from detergents would eliminate 50% of the phosphate delivered to water from isolated dwellings and small communities, situations in which any other kind of control would be virtually impossible to attain. Needless to say, benefits of such action would not be restricted to the lower Great Lakes basin.

Simultaneously with the release of the Summary Report from its Advisory Boards, the Commission arranged a series of public hearings in six communities spread around the lower Great Lakes drainage basin. The purpose of the hearings was to determine the reactions of other segments of society to the Advisory Boards' report. Hearings were scheduled for late January and early February, 1970, allowing adequate time for any affected parties to make their own assessment of the report.

A different set of hearings on a closely related subject took place on December 15 and 16, 1969, in Washington, D.C. The Washington hearings were called by a Subcommittee of the U.S. House of Representatives Committee on Government Operations, headed by the Hon Henry S. Reuss (Democrat, Wis.). The purpose of the hearings was to determine why the federal agency involved in the U.S. Joint Industry/Government Task Force on Eutrophication had been ineffectual in accelerating a search for suitable replacements for phosphates in detergents. So far as Mr Reuss could see, the only product of 3 years of "intense" governmental effort of the Task Force had been a research grant for $99,896, the development of a "provisional algal assay procedure," and some talk of a movie on eutrophication.

One of the more revealing parts of the testimony, presented at the hearings of the Reuss Committee, was a series of questions Mr Reuss directed to Mr Carl L. Klein, Assistant Secretary of the Interior for Water Quality and Research during the early part of the Nixon administration[26]:

> *Mr Reuss* Isn't it a fact that only 15% of the people of this country are now served by advanced waste treatment plants?
>
> *Mr Klein* I don't think that it is even that high yet.
>
> *Mr Reuss* Is it less than that, then?
>
> *Mr Klein* Yes.
>
> *Mr Reuss* And by and large the phosphate which shows up at sewage disposal plants comes from two main sources, does it not — household detergents and human wastes?
>
> *Mr Klein* Yes, Sir.
>
> *Mr Reuss* And household detergents are made by three major manufacturers?
>
> *Mr Klein* That is correct.

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[26] See "House of Representatives" in the References.

Mr Reuss And human wastes are made by a couple [of] hundred million manufacturers; is that correct?

Mr Klein Yes, Sir.

Mr Reuss Well, doesn't it occur to you that it is easier to do something about three than about a couple [of] hundred million?

Mr Klein agreed, but went on to say that regardless of the detergent question, facilities would still have to be installed in major cities for removal of phosphates arising from physiological wastes. Mr Reuss concurred, but pointed out the time lag, because of the people involved, and the need for "getting phosphates removed from where most of them come from."

In the brief that the U.S. Soap and Detergent Association presented to the Reuss Committee (later repeated at the hearings of the International Joint Commission) the recurrent themes were the essential role of phosphates in cleansing action and the complexity of the process of eutrophication. The question was not whether people could have clean clothes *and* clean lakes, but whether North American society could maintain its standards of cleanliness and sanitation without any phosphate in detergents.

The culmination of the detergent issue came during the first week of February 1970, at hearings of the International Joint Commission, when high-ranking officials from federal water pollution control agencies on both sides of the border announced their intention to eliminate phosphates from detergents. When the big three detergent manufacturers and their phosphate suppliers heard these words they knew their case was lost. For the second time in a decade, the detergent industry had been identified as an international polluter: first, from foams due to nonbiodegradable detergents that transformed some areas of nature into what seemed like environmental washing machines, and now from phosphates as related to cultural eutrophication.[27]

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[27] Persistent foams from synthetic surfactants were acute problems in many areas of North America and other parts of the world during the late 1950s and early 1960s. The problem was solved in 1965 by the introduction of biodegradable surfactants.

The impact of the pronouncements was mildly dramatic, as the public slowly began to realize a major conflict existed between the soap and detergent industry and the two governments. In the resulting confusion, representatives of the press, radio, and TV scurried to ecologists to find out what eutrophication meant. Housewives, who had taken care to buy detergents with a *biodegradable* label on the box, learned to their surprise in 1970, that the phosphate issue had nothing to do with biodegradability; nonbiodegradable surfactants had been replaced years before. Few citizens realized that heavy-duty laundry detergents (those used in automatic machines) and automatic dishwashing detergents contained phosphates, let alone why phosphates were there or their effect on lakes and streams. Some public antipollution groups, however, were well aware of what phosphates and eutrophication meant, and started campaigning for laws to take phosphates out of detergents.

While all this was going on, other events were taking place behind the scene. Manufacturers and their phosphate suppliers were pressuring the two governments to avoid precipitous action that might throw the industry into chaos. Manufacturers stated that phosphates were essential for the cleaning power of household laundry and automatic dishwashing detergents. They claimed that in spite of an intense search, not a single material or combination of materials had been found that could fulfill all the vital functions of phosphates, with no adverse effect on water quality. Unknown to the two governments, support for one aspect of the industrial stand was materializing from an unexpected source.

Two Canadian journalists, Robert F. Legge and Douglas Dingeldein, lashed out at the International Joint Commission, its Advisory Boards and a member of the Editorial Committee in a series of articles in *Canadian Research & Development* entitled "We Hung Phosphates Without a Fair Trial."[28] With a crash self-education course on lakes and eutrophication, the authors claimed to reveal for the first time "a new account of a principle process of eutrophication that shows carbon, not phosphorus, to be the controlling nutrient in the production of algal bloom."

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[28] See Legge and Dingeldein (1970).

The scientific basis for the articles arose from investigations of three researchers: Dr Willy Lange, University of Cincinnati; Dr L. E. Kuentzel, Wyandotte Chemicals Corporation; and Miss Pat C. Kerr, U.S. Environmental Protection Agency.[29] All three claimed carbon dioxide was the major factor limiting the production of algal blooms.

The introductory sentence of the articles by Legge and Dingeldein on the Lange–Kuentzel–Kerr thesis illustrates the vigorous tone[28]:

> "Has the International Joint Commission, in one fell swoop, tried to discredit the research and testimony of reputable scientists, apparently twisted government science to political ends, apparently ignored gross violations of the Treaty of January 11, 1909, to which it owes its existence, and been a party to what may prove to have been the most incredible scientific/political hoax in the history of Canadian and American relations?"

An overnight best-seller in the detergent world, reprints were ordered by the industry and widely distributed among industrial magnates and governmental pollution control authorities. Within weeks, copies appeared in every country of the western world where the detergent issue was at stake, even some behind the Iron Curtain.

Government officials were concerned that the phosphate issue might be shelved indefinitely, due to public confusion over what appeared to be (but was not) a scientific controversy.

After initial governmental fears subsided over possible reactions from an uninformed public, matters returned to their former state. The wild and emotion-packed claims slowly dwindled into insignificance. Toward the end of 1970, most manufacturers seemed prepared to go along with what was then governmental policy of both Canada and the United States — to remove phosphates from detergents. Before examining in detail the position adopted by the U.S. Soap and Detergent Association in the phosphate–eutrophication controversy, the meaning of the word *detergent* as it is commonly used needs explanation.

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[29] See Kuentzel (1969); Lange (1967); and Kerr et al. (1970).

A detergent is a cleansing product in which the one essential ingredient is a *surfactant,* the true cleansing agent. In addition to surfactants, detergents may contain "*builders,*" ingredients with little or no cleansing power that make the surfactant work better by complexing the calcium and magnesium ions involved in water hardness; *fillers,* ingredients that reduce overall manufacturing cost or act in other seemingly mysterious ways; and a variety of other substances such as artificial brighteners and perfumes that make the product seem good.

In most synthetic detergents used in the 1960s the surfactant was the sulfate of a fatty alcohol, synthesized from petroleum products. (In soaps, the surfactant is the sodium salt of a fatty acid, derived from animal tallow or vegetable oils.) The surfactant disperses particles and stains on dirty surfaces, causing them to be suspended and removed in the wash water. In solid detergents designed for use in automatic laundry and dishwashing machines, the surfactant is a relatively minor component, typically forming only 15–20% of the weight of the product. Much of the remainder consists of builders, typically (in 1969) phosphate-rich ingredients that formed from 30 to 70% of the product. The most commonly used builders at the time of the phosphate–eutrophication controversy were sodium triphosphate in "heavy-duty" detergents designed for use in laundry machines, and other types of phosphates (pyrophosphates and metaphosphates) in products designed for automatic dishwashing machines.

Light-duty detergents, such as liquid detergents, are products designed for washing dishes and delicate fabrics by hand. They do not contain phosphate builders to any appreciable degree. Why not? Because in most instances they aren't necessary. When articles are washed by hand the human eye locates spots and stains, and the mechanical energy of the body scrubs them away. The problem with machines is, being blind, they are unable to apply their mechanical energy where it is needed most. As a result, additional ingredients (builders) have to be added to improve the cleansing power. There is also a technical reason for the lack of phosphates in liquid detergents. Phosphate polymers slowly break down in the presence of water, losing their effectiveness as builders.

Now that the purpose of detergent builders and their link with automation has been established, the next step is to examine how well the role of builder was filled by polymeric phosphate compounds used in 1969. In the presentation the U.S. Soap and Detergent Association made to the Reuss Committee and International Joint Commission, seven functions of phosphates in detergents were listed.

Phosphates were said to:

(1) increase efficiency of the surfactant;
(2) keep dirt particles in suspension;
(3) furnish necessary alkalinity for proper cleaning;
(4) buffer water against changes in alkalinity;
(5) emulsify oily and greasy soils;
(6) soften water by tying up objectionable minerals (iron, calcium, magnesium);
(7) reduce levels of germs on clothes.

Given such a list, it seems inconceivable that any other single ingredient could be found to fulfill all seven essential functions. On closer inspection, however, the functions turn out to be three:

(a) to soften water (numbers 1 and 6);
(b) to create and maintain high alkalinity (numbers 3 and 4);
(c) to remove dirt particles (numbers 2 and 5).

The role of detergent phosphates in reducing germs on clothes was perhaps primarily mentioned for its psychological effect. If detergent phosphates had been that essential for the elimination of germs, they would have found unique application in medicine, rather than in washing machines.

The prime function of detergent phosphates among the three listed is in softening water, thereby preventing calcium and magnesium ions from forming inactive complexes with surfactants and insoluble precipitates with soaps. *Detergent phosphates, in other words, are primarily disposable water softeners.* There is nothing unique about them, either in this regard or in the creation and maintenance of high alkalinity. Detergent phosphates do, however, have a special effect in suspending particles of dirt and soil, but the high concentrations used in 1969 were quite unnecessary for that purpose.

For those who might ask why a water softener has to be disposable, the answer is that it doesn't. An ordinary water softener (or, for that matter, soft water) in the supply line to a washing machine can achieve the same result as any disposable water softener. A major part of the problem of detergent phosphates is that manufacturers understandably want to make sure their product works well under the worst conditions. They therefore added far more builder than is necessary in most areas, in order to guarantee good performance in areas of very hard water. This matter will be returned to later, when the balance between clean clothes and clean lakes is examined. Before that, however, some of the environmental arguments used by the detergent industry deserve a "hearing" on their own.

Several environmental arguments were brought forward by the U.S. Soap and Detergent Association and the scientists who supported their stand at hearings of the Reuss Committee and the International Joint Commission. These tended to minimize the importance of phosphate (particularly detergent phosphates) as a factor in the cause and control of eutrophication. A detailed examination of these arguments leads one to conclude that at the time of the hearings, one or both of two things must have been true: detergent manufacturers were either incredibly ignorant of the environmental impact of their products, or they realized the impact but decided to ignore it. To bring this out, a few of the more prominent environmental arguments are cited, together with errors and a statement of rebuttal.

> *Argument 1* "There is no conclusive proof at this time that detergent phosphates are the key element in accelerated cultural eutrophication. Indeed, there is a growing body of facts in scientific circles that suggests that nutrients other than phosphates or combinations of nutrients may be much more critical and perhaps more easily controlled in triggering this water problem . . . To single out only one nutrient, such as phosphate,

is unrealistic in attempting to control the accelerated growth of algae and other symptoms of eutrophication." (Quoted from the statement of the U.S. Soap and Detergent Association at the Reuss Committee and IJC hearings.)

Error The real problem was not the cause of man-made eutrophication, but how to bring man-made eutrophication under control. Since heavy-duty laundry detergents in 1970 contained phosphates, they were implicated as contributing factors to both cause and control. The Association not only confused cause with cure, but created the erroneous impression that there is something unique about detergent phosphates in regard to eutrophication, which there is not. They added further chaos by magnifying, out of all proportion, exceptions to the rule. This was irresponsible in an area of major public concern.

Rebuttal The topic under discussion was control of eutrophication, not cause (except insofar as it pertained to control). *Among the various nutrient elements required by aquatic plants, only phosphorus is controllable by man to an extent that can reduce the incidence of algal blooms.* By reducing man-made supplies of phosphorus to lakes, phosphorus can be made growth-controlling, regardless of whether it is or is not at the start. Finally, the removal of phosphate from sewage has the same effect on algal growth in most receiving waters as the removal of all nutrients combined.

Argument 2 "Complete elimination of phosphorus from detergents, sewage, and industrial wastes discharged into Lake Erie would still result in average phosphorus concentrations of 40 micrograms per liter, four times the accepted level for algal control." (Quoted from the statement of the U.S. Soap and Detergent Association at the Reuss Committee and IJC hearings.)

Error Whoever made this calculation neglected to take into account the fact that 85% of phosphorus entering Lake Erie each year is removed from the water by natural processes, and deposited as sediment. Also, the "commonly accepted level" of phosphorus for algal control is 10 micrograms of *inorganic* phosphorus per liter. The corresponding level of *total* phosphorus (more pertinent to this calculation) is two to three times that amount.

Rebuttal Taking both errors into consideration, the calculated level of inorganic phosphorus in Lake Erie under the stated conditions should have been 3 micrograms per liter, well below the accepted level for algal control. (Actually, it is very doubtful if the true level in late winter could ever be as low in the western basin as this calculation suggested.)

Argument 3 Phosphates released from sediments in shallow lakes will stimulate algal growth even after removal of phosphates from detergents and at sewage treatment plants. (My summary of a statement presented by the U.S. Soap and Detergent Association at the Reuss Committee hearings.)

Error This was a tactical error as it suggested the importance of phosphate to algal growth. More significantly, it showed a lack of understanding of the behavior of phosphorus in lakes.

Rebuttal The *net* flow of phosphorus is from water to sediment, rather than the other way around. If, however, the release of phosphorus from sediments is as important as claimed, it adds more weight to the immediate necessity of a program for phosphorus control. The logic is simple — the more phosphorus that goes into a lake, the more stored in sediments available for release at a later time, and the longer it will take to control man-made eutrophication once it has started.

Argument 4 The addition of nutrients to samples of water from the western end of Lake Erie shows that phosphorus is neither the sole nor the main factor limiting algal growth. *Nitrogen limits algal growth more than phosphorus.* The removal of phosphates from detergents and at sewage treatment plants will therefore not solve eutrophication problems in Lake Erie, because phosphate is not the main controlling factor. (My summary of the statement of Dr Willy Lange at the hearings of the International Joint Commission.)

Error The cause of eutrophication (nutrient enrichment) is confused with the suggested cure (phosphate depletion). Also, the fact that nitrogen limits algal growth more than phosphorus in the western end of Lake Erie can be interpreted as evidence of phosphate pollution.

Rebuttal Sewage effluents contain high concentrations of phosphorus relative to other elements required for the growth of aquatic plants. As a result, one of the typical responses of unpolluted lakes to the addition of sewage effluents is the change from a state of phosphorus deficiency to a state of nitrogen deficiency. This is because of the high ratio of inorganic phosphorus to inorganic nitrogen in sewage (1P:4N by weight) relative to the needs of plants (1P:7N by weight) and the supply from natural sources (1P:14N by weight). The fact that in 1969, algal growth in the western end of Lake Erie was more limited by nitrogen than phosphorus only showed that the area was heavily polluted with phosphorus, probably from detergents.[30] The elimination of man-made supplies of phosphorus may not solve all of the eutrophication problems of Lake Erie, but it will certainly reduce those brought about by man.

Other arguments could be used to illustrate the unfortunate position of the detergent industry in greater detail; however, the four cited above suffice to make the point. The industry was environmentally illiterate at the time.

It remains now to ask how a better balance can be achieved between clean shirts and clean lakes. In a number of similar environmental controversies since World War II the scales have been tipped sufficiently to merit discontinuation of atomic explosions in the atmosphere and the use of mercury and DDT, to mention only three

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[30] Nutrient deficiences in nutrient-polluted lakes can be very misleading and should never be used as a basis for control measures. The important facts are what the limiting nutrient was *before* nutrient pollution, and the extent to which the total supply to water can be controlled by man.

instances. There is one case, however, well known to the manufacturers of detergents in which the scales were tipped and readjusted with considerable success. This was in relation to biodegradability of surfactants in detergents.

When synthetic surfactants were first introduced on a large scale at the close of World War II, they were greeted with enthusiasm. They cleaned dishes and clothes efficiently and without formation of insoluble precipitates and greasy scums, as had been the case with soaps. During the 1950s however, environmental problems appeared. In the vicinity of sewage treatment plants, and in waters downstream from major communities, unsightly and persistent foams accumulated wherever water was churned. In some areas dirty, brown-colored foams blew for miles around the countryside on windy days, creating health hazards and unpleasant sights (Fig. 3).

Under U.S. governmental pressure the detergent industry solved the problem. A relatively minor change was made in the chemical structure of synthetic surfactants that made them more susceptible to biological degradation. The foams disappeared. Detergency remained unimpaired. The entire ecosystem benefitted.

The phosphate problem, on the other hand, was not one that biodegradation could solve. The polyphosphate compounds used in detergents readily break down in water to form inorganic phosphate ions, which are then actively taken up by organisms, but not broken down.

The possible solutions to man-made eutrophication, that can be achieved through treatment of sewage to remove phosphate, were examined in the chapter "The Environmental Physician." The question now is how the amounts of phosphorus used in detergent formulations might be separately reduced.

Three important components of the cleansing process are often overlooked in our obsession with detergents as an essential feature of modern life. These are water, mechanical energy, and high alkalinity (*p*H). Water acts by its solvent effects, mechanical energy by loosening dirt and exposing the surface to be cleaned, and alkalinity by loosening and suspending particles of dirt. On the banks of the Ganges many women wash clothes of the well-to-do without any soap or detergent at all. They use washing soda (sodium carbonate — an alkaline salt), water, and muscle power. The clothes come out spotlessly clean.

The importance of water as a cleaning agent was neatly brought out during the hearings of the Reuss Committee by citing the results of tests conducted at Marquette University in the United States. These tests involved a comparison of the cleaning power of; (1) Heinecke's "no-phosphate B-5"; (2) Procter & Gamble's Tide; and (3) water alone. Here is the story as it was presented[31]:

> "Four dozen new white cotton diapers were employed for the test. All except three diapers were soiled thoroughly with water containing garden soil, and dried. Just prior to washing, the corners of all the diapers were stained with a barbecue sauce and randomly divided into three piles of 14 diapers each. Three soiled diapers were set aside for comparable purposes. Each load of diapers was washed separately in a recent model automatic clothes washer using a hot water wash for 14 minutes and warm rinse. One load was washed in plain water (Milwaukee water hardness is about 120 milligrams per liter as $CaCO_3$), the other was washed with one cup of Tide (77 grams), and the third was washed with the same weight of B-5 (77 grams). After the washing cycle, the clothes were dried for 40 minutes in a gas dryer. The three loads were compared with the original new diapers, the soiled diapers and with each other. ....
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> "Admittedly it is difficult to come to any final conclusion on detergency on the basis of the limited data available. A visual comparison was made of the three loads in comparison to new diapers and the soiled diapers. Below are presented the relative results of six observers (three men and three women)

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[31] See "House of Representatives" in the References.

under daylight, incandescent, and fluorescent lighting conditions. The lowest number indicates the best detergency conditions."

	Water	Tide	B-5
I. Whiteness (none matched whiteness of new fabric)	2	1	3
II. General cleanliness (removal of soiling)	1	1	1
III. Stain removal	1	3	2

Quite different results would probably have been obtained, of course, had the tests involved grease spots or soils on cuffs or collars of shirts. Nevertheless, the results illustrate superbly the importance of water as a cleansing agent.

To the three factors of water, mechanical energy, and alkalinity, a surfactant is added that spreads out and emulsifies greasy and oily materials. Last is the builder, which is there primarily to complex ions that interfere with the efficiency of the surfactant. Looking at it this way, the detergent phosphate problem doesn't seem hard to solve. Here are some of the possible solutions:

(1) Do away with automatic machines since they are the only places where phosphate builders are extensively used. (An unnecessary step that would create as many or more problems than it solved.)

(2) Shift over to European-type washing machines that operate at higher temperatures, use less water and less detergent.

(3) Revert to soap. (Only a few eco-freaks and some mothers with children in diapers are in favor of that on a large scale.)

(4) Package builders separately from the remaining components, adjusting the amount of builder to the hardness of water in each home.

(5) In hard-water areas, use an ordinary water softener for water leading to automatic washing machines.

(6) Use a liquid detergent in conjunction with washing soda for laundry operations, automatic or not. (Dr Alan Prince, Director General of Environment Canada's Inland Waters Directorate in 1970, said his wife had been doing this for years.)

(7) Reduce phosphate content of heavy-duty laundry detergents to less than 5% expressed as P_2O_5. This would have only a negligible effect in homes supplied with soft water, though it would reduce cleansing efficiency in hard-water areas.

(8) Develop replacement builders that are more friendly to the environment.[32]

(9) Be a little dirtier with a more "human" smell (not appealing to many members of society).

When the detergent industry addressed itself to the problem, only number (8) was seriously considered as a solution. Although several hundred replacements for sodium triphosphate had been tested, only a few showed promise in terms of all requisites to be fulfilled — cost, fabric safety, enhancement of cleansing power, machine safety, environmental acceptability, and lack of hazards to human health. In 1970 a compound called NTA, sodium nitrilotriacetate, was the most prominent of all the contenders. Its history is discussed next.

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[32] All governments have wisely been extremely cautious in giving even the slightest suggestion of approval to any replacement for detergent phosphates. This is particularly true of the United Kingdom, many European countries, and a number of areas in the United States where the recycling of water because of high population density can be appreciable. In some areas it is not uncommon to find 3–30% of ordinary tap water is derived from domestic and industrial wastes upstream. Under such conditions toxicity and biodegradability become of paramount importance.

Chapter 8

THE YEAR OF NTA

In which the hazards of NTA to the environment, human health, and politicians are described in the context of the detergent phosphate controversy in North America.

It is often half-jokingly said in scientific circles that, for every chemical compound headlined by science or industry today, there is always some German chemist who first isolated or synthesized it in the 19th century. Nitrilotriacetic acid (NTA) is not an exception to this rule. W. Heintz of Germany first described its isolation and synthesis in an article published in *Annalen der Chemie* in 1862.

Heintz was studying the reaction products formed when ammonia and chloroacetic acid were mixed together. He identified four products, all derivatives of acetic acid — hydroxyacetic acid, aminoacetic acid, iminodiacetic acid, and nitrilotriacetic acid (NTA). So far as is known, Heintz gave no thought to the possible industrial significance of any of these compounds, nor did any other chemist for a period of 73 years.

In 1935 Dr F. Muntz, working at the I. G. Farbenindustrie plant in Mainkur, Germany, began examining the possibility that aminopolycarboxylic acids such as NTA might be of use in the dyeing and textile industries. When Muntz repeated Heintz's study of the reaction between ammonia and chloroacetic acid he noticed an unusual property, one that turned out to be of considerable importance to the commercial interests of I. G. Farbenindustrie. Muntz observed that something in the reaction mixture interfered with the precipitation of calcium and magnesium salts.

The significance of this observation lay in the fact that doubly and triply charged ions, such as calcium, magnesium, iron, and aluminum, are a common cause of problems in dyeing processes due to formation of insoluble precipitates with dyes. If these or other metallic ions reach appreciable concentrations in dye baths, uneven and unpredictable coloration of fabrics can result. Following the general rule that an ounce of prevention is worth a pound of cure (as true in the chemical industry as it is in medicine) Farbenindustrie was actively searching for materials that could prevent the formation of precipitates.

When Muntz discovered the principal calcium-binding compound in the reaction mixture was NTA, Farbenindustrie immediately took out patents for its use in the dye and textile industry. Production was initiated in 1936 and the first lots distributed under the trade name Trilon A in 1937.

Another compound similar in general structure to NTA was also marketed by Farbenindustrie at about the same time. Originally called Trilon B, it is now more commonly referred to as EDTA (ethylenediaminetetraacetic acid). As a result of its lower production cost and greater complexing strength, EDTA rapidly eclipsed NTA in terms of scientific and industrial use.

NTA and EDTA are members of a class of chemicals known as aminopolycarboxylic acids. Similar to amino acids that make up body proteins, the principal significance of these compounds lies in their ability to form water-soluble complexes with metal ions. The structure of the NTA-metal complex resembles that of a human hand enclosing a tennis ball — the thumb corresponding to the amino group of NTA, three of the fingers to the carboxyl groups of NTA, and the tennis ball to a metal ion.

Complexing lowers the concentration of free metal ions in solution, preventing participation of these ions in other chemical reactions. For example, NTA and EDTA are effective in preventing formation of boiler scale (calcium carbonate) and beer stone (calcium oxalate). They can also be used to dissolve precipitates.

The use of EDTA in the dyeing and textile industry was followed by its application in electroplating, developed by H. Brintzinger in Germany during the early part of World War II. Shortly after this, Gerold Schwartzenbach of Zürich began a detailed series of investigations of the structure and properties of aminopolycarboxylic acids. Since that time EDTA has found a wide variety of applications — in water softening and removal of boiler scale; in cosmetic and pharmaceutical industries; in manufacture of rubber, polymers, and plastics; in the leather industry; in photographic processes; as a food preservative; in plant nutrition studies; as a food additive; and in beverages. The principal role played by EDTA in these various applications is the complexing of metal ions, thereby preventing formation of unwanted precipitates or oxidation reactions catalyzed by metal ions.

In contrast to EDTA, NTA remained as a "specialty" chemical because of its comparatively high cost per unit weight of complexing power. This changed in 1959 when the U.S.-based Hampshire Chemical Corporation, later to become a division of W. R. Grace & Co., developed a new process that not only reduced the manufacturing cost of NTA but also increased the purity of the product. The first commercial use of NTA was as a water-softening and water-conditioning agent.

When the capability for U.S. production of NTA increased in 1966 with the expansion of Hampshire Chemical's facilities, widespread consideration was given to other possible uses—among them, the possibility that NTA might replace sodium triphosphate (STP) in detergents. NTA was more expensive than STP, roughly 12–14¢ versus about 8¢ per pound (U.S. prices) in large industrial lots, but it was also 1.4–1.8 times more effective than STP in water softening per unit of weight. The cost differential still favored STP as costs are calculated by industry. The true comparison was unknown in terms of overall ecosystem costs — the total costs, taking all human and environmental matters into consideration.

One of the first companies to scrutinize NTA as a detergent "builder" was Procter & Gamble. This was not accidental. It illustrates a general evolutionary rule, as true in the competitive world of industry as it is in the competitive world of biology, that as soon as a new product meets with success on the market, work begins to develop newer and better substitutes.

Procter & Gamble was responsible for the introduction of Tide in 1947, a product that received a phenomenal reception from the buying public. The secret of Tide lay in the combination of a synthetic surfactant with STP. Both these chemicals were being produced industrially in the 1930s, although for separate purposes. Procter & Gamble chemists discovered that when the two were put together a super-detergent product was created. When Tide was being developed, however, STP was not available in the quantities required. New manufacturing facilities had to be constructed and extended purchasing commitments made before it became a commercial reality. Building on the tremendous success of Tide, P & G continued to search for new and improved formulations.

By the time of the phosphate controversy in 1969–70, Procter & Gamble had processed several hundred compounds as potential replacement builders for STP. Each of these, alone and in combination with other detergent ingredients, had to pass through screening tests designed to meet four primary criteria — effectiveness in enhancing cleansing action; safety to fabrics and washing machines; safety in terms of household use and human health; and environmental acceptability. While none of the compounds tested showed the same across-the-board performance as STP, there was one that looked exceedingly good as a partial replacement. It was NTA.

From information presented by Procter & Gamble to the Subcommittee on Air and Water Pollution, chaired by Senator Edmund Muskie, in the spring of 1970 it emerged that the company had been working on NTA since 1961, one year before the Hampshire patent was issued. Procter & Gamble further told the Muskie Subcommittee that between 1965 and 1969 more than $11,000,000 had been spent on development and testing of replacements for STP. The estimated budget for 1970 was $3,500,000.

In spite of the fact that Procter & Gamble, more than any other company, had the largest body of information on all aspects of NTA, it was not the first company to market a detergent product containing the compound. That honor, or discredit as the case may ultimately be viewed, belongs to A. B. Helios in Sweden, who began marketing detergents containing NTA as a partial replacement for STP in 1967.

The extent to which A. B. Helios tested the environmental and human health safety of NTA is not entirely clear, though it was far less than Procter & Gamble had done. As a result of the happy combination of a good sales promotion, effective products, and a phosphate-conscious public, by 1970 NTA-containing detergents had captured 15% of the laundry detergent market in Sweden.

Why did Procter & Gamble delay doing anything other than test-marketing two products slightly enriched with NTA? One reason was the stickiness of the trisodium salt of NTA. Even when mixed and diluted by other ingredients it tended to collect moisture, becoming stickier than salt in a shaker on a humid day.[33] The problem is not insoluble, but it does create difficulties in both manufacturing and packaging. Another reason Procter & Gamble held off — hard as it may be for environmentalists to understand — was that the company did not feel there was sufficient environmental and human safety information about NTA at that time. Knowing more than any other company was evidently not enough. The reason? Perhaps because, as is the case with all large companies, P & G is so visible it cannot be irresponsible and survive.

The year 1970 will go down in the annals of detergent history as the year of NTA. NTA burst into leaf in February and then, one day in December, was suddenly killed by a frost. From the controversy over its use in detergents, discussed at the highest levels of government in the United States, Sweden, and Canada, it is uncertain

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[33] Since STP breaks down (hydrolyzes) in the presence of water, its use is restricted to solid detergent products. NTA does not readily hydrolyze in water and can be used in liquid products.

whether it will ever flower again. The case is of particular interest because NTA had been studied more than most synthetic chemicals for its effects on human health and the environment. An analysis of the way it was viewed by government, industry, and the public in 1970 shows how drastically views on the environment had changed since World War II.

The year began with the hearings of the International Joint Commission on water pollution in lakes Erie and Ontario, in late January and early February. Those present at the six hearings saw little need to await the final report of the Commission in regard to the recommendation on phosphates in detergents. From statements made by representatives of the two governments at the hearings, it looked as though Canada, the United States, and the Commission would probably all push for a zero level of phosphate in detergents "soon," if not by the end of 1972. Canada announced it would introduce preliminary regulations on the phosphate content of detergents within 6 months.

Even before the representatives of government and industry departed for their homes, steps were being taken at their head offices to prepare the ground for the next strategic moves. Recognizing the rules had completely changed, a number of detergent manufacturers rolled up their sleeves to meet the new situation. Among the various replacements discussed were: NTA, citric acid, polycarboxylates, carbonates, and silicates. Assuming that NTA would become a "chemical of consequence," government workers immediately planned a broad assessment of the environmental effects of NTA.

Aware of variations in composition of different batches of chemicals produced on a large scale, the manufacturing industry made available a ton of NTA from several sources for various scientific tests. The sample was thoroughly mixed and subpackaged by a U.S. government agency for distribution to various other agencies in Canada, Sweden, and the United States.

Government plans called for a diversified array of environmental tests. Among these were the effects of NTA on: fish and other forms of aquatic life, photosynthesis and reproduction of algae, release of heavy metals from sediments, sewage treatment processes, integrated behavior of freshwater ecosystems, movements of metallic ions in groundwater, soil systems, and last, but not least, human health.

In addition, studies were made of the breakdown rate of NTA under various natural conditions, adaptation times of microorganisms prior to metabolizing NTA, susceptibility of various NTA-heavy metal complexes to biological breakdown, decomposition, products and prediction of equilibrium concentrations of NTA and NTA-heavy metal complexes under various conditions.

One of the more amusing, though frustrating, incidents during these investigations was the complete destruction by the resident muskrat population of a long-term experiment involving 20 plastic enclosures suspended on floats in Clear Lake, Man. Dr Robert D. Hamilton, in charge of the Fisheries Research Board of Canada's (now Fisheries and Marine Service, Department of the Environment) work on NTA, couldn't quite believe it when he heard the news. Burrowing into the floats of the platform supporting the tubes, a family of muskrats had found styrofoam to be a modern home-building material very much to their taste. Easy to chew and with excellent insulation qualities, the muskrats were more than delighted with the improved living conditions Dr Hamilton provided.

When the research team arrived one day to take their weekly samples from the tubes, they found everything in chaos. Fooling around on top of the float, some muskrats had fallen into the open tubes, scratching and biting through the thin plastic in order to escape. All the plastic enclosures were ruptured. To complete the farce, the muskrats chewed off the four guy lines that anchored the float, setting the raft adrift on the lake. As Hamilton dejectedly viewed the mess, he couldn't refrain from thinking what an excellent coat the muskrats would have made, valued at about $50,000 in terms of the damage done.

One of the most serious deficiencies in regard to NTA at the beginning of 1970 was the lack of a sensitive, specific, and accurate method of analysis for use in natural environments. The only standard technique available was based on the complexing power of NTA for metal ions. The problem was that in natural soils, sediments, and water, there are many natural complexing agents. Under ordinary conditions of analysis with the standard technique, these were indistinguishable from NTA.

Fortunately, before most of the studies were under way, Dr Peter Goulden and Dr B. K. Afghan of Environment Canada's Water Quality Branch developed a specific and sensitive polarographic method for analysis of NTA. Within a few months several other methods based on gas chromatography of NTA derivatives were also available. Without these methods, many questions regarding NTA would have remained unanswered at a critical time. At the start of 1970 the standard method was nonspecific and only useful for concentrations of NTA above 0.2 part per million of water. At the close of 1970, several specific methods had been developed permitting specific detection of 0.01–0.02 part per million of water. Methods are now available that can detect as little as 0.001 part per million of NTA in water.

As tests to determine environmental acceptability of NTA were being developed by scientists working in various government agencies, industries, and universities, new products started appearing on supermarket shelves with "no phosphate" labels. What they contained was almost anyone's guess, for there were no legal requirements for labeling at the time in either Canada or the United States. Some contained NTA, while in others borax and washing soda (old-fashioned chemicals for softening water) took the place of STP. On chemical analysis one product turned out to contain 50% of common salt, an ingredient that could only have been used to make the weight of the box seem good for the price.

The reports of the Reuss Committee and the International Joint Commission appeared in early spring 1970, both recommending the elimination of phosphates from detergents by 1972. Procter & Gamble beat them to the gun with a full-page advertisement in a number of prominent U.S. and Canadian newspapers stating they were on the team. Without admitting any proven connection between detergent phosphates and man-made eutrophication, the advertisement said that P & G was prepared to cooperate just on the *possibility* such a connection might exist. A Procter & Gamble product would soon appear on the market with a 25% replacement of STP by NTA.

Other manufacturers likewise came out with new products and packages. Companies with a small cut of the detergent market entered in a burst of glory with grandiose claims, while large companies apologized for being forced to market products that, while good, were said to be inferior to their previous products. Detergent products began to appear from manufacturers that no one had heard of before. There were persistent rumors that the Mafia had entered the field. For a while it seemed as though cleanliness and even sex appeal had been replaced by environment appeal — witness the names of products such as *Concern*, *Ecolo-G*, and *Un-Polluter*. New STP substitutes, including NTA, were slowly entering the environment.

As the year of NTA advanced, reasons for the importance attached to NTA as a replacement builder became apparent. In testimony before the "Muskie" Subcommittee on Air and Water Pollution (of the Senate Public Works Committee) in May, William C. Krumrei of Procter & Gamble revealed the extensive testing of NTA the company had performed in regard to human and environmental safety. Because of possible interactions with other compounds many tests had to be performed not only with the trisodium salt of NTA (the probable form of NTA in detergent formulations) but with NTA as part of specific formulations likely to be used. The list of human safety tests performed by P & G, reproduced below from testimony presented by William Krumrei, reveals some of the many questions to be answered by a responsible company, before a product is marketed in the modern world. The Chronic Feeding Study involved three levels of NTA in diets fed to rats over a period of 2 years. Headings discussed by Krumrei in relation to human safety were as follows:

> Routine-Type Animal Studies (acute oral toxicity, emetic activity, eye irritation, percutaneous toxicity); Human Skin Studies (sensitization tests, laboratory skin tests, clinical mildness tests, diaper clinical test); Metabolism Studies; Reproduction and Embryogenic Studies; Sub-Acute Feeding Studies

(mineral excretion, manifestations of toxicity); Chronic Feeding Study; Estimation of Maximum Level of Human Ingestion of NTA from Detergents (residue from dishes, pots and pans, residues in tap water); Determination of Factors of Safety (chronic toxicity, teratogenesis); Safety as Regards NTA Contribution to Nitrate Levels; Inhalation Studies; Carcinogenicity Testing; Mutagenicity Testing; Enzyme Studies.

In addition to the above, P & G had done sufficient testing to be assured that NTA was biodegradable in sewage treatment and the natural environment, and that there was no danger to human health or the environment at a level of 25% replacement of STP. In the text of the prepared statement released in May 1970, the company indicated that in order to meet its objective of a 25% replacement, orders had been placed for $167,000,000 of NTA. The company had also committed $6,800,000 as capital expenditure to modify existing facilities. Procter & Gamble was going all the way.

Dr Samuel S. Epstein of the Children's Cancer Research Foundation, Inc., and the Harvard Medical School also presented testimony before the Muskie Subcommittee in May 1970. Dr Epstein raised many unanswered questions about NTA. One was the possible significance of NTA in increasing nitrate levels in water. (Nitrates and nitrites are implicated in methemoglobinemia, a condition of reduced oxygen transporting power of the blood due to inactivation of hemoglobin by nitrite. Infants are especially sensitive to this condition.) He also raised the specter that NTA transformation products might be carcinogens (cancer-causing agents), teratogens (agents causing birth defects), or mutagens (agents causing mutations in cell nuclei). Finally, would use of NTA in detergents create problems in redistributing heavy metals or enhancing their toxicity to humans?

In contrast to this last suggestion, one of the earliest proposed uses of NTA in the environment was to *reduce* the toxicity of metals such as zinc and copper to fish. Dr John Sprague, then at St. Andrews Biological Station of the Fisheries Research Board of Canada (now Fisheries and Marine Service, Department of the Environment), had shown that NTA protected Atlantic salmon and other fish from toxic effects of copper and zinc released from base-metal mining activities.[34] From a fish's point of view NTA apparently looked good. But what was the case for humans?

Toward the end of the summer of 1970, plans were developing for a closed meeting of government scientists from Canada, Sweden, and the United States to assess the environmental acceptability of NTA. The meeting was scheduled for the Canada Centre for Inland Waters in Burlington, Ontario, December 8–10, 1970.

As delegates assembled the night before the meeting, it was apparent something unusual was in the wind. The next day, Dale Chernoff and Diane Courtney, two scientists from the U.S. National Institute of Environmental Health Sciences (NIEHS), presented results interpreted as showing that NTA had enhanced the toxicity and teratogenicity (production of birth defects) of cadmium and methyl mercury administered to rats and mice.

The primary question was whether the experiments were pertinent to normal household use of NTA-containing detergents. The cadmium experiments were performed by injecting solutions into experimental animals. The concentrations of chemicals used were high. More problematic, some of the supposedly inert components of the test materials were varied in an unsystematic way, invalidating certain conclusions. The investigators themselves stated they did not know how to place the results in the perspective of real life. In short, the experiments were poorly designed, with no interpretation of how the results pertained to the projected use of NTA.

Following the presentation of results from other NTA experiments, none of which was damning, the general feeling on the part of scientists present was that NTA would hang under a heavy cloud of suspicion until the NIEHS report could be properly interpreted. The results had to be released because of their possible importance. Yet, without time for documentation and perspective, what official stand could be taken, but against NTA? Having taken such a stand,

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[34] The rationale for these first environmental studies on NTA was based on fish protection. Perhaps environmental benefit should be a basis for selecting components of detergent formulations.

could NTA ever recover, even if lily-white pure? For all practical purposes, it looked as if NTA was as good as dead, perhaps more for psychological reasons than for considerations based on environmental or human health.

In terms of a zero-risk policy there was only one thing to do — stop the use of NTA until the situation with respect to human health could be more clearly defined. At least, that was the U.S. government view. As will be seen later, Canada and Sweden took a different stand.

Events moved rapidly in Washington after the December 8–10 meetings in Burlington. Following high-level discussions, a series of calls went out to manufacturers connected with the soap and detergent industry on Wednesday, December 16. The message simply stated that corporate officials of the various companies might wish to attend a meeting pertaining to an urgent decision on NTA, at 4:00 PM, Thursday, December 17.

At the appointed hour, the U.S. Surgeon General and the Environmental Protection Agency Administrator told the Industrial executives the Chernoff–Courtney findings. Without any time to digest the findings, the big three detergent manufacturers agreed to cease production of NTA-containing detergent products. The executives were disturbed by the knowledge that U.S. government officials had discussed the findings with scientists from other countries before revealing them to U.S. manufacturers.

On December 18, 1970, a joint statement was issued by the Surgeon General and EPA Administrator. It began, "We commend the major detergent manufacturers for their voluntary action to discontinue the use of NTA (nitrilotriacetic acid) in the manufacturing of detergents, pending further tests and review of recently completed animal studies[35] ...."

Repercussions from the December 18, 1970, NTA announcement were still being felt in some quarters in 1972 and perhaps may continue for years. The suddenness of the shock, lightning reactions, and governmental pressure still seem incredible to those adversely

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[35] STP was not put through all the tests that NTA had to pass. If the situation had been reversed, it is doubtful if STP would have survived the screening.

affected. The ignition keys to the NTA production engines at Hampshire Chemical and Monsanto were turned off even before company representatives had returned from Washington. Detergents lacking both phosphates and NTA began an upward surge in sales. The costs to some industries were immense. It is said that Procter & Gamble wrote off $7,100,000 in binding contracts to purchase NTA.

With the U.S. federal government holding off any official regulations to limit the phosphate content of detergents, states and municipalities began to take action on their own. Regulations were enacted in New York and Indiana similar to those in Canada; and in 1972 bills were pending in many other parts of the country. Russell Train, Head of the Council on Environmental Quality, and Dr Charles C. Edwards, Head of the Food and Drug Administration, joined Surgeon General Steinfeld and EPA Administrator Ruckelshaus for the next major announcement, issued September 15, 1971. Without any specific evidence of harmful effects, and despite a refutation of the Chernoff–Courtney work, they urged that NTA "should not be used in detergents at this time because of unresolved questions concerning its possible long-term effects on health and the environment." Cautioning against increased use of detergents containing caustic materials as substitutes for phosphates, they advised the states and their political subdivisions to "reconsider policies that unduly restrict the use of phosphates in laundry detergents." The message seemed to be — phosphates in detergents are good, let's keep them and get on with removing phosphate at municipal treatment plants.

An editorial in the Toronto Globe and Mail called the statement a "shabby turn-about." H. W. Poston, Commissioner of Environmental Control for Chicago, and Jerome Kretchmer, New York City Environmental Administrator, termed the federal pressure for removal of phosphates at sewage treatment plants as tantamount to a federal order for subsidization of the detergent industry by taxpayers in Chicago and New York City.

* * *

The Canadian reaction following the presentation of the Chernoff–Courtney report at the December 8–10, 1970, meetings contrasted with that of the United States.[36] The first step was to dispatch a team of experts from the departments of National Health and Welfare, and Environment to the U.S. National Institute of Environmental Health Sciences in Chapel Hill, North Carolina, where the Chernoff–Courtney findings were discussed in detail.

Next there was a meeting of government scientists on January 6, 1971, to discuss the scientific basis of policy recommendations to be made to the Hon Jack Davis, Minister-designate of the new Canadian Department of the Environment. In the opinion of those present, the Chernoff–Courtney experiments were not considered pertinent to real life. The experimental design was defective and, although of interest, the results from injecting NTA in experimental animals were uninformative in terms of intended use. There was cause for a cautious approach to NTA, but in the opinion of the Canadian environmental scientists, not one that called for a ban.[37]

What the Canadian scientists said in effect was — there is no such thing as a no-risk policy. Everything in life, even decisions not to do something, inevitably carry a risk. From environmental and human health points of view, if a fraction of a part per million of NTA in natural waters looked bad, then the occurrence of several hundred parts per million of EDTA as additives in some human foods looked worse. The group recommended the Chernoff–Courtney experiments be repeated, extended, and interpreted in an environmental context; that possible effects of EDTA as a food additive be examined; that the NTA question be recognized; but no recommendation on NTA pro or con be given.

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[36] Canada had already enacted a regulation under the Canada Water Act, limiting the phosphate content of heavy-duty laundry detergents to a maximum of 20% as P_2O_5 (8.7% as P) after August 1, 1970. This was the first regulatory action taken in North America to limit the phosphate content of detergents.

[37] To the time of writing no government has imposed any ban or restriction on the use of NTA. The U.S. action merely forced the three major detergent manufacturers to desist from marketing NTA-based detergents for an interim period until further health tests could be performed.

After receiving this information, Mr Davis scheduled a meeting for February 17, 1971 with leading Canadian manufacturers involved directly or indirectly in the soap and detergent industry. Stating that he intended to announce governmental policy on maximum phosphate levels in detergents in a few weeks, he asked industrialists to express their views as to what he should say — either at the meeting or by separate mail. The industrialists did both. As agreed, the Minister-designate of the Department of the Environment held the industrialists' views in confidence.

On April 8, 1971, Mr Davis issued a news release indicating the maximum permissible levels of phosphates in detergents previously set at 20% P_2O_5 (8.7% as P) on August 1, 1970, would be further reduced to 5% as P_2O_5 (2.2% as P) on December 31, 1972. Despite pressure from segments of industry, he said nothing about NTA. After a review of new information and a further meeting with industrial representatives on May 11, 1972, Mr Davis reaffirmed his position and the regulation went into effect January 1, 1973.

Where does this leave us with respect to NTA? Unfortunately there is no simple answer, other than to say that it is a matter of scientific evaluation by specialists and of public desire. None of the evidence I have seen (up to 1974) suggests NTA or its metabolites would cause mutations, cancer, embryonic malformations, or enhanced toxicity of heavy metals more than STP under the same conditions. While some deleterious effect could always turn up, NTA has been examined in far greater detail than most synthetic compounds in use. In the final analysis, the only effective test of acceptability of NTA will be through a slow buildup in use, with close monitoring along the way. This started in Sweden in 1967 and in Canada in 1970.

In a report dated April 1, 1972, Arthur D. Little, Inc., listed concentrations of NTA in samples of tap water from communities in Long Island, N.Y., and several Ontario cities. The results averaged less than 0.025 part per million (the level of detection), with some waters extending into the range of 0.025–0.10 part per million. These values were in line with predictions and within allowable limits using a safety factor of 100. (A safety factor of 100 assumes daily intake could be up to 100 times the maximal predicted amount without evidence of harm.) The report concluded that there was a very low probability of environmental or human hazard, but advised continued monitoring and research to assure environmental and human safety.

Perhaps, in the end, the separate decisions of Canada and the United States were both wise. Because of its lower population size and abundance of water Canada has more flexibility than the United States in relation to "chemicals of environmental consequence," particularly for wastes with water-borne effects. With the same per capita production of wastes, environmental outputs are in the ratio of 1 Canada to 10 United States. In terms of NTA as a replacement for STP in 1970, it meant 50 million kilograms (110 million pounds) in Canada versus 500 million kilograms (1100 million pounds) in the United States. More important, should the population in both countries double between 1970 and 2010 and per capita use remain the same, the increase in NTA for Canada would be only 50 million kilograms (110 million pounds) as compared to 500 million kilograms (1100 million pounds) in the United States.

A number of things pertaining to more general matters have been learned from the tête-à-tête with NTA. Those I consider important are as follows:

(1) Prior to 1960 any governmental official who made adverse statements about a major industrial product on the basis of tenuous evidence would have suffered politically. In 1970, at least with regard to NTA, exactly the opposite was true. Government officials in all countries wisely feared the consequences of approving a chemical that might later turn out to be a teratogen. This conversion of "go-go" proponents of development into environmental conservatives is a healthy sign. We operated the other way when growth was needed in North America; now it is time to change to a more balanced view.

(2) There is a useful place in society for persons such as Dr Samuel S. Epstein, who persistently draw attention to possible consequences of synthetic chemicals used in high quantities. Even though, up to 1973, none of Dr Epstein's claims that NTA or one of its decomposition products could be a mutagen, teratogen, or carcinogen were proven correct, his challenges created an atmosphere of caution. Who knows, he may eventually turn out to be right? When any chemical is studied in great detail for its total ecosystem effects, something harmful is almost certain to show up. Ultimately, we must learn to be more thorough in our analysis of new chemicals, examining risk-benefit relationships in detail, after placing some maximum limits on risk.

(3) In the final analysis the most important component of the biosphere, to man, will always be "me." That is something we may modify, but cannot appreciably change. In terms of the effects of chemicals, man comes first, property next, and the wild environment last. This is not as bad as it sounds for the wild environment, for it contains many things of interest, if not of crucial importance to man. As we come to understand in more detail what these are, we will protect them with the same fervor we use to protect our more immediate selves.

(4) In his book, *The Closing Circle*, Barry Commoner pointed out that new technological products contributed more to increase the levels of pollution between 1945 and 1970 than growth of either population or affluence. As examples, he cited the use of mercury in the chloralkali industry, non-returnable bottles, fertilizer nitrogen, detergents, and plastics. NTA is a chemical that falls into Commoner's "changing technology" class. In the statements to U.S. officials on NTA, the total quantities involved were said to have played an important part in the decision. High-level government officials should have repeated this 100 times and related the quantities to population.

(5) There is a "demophoric" (population multiplied by technology) growth factor that must be considered in dealing with all "chemicals of consequence" such as NTA.[38] The NTA-on and STP-off switch in the USA in 1970 involved quantities of about 500 million kilograms (roughly 1.1 billion pounds) of NTA. It pertained to 211 million people living in a fossil-fuel powered, high gear, technological state. A comparable decision in 1870 in the USA would have pertained to only 40 million people in a horse-drawn, low gear, technological state. The difference is like making a turn in a car traveling 10 kilometers (6 miles) per hour compared to the same turn in a 20-ton truck at 100 kilometers (60 miles) per hour. The United States has lost considerable flexibility in decisions of this sort, not just because of technology, but because of population and technology combined.

(6) Ecosystem protocols are needed for new chemicals of environmental consequence. These protocols are descriptions of specific tests an industry must perform before governmental approval is given for a particular use. Protocols exist for drugs and food additives intended for human consumption. Now we need them for chemicals of environmental consequence. One of the lessons from NTA is that a sensitive and specific method of analysis *for use in natural environments* must be a requirement of any ecosystem protocol.

(7) Because of the costly nature of obtaining extensive data before even preliminary approval is given to chemicals of environmental consequence ($1–10 million per chemical), some premeditated form of international cooperation is needed. Current (1974) international arrangements are haphazard and unsystematized.

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[38] Demophoric refers to the combined effects of human population and technological production/consumption. The concept of a demophoric explosion expresses more exactly than population explosion and technological revolution what has taken place in the past 200 years. See section on Terms and Definitions also Vallentyne (1972).

(8) Through controversies, such as those involving phosphates and NTA, citizens will eventually come to realize that specialists, including scientists, exist to provide information, not to make communal judgments or be responsible for public ethics. Regardless of what the facts may be the specialists' opinions and interpretations are their own. Citizens and specialists in other fields must realize that if they give their proxies to a specialist, the proxy is for a vote based on the viewpoint of a specialist.

(9) Because of our preoccupation with cleanliness, efficiency, and costs, we tend to automatically assume that when one good thing goes out another equally good thing must come in. Perhaps through NTA, governments may realize this will not always be so, particularly when a country or area is "demophorically fat." Not one, but several kinds of substitutes for STP, may have to be used. Waste diversification for environmental stability may turn out to be just as important as product diversification for economic stability in an industrial or national sense.[39] The two, in fact, ultimately become one and the same. In the 1960s, the detergent industry was not diversified in relation to alternatives to STP. It was like a country dependent for its survival on the culture and export of a single crop.

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One might think from the healthy scepticism governments had of NTA in 1970 that we have entered a new age, with a more balanced view of technological products such as STP and NTA.

Nothing could be further from the truth. NTA just surfaced as a "political" chemical. Other synthetic chemicals in everyday use remain, with long-term consequences largely unknown and little studied, or known and ignored such as the effects of chlorine in swimming pools on eyes of children; of EDTA (a common food

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[39] This is referred to as the "cocktail" principle in Canadian environmental circles.

additive) on human health; of cosmetics on skin; of drugs on the mind; and of alcohol on the body.

While research was continuing on possible adverse effects of NTA and U.S. Government officials were expressing their concern over certain caustic replacements for STP in detergents, another product of technology in the United States was implicated in 56,000 deaths, 250,000 serious injuries and 2,000,000 minor injuries in 1971. Its name was *automobile*, a killer, particularly when combined with youth and alcohol. To ban it was out of the question. We were "hooked" on the car far more than on phosphate or DDT.

Chapter 9

SIGNS OR SOLUTIONS?

In which man-made eutrophication is interpreted as a sign that our innate biological drive for survival is impairing our ability to survive.

The most detailed, even though fanciful, account of the life of Doctor John Faust, alias Johannes Faustus, George Faust, and George Sabellicus, is given in the *Faustbuch* published by Johann Spiess in 1587, about 50 years after the necromancer's death. Based on documents reputedly given him by Faust's servant, Wagner, the author tells how, after completing a degree in divinity at the University of Heidelberg, Faust was persuaded by Mephistopheles to shun God for mischievous and evil ends. In a note written and signed in blood, Faust agreed to yield his body and soul to the Devil at the end of 24 years, on condition that the Devil and Mephistopheles, "fulfill my desire in all things, as they have promised and vowed unto me, with due obedience to me."[40]

Immortalized later in the writings of Marlowe and Goethe, Doctor Faustus has become the legendary symbol in the western world of an insatiable lust for power, a person whose curiosity is all-consuming, whose knowledge is infinite, yet who fails to comprehend any meaning in the ultimate. Faust never really solved problems; he merely replaced problems with other problems.

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[40] See Bates (1969).

In an article entitled, "Faustian Power and Human Choices," two futurologists, Herman Kahn and Anthony J. Wiener, examined some of the major technological issues likely to confront humanity from 1970 to 2020.[41] They told of bizarre and incredible visions of the future — human hibernation, giant earth-moving projects, genetic engineering, choosing the sex of children prior to conception, electronic stimulation of pleasure centers in the brain, excessive narcissism, and others.

Among the various forecasts was one that attracted little attention, perhaps because of its unpretentious nature among such novel and weird companions. The modern soothsayers suggested that increased food production could become a major problem in the future — not too little food, but *too much food.* They reasoned that removal of the danger of major famine in some nations could negate any serious attempts at birth control, thereby rendering futile measures for improvement of education and economic development until stabilization of population could be achieved. If no attempt was made to use the extra labor in a constructive manner, they predicted that the results could be politically, socially, and economically disastrous.

The authors referred to this as a "reverse Malthusian problem," a case of overpopulation in which stomachs are full rather than empty. The suggestion is revealing in two respects: (1) unlike famine, which self-corrects overpopulation, provision of increased food can be expected to exacerbate overpopulation problems: and (2) application of technology to agriculture during the 20th century has dramatically increased production of food. With the help of fossil fuels, one farmer in the United States now feeds more than 40 people rather than the four he could feed 100 years ago; and with new varieties of grain from the "green revolution," India was said, in 1972, to have a sufficiency of food.

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Analysis of the ultimate causes of man-made eutrophication gives additional confirmation of the Faustian nature of man. In this

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[41] See Kahn and Wiener (1968).

analysis eutrophication emerges as a sign, an indication that we have not been solving our problems. In failing to distinguish between removal of signs and achievement of true solutions we have been, like the learned Faustus, merely replacing problems with other problems. True to the legend, it is only now, in the final act of the drama, that we are beginning to comprehend the significance of the agreement to which we have unwittingly affixed our biological signatures.

In discussing man-made eutrophication, attention up to this point has been focused on rates of supply of nutrients to water and the biological transformations taking place in lakes. Compounds of phosphorus and nitrogen have been identified as the causes of eutrophication; and phosphorus, by its removal, as the key to control. Leaving the matter there, concluding that eutrophication is caused by an increase in the rate of supply of plant nutrients to water, would not be scientifically incorrect, but it would be incomplete. Nutrient enrichment is only the immediate cause of eutrophication — according to many, just the definition of the word.

To unearth intermediate and ultimate causes it is necessary to probe more deeply into behavioral forces at work in human societies, mental forces that in diverse and little-understood ways act to determine the patterns and quantities of nutrient flow. Any claim to an overall understanding of the causes of man-made eutrophication without a detailed appreciation of what these forces are and how they act would be absurd.

Yet, by their very nature, ultimate analyses are fraught with interpretational difficulties and uncertainties at every step. Even when physical causes are known in an intermediate sense, interpretation of human motivations behind them can rarely advance beyond a conjectural stage. Yet, if no serious attempts are made to understand the forces that motivate our behavior, our survival as individuals, perhaps even as a technological species, may be at stake. Cartoonist Walt Kelly expressed this notion well when his comic strip character, *Pogo,* said in speaking of pollution: "We have met the enemy and he is us."

The first link connecting the immediate to the ultimate causes of man-made eutrophication is the recognition of an intermediate connection — the role of the water transport system of waste disposal. It was this measure, first introduced on a major scale in the latter part of the 19th century, that permitted the immediate cause of eutrophication (increased delivery of nutrients to water) to express itself. The effect of the change is illustrated in the accompanying diagram showing nutrient flow, old and new (Fig. 4).

As outlined in the chapter "Lakes and Man," the introduction of the water transport system of waste disposal resulted in four direct consequences: (1) increased water pollution from physiological wastes because of the by-passage of soil; (2) increased production of fertilizers to replace nutrients removed from the soil as crops, passed through the intestines and kidneys of man, and delivered to sediments and the sea; (3) increased cost of treating wastes composed of more than 99.99% water; and (4) man-made eutrophication. The introduction of automatic washing machines and phosphate-based detergents after World War II doubled the annual flow of phosphate to sewage, exacerbating the eutrophication problem. Everybody now keeps busy making and distributing phosphate and nitrogenous fertilizers; but, for those who have

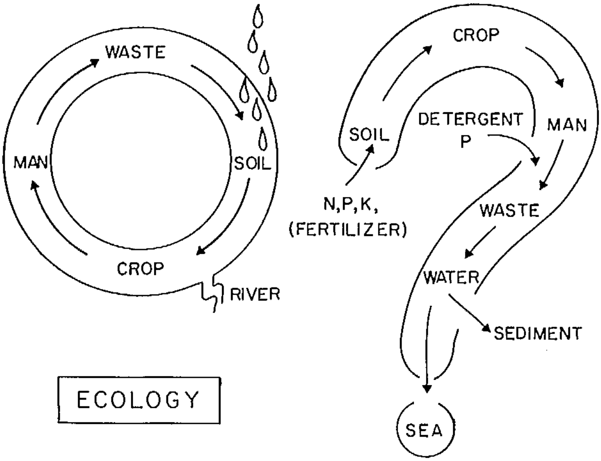

FIG. 4. *Nutrient flow, old and new.*

better things to do than to play the game of "make work," the system is rather senseless.

With these and other penalties mentioned below, it might well be asked: have the costs exceeded the benefits? But, even before the question is asked, the answer is obvious; the purpose of the water transport system of waste disposal was to improve health, and improved health is worth the cost at any price.

In order to appreciate the extent to which improved health was needed in the 19th century, it is necessary to understand conditions existing then, particularly in densely populated areas. Infant mortality rates in urban centers of Europe and North America were commonly double those in adjacent rural regions, and both were 10–20 times greater than those existing today. In the larger cities, one out of every four children died before the age of one year. Of the remaining three, another would depart before the age of five. And of those who survived with a debilitating sickness or physical injury, it might easily be said, by others, they would have been better off dead.

Two quotations from Henry Jephson's book, *The Sanitary Evolution of London*, serve as a reminder of what life was like in London, the thriving capital of the British Empire, in the middle of the 19th century.[42] Jephson, a responsible member of London City Council, quotes Mr J. Phillips, who appeared as a witness before the Metropolitan Sewers Commission in 1847:

> "In pursuance of my duties, from time to time, I have visited very many places where filth was lying scattered about the rooms, vaults, cellars, areas, and yards, so thick, and so deep, that it was hardly possible to move for it. I have also seen in such places human beings living and sleeping in sunk rooms with filth from overflowing cesspools exuding through and running down the walls and over the floors . . . . The effects of the stench, effluvia, and poisonous gases constantly evolving from these foul accumulations were apparent in the haggard, wan, and swarthy countenances, and enfeebled limbs, of the poor creatures whom I found residing over and amongst these dens of pollution and wretchedness."

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[42] See Jephson (1907).

In discussing the dismal state of water supplies (all provided by private companies at the time) Jephson quoted extensively from unpublished reports of various Medical Officers of Health:

> "From Shoreditch (1860), the Medical Officer of Health wrote: 'I have hardly ever exposed a sample of town spring water to the heat of a summer day for some hours without observing it to become putrid.' In St. Giles (1858–59), 'the water of the wells was not deemed good enough (on analysis) for watering the roads.' In St. Marylebone '44 public wells supplied water which was for the most part offensive to taste and smell.' In Kensington (1860) 'all the well waters of the parish were foul.' In Rotherhithe (1857), 'The water from the tidal well smelt as if it had recently been dipped from a sewer.' The Medical Officer of Health for Lambeth declared (1856) that 'the shallow well waters of London combined the worst features . . . they represent the drainage of a great manure bed.'
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> The people were driven to the use of the water from these wells owing to the deficient and intermittent supply of water by the various Water Companies . . . water supplied for less than an hour a day by one single standpipe in a court containing hundreds of people . . . water supplied every second and third day, and none on Sundays, the day of all others on which it was most wanted; and the house-owners had provided no cisterns or reservoirs of proper capacity, and the Vestries had not compelled the house-owners to do so.
>
> In some parishes hundreds of houses had no supply at all. In some houses which had a supply the tenants were deliberately deprived thereof by the Water Companies, because the house-owner had not paid the water-rate."

After reading such descriptions, is there any human so devoid of compassion for his fellow man that he could resist improved measures for more sanitary living conditions?[43]

And yet, these measures for improvement of public health have permitted another consequence to come about, more costly than all four of the previously mentioned consequences combined — *urbanization,* a problem that has yet to reach its fullest and most revengeful expression. By removing a major health barrier to increased population density, all of the economic and behavioral forces that cause humans to cluster together were unleashed. In

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[43] Jephson recorded there were some who objected: merchants and members of the municipal and county councils who did not want to pay higher taxes.

this sense, a fair share of every unwanted attribute of urbanization — slums, smog, overcrowding, noise, traffic congestion, murder, riots, alienation, and lead poisoning in children who nibble at old wall paint — can be attributed to installation of improved measures for urban sanitation.

But, to single out the water transport system of waste disposal or any other of innumerable measures adopted for improved health since the middle of the 19th century, would be like accusing weapons of aggression, or garbage of flies. While there is more than a semblance of truth to such assertions, the real causes are more deeply ingrained in human motivations that lie behind the acts. The true fault is ultimately seen in our failure to conform to the balance of nature by paralleling the introduction of death controls with the introduction of birth controls. Postponement of death, prolongation of life, improvement of health, whatever one wishes to call it, can have only one effect if not balanced by a reduction in births. Population has to increase.

Why do we fail to recognize the need for a balance in this respect? Do we not know that water rises and eventually overflows the sink when we maintain the same income from the tap and continually reduce the flow down the drain? Do we not realize that reduction in the output of a factory has to be balanced by reduction in the input of goods? Otherwise stock will go up and money lenders come knocking at the door.

Why do so many humans disapprove of abortion early in pregnancy when the fetus is incapable of an independent life? Why does the U.S. Congress typically vote more money each year for cancer research than the Department of Health, Education and Welfare requests? Why are defense budgets so high in many countries? Why do we fear death?

There can be only one answer to these complex questions. We do these things rationally or irrationally, rightly or wrongly, because we connect them with our survival. They are the products of hidden forces within us that we can neither fully comprehend nor control, biological forces that under more primitive conditions of life helped our ancestors to survive. The problem now is that under modern and improved conditions of life these deep-rooted instincts are returning to threaten our existence with runaway population and technological growth. Our innate biological drive for survival is impairing our ability to survive.

The extent to which this is true can be appreciated by asking why any measure for improved health should be undertaken. The answer, *for human health,* is sufficient. No other answer need be given.

Part of the problem is the difficulty we have in relating ourselves as individuals to humanity and evolutionary change. Our instinctive preoccupation with individual survival inhibits our mental ability to realize we have no existence other than as part of a larger whole. We also seem incapable of understanding how the multiplication of an individual act by all individuals in a population can add up to an undesirable result.

Nor do we realize the time lag in matters associated with human populations, changes that may take up to a century to be expressed or controlled. One of these now in the process of development is the current (1968–??) wave of unemployment in North America, a result of the post-World War II baby boom. Nobody bothered to deal with the matter in terms of later, inevitable consequences to jobs when it originated. Schools were built, first primary, then secondary, then expansions of universities, but the impact on employment seemed too far away to consider until it was actually there. When the cause of the problem originated after World War II, neither people nor politicians were prepared to interfere with the right of an egg to be fertilized or, if fertilized, to be conceived. Even now, who is planning for the time when this preponderance of young people moves through history to become, in another 40 years, a preponderance of aged and infirm living in "high-rise" urban slums?

Although citizens may be amazed to know it is true, and politicians will at first vigorously deny it, virtually all countries of the world have a population policy and practice population control. The policy in practically every case is population growth, brought about by death postponement (improved health) and a laissez-faire (do-as-you-please) policy on birth. Some countries, like Canada, even have monetary birth rewards in the form of monthly baby bonus cheques.

Governments, even more than ordinary people, have failed to understand the concept of balance in nature — that in the absence of birth control, a reduction in deaths simply causes population to increase until the death rate rises to parallel the birth rate again. The balance can be postponed, but not avoided; and if we do not create the balance, nature will.

Another part of the problem, as the analysis of man-made eutrophication has shown, is that environmental deterioration is not caused by population alone, but by population and technology combined. The effects of one are compounded with the other as gravity and increasing slope are compounded in accelerating the downhill momentum of an avalanche or brakeless train. For this and other reasons, *Homo sapiens* has to be recognized as a species with internal (biological) and external (technological) components of mass and metabolism. This is implicit in the concept of a "demophoric" explosion, an explosion of population and technology combined, in which the effects of the two are multiplicative.

As a result of combined increases in population and technology, events happen so rapidly in the modern world that we do not have time for history. Our concept of time has become blurred as space has constricted with more rapid means of transportation and communication. Automotive and TV fans of today find it weird to consider that 150 years ago sailing vessels commanded the seas, airplanes were unknown, and neither automobiles nor television sets existed. It seems incredible that when Napoleon fled from Moscow to Paris in 1812, on the best roads available and with a change of horse at every fleeting stop, he made no better time than Caesar could have made in his day. What has happened is that in each successive unit of time since the beginning of the 19th century, the velocity of locomotion has increased more than in all previous history combined. The same is true of population and most other aspects of technology, including power production and use of fertilizers.

If the onset of the "demophoric" explosion is taken as 1780 (2 years before James Watt patented his revolutionary engine) the situation in Europe and North America would be as shown in Table 1 for a doubling of velocity every 20 years.[44] The process starts in 1780 with a man and woman leisurely riding along a country road on a bicycle built for two. It ends in the year 2000 with 15–20 people squeezed in an oversized car clipping along a paved road at 200 kilometers (125 miles) per hour.

TABLE 1. The mass, velocity, and momentum of a "man-machine" starting in 1780 with 2 persons riding a tandem bicycle and ending in the year 2000 with 20 persons riding a 5-ton car (Momentum = mass × velocity). This fictional example shows the importance of viewing change in terms of momentum.

		Metric units		English units	
Date	Mass (*tons*)	Velocity (*km/hr*)	Momentum (*ton–km/hr*)	Velocity (*miles/hr*)	Momentum (*ton–miles/hr*)
1780	0.15	0.1	0.015	0.06	0.01
1800	0.2	0.2	0.04	0.12	0.02
1820	0.3	0.4	0.12	0.25	0.07
1840	0.4	0.8	0.32	0.50	0.2
1860	0.6	1.6	0.96	1.0	0.6
1880	0.8	3.2	2.6	2	1.6
1900	1.2	6.3	7.6	4	4.8
1920	1.6	12.5	20	8	13
1940	2.4	25	60	16	38
1960	3.2	50	160	31	99
1980	4.8	100	480	63	302
2000	6.4	200	1280	125	810

The projected view is frightening not just because of the increase in the mass of the "man-machine," nor its velocity; but because of the rate of increase of momentum, the product of mass and velocity combined. If, for some reason or other, the global man-machine

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[44] Note that the average velocity of the pre-1900 "bicyclists" permits numerous leisure stops for tea and cookies.

is required to slow down for a section of the road not yet completed or due to some unexpected turn, the entire system could easily sway and suddenly veer out of control.

Perhaps, as many politicians, economists, and industrialists have suggested, we can press our luck for another generation and still come out on top. But the truth of the matter is that we do not know the conditions and nature of the road ahead, nor the behavioral reactions of the passengers. It is a road of the future, one that has never been traversed before. We are like an engineer designing a skyscraper without knowing the forces to which it will be subjected, a task no sane engineer would ever undertake.

What is the solution to this deep Faustian problem rising up before us even more rapidly than predicted a decade ago? Would it have been better never to have inquired into the ultimate causes of man-made eutrophication; to have left matters where they stood at the end of the chapter on NTA? Does a rational solution exist?

A solution does exist, but whether it can be realized before events become uncontrollable remains, for the moment, uncertain. It hinges on the combined action of individuals, communities, and nations, collective kinds of actions that, because of preoccupation with individual survival, we find it most difficult to achieve. There are three principal needs: (1) to improve our individual understanding of man-dominated ecosystems, viewing them from within, rather than as something separate and isolated; (2) to recognize that the removal of signs will not bring about solutions unless ultimate causes are controlled; and (3) to use the excess energy previously invested in growth to protect and improve what we already have. If we fail to act on these, instability could easily result and all our past gains and future hopes be lost.

There is one prerequisite to fulfillment of these needs; the rate at which global "demophoric" momentum is *accelerating* must be reduced. Making an analogy to a car, this does not mean we should stop. To do that would be suicidal. Nor does it necessarily mean we must maintain constant velocity. Velocity could increase, though at a much slower rate than is now the case. What it does mean is that we must reduce the rate at which velocity and momentum *are* *accelerating.* If we don't reduce the acceleration, we will be unable to maintain control of the car.

The likelihood of an ultimate solution and satisfactory ending will depend on the extent to which we as individuals understand our connection with the greater whole. If we should come to realize our lives, our jobs, and our aspirations for the future are being threatened by runaway "demophoric" growth, then the innate biological drive for survival within us will rise to do the rest. It will enable us to distinguish the removal of signs from ultimate solutions, the distinction that Faust was never able to make.

If, through ignorance of possible consequences or unforeseen events, we should fail to take these measures, if we should fail to look toward inward causes instead of outward signs, there can be only one result.

Our heads will be anointed with oil and algae when we go to the beach for a swim. Our cups will run over because no one will want to drink what is in them. And goodness and mercy will follow the Lord, but not us — for we shall dwell in the house of our wastes forever.

ACKNOWLEDGMENTS

The very act of posing as an author suggests a certain conceit and callous disrespect for friends, teachers, colleagues, and books. To correct any notions that I might possess such thoughts, my first expression of indebtedness must be to those who have developed scientific knowledge about lakes during the past 100 years. Without their collective efforts it would have been impossible for me to write in a simple and yet comprehensive way about limnology, the science dealing with inland waters.

Secondly, I am indebted to four persons who contributed immensely to the preparation of this book. These are: Dr G. Evelyn Hutchinson of Yale University, by virtue of his knowledge and understanding of lakes, which I first sampled as a student; Dr W. E. Johnson, former Director of the Freshwater Institute, Winnipeg, for constantly showing, by example, the value of directness and simplicity in approaching any problem; Dr David W. Schindler, Leader of the Freshwater Institute's Experimental Lakes Area Project; and Dr Arnold Nauwerck, former Head of the Fisheries Research Board detachment on the Great Lakes.

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TERMS AND DEFINITIONS

(Stressed syllables *italicized*)

*Al*gae — primitive photosynthetic plants that occur as microscopic forms suspended in water (phytoplankton), and as unicellular and filamentous forms attached to rocks and other substrates. About 15,000 species of freshwater algae are known.

Amm*on*ia — a nitrogen compound that occurs as a gas (NH_3) or, when dissolved in water, as an ion (NH_4^+).

*Ben*thos — the community of organisms living in contact with the bottom of a lake, often subdivided into phytobenthos (plants) and zoobenthos (animals).

*Bio*sphere — the region of the earth inhabited by living organisms. The biosphere includes the lower part of the atmosphere, the entire hydrosphere (lakes, rivers, oceans), and the lithosphere (soil and rock) to a depth of several kilometers (miles).

Bloom or water bloom — a sudden increase in the abundance of planktonic algae, especially at or near the water surface. A condition when water looks green because of the abundance of planktonic algae.

BOD — biological or biochemical oxygen demand. The amount of oxygen in milligrams per liter consumed in the biological decomposition of organic matter initially present in an enclosed sample of water. BOD_5 is the biochemical oxygen demand over a period of 5 days at 20° Centigrade (68° Fahrenheit).

*Buf*fer — a chemical that absorbs hydrogen ions and hydroxyl ions, thereby stabilizing solutions against

	dramatic changes in *p*H on addition of an acid or base.
Buffering capacity	— a quantitative measure of the extent to which a solution or water sample resists a change in *p*H on addition of an acid or base.
Carbon	— a chemical element that occurs in inorganic (nonburnable) form or in the form of organic (burnable) compounds such as fats, oils, carbohydrates, and proteins.
*Cen*tigrade	— (=Celsius) the temperature scale of the metric system in which freezing and boiling points of water at sea level are 0° C(= 32° F) and 100° C (= 212° F). To convert from Fahrenheit to Centigrade, subtract 32 and multiply by $\frac{5}{9}$. To convert from Centigrade to Fahrenheit, multiply by $\frac{9}{5}$ and add 32.
Demo*phor*ic	— a term referring to human population and technological production considered jointly.
*Eco*system	— any combination of living and nonliving components that, with a supply of matter and energy, is self-sustaining over a defined period of time. An ecosystem can be an ocean, lake, small plot of land, the entire biosphere, or an aquarium, depending on the context of use.
EDTA	— ethylenediaminetetraacetic acid; a complexing agent similar to NTA.
Efficiency	— the energy output of a process expressed as a percentage of the energy input.
Enzymes	— specific types of proteins formed in living cells that accelerate chemical reactions.
Epi*lim*nion	— (plural, epi*lim*nia; adjective, epilim*net*ic) the uniformly warm upper layer of a lake when it is thermally stratified in summer. The layer above the metalimnion.
Eutrophic	— see Lake classification.

*Eu*trophi*ca*tion— the complex sequence of changes initiated by the enrichment of natural waters with plant nutrients. The first event in the sequence is an increased production and abundance of photosynthetic plants. This is followed by other changes that increase biological production at all levels of the food chain, including fish. Successional changes in species populations occur in the process. The original meaning of eutrophication was simply nutrient enrichment. In recent years it has become more common to use the term in connection with the results rather than the cause (that is, an increase in trophic state caused by nutrient enrichment).

*Fah*renheit — a temperature scale; see Centigrade.

Geo*chem*istry — the science dealing with chemical reactions that take place naturally on earth.

Hypo*lim*nion — (plural, hypo*lim*nia; adjective, hypolim*net*ic) the uniformly cool and deep layer of a lake when it is thermally stratified in summer. The layer below the metalimnion.

Ion — an atom or molecule that, as a result of gaining or losing electrons, bears a positive or negative charge.

*Kil*ogram — a unit of weight in the metric system, numerically equal to 2.2 pounds.

Lake classification — one of the more commonly used lake classification systems recognizes two general categories of lakes; dystrophic lakes with brown colored water, rich in humic materials derived from plants, and oligotrophic–eutrophic lakes with "unstained" water.

Oligotrophic lakes are poorly supplied with plant nutrients and support little plant growth. As a result, biological productivity is generally low, the waters are clear, and the deepest layers are well supplied with oxygen throughout the year. Oligotrophic lakes tend to be deep, with average depths greater than 15 meters (49 feet) and maximum depths greater than 25 meters (80 feet).

Mesotrophic lakes are intermediate in characteristics between oligotrophic and eutrophic lakes. They are moderately well supplied with plant nutrients and support moderate plant growth.

Eutrophic lakes are richly supplied with plant nutrients and support heavy plant growths. As a result, biological productivity is generally high, the waters are turbid because of dense growths of phytoplankton, or contain an abundance of rooted aquatic plants; deepest waters exhibit reduced concentrations of dissolved oxygen during periods of restricted circulation. Eutrophic lakes tend to be shallow, with average depths less than 10 meters (33 feet) and maximum depths less than 15 meters (50 feet).

Lim*nol*ogy — the scientific study of inland waters.

*Li*ter — a unit of volume in the metric system, numerically equal to 1.057 U.S. quarts (liquid) or 0.88 British quart.

*Me*so*tro*phic — see Lake classification.

*Me*ta*lim*nion — (plural, *me*ta*lim*nia; adjective, *me*talim*net*ic) the zone in which temperature decreases rapidly with depth in a lake when it is thermally stratified in summer. The metalimnion lies between the epilimnion and hypolimnion. The term is roughly equivalent to *thermocline* in ordinary usage.

*Mil*ligram — one thousandth of a gram; one millionth of a kilogram; 0.0000022 pound (avoirdupois).

*Ni*trate — a negatively charged ion composed of one atom of nitrogen and three atoms of oxygen.

*Ni*trogen (N) — a chemical element that occurs naturally in elemental form in air as nitrogen gas (N_2). Other

		inorganic forms of nitrogen are ammonia (NH_3), nitrite (NO_2^-), and nitrate (NO_3^-).
NTA	—	nitrilotriacetic acid; a complexing agent commonly sold in the form of its trisodium salt and used to bind positively charged ions.
*Ol*igo*troph*ic	—	see Lake classification.
*p*H	—	negative logarithm of the concentration of hydrogen ions. A low *p*H means acidic conditions and a high concentration of hydrogen ions.
*Phos*phate (PO_4)	—	a negatively charged ion composed of one atom of phosphorus and four atoms of oxygen.
*Phos*phates	—	salts containing phosphate ions.
*Phos*phorus (P)	—	a chemical element. When used alone this term refers to the element in any chemical form.
Photo*syn*thesis	—	the process by which green plants convert the sun's energy into chemical energy in the form of carbohydrates, fats, and proteins.
*Phy*to-p*lank*ton	—	plant plankton; see Plankton.
*Plank*ton	—	community of microorganisms, consisting of plants (phytoplankton) and animals (zooplankton), inhabiting open-water regions of lakes and rivers.
Quart	—	a unit of volume. One U.S. quart (liquid) is equal to 0.946 liter. One British quart is equal to 1.138 liters.
Respi*ra*tion	—	the processes of enzymatic breakdown of organic substances in living cells that release energy for various biological activities.
*Sec*chi depth	—	depth at which a Secchi disc (a small white disc, 20 centimeters or 8 inches in diameter) disappears from view when lowered into water. A measure of water transparency.
Seiche	—	(pronounced *saysh*) oscillation of the surface of a lake (surface seiche) or interface between water layers of different density (internal seiche) with

periodic times generally ranging from minutes to hours. Seiche movements are commonly initiated by prolonged unidirectional winds or gradients in barometric pressure.

*Ther*mocline — literally, thermal or temperature gradient in a thermally stratified lake in summer; occupying the zone between the epilimnion and hypolimnion and more-or-less equivalent to the term *metalimnion.*

*Tro*phic state — characterization of a body of water in terms of position in a scale ranging from oligotrophy to eutrophy.

Tropho*gen*ic zone — (nourishment-producing) the upper well-illuminated region of a water body in which photosynthesis predominates.

Z*oo*p*lank*ton — (pronounced as in zoology) animal plankton; see Plankton.

APPENDIX

Status of Eutrophication Problems in 1974

My intent in preparing "The Algal Bowl" was to produce an account of lakes and eutrophication that would bring out the fundamental principles and factors involved in the interactions between man, nutrients, and water. Being timeless, these principles give no indication of the current state of affairs, regarding the occurrence and control of man-made eutrophication. Hence, a general assessment of the current situation is needed.

The general trend of an exponential increase in global incidence of man-made eutrophication appears to be continuing unabated. With the projected growth of human population and technology anticipated in the decades ahead it is likely that many waters, now near the threshold in terms of nutrient supply, may pass into undesirable states in terms of eutrophy. A more specific statement than this cannot be made at the present time because of the lack of knowledge of the position of most water bodies in relation to this threshold.

Some areas are more predisposed to man-made eutrophication problems than others. This is particularly true of geographic regions in which river courses are interrupted by standing bodies or expanses of water, a not uncommon situation in Canada, Scandinavia, and in foothill areas adjacent to mountainous terrain. In regions devoid of lakes there is generally only slight concern over eutrophication problems.

The necessity of phosphate removal for the control of eutrophication is now generally recognized. Sweden and Switzerland are the countries with the longest history of sewage treatment for phosphate removal. The United States and Canada are following their lead in regard to phosphorus control in the St. Lawrence drainage basin. Although pollution control authorities in a number of countries agree on the desirability of reducing inputs of detergent phosphates to natural waters, specific legislation limiting the phosphorus content of detergent products has been introduced only in Canada and some states and municipalities of the United States. NTA was first used on a significant scale in detergent products in Sweden in 1967, and in Canada in 1970. The concentrations of NTA in natural waters are being carefully monitored in both cases. At the end of 1973, the government of the United States had not reversed its stand-off policy with respect to NTA.

Beginning January 1, 1973, the maximum permissible level of phosphates in detergents manufactured in or imported into Canada was set at 2.2% P. As of January 1, 1974, there was no comparable federal regulation in the United States. On the other hand, there was legislation limiting the phosphorus content of heavy-duty laundry detergents to a maximum of 8.7% P in Connecticut, Florida, Indiana, Maine, Michigan, and a number of counties and cities in other states. At the beginning of 1974 there was a total ban on phosphates in detergents in New York, Indiana, and some local city and/or county governments in Florida, Illinois, Maine, Maryland, New Hampshire, and Ohio.

Detergent companies are pursuing expanded research programs in an effort to develop new and improved substitutes for sodium triphosphate as a detergent builder. In the autumn of 1970, Procter & Gamble announced they had developed a modified surfactant requiring less phosphate builder, thereby reducing the necessary phosphate for a given level of cleaning by 50%. It is probable other major breakthroughs will appear during the 1970s, permitting an improvement in the relationship between clean clothes and clean lakes.

The most significant event in North America since the main part of this book was written was the signing on April 15, 1972, of a Great Lakes Water Quality Agreement by President Richard Nixon of the United States of America and Prime Minister Pierre Trudeau of Canada. This agreement, valid for a period of 5 years, assigned specific responsibilities and functions to the Canada–United States International Joint Commission for development and implementation of cooperative programs, designed to improve water quality of the Great Lakes system. Mr Trudeau said at the time of signing this agreement:

> "The importance of what we have done this morning cannot be described or measured by conventional means, for this agreement does not fall within the normal categories of international activity. It will not contribute materially to the economies of either of our countries; it makes neither of us more secure in our relations with one another or in the world beyond; it does little to diminish or remove any of the social problems which worry Americans and Canadians alike.
>
> "Yet while doing none of these things it accomplishes much more. For it marks our recognition of the fragility of our planet and the delicacy of the biosphere on which all life is dependent. This agreement deals with the most vital of all issues — the process of life itself. And in doing so it contributes to the well-being of millions of North Americans, for it promises to restore to a wholesome condition an immense area which, through greed and indifference, has been permitted to deteriorate disgracefully."

Let us hope this will be so. The eyes of the world will be watching.

Tables and Figures

TABLE A1. Concentrations of essential elements for plant growth in living tissues of freshwater plants (demand), in mean world river water (supply) and the plant:water ratio of concentrations (demand:supply)[a] (< = less than).

		Demand	Supply	Demand: supply
Element	Symbol	Plants %	Water %	Plant:water (approx)
Oxygen	O	80.5	89	1
Hydrogen	H	9.7	11	1
Carbon[b]	C	6.5	0.0012	5,000
Silicon[c]	Si	1.3	0.00065	2,000
Nitrogen[b]	N	0.7	0.000023	30,000
Calcium	Ca	0.4	0.0015	<1,000
Potassium	K	0.3	0.00023	1,300
Phosphorus[b]	P	0.08	0.000001	80,000
Magnesium	Mg	0.07	0.0004	<1,000
Sulfur	S	0.06	0.0004	<1,000
Chlorine	Cl	0.06	0.0008	<1,000
Sodium	Na	0.04	0.0006	<1,000
Iron[d]	Fe	0.02	0.00007	<1,000
Boron	B	0.001	0.00001	<1,000
Manganese	Mn	0.0007	0.0000015	<1,000
Zinc	Zn	0.0003	0.000001	<1,000
Copper	Cu	0.0001	0.000001	<1,000
Molybdenum	Mo	0.00005	0.0000003	<1,000
Cobalt	Co	0.000002	0.000000005	<1,000

[a] Concentrations listed for freshwater plants were derived from approximately 20 scientific papers dealing with chemical composition of algae and rooted aquatic plants. Averages were weighted for annual production ratios of about 7 units algae to 1 rooted plant, with diatoms comprising 30% of total algal production. Concentrations of the same elements in water (except for phosphorus) were derived from estimates of the composition of mean world river water (Livingstone 1963). The estimate for phosphorus supply is my intuitive estimate for mean world river water.

[b] Concentrations of carbon, nitrogen, and phosphorus in water are given for inorganic forms only.

[c] Silicon is essential for growth of diatoms, some flagellates and perhaps some higher plants (*Equisetum*). It plays no essential role in the growth of other plants so far as is known.

[d] The listed value of the plant:water ratio is deceptively low for iron, since much of the iron in water is not in a form readily available to plants. True values may be several hundred times higher in some lakes.

TABLE A2. Average annual output of nitrogen and phosphorus per capita of human population, and the average annual amounts delivered from the source to natural waters. Based on United States statistics for 1965–70.

	Kilograms/capita-year	
	Nitrogen	Phosphorus
Sewage		
physiological waste	4.5	0.6
detergents	0.0	1.1
industry, etc.	0.5	0.1
total output	5.0	1.8
delivered to water[a]	4.5	1.6
Agriculture		
physiological waste	45	6
synthetic fertilizers	20	8
total output	65	14
delivered to water[a]	8	0.3

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[a] It is assumed that 90% of the nitrogen and phosphorus in sewage is transferred directly to water in this example; and 2% of phosphorus and 12% of nitrogen added to soil as manures and artificial fertilizers are transferred from land to water. These values can be expected to vary markedly from place to place.

TABLE A3. Density (D) of water as a function of temperature (T) at a pressure of one atmosphere, together with the density difference per degree Centigrade lowering of temperature (DD/°C). Abbreviations: C (Centigrade); g (grams); cm^3 (cubic centimeter).

T (°C)	D (g/cm^3)	DD/°C ($10^{-5}g/cm^3$)	T (°C)	D (g/cm^3)	DD/°C ($10^{-5}g/cm^3$)
0	0.999867				15.7
		6.0	16	0.998970	
1	0.999927				16.8
		4.1	17	0.998802	
2	0.999968				17.9
		2.4	18	0.998623	
3	0.999992				19.0
		0.8	19	0.998433	
4	1.000000				20.1
		0.8	20	0.998232	
5	0.999992				21.1
		2.4	21	0.998021	
6	0.999968				22.2
		3.9	22	0.997799	
7	0.999929				23.2
		4.3	23	0.997567	
8	0.999876				24.1
		6.7	24	0.997326	
9	0.999809				25.2
		8.1	25	0.997074	
10	0.999728				26.1
		9.5	26	0.996813	
11	0.999633				27.1
		10.8	27	0.996542	
12	0.999525				28.0
		12.1	28	0.996262	
13	0.999404				28.8
		13.3	29	0.995974	
14	0.999271				29.8
		14.4	30	0.995676	
15	0.999127				

TABLE A4. Percentage of light of different wavelengths absorbed by a 1-meter column of pure water at room temperature. A nanometer is 0.000000001 meter.

Color	Wavelength (*nanometers*)	% of light absorbed per *meter*
Infrared (invisible)	820	91.1
	800	89.4
	780	90.1
	760	91.4
	740	88.5
Red	720	64.5
	700	45.0
	680	36.6
	660	31.0
Orange	640	26.6
	620	23.5
Yellow	600	19.0
	580	7.0
	560	3.9
Green	540	3.0
	520	1.6
	500	0.77
Blue	480	0.52
	460	0.52
	440	0.70
	420	0.92
Violet	400	1.63
	380	2.10

TABLE A5. Composition of world-average river water in terms of the major ions present. Concentrations are given both in terms of milligrams per liter (parts per million) and equivalents per liter.

Positive ions	Concentration (*mg*/*liter*)	Concentration (eq./*liter*)	Negative ions	Concentration (*mg*/*liter*)	Concentration (eq./*liter*)
Calcium (Ca^{++})	15.0	0.75	Bicarbonate (HCO_3^-)	58.4	0.96
Sodium (Na^+)	6.3	0.27	Sulfate ($SO_4^=$)	11.2	0.23
Magnesium (Mg^{++})	4.1	0.34	Chloride (Cl^-)	7.8	0.22
Potassium (K^+)	2.3	0.06	Nitrate (NO_3^-)	1.0	0.017
Total		1.42			1.427

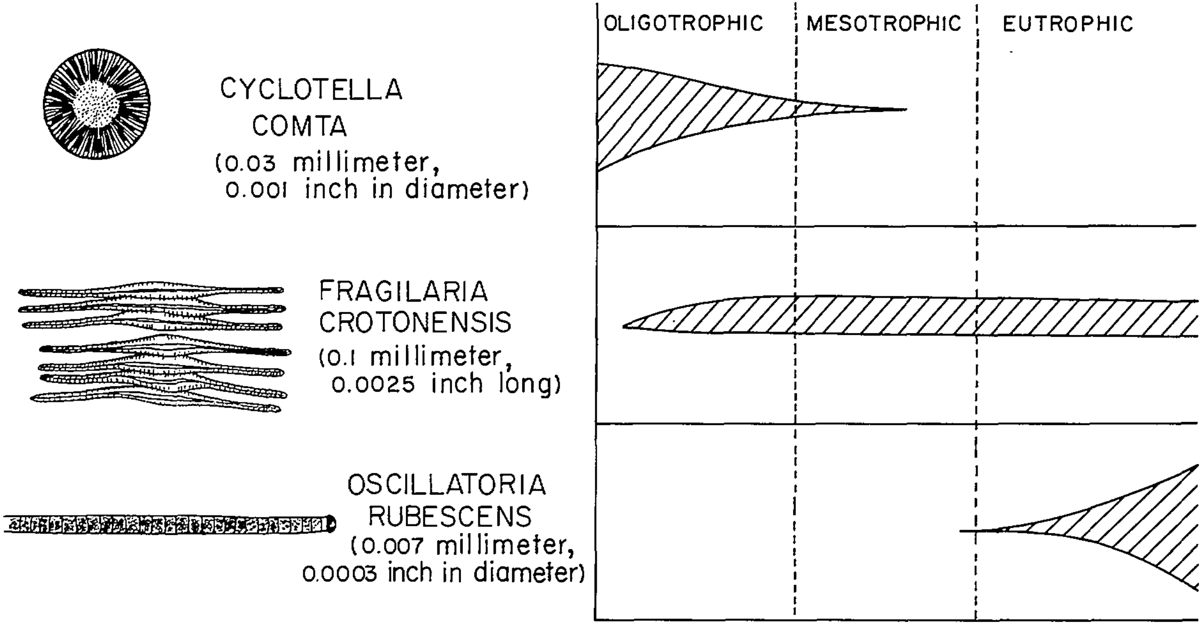

FIG. A1. *Relative abundance of three species of planktonic algae in oligotrophic, mesotrophic, and eutrophic lakes:* Cyclotella comta (*a diatom*); Fragilaria crotonensis (*a diatom*); *and* Oscillatoria rubescens (*a blue-green alga*). *Designed by Dr K. Patalas.*

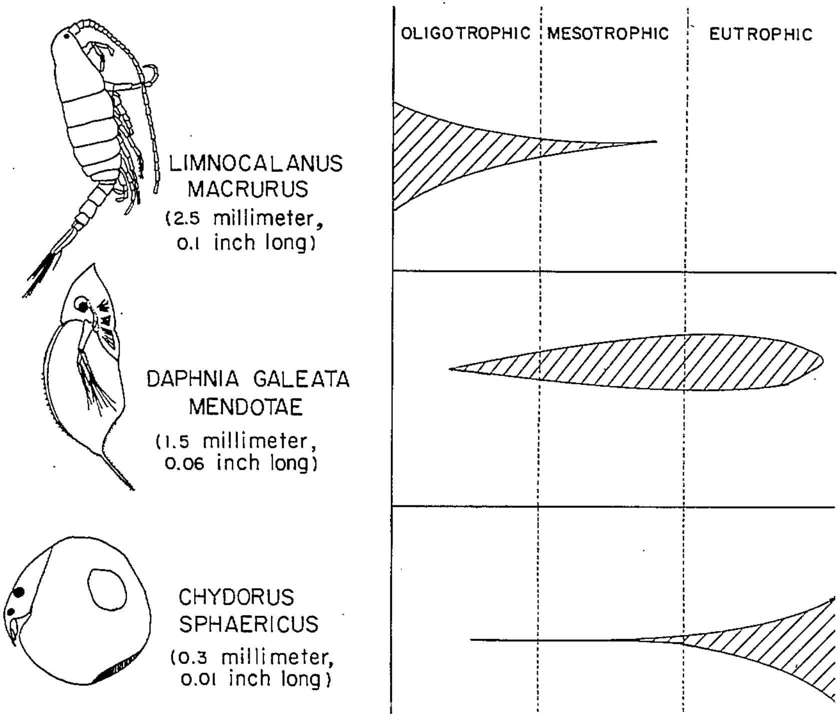

FIG. A2. *Relative abundance of three species of planktonic crustaceans in oligotrophic, mesotrophic, and eutrophic lakes:* Limnocalanus macrurus (*a copepod*)*;* Daphnia galeata mendotae (*a cladoceran*)*;* Chydorus sphaericus (*a cladoceran*). *Designed by Dr K. Patalas.*

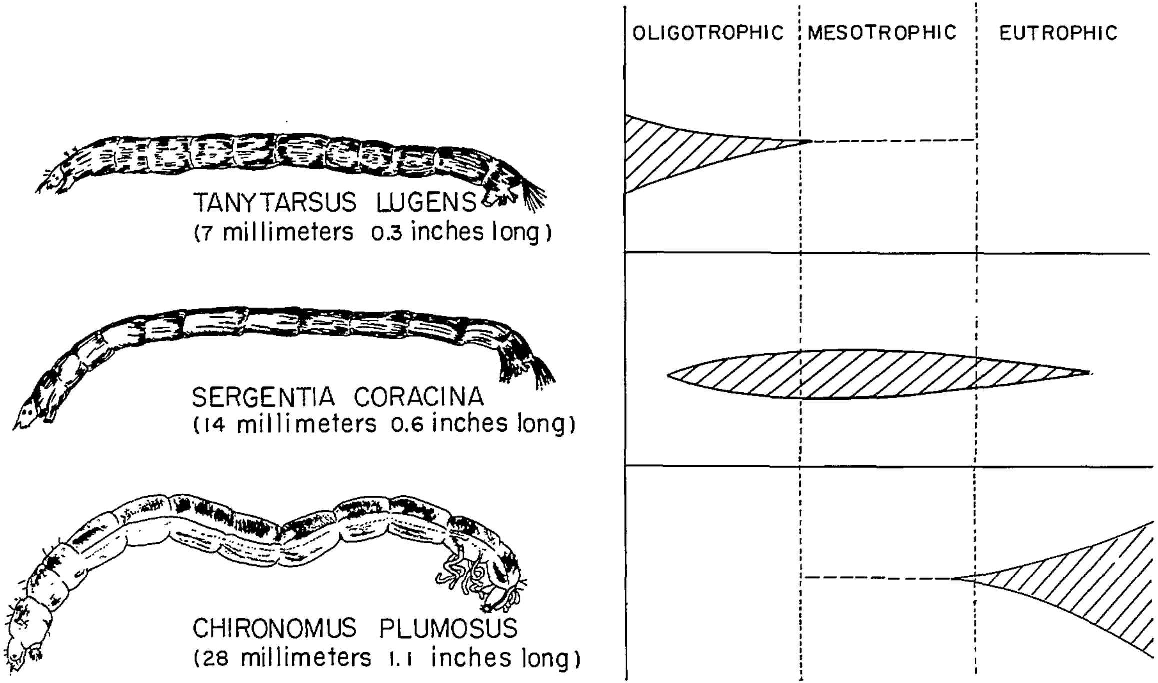

FIG. A3. *Relative abundance of three species of chironomid (midge) larvae in oligotrophic, mesotrophic, and eutrophic lakes. These insect larvae live in bottom sediments, "breathing" by means of gills. Designed by Dr O. Sæther.*

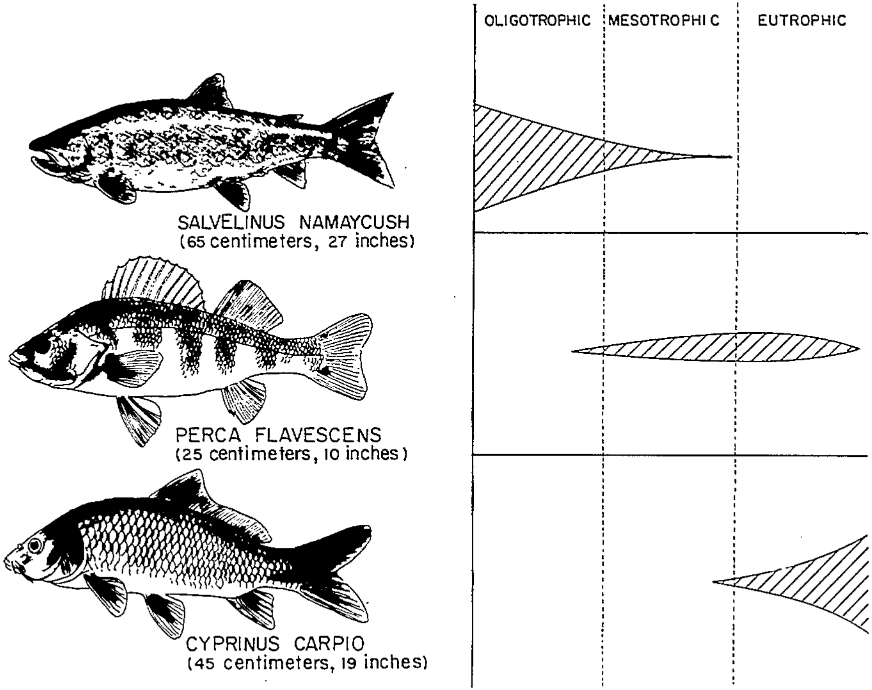

FIG. A4. *Relative abundance of three species of fish in oligotrophic, mesotrophic, and eutrophic lakes:* Salvelinus namaycush (*lake trout*)*;* Perca flavescens (*yellow perch*)*;* Cyprinus carpio (*carp*). *Designed by Dr K. Patalas.*

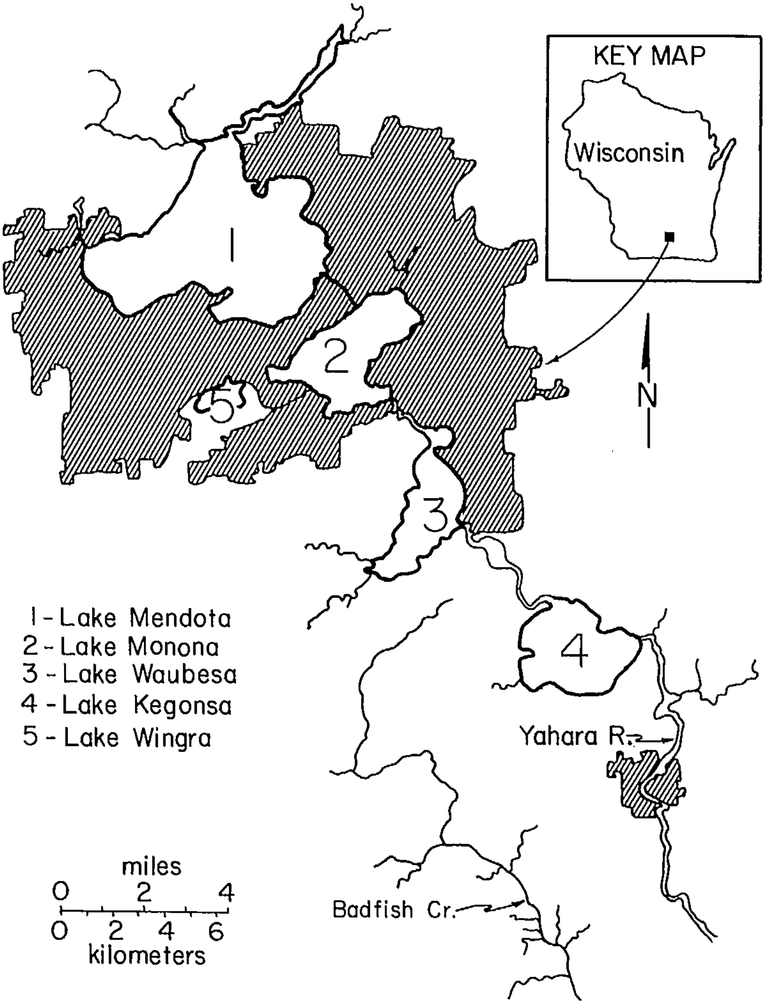

FIG. A5. *Map of the four lakes around Madison, Wis., showing urban areas (1970) in cross hatching. The first diversion of effluent from the Madison sewage treatment plant entered the Yahara River between Lake Mendota and Lake Monona. The second diversion entered the Yahara River between Lake Monona and Lake Waubesa. The third diversion shifted the effluent to Badfish Creek which enters the Yahara River downstream to the area shown in the figure. See p. 26–28 for further information.*

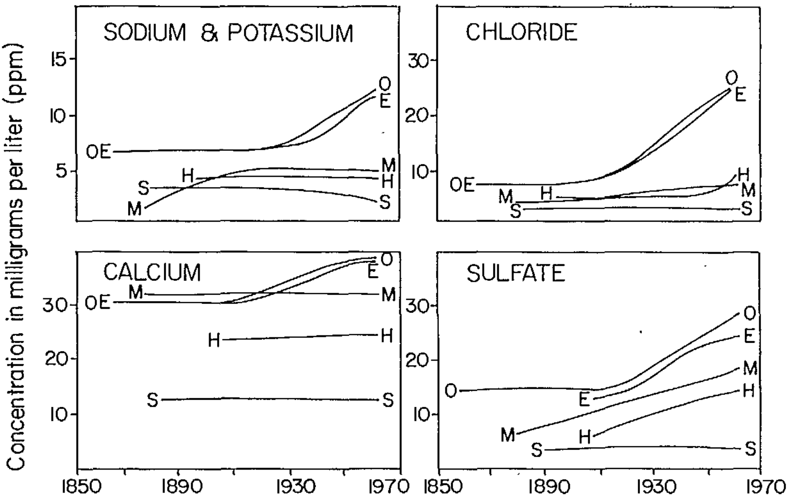

FIG. A6. *Changes in the chemistry of the St. Lawrence Great Lakes, 1850–1967. Abbreviations: S, Lake Superior; M, Lake Michigan; H, Lake Huron; E, Lake Erie; O, Lake Ontario. Redrawn from a figure originally prepared by Dr A. L. Beeton. Lake Superior has remained essentially unchanged in chemical composition throughout the period, whereas lakes Erie and Ontario have been markedly affected. (Lake Erie flows into Lake Ontario via the Niagara River.) See p. 28–32 for further information.*

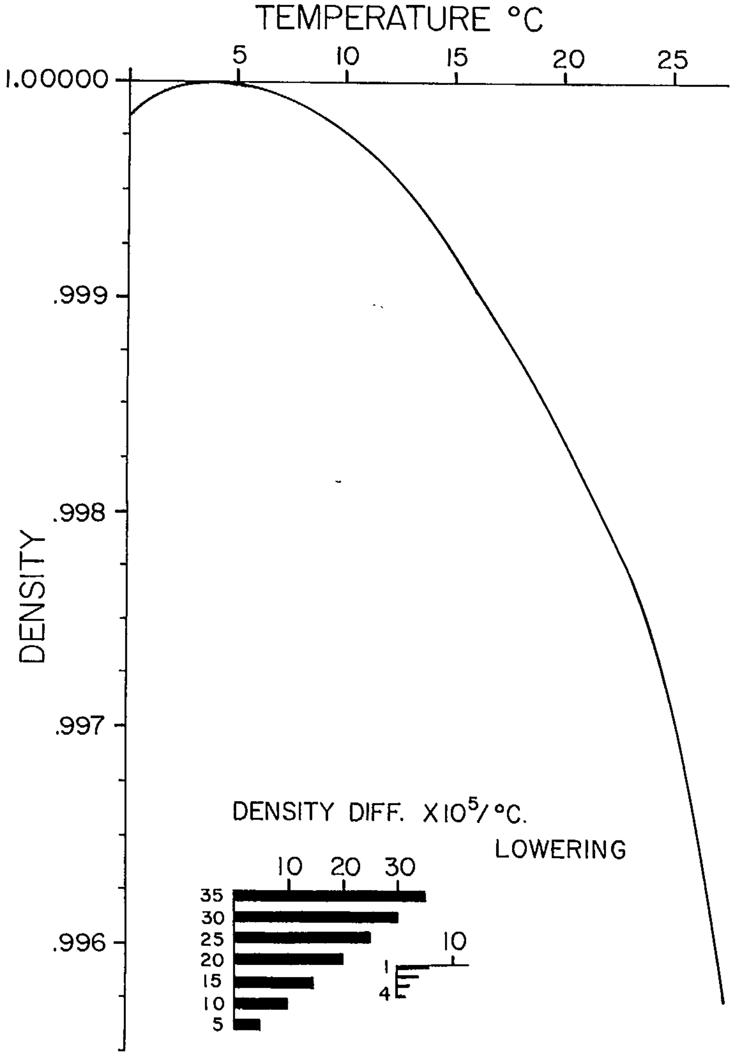

FIG. A7. *Variation in density of water with temperature. Lower insert shows the difference in density per degree Centigrade of temperature lowering for various temperatures. Note maximum density of water at 4° C and the nonlinear change of density with temperature above and below 4° C. See p. 40–45 for further explanation.*

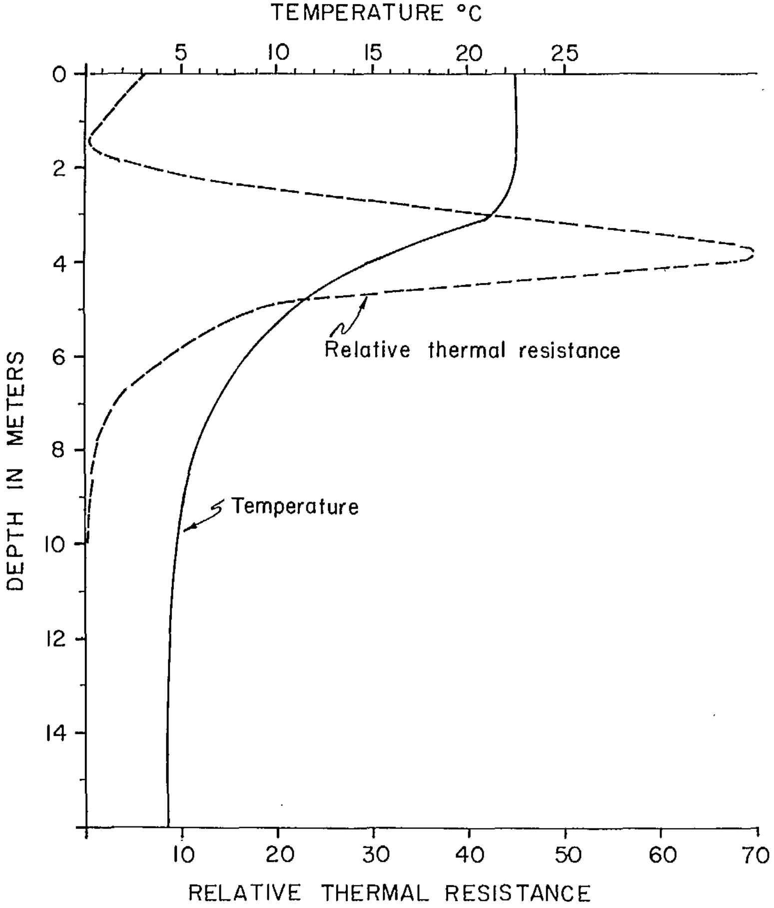

FIG. A8. *Temperature (solid line) and relative thermal resistance (RTR) to mixing (broken line) in Little Round Lake, Ont., during summer. RTR is expressed as difference in density between the top and bottom of each half-meter depth interval, calculated on the basis of temperature. For convenience in expression, RTR values were multiplied by* 10^5. *See p. 44 for further information.*

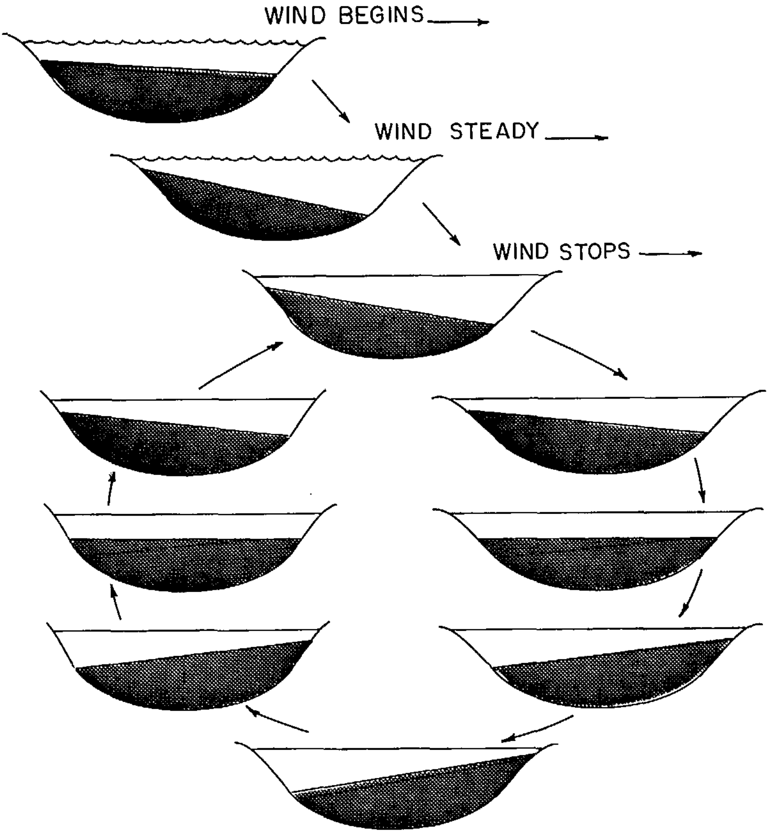

FIG. A9. *Diagram showing motions of an internal seiche in a lake following a steady wind. The clear upper layer represents the epilimnion and the lower stippled area, the hypolimnion. Note that the slope of the interface between the two water masses rises upwind when the wind is blowing. See p. 50–51 for further explanation.*

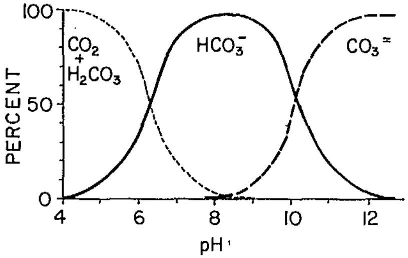

FIG. A10. *Relative abundance of various forms of inorganic carbon at various* pH *values in fresh water. At a* pH *of 4, all inorganic carbon occurs as* $CO_2 + H_2CO_3$*; at a* pH *of 8, all inorganic carbon occurs as* HCO_3^- *(bicarbonate); at a* pH *of 12, all inorganic carbon occurs as* $CO_3^=$ *(carbonate). Most natural waters have* pH *values in the range of 6–8. See p. 59–64 for further explanation.*

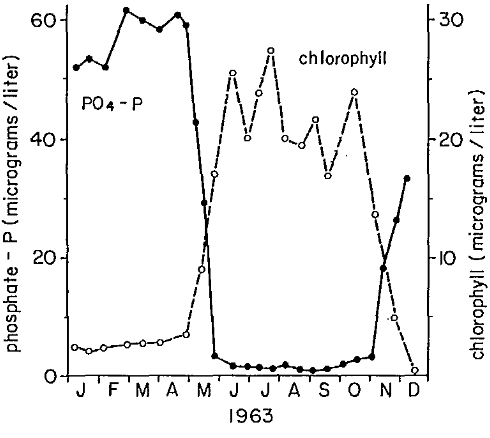

FIG. A11. *Seasonal relationship between dissolved phosphate and chlorophyll in the epilimnion of Lake Washington, USA. Note how dissolved phosphate accumulates in winter and disappears in summer with phytoplankton growth (measured by chlorophyll). Redrawn from data of Dr W. T. Edmondson. See p. 101–103 for further explanation.*

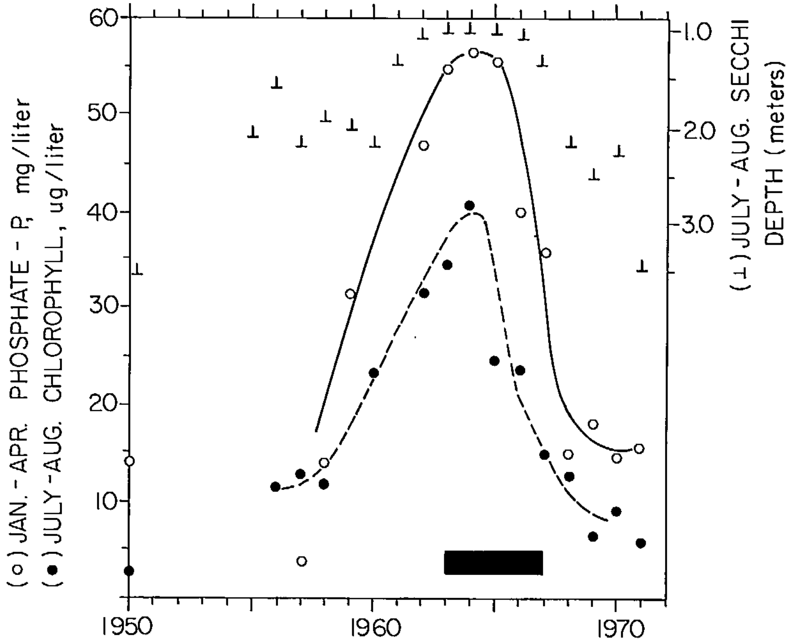

FIG. A12. *Changes in average values for dissolved phosphate (winter), Secchi disc visibility (summer), and chlorophyll (summer) in the upper 10 meters (33 feet) of Lake Washington, 1950–71. The darkened area shows the time from the beginning of the sewage diversion in 1963 to completion in 1968. Algal abundance (chlorophyll) declined and water clarity (Secchi depth) increased, paralleling reduction in winter phosphate after 1963. The primary effect of the diversion on algal growth was brought about by reduction in phosphate. See p. 101–103 for further explanation.*

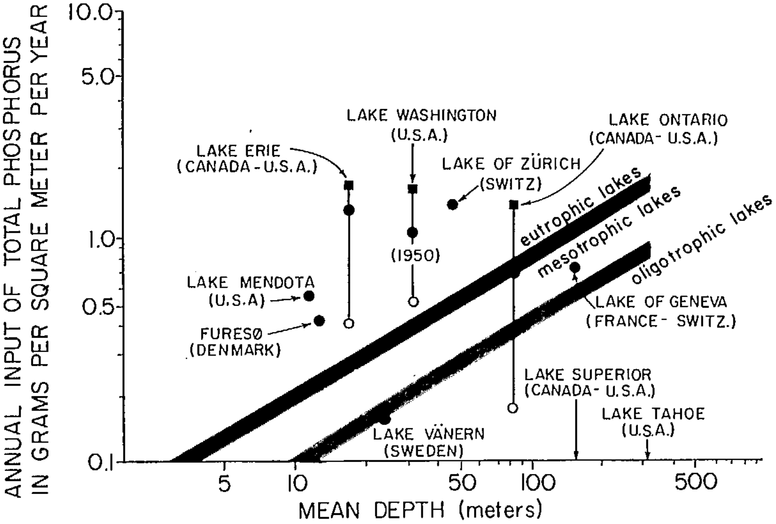

FIG. A13. *Phosphorus inputs to several European and North American lakes based on a chart originally prepared by Dr R. A. Vollenweider. Solid circles indicate 1968 states. Solid squares indicate predicted states, 1985–90, without any attempt at phosphorus control. Open circles indicate predicted states, 1985–90, with phosphorus control. Oligotrophic lakes lie below the lower hatched line; eutrophic lakes lie above the upper hatched line; and mesotrophic lakes lie between two hatched lines. See p. 103 for further explanation.*

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