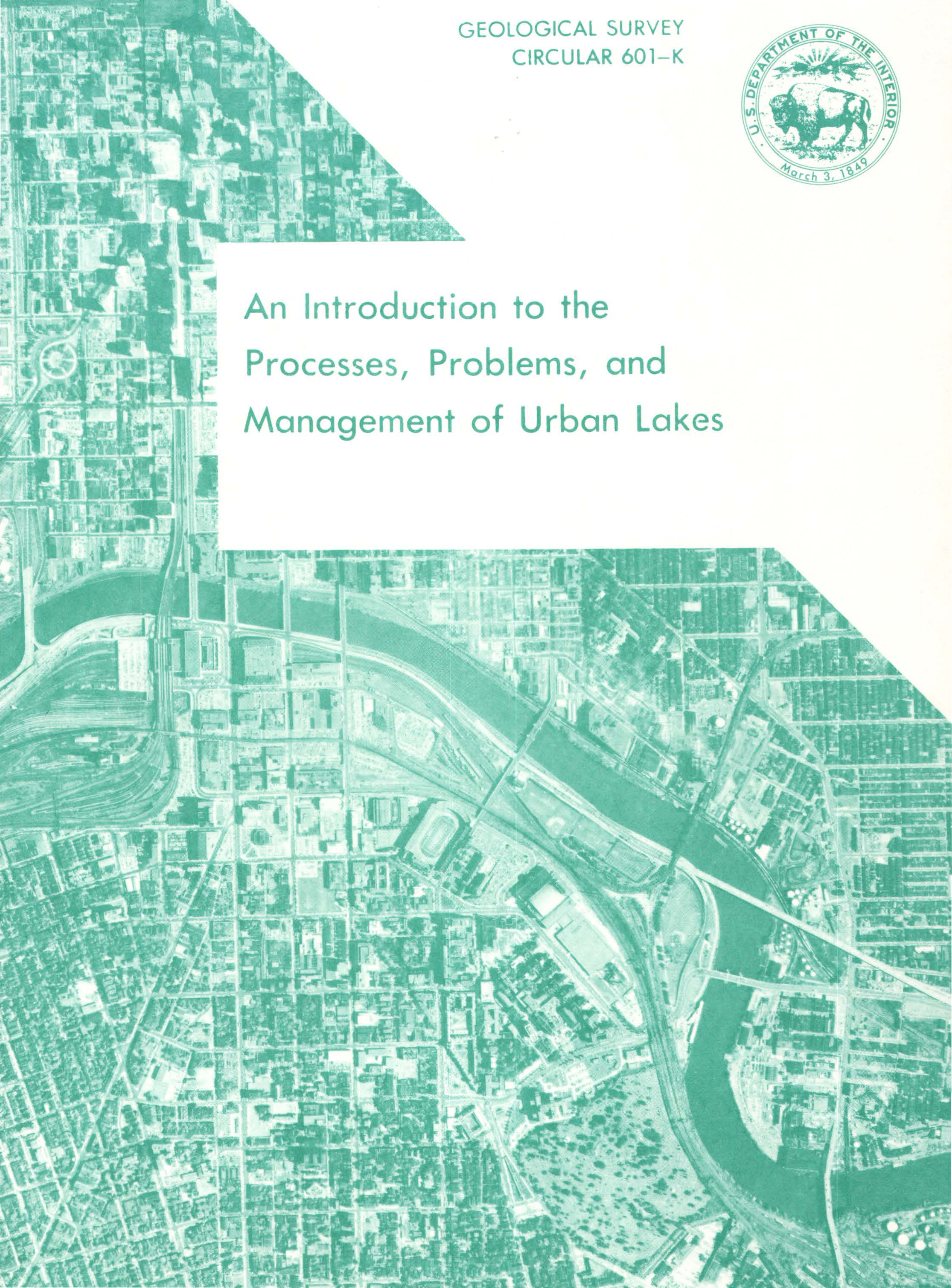
GEOLOGICAL SURVEY
CIRCULAR 601-K

An Introduction to the Processes, Problems, and Management of Urban Lakes



An Introduction to the Processes, Problems, and Management of Urban Lakes

By L. J. Britton, R. C. Averett, and R. F. Ferreira

WATER IN THE URBAN ENVIRONMENT

GEOLOGICAL SURVEY CIRCULAR 601–K

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CONTENTS

	Page
Glossary of selected terms	IV
Conversion factors	VI
Abstract	1
Man and his lakes	1
What this report is all about	2
Physics, chemistry, and biology of lakes	2
Physical characteristics	2
Light penetration	2
Temperature	3
Suspended sediment	5
Morphology	5
Chemical characteristics	5
Major chemical constituents	5
Minor chemical constituents	5
Major plant nutrients	6
Dissolved gases	6
Biological characteristics	6
Plankton	6
Benthos	6
Nekton	6
Processes in lakes	9
Photosynthesis and respiration	9
Eutrophication	10
The biogeochemical cycle	10
Sedimentation	11
Nutrient cycling	11
Planning and management of watersheds and lakes for water quality control	12
Lake basin planning	12
Planning and management of watersheds and lakes for water quality control—Continued	
Watershed management	13
Lake management	13
Water quality control	13
Algal blooms	13
Anaerobic conditions	14
Fish kills	15
Sediment deposition	15
Summary of management options	15
Conducting lake studies	15
Measuring the properties of lakes	16
Physical measurements	16
Mapping	16
Temperature	16
Light penetration	17
Chemical measurements	17
Dissolved oxygen	17
Alkalinity and pH	17
Major chemical constituents and specific conductance	17
Minor chemical constituents	18
Major plant nutrients	18
Biological measurements	19
Phytoplankton and periphyton	19
Zooplankton	20
Benthic invertebrates	20
References cited	21

ILLUSTRATIONS

	Page
Figure 1. The major life zones of a lake	3
2. Seasonal thermal profiles of a warm monomictic lake	4
3. Representative lake organisms	9
4. Effect of man upon the eutrophication of lakes	11
5. Sources and cycling of elements in a lake	12
6. Typical growth pattern of blooming unicellular algae	14

TABLE

	Page
Table 1. Common forms, minimum requirements, and some sources of elements essential for the growth of algae	7

GLOSSARY OF SELECTED TERMS

[Many of the definitions in this glossary were obtained or modified from Slack and others (1973).]

Absorption (n). To take up and incorporate within the body.

Adsorption (n). To take up and hold by adhesion to the surface.

Aerate (v), **aerator** (n). To charge or treat with air or other gases, usually with oxygen.

Aerobic (adj). Having oxygen.

Alga, algae (n), **algal** (adj). A group of simple primitive plants that live in wet or damp places, and generally are microscopic in size, containing chlorophyll and lacking roots, stems, and leaves.

Algal bloom (n). A high concentration of a particular algal species, amounting to ½ million to 1 million cells per litre of water or more.

Algicide (n). A chemical that kills algae.

Anaerobic (adj). Devoid of oxygen.

Assimilation (n), **assimilate** (v). To take up or incorporate within the body. Technically, secondary productivity plus respiration and other losses.

Autumn overturn (n). The mixing of the entire water mass of a lake in the autumn.

Bacterium, bacteria (n), **bacterial** (adj). Microscopic unicellular organisms. Some bacteria cause disease while others perform an essential role in the recycling of materials.

Benthos, benthic zone (n). Organisms living in or on the bottom of an aquatic environment. The bottom of a lake or stream.

Biochemical oxygen demand (BOD) (n). The quantity of dissolved oxygen, in milligrams per litre, used for the decomposition of organic material by microorganisms, such as bacteria.

Biomass (n). The amount of living matter present in a unit area or volume, at any given time.

Biota (n), **biotic** (adj). All the plants and animals in a particular area.

Blue-green algae (n). A group of algae with a blue pigment, in addition to the green chlorophyll. Blue-green algae group usually causes nuisance conditions in water.

Carbohydrate (n). Chemical compounds containing carbon, hydrogen, and oxygen, such as sugars, starches, or celluloses. Most are formed by green plants and serve as basic food units for animals.

Compensation level or depth (n). The depth of water at which oxygen production by photosynthesis balances oxygen uptake by respiration of plants and animals. The depth is usually where light intensity is reduced to about 1 percent of the surface light (Odum, 1971, p. 301).

Consumer (n). An organism that is unable to manufacture its food from nonliving matter and is dependent on the energy and materials stored in other living things.

Decomposition, decomposer (n). The breakdown of dead plant and animal tissue by bacteria to the elemental state.

Density (n). The quantity or mass of a substance per unit volume. Computed as grams per cubic centimetre, in the case of water.

Detritus (n). Fragmented material of inorganic or organic origin.

Diatom (n). A unicellular or colonial alga having a siliceous shell.

Dinoflagellate (n). A typically yellow-brown unicellular alga that swims by means of two laterally attached appendages called flagella (fig. 3).

Dystrophic (adj). Brown-water lakes with a very low lime content and a very high humus content, often characterized by a severe lack of nutrients (Ruttner, 1963, p. 254).

Ecosystem (n). The community of plants and animals interacting together with the physical and chemical environment.

Emersed plant (n). A rooted aquatic plant with leaves or other structures extending above the water surface (sometimes called emergent plant).

Enrichment (n). Addition or accumulation of plant nutrients within a body of water (Greeson, 1971, p. 139).

Environment (n). The sum of all the external physical, chemical, and biological conditions and influences that affect the life and development of an organism.

Epilimnion (n), **epilimnetic** (adj). The upper, relatively warm, circulating zone of water in a thermally stratified lake.

Erosion (n). The general process or group of processes whereby the materials of the Earth's crust are loosened, dissolved, or worn away, and removed from one place to another by weathering, solution, corrasion, and transportation (Gary and others, 1972).

Euphotic zone (n). That part of the aquatic environment where light penetration is sufficient for photosynthesis. Refers to the combined littoral and limnetic zones of lakes.

Eutrophication (n), **euthrophic** (adj). The natural process of enrichment and aging of a body of water that may be accelerated by the activities of man. Pertains to water bodies in which primary production is high because of a large supply of available nutrients. (See also **Dystrophic**, **Mesotrophic**, and **Oligotrophic.**)

Fauna (n), **faunal** (adj). A collective term for all the types of animals in an area.

Food chain (n). The transfer of food energy and materials from plants through other organisms, with repeated eating and being eaten.

Fungus, fungi (n). Plants lacking chlorophyll, including molds, yeasts, mildews, rusts, and mushrooms.

Grab (n). An instrument designed to "bite" into the bottom sediment of a lake or stream to sample the bottom materials and the benthos.

Green algae (n). Algae that have pigments similar in color to those of higher green plants. Some forms produce algal mats or floating "moss" in lakes.

Heterotroph (n), **heterotrophic** (adj). An organism that requires organic material as a source of nutrition; includes all animals and most bacteria.

Homothermous (adj). At the same temperature throughout.

Hypolimnion (n), **hypolimnetic** (adj). The lower, relatively cold, non-circulating water zone in a thermally stratified lake.

Interpretative (adj). A type of sampling program or study designed to collect information useful in describing a system, and cause-and-effect relationships within the system.

Invertebrate (n). An animal without a backbone. Common aquatic examples include worms, insects, snails, and crayfish.

Ion (n). An electrically charged particle of matter dissolved in water. For example, in water, salt forms sodium ions (Na^+) with positive charges, and chloride ions (Cl^-) with negative charges.

Larva, larvae (n), **larval** (adj). An active immature stage of an animal during which its bodily form differs from that of the adult. (See also **Nymph.**)

Limnetic zone (n). The open-water zone of a water body above the compensation level.

Limnology (n). The science or study of inland waters.

Littoral zone (n). The shallow zone of a body of water where light penetrates to the bottom.

Mesotrophic (adj). Intermediate stage in lake classification between the oligotrophic and eutrophic stages, in which primary production occurs at a greater rate than in oligotrophic lakes, but at a lesser rate than in eutrophic lakes. This is due to a moderate supply of nutrients. (See also **Eutrophic** and **Oligotrophic.**)

Metabolism (n). The sum of the chemical reactions in living cells in which energy is provided for vital processes and materials are assimilated for growth and tissue repair.

Metalimnion (n), **metalimnetic** (adj). The middle layer of water in a thermally stratified lake, in which temperature decreases rapidly with depth.

Monitoring (n). A type of sampling program designed to determine time-trend changes.

Monomictic (adj). Lakes having only one circulation period per year.

Nekton (n). Actively swimming aquatic organisms, such as fish.

Nutrient (n). Any chemical element, ion, or compound that is required by an organism for the continuation of growth, reproduction, and other life processes.

Nymph (n), **nymphal** (adj). An immature stage of an insect in which the body form resembles the adult. (See also **Larva.**)

Oligotrophic (adj). Pertaining to waters in which primary production is low as a consequence of a small supply of available nutrients.

Organic (n). Pertaining or relating to a compound containing carbon.

Oxidation (n). The process in which oxygen chemically combines with a substance, or in which an element loses electrons.

Periphyton (n), **periphytic** (adj). The community of microorganisms, such as algae, that are attached to or live upon underwater surfaces.

Photosynthesis (n), **photosynthetic** (adj). The process whereby green plants utilize light as an energy source and convert chemical compounds to carbohydrates. In the process, carbon dioxide is consumed and oxygen is released.

Phytoplankton (n), **phytoplanktonic** (adj). The plant part of the plankton.

Plankton (n), **planktonic** (adj). The community of floating organisms which drift passively with water currents.

Primary production (n). The synthesis of organic compounds by green plants in the presence of elements and light energy.

Producer (n). An organism that can directly utilize raw materials to form organic matter. Includes all green plants and some bacteria.

Production (n). The total amount of energy or organic matter produced from raw materials in an area per unit time, regardless of the fate of the material.

Profundal zone (n). The deep zone of a water body in which plant growth is limited by the absence of light.

Reconnaissance (n, adj). A type of sampling program or study designed to determine the present status of something; a preliminary survey.

Reduction (n). The process in which a substance loses oxygen, or in which an element gains electrons.

Respiration (n). A life process in which carbon compounds are oxidized to carbon dioxide and water. The liberated energy is used in the metabolic processes of living organisms.

Rotifer (n). A group of many-celled, microscopic zooplankton (fig. 3).

Secondary productivity (n). The rate of growth of the heterotrophs of the community.

Secondary waste treatment (n). A step in waste treatment in which most of the organic matter of sewage is removed.

Sediment (n). Fragmental material, both mineral and organic, that is in suspension or is being transported by the water mass or has been deposited on the bottom of the aquatic environment (Gary and others, 1972).

Sedimentation (n). The process of forming, transporting, and depositing sediment.

Sorption (n), **sorb** (v). To take up and hold by either adhesion or incorporation. A collective term for absorption and adsorption.

Species (n, sing. and pl.). The basic or final unit for the classification of organisms.

Stagnation period (n). The period when warming or cooling of the surface water in lakes forms a thermal-density stratification, preventing the mixing of the entire water mass.

Substrate (n). The physical surface upon which an organism lives.

Submersed plant (n). An aquatic plant that lives entirely below the surface of the water (sometimes called submerged or submergent).

Suspended sediment (n). Fragmental material, both mineral and organic, that is maintained in suspension in water.

Taxonomy (n). The division of biology concerned with the classification and naming of organisms.

Tertiary waste treatment (n). An advanced step in waste treatment, in which excess nutrients, suspended matter, color, odor, and most of the organic matter is removed.

Thermal stratification (n). A temperature distribution in which the lake water is distinctly layered because of thermal-density differences.

Toxin (n), **toxic** (adj). A poisonous substance.

Turbidity (n), **turbid** (adj). The ability of materials suspended in water to disturb or reduce the penetration of light.

Water pollution (n). Any impairment of the suitability of water for any of its beneficial uses, actual or potential, by man-caused changes in the quality of the water (Warren, 1971, p. 14).

Water quality (n). That phase of hydrology that deals with the kinds and amounts of matter dissolved and suspended in natural water, the physical characteristics of the water, and the ecological relationships between aquatic organisms and their environment.

Watershed (n). The area drained by, or contributing to, a stream, lake, or other body of water.

Zooplankton (n), **zooplanktonic** (adj). The animal part of the plankton.

CONVERSION FACTORS

Factors for converting English units to the International System of Units (SI) are given below to four significant figures. However, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	*Multiply by*	*Metric*
ft (foot)	3.048×10^{-1}	m (metre)
in (inch)	2.540	cm (centimetre)
in^2 (square inch)	6.452	cm^2 (square centimetre)

Water in the Urban Environment

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ABSTRACT

Lakes are bodies of water formed in depressions on the earth's surface, and as such, act as depositories for a variety of chemical and biological materials. The study of lakes has become increasingly prevalent in recent years. Lakes are a valuable resource, and their multiple uses have made them susceptible to water-quality problems such as algal blooms, sediment deposition and fish kills. These problems are products of the eutrophication process (enrichment, aging and extinction of lakes), which is often accelerated by man. Therefore, it becomes important to understand the properties and processes of lakes which govern lake enrichment, and the measures available to control enrichment.

Lakes are described in terms of their physical (light penetration, temperature, sediment, and morphology), chemical (chemical constituents, plant nutrients, and dissolved gases) and biological (plankton, benthos, and nekton) properties. These properties are all interrelated, and are important variables to measure to evaluate water quality. In addition, lake processes, such as photosynthesis, respiration, eutrophication, and biogeochemical cycling, are important factors in determining the sources and extent of enrichment, and managing a lake for maximum benefit. Meeting demands for water of high quality requires a general knowledge of lake properties and processes, coupled with lake-basin planning, watershed and lake management, and water-quality control. There are many lake-management and control practices, but the best tools for quality control are preventive measures. Once extensive enrichment has occurred, there are few management or control options available.

As lake studies become more common, sampling techniques for data collection need increased accuracy and consistency, in order to make meaningful comparisons between different lakes. Therefore, the report discusses the main factors involved in conducting lake studies. These factors include the types and frequency of measurements useful in lake reconnaissance studies and a review of literature on sampling equipment and techniques. A glossary of selected terms begins the report, which is intended for guideline use by urban planners and managers.

MAN AND HIS LAKES

Lakes and reservoirs are significant and ever-changing features of the landscape. Because they form in depressions on the earth's surface, they are depositories for material moved by both air and water. Their ultimate fate is to become filled with sediment and support terrestrial life.

Man's attraction to lakes is well marked in his history. Yet, in spite of his long use of lakes and reservoirs for water supplies, waste disposal, power generation, navigation, and recreation, he understands very little of their characteristics. The study of inland waters (limnology) is less than 100 years old (Welch, 1952, p. 4) and only in the past several decades has a significant literature developed.

Much recent literature on limnology has been concerned with eutrophication, the enrichment and filling of lakes with plants and sediment. Today, accelerated eutrophication, resulting from man's activities, is a serious problem in many lakes. As a result, new approaches to lake and reservoir management are being sought, and public awareness of the need for lake management is increasing.

Many lakes and reservoirs, which were once far removed from significant human impact, are now found near the edges and sometimes well within urban areas. Thus urban planners are now faced with the task of managing lakes for maximum public benefit.

Urban lakes and reservoirs have a multitude of uses, and lake management must take these uses into consideration. In many areas, natural lakes are scarce, and reservoirs have been formed to provide water for agricultural and domestic consumption, as well as for recreation.

While reservoirs differ somewhat from natural lakes, both have a number of characteristics and problems in common. Unless otherwise specified, the term "lake" will be used in this report to denote both natural and manmade standing bodies of water.

The framework for this circular is based upon experience in studying lakes of the San Francisco Bay area. While urban lakes in other parts of the country may have somewhat different physical, chemical, and biological characteristics than those near San Francisco, all such lakes have one thing in common––intensive use of their water and watersheds by the public. The result is a need for greater understanding of lake processes, and how lakes can be managed to insure the highest possible quality of water compatible with optimum use.

Ownership and management of urban lakes are under the jurisdiction of various agencies. Too often each agency collects limnological data independently of the other agencies, and a comparison of results between lakes is difficult to make. Consequently, there is a need for consistency and accuracy of sampling and sampling techniques if a meaningful comparison is to be made.

WHAT THIS REPORT IS ALL ABOUT

This circular was written as a part of a comprehensive reconnaissance of the physical resources of the San Francisco Bay area begun in 1969 by the U.S. Geological Survey, in cooperation with the Department of Housing and Urban Development.

Specifically the circular has three major objectives:

1. To provide the urban planner with a brief introduction to the properties and processes of lakes and how these properties and processes affect water quality.
2. To inform the urban planner of common lake problems and possible management solutions to these problems.
3. To provide the urban planner with guidelines for making lake reconnaissance surveys.

Pertinent literature on the various subjects discussed is referenced, and the reader is urged to consult the literature for a more thorough discourse. Problems and management of real-estate lakes, lakes created for particular housing or commercial areas or developments, have been thoroughly covered in a report by Rickert and Spieker (1971). This document should be consulted by planners concerned with real-estate lakes. Many of the problems of real-estate lakes are common to all lakes, and some overlap between the circular by Rickert and Spieker and the present report is inevitable.

A glossary of the technical terms used in this report follows the contents.

PHYSICS, CHEMISTRY AND BIOLOGY OF LAKES

The physical, chemical and biological systems of lakes are complex and interrelated. Any one influences and is influenced by the others. For example, sunlight penetrating the water triggers the growth of phytoplankton (floating one-celled plants). If conditions are favorable, the phytoplankton become so numerous that they reduce light penetration. Reduced light penetration may not only result in the arrest of continued phytoplankton production, but it may also influence the rate of warming of the lake water by the sun (Welch, 1952, p. 176). Thus a biological process (phytoplankton production) is influenced by and influences light penetration, which in turn influences the heat balance of the lake.

PHYSICAL CHARACTERISTICS

LIGHT PENETRATION

Limnologists have defined distinct zones in lakes, based upon the extent of light penetration in the water (fig. 1). The *littoral zone* is the shallow-water area where light reaches the bottom. At times, wave action may cause shoreline erosion and bring materials into suspension in the water. These suspended materials may cause a "turbid" condition and reduce the penetration of light and thus the depth of the littoral zone. Emersed (above water) and submersed (below water) rooted green plants grow in the littoral zone.

The *limnetic zone* is the open-water area of a lake that extends from the surface to the depth where light intensity is reduced to about one percent of the surface light (Odum, 1971, p. 301). In theory, the lower boundary of this zone is the *compensation level,* which is the depth at which oxygen uptake by bacteria, plant, and animal respiration equals photosynthetic oxygen release by green plants. The depth of the compensation level depends upon the light-scattering and absorbing material in the water. The limnetic zone is inhabited by free-floating and swimming organisms, such as plankton and fish. The combined littoral and limnetic zones are referred to as the *euphotic zone,* the area where there is sufficient light for photosynthesis.

The *profundal zone* is the deepwater area where only respiration and decomposition occur. Light intensity is

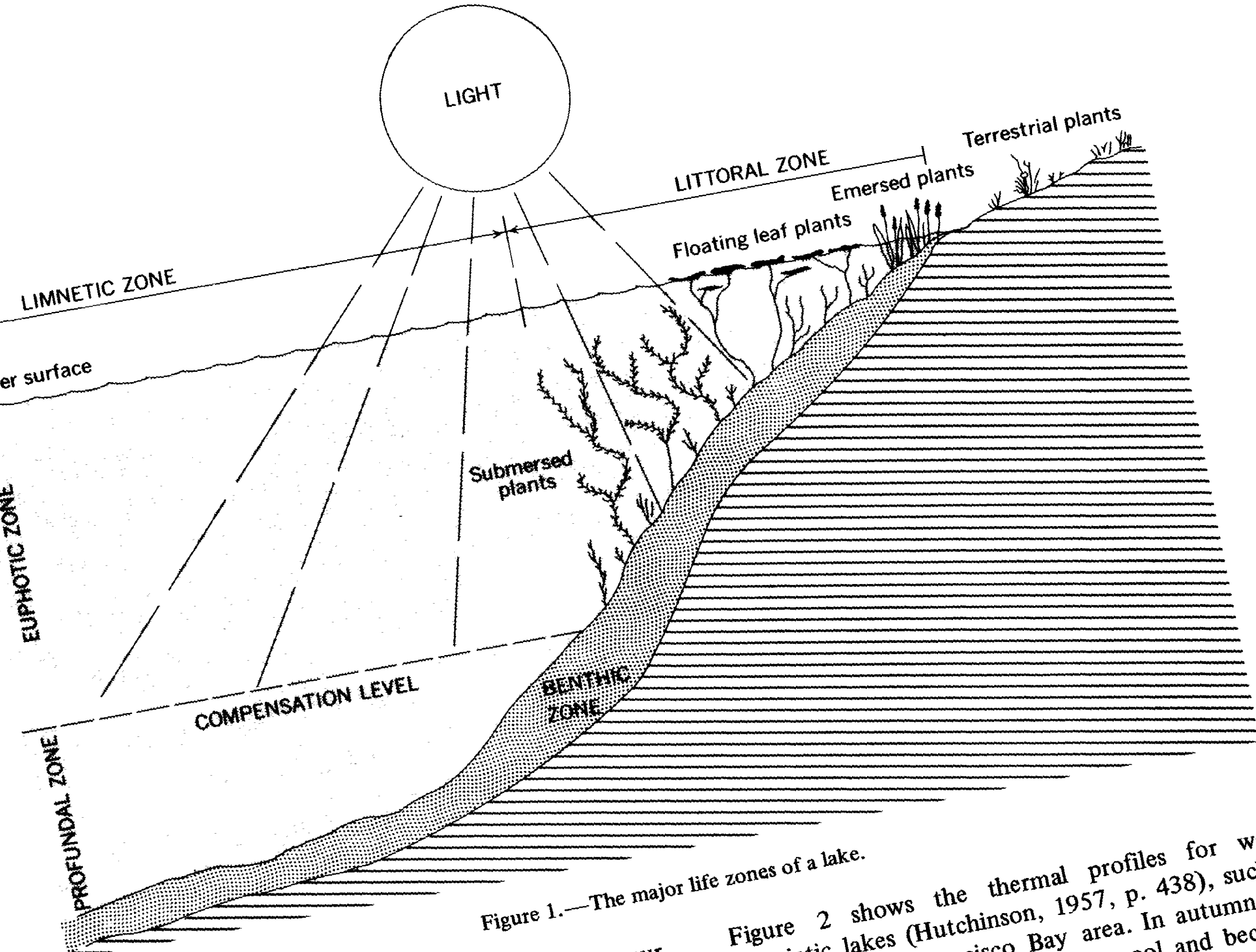

Figure 1.—The major life zones of a lake.

too low in the profundal zone for photosynthesis to occur. Therefore, organisms that live in the profundal zone depend upon food produced in the euphotic zone. Major profundal-zone organisms are zooplankton, benthic invertebrates, fungi, and bacteria.

The *benthic zone* is the lake bottom, where falling material accumulates and decomposes. It is inhabited by numerous types of burrowing animals.

TEMPERATURE

The thermal properties of a lake are controlled by the length of exposure and intensity of the sun on the lake, by materials in the water which scatter and absorb light, and by wind mixing. Thermal stratification is most pronounced during the summer in lakes of the warmer latitudes, and water-quality conditions often become critical in the deep water because the water is stagnant.

Water is unique in that it reaches its greatest density at 4°C (actually 3.98°C). At temperatures above or below 4°C, the density of water decreases. This property of water results in a regular pattern of seasonal mixing and stratification in many lakes.

Figure 2 shows the thermal profiles for warm monomictic lakes (Hutchinson, 1957, p. 438), such as those in the San Francisco Bay area. In autumn, the surface water of the lake begins to cool and becomes more dense. The cool, dense surface water sinks or is circulated by the wind, and mixes with the warmer, less dense water below. Wind action aids the mixing process until the entire water mass becomes *homothermous* (same temperature) and has the same density throughout. The lake is then in its most unstable condition, and wind action can mix the entire water mass. At this time the lake is in the autumn overturn period, and the deeper water becomes oxygenated.

With the onset of winter, cool air continues to lower the temperature of the lake water. During the winter the lake remains homothermous and well mixed, resulting in a uniform distribution of the chemical constituents in the lake.

In the early spring, increasing exposure to the su warms the surface water, which becomes less dense tha the cooler underlying water. Continued heating durin late spring and summer results in thermal and densi

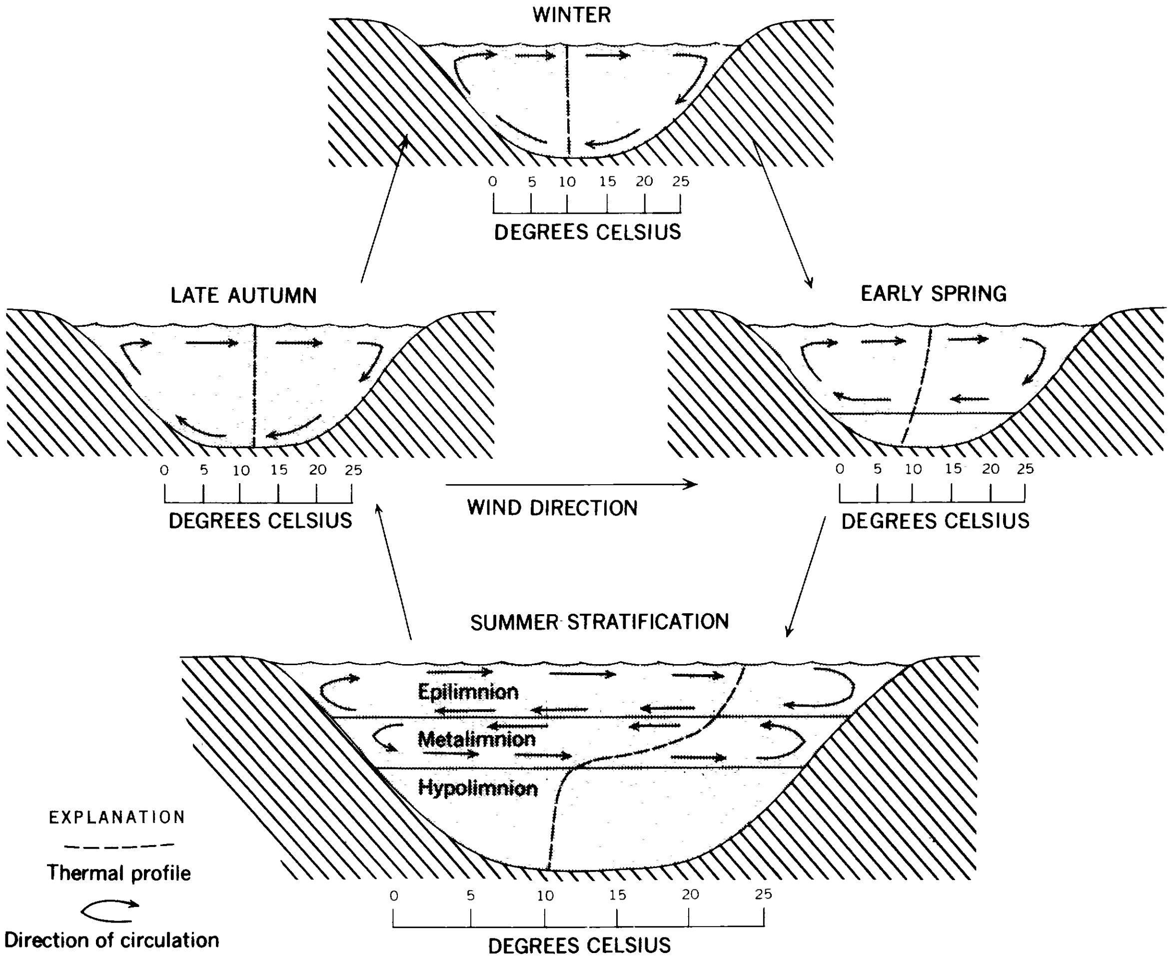

Figure 2.—Seasonal thermal profiles of a warm monomictic lake.

stratification, which limits wind mixing to the upper water layer. The result is the formation of three water layers. The upper water layer, the *epilimnion,* is thermally uniform and contains the warmest water in the lake. The lower water layer, the *hypolimnion,* is usually thermally uniform and contains the coldest and most dense water in the lake. Between these two layers is the *metalimnion,* a water mass with a temperature that rapidly decreases with depth. When these three water layers are distinct, the lake is thermally stratified and is referred to as being in the summer stagnation period (Welch, 1952, p. 59). With the cooler air of autumn, the surface water of the lake begins to cool, and the annual thermal cycle repeats itself.

There are many variations in the thermal cycle. In colder areas, the surface water freezes in the winter. Once the lake surface is frozen, circulation by wind action is prevented, and further loss of heat to the atmosphere is reduced. The water just below the ice is near freezing, but the water at greater depths may only cool to the temperature of maximum density (4°C). Thus, inverse thermal stratification may occur in these lakes during the winter.

Many shallow lakes become stratified during periods of calm, but may be completely mixed by moderate winds. Moreover, shallow lakes of small surface area are more quickly heated or cooled by atmospheric or other external influences than deep lakes of relatively larger surface area. Other lakes are continuously mixed and thermal stratification never occurs.

There are several schemes for the classification of lakes, but that proposed by Hutchinson (1957, p. 438) is perhaps the most useful. His classification is based upon the thermal and circulation patterns of lakes. For example, the San Francisco Bay area lakes would be classified as *warm monomictic* lakes. This classification refers to lakes in warmer latitudes where the temperature of the water is never below 4°C at any depth, complete circulation occurs once a year in late autumn or winter, and thermal stratification occurs during the summer.

SUSPENDED SEDIMENT

The amount of suspended sediment in water is very important from a water-quality standpoint. Streams entering lakes carry suspended sediment, which rapidly settles and fills the lake basin. If the streamborne sediment has a high organic content, it may also increase oxygen demand in the bottom water. Moreover, several minor chemical constituents and plant nutrients are commonly adsorbed by suspended material, especially clay. Consequently, suspended sediment transports many substances essential for plant growth. Suspended sediment may also enter the lake from runoff or wave action.

MORPHOLOGY

Light, temperature, and suspended sediment are important physical characteristics of lakes. However, other characteristics also provide meaningful information, and are frequently measured during lake surveys. These include:

Flow-through or *retention time*—The time necessary for the volume of a lake to be replaced by inflowing water.
Maximum depth—The greatest vertical distance between the surface and the bottom of a lake.
Mean depth—The volume of a lake divided by its surface area.
Maximum length—The longest straight-line distance over the surface of a lake.
Maximum width (breadth)—The longest straight-line distance perpendicular to the long axis of a lake.
Shoreline length—Circumference of a lake.
Stage—The elevation of a lake surface.
Surface area—The total water surface enclosed within a lakeshore.
Volume—The amount of water in a lake basin at any given time. *Maximum volume* refers to total capacity of a lake.
Watershed (drainage area)—The total land and water surface area that is drained through the outlet of a lake.

CHEMICAL CHARACTERISTICS

Chemical constituents in water consist of dissolved solids, such as calcium and magnesium, gases, such as oxygen and carbon dioxide, and organic compounds. The chemical characteristics of lakes are very important from the standpoint of water quality. Useful categories for discussing the chemical properties of water are (1) major chemical constituents, (2) minor chemical constituents, (3) major plant nutrients, and (4) dissolved gases. A complete discussion of the individual constituents in these categories is given in Hem (1970).

In the analyses of water for chemical constituents and major plant nutrients, the constituents may be in solution or sorbed (taken up) by particulate matter. The separation of dissolved and particulate materials is accomplished by filtration. Usually a filter having a pore size of 0.45 micrometre is used. However, some of the materials that pass through a filter of this pore size may be colloidal and not truly in solution (Hem, 1970, p. 87–88). But from a practical standpoint, dissolved materials are those not removed when the water is filtered.

MAJOR CHEMICAL CONSTITUENTS

The major chemical constituents of dissolved solids in freshwater are listed below. The concentration of major chemical constituents is usually expressed in mg/l (milligrams per litre). Simple and accurate methods are available for their analysis, and for this reason, they are commonly determined in most lake studies. Under natural conditions, the concentrations of these constituents are related primarily to the minerals in the surrounding rocks. However, man's waste materials may add significant amounts of these constituents to water. An analysis of major chemical constituents is of value in assessing pollution and eutrophication problems in lakes. Most, if not all, of the major chemical constituents are essential for the growth of plants.

Major chemical constituents

Silica (SiO_2)	Carbonate (CO_3)
Calcium (Ca)	Sulfate (SO_4)
Magnesium (Mg)	Chloride (Cl)
Sodium (Na)	Fluoride (F)
Potassium (K)	Nitrate (NO_3)
Bicarbonate (HCO_3)	

MINOR CHEMICAL CONSTITUENTS

The minor chemical constituents occur in low concentrations in water (generally less than 1 mg/l). Their concentrations are usually expressed in μg/l (micrograms per litre), which is one thousandth of 1 mg/l. Minor chemical constituents are important in water, as most of them are essential plant nutrients. Moreover, when found in even modest concentrations, some may be toxic to plants and animals. Some of the minor chemical constituents found in freshwater are listed on page 6.

Minor chemical constituents

Aluminum (Al)	Copper (Cu)
Iron (Fe)	Lead (Pb)
Manganese (Mn)	Mercury (Hg)
Boron (B)	Molybdenum (Mo)
Arsenic (As)	Nickel (Ni)
Bismuth (Bi)	Titanium (Ti)
Cadmium (Cd)	Vanadium (V)
Chromium (Cr)	Zinc (Zn)
Cobalt (Co)	

MAJOR PLANT NUTRIENTS

A nutrient is any substance necessary for the promotion of growth, repair of tissue, or energy needs of an organism (Fruh, 1967). Nitrogen, phosphorus, and carbon (in their several forms) are considered to be the major plant nutrients because their concentrations in water are most likely to be exhausted by phytoplankton and limit further growth (Talling, 1962). However, a literature review by Greeson (1971, p. 75) revealed that there are at least 21 elements, in some chemical combination, essential for the growth of phytoplankton (table 1). Most of these elements do not become limiting in water.

DISSOLVED GASES

The dissolved gases that are commonly measured in water are oxygen and carbon dioxide. While carbon dioxide is the end product of respiration, it is also a form of carbon that green plants can use in photosynthesis to form organic compounds used for cell structure and metabolism. During the photosynthetic process plants consume carbon dioxide and produce oxygen. This oxygen may be reused by plants and animals in respiration.

Usually the carbon dioxide concentration in water is not measured directly because of analytical difficulties. Dissolved oxygen, however, can be accurately determined using field techniques. As a result, oxygen is the gas commonly measured during lake surveys.

BIOLOGICAL CHARACTERISTICS

Lakes support a great variety of bacteria, plankton, higher plants, insect and fish species (fig. 3). These organisms can be placed into three broad categories: plankton (drifters and some swimmers), benthos (bottom-dwellers), and nekton (swimmers). The relationships and interactions among these various groups of organisms must be considered if a lake is to be successfully managed for aquatic crop production or for the control of biological nuisances.

Plant and animal life are affected by changes in water quality. Lakes are relatively closed systems, and interacting organisms remain in balance only in suitable water-quality conditions. The introduction of excessive amounts of inorganic and organic materials in the water disrupts the organism balance. This may lead to an unstable ecosystem, often resulting in conditions adverse to man's use of the water.

PLANKTON

The planktonic community is composed of organisms that inhabit all the water zones of a lake. Two major categories of plankton are recognized---phytoplankton (plants) and zooplankton (animals). Phytoplankton are mostly microscopic, whereas zooplankton can frequently be seen with the unaided eye. Phytoplankton usually drift with the currents, while some zooplankton are strong swimmers. Phytoplankton growth depends upon solar radiation and nutrient elements, while zooplankton feed on phytoplankton, bacteria, or dead organisms.

The phytoplankton community (primary food producers) includes several major groups of plants collectively known as algae. The most common groups of free-floating algae are the diatoms, green algae, and blue-green algae. Usually it is the blue-green algae that become overabundant and cause esthetic, taste, and odor problems in lakes.

Other types of plants which may inhabit lakes are the algae attached to solid surfaces (periphyton) and rooted submersed and emersed higher plants. Rooted plants are found in the littoral zone of lakes, where sufficient sunlight for photosynthesis reaches the bottom.

The zooplankton community (primary consumers) is dominated by small crustaceans and rotifers. Typically the zooplankton spend the daylight hours in the deeper water and rise toward the surface in late afternoon and early evening. The kinds and numbers of zooplankton in a lake are closely controlled by the available food supply and by grazing of predators such as fish.

BENTHOS

The benthic community (consumers and decomposers) includes a number of different types of organisms, such as bacteria, insect larvae and nymphs, snails, clams, and crayfish. These organisms are an integral part of the food chain of an aquatic environment. Benthic organisms feed on both plants and animals, and they in turn are fed upon by higher organisms. The bacteria and fungi are especially abundant on the lake bottom and decompose the organic materials that settle there.

NEKTON

The nektonic community (consumers) consists of relatively large free-swimming organisms. This community consists primarily of fish and certain insects. Nektonic organisms feed on benthos and plankton in the lake. In most lakes, fish are at the end of the food chain

Table 1.—*Common forms, minimum requirements, and some sources of elements essential for the growth of algae*

[The minimum nutrient requirements of algae in the aquatic environment are difficult to determine, and this uncertainty is shown by the wide range of concentrations in the table. "Trace" quantities generally refer to concentrations less than 1 mg/l, and more exact concentration requirements for these elements have not been determined. "Quantities always sufficient in surrounding medium" refers to those elements that are never below minimum concentrations so as to limit algal growth]

Element[1]	Symbol	Some common forms in water[1, 2]	Minimum requirements[3]	Examples of natural sources[1, 4]	Examples of manmade sources[5, 6, 7]
Aluminum....	Al	Al^{+3}, $AlSO_4$, AlO_2, (salts of aluminum)	Probably trace quantities	Clay minerals, silicate rock minerals	Domestic sewage, industrial wastes, mine drainage.
Boron	B	B, H_3BO_3	100 μg/l	Evaporite deposits, igneous rock minerals, springs, volcanic gases	Cleaning aids, detergents, industrial wastes, irrigation, sewage.
Calcium	Ca	Ca^{+2}, $CaCO_3$, $CaSO_4$	20 mg/l	Igneous rock minerals, rainwater, sedimentary rocks, soil	Industrial wastes (metallurgy, steelmaking), treatment plant wastes.
Carbon	C	CO_2, CO_3, HCO_3, H_2CO_3, $CaCO_3$	Quantities always sufficient in surrounding medium	Atmosphere, organic compounds and decay products, rainwater, soil	Industrial wastes (carbonation, metallurgy, pulp and paper, soda, and steelmaking), domestic sewage.
Chlorine	Cl	Cl^{-1}, (oxides of chlorine)	Trace quantities	Evaporite deposits, igneous rock minerals, ocean water, rainwater, sedimentary rocks, volcanic gases	Chlorinated hydrocarbon process, cleaning aids, industrial wastes (petroleum and refining), irrigation, salt mining.
Cobalt	Co	Co	500 μg/l	Coal ash, soil, ultramafic rocks	Manufacturing wastes (tools and instruments), metallurgy.
Copper	Cu	Cu^{+2}, Cu, $CuSO_4$	6.0 μg/l	Crustal rocks, ground water, marine animals	Industrial wastes (fabrication of pipes, refining, smelting), manufacturing wastes (electrical, foods), mill tailings, mine wastes, ore dumps, treatment plant wastes.
Hydrogen	H	H^+, H_2S, H_2O, HCO_3, H_2CO_3, OH	Quantities always sufficient in surrounding medium	Atmosphere, oxidation processes, rainwater, volcanic activity	Industrial wastes (hydrocarbon process), oils.
Iron.........	Fe	Fe^{+2}, Fe^{+3}, $FeSO_4$, $Fe(OH)_2$	0.65–6,000 μg/l	Ground water, igneous rock minerals, iron minerals, organic decomposition, soil	Acid drainage from mines, industrial wastes (steelmaking), iron ore mining, manufacturing wastes, oxides of iron metals (car bodies, refigerators).
Magnesium ...	Mg	Mg^{+2}, $MgSO_4$	Trace quantities	Igneous rock minerals, ground water, rainwater, sedimentary rocks	Irrigation, manufacturing wastes (transportation vehicles).
Manganese ...	Mn	Mn^{+2}, MnO_2	5.0 μg/l	Ground water, plants, rocks, soil, tree leaves	Acid drainage from coal mines, industrial wastes (steelmaking).

Table 1.—*Common forms, minimum requirements, and some sources of elements essential for the growth of algae*—Continued

Element[1]	Symbol	Some common forms in water[1 2]	Minimum requirements[3]	Examples of natural sources[1 4]	Examples of manmade sources[5 6 7]
Molybdenum . .	Mo	Mo, MoO_4	Trace quantities	Ground water, rocks, soil	Industrial wastes (electrical devices, metallurgy, steelmaking), manufacturing wastes (alloys).
Nitrogen	N	N, NO_2, NO_3, organic nitrogen, NH_3	Trace quantities to 5.3 mg/l	Atmosphere, bacterial and plant fixation, limestone, rainwater, soil	Agricultural wastes (feedlots, fertilizers), domestic sewage, industrial wastes, storm drainage.
Oxygen	O	O_2, H_2O, oxides	Quantities always sufficient in surrounding medium	Atmosphere, oxidation processes, photosynthesis, rainwater	Industry (metallurgy).
Phosphorus . . .	P	P^{+5}, PO_4, HPO_3, organic phosphorus	0.002–0.09 mg/l	Ground water, igneous and marine sediments, rainwater, soil, waterfowl	Agricultural wastes (feedlots, fertilizers), domestic sewage (detergents), industrial wastes.
Potassium	K	K^+ (salts of potassium)	Trace quantities	Evaporite deposits, igneous rock minerals, plant ash, sedimentary rocks	Agricultural wastes (feedlots, fertilizers), industrial wastes (preservatives, pulp ash).
Silicon	Si	Si^{+4}, SiO_2	0.5–0.8 mg/l	Diatom shells, igneous rock minerals, metamorphic rocks	Domestic sewage, industrial wastes.
Sodium	Na	Na^+, Na salts (NaCl, $NaCO_3$	5.0 mg/l	Ground water, igneous rock minerals, ocean water, soil	Industrial wastes (paper and pulp, rubber, soda, water softeners), manufacturing wastes (dyes and drugs).
Sulfur	S	SO_2, HS, H_2S, SO_4	5.0 mg/l	Animal and plant decomposition, igneous rocks, rainwater, sedimentary rocks, springs, volcanic activity	Agricultural wastes (fertilizers), industrial wastes (fuels, paper and pulp).
Vanadium	V	V^{+2}, V^{+3}, V^{+4}, V^{+5} (salts and oxides of vanadium)	Trace quantities	Ground water, plant ash	Industrial wastes.
Zinc.	Zn	Zn^{+2} (salts of zinc), ZnO_2	10–100 µg/l	Igneous and carbonate rock minerals	Industrial wastes (piping, refining), mine wastes.

1. Hem (1970).
2. McKee and Wolf (1971).
3. Greeson (1971).
4. Reid (1961).
5. Gurnham (1965).
6. Nebergall, Schmidt, and Holtzclaw (1963).
7. Sawyer and McCarty (1967).

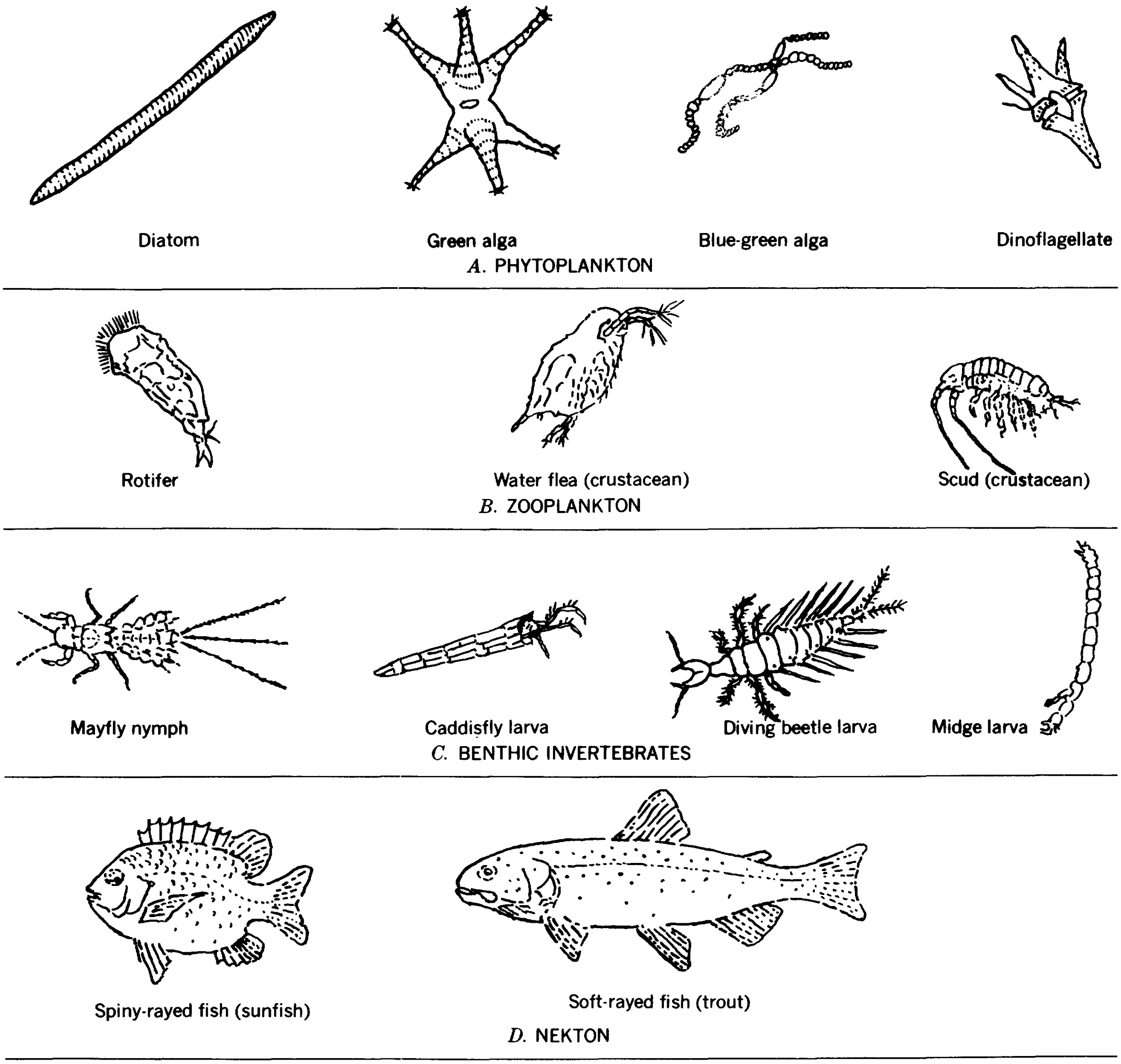

Figure 3.—Representative lake organisms.

and are often the most economically important organisms to man.

PROCESSES IN LAKES

Most of the properties and materials of lakes are easy to measure and describe. In contrast, their interactions as they relate to plants and animals are somewhat more difficult to describe, and measurements of these processes often more difficult to make. As a result, some of the processes in lakes are not well understood. Energy and material transport between plants and animals, and between animals themselves, is among several of the poorly understood biological processes in lakes. Other processes, such as photosynthesis, respiration, eutrophication, and basic geochemical cycles are somewhat better known, and can be described in general terms.

PHOTOSYNTHESIS AND RESPIRATION

Photosynthesis is carried out only by green (chlorophyll-containing) plants and some bacteria. Respiration is carried out by both plants and animals. Both processes are essential to life and have a profound effect upon water quality in lakes.

As mentioned earlier, photosynthesis is the process whereby green plants take up carbon and synthesize carbon compounds, while producing oxygen. When plants take up carbon, generally as carbon dioxide, they combine hydrogen, sulfur, nitrogen, or phosphorus with the carbon, to form cellular materials such as carbohydrates, proteins, and fats. The oxygen produced during this process goes into solution.

Respiration is the process whereby organisms obtain their energy by oxidizing food (organic material) to carbon dioxide and water. Because their energy need is continuous, all organisms respire throughout their lives. Plants emit oxygen as a result of photosynthesis, but they must also use oxygen for respiration.

Photosynthesis and respiration result in daily and seasonal fluctuations of dissolved oxygen and carbon dioxide levels in lakes. As a result, the carbon dioxide and dissolved oxygen concentrations are not always in balance. These imbalances have a significant effect upon the quality of water. For example, all lakes contain some algae, but in the presence of sufficient sunlight and plant nutrients, photosynthesis by phytoplankton may result in an excessive production of oxygen. At this time, the phytoplankton may increase to concentrations of a million cells per litre, a condition known as an algal bloom (Lee, 1970, p. 19).

Respiration removes dissolved oxygen from the water. For example, in a thermally stratified lake during the summer, respiration by bacteria may oxidize organic materials at such a rapid rate in the bottom water that the dissolved oxygen becomes drastically depleted. Thus, when large quantities of decomposable organic wastes are introduced into natural water, severe oxygen depletion can occur.

Decreases in oxygen concentration also affect the solubilities of compounds contained in sediment. For example, iron in natural water is found in either the ferrous (Fe^{+2}) or the ferric (Fe^{+3}) state. Under aerobic (oxygenated) conditions, iron is in the ferric (or highly oxidized) form as a complex with other inorganic constituents, and as simple decomposition products (Reid, 1961, p. 193). Under anaerobic conditions, the insoluble ferric complex in the lake sediment loses oxygen and is reduced to the more soluble ferrous state. This not only puts more iron in solution, but also releases other combined constituents, such as silicate, phosphate, and bicarbonate. The ions that go into solution all act as plant nutrients.

EUTROPHICATION

Eutrophication is the enrichment of lakes by nutrients and filling by sediment. Although eutrophication is a natural phenomenon, recent concern has been with the acceleration of this process by man's activities. Presently, it is a major problem of many lakes and reservoirs.

The aging process of a lake begins with its formation in a basin. As the lake accumulates plant nutrients and sediment deposits, plant production increases and shoreline vegetation invades the lake. As the depth of the lake decreases and emergent vegetation increases, the lake becomes a bog and is referred to as a *dystrophic* system. Eventually the original lake becomes land.

Unenriched lakes are classified as *oligotrophic*. Oligotrophic lakes have high concentrations of dissolved oxygen at all depths, low concentrations of dissolved substances, and usually clear waters. Although sufficient oxygen is available to support life throughout the water mass of oligotrophic lakes, the low quantity of dissolved materials and plant nutrients limits plant production and thereby restricts the abundance of animal life. Many newly created real-estate lakes and reservoirs are oligotrophic. However, many older reservoirs and natural lakes, such as Lake Tahoe, may still be considered oligotrophic because they contain minimal plant nutrient concentrations (Goldman and Carter, 1965; Crippen and Pavelka, 1970).

The second enrichment stage of a lake is *mesotrophy*. This stage is characterized by increased concentrations of dissolved materials and plant nutrients, and thus increased plant production. A mesotrophic lake may support a large plant population but generally plant production is not so excessive as to be undesirable, in terms of human use of the water, nor to seriously deplete the dissolved oxygen concentration.

The third stage of the enrichment process is called *eutrophy* (hence eutrophication). This is the final stage of the lake before filling and extinction are complete. The symptoms of a eutrophic lake are high concentrations of dissolved materials, excessive numbers of phytoplankton represented by only a few tolerant species, and oxygen depletion in the deeper water. The reduction of oxygen is caused by bacterial decomposition of organic matter (Redfield and others, 1963, p. 27) and may result in fish kills. Other characteristics of eutrophic lakes may be discolored water from excessive algae production and unpleasant odors attributable to decay.

The effect of man on the eutrophication process is shown in figure 4. The diagram shows the effect of nutrient enrichment upon the natural eutrophication of lakes. Regardless of the enrichment status of lakes, nutrient inputs by man can hasten lake extinction. However, the rate of eutrophication, and thus the extinction of lakes, can be retarded by nutrient removal.

THE BIOGEOCHEMICAL CYCLE

Materials that enter a lake from tributaries or from the atmosphere may settle in the lake basin, be removed

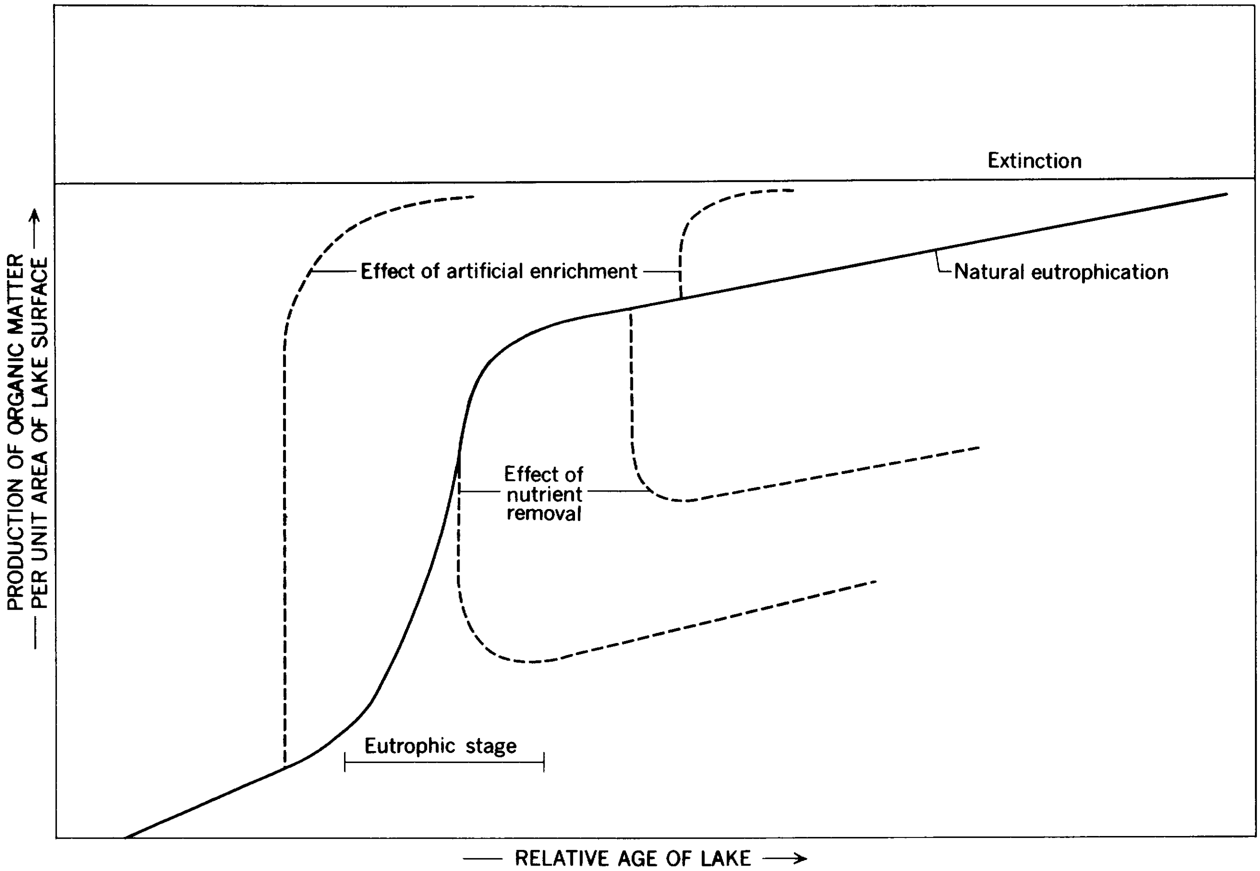

Figure 4.—Effect of man upon the eutrophication of lakes. After Greeson, 1971; modified from Hasler, 1947.

through the outlet, or remain in solution. Those that remain in solution, and that are required for plant production, may be incorporated into living tissue.

SEDIMENTATION

The major pathway for the flow of plant nutrients and other elements into a lake is sedimentation. Sedimentation is the process whereby fragmental material originates from the disintegration of rocks and from other sources, is transported, and is deposited in layers or remains suspended in the water (Colby, 1963, p. A3). Lakes receive sediment from both inflowing water and from the wind. The sediment accumulates permanently in areas little affected by wave action. Because most lake-bottom sediments are relatively permanent deposits, sediment deposition is a major cause of the aging and extinction of lakes.

Many lakes retard inflow sufficiently to trap all incoming coarse sediment, as well as part of the fine sediment. The trap efficiency of a lake depends in part upon the fall velocities of the sediment particles, the density of the water, and how much the water is slowed as it passes through the reservoir (Brune, 1953). As a lake fills with sediment, its trap efficiency usually decreases (Colby, 1963, p. A35).

Besides being a mechanism for lake filling, sedimentation introduces plant nutrients and dissolved materials into lakes. The quantity of plant nutrients sorbed by sediment particles may be high, and the nutrients can become more soluble upon entering the different chemical environment of a lake. Once in the lake, plant nutrients are subjected to cycling.

NUTRIENT CYCLING

A generalized scheme of element sources, losses, and cycling in lakes is shown in figure 5. Some elements, such as phosphorus, nitrogen, silicon, and perhaps soluble carbon, may undergo such extensive use by plants that these nutrients are virtually depleted in the water. Thus, they may become limiting nutrient elements to plants and restrict plant production until the elements are recycled or new supplies enter the lake.

Many elements are cycled through a number of chemical forms. For example, nitrogen may be taken up by plants as the stable nitrate ion (NO_3^-). In the plant cell it is reduced and makes up an important part of plant and animal protein. Upon death of the organism, the nitrogen may be released either as ammonia gas (NH_3), or the

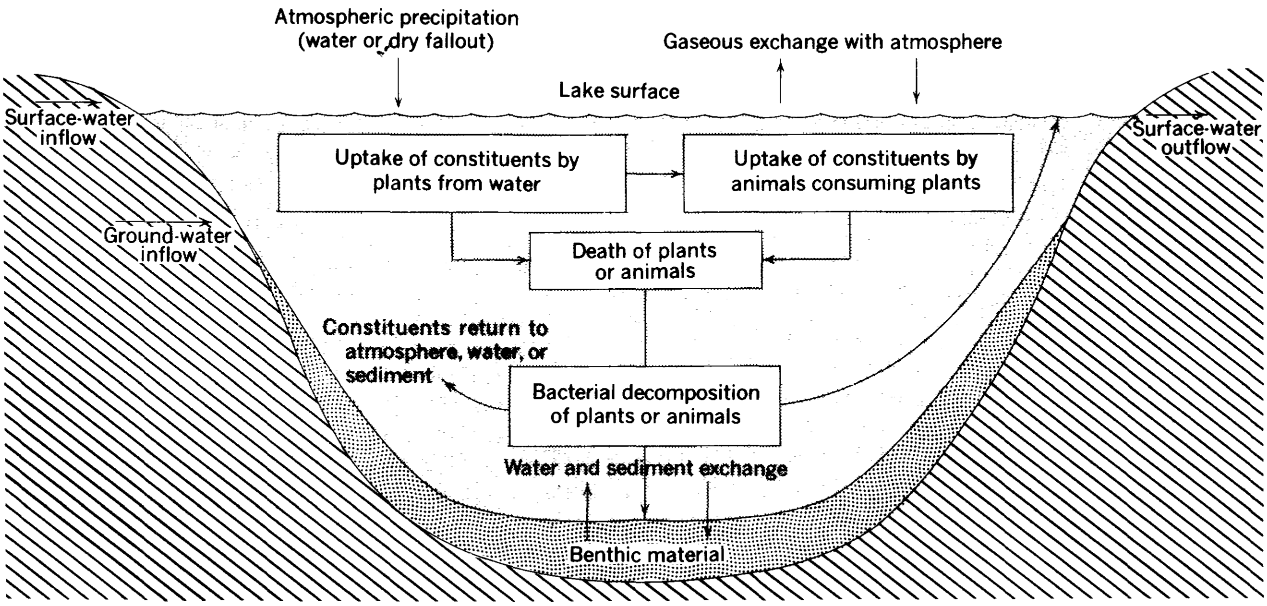

Figure 5.—Sources and cycling of elements in a lake.

ammonium ion (NH_4^+). Further oxidation of these forms by specific bacteria results in the unstable oxidized form, nitrite (NO_2^-). Further oxidation of the nitrite by other bacteria results in the stable nitrate form, thus completing the cycle.

Phosphorus (P), inorganic phosphate (PO_4^{-3}), and organic phosphorus (OP—the fraction bound in plant and animal cells) follow a cycle similar to nitrogen. Carbon also occurs in several forms. In water it is found as carbon dioxide gas (CO_2), as the inorganic ions bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}), or as the solid compound calcium carbonate ($CaCO_3$). Organic carbon is that fraction of total carbon within plants and animals.

The sorption (absorption and adsorption) of chemical elements and compounds by sediment is well known. Lake bottom sediment is often a rich source of plant nutrients. The release of these nutrients from the sediment is regulated by various factors, such as temperature, pH, and dissolved oxygen. For example, a lack of oxygen in the bottom water of lakes (hypolimnion) may trigger the release of phosphorus compounds from the sediment. When the bottom water becomes oxygenated again, the phosphorus compounds precipitate and reenter the sediment. There they are unavailable as plant nutrients until oxygen depletion again occurs in the hypolimnion.

PLANNING AND MANAGEMENT OF WATERSHEDS AND LAKES FOR WATER-QUALITY CONTROL

The foremost goals in lake management are to prevent or reduce the undesirable effects of eutrophication and to provide water of high quality. Factors associated with eutrophication of lakes are excessive algal production, dissolved oxygen depletion in the hypolimnion, objectionable taste and odor, and general esthetic depreciation of the environment. In the past, management of lakes was commonly limited to volume manipulation and water releases. In recent years, intensified demands for water of high quality have caused more attention to be focused on lake-basin planning, watershed and lake management, and water-quality control (Keup and Mackenthun, 1970).

LAKE BASIN PLANNING

Good lake-basin planning can minimize water-quality problems. The selection of an appropriate site for a reservoir is of paramount importance. A preimpoundment survey of the physical, chemical, and biological characteristics of the proposed lake basin is most beneficial when done before construction begins. In addition, basin planning and dam construction should take seismic safety into consideration. This becomes especially important in fault regions like the San Francisco Bay area.

A primary characteristic of a good reservoir is a high ratio of volume to surface area, which is desirable for land conservation and water-quality control (Linsley and Franzini, 1964, p. 168). For example, a deep reservoir is preferable to a shallow one because of lower land costs per unit of capacity, less evaporation loss, and less area for weed growth. The watershed, of course, must have a suitable damsite, and the reservoir site must have enough capacity for its intended use. If a reservoir site has tributaries which produce much sediment and plant nutrients, rapid eutrophication may result after construction of the reservoir. Therefore, a preimpoundment survey that includes a nutrient-loading estimate of at least nitrogen and phosphorus for all waters entering the planned impoundment will enable the planner to assess the eutrophication potential. Open mines in the basin may cause toxic water conditions. Reconnaissance surveys of reservoir sites can reveal such potential problems, so plans can be formulated to avoid or deal with them.

An important step, after selection of an appropriate reservoir site, is to remove trees and vegetation from that part of the basin that will be inundated, because the decomposition of this organic material may cause oxygen depletion and undesirable taste and odor in the reservoir water. The ideal practice is to remove the topsoil and contained plant nutrients also, but the cost of such an operation may be prohibitive in large reservoir basins (Houghton, 1966, p. 180). If the topsoil is not removed when the reservoir is cleared, removal of vegetation from the site with as little disturbance of the soil as possible will reduce the amount of plant nutrients released from the soil and decrease the incidence of algal blooms (Houghton, 1966, p. 180).

WATERSHED MANAGEMENT

Effective watershed management can prevent or reduce the rate of eutrophication; thus attention must be given to the quality of inflowing water.

The disturbance of soil in the watershed from natural events and human activities increases the transport of sediment and combined plant nutrients into the lake. Maintaining a good vegetative cover around the lake will help prevent excessive erosion of the watershed. However, if the soil in the watershed must be disturbed, construction of sediment traps (temporary debris basins) below the disturbance will minimize the amount of sediment entering the lake (Rickert and Spieker, 1971). Because fertilizer is a rich source of plant nutrients, its use should be limited within the lake basin.

Control or diversion of all waste inflows (wastes high in biochemical oxygen demand or rich in nutrients) is probably the best way to control lake enrichment. This can be accomplished by re-routing the effluent to the outlet of the lake. Advanced methods of sewage treatment, rather than the use of septic tanks, reduce the seepage of nutrients into the lake. If sewage discharges into the lake cannot be avoided, then sewage that has had secondary treatment, but preferably tertiary treatment, will keep nutrients entering the lake to a minimum. Secondary and tertiary treatment of wastewater reduces the oxygen demand, disease potential, and nutrient levels of wastes.

Inflowing streams, or lakes themselves, may receive heated effluent from industrial plants. Heat can greatly alter the chemistry and biology of the water. Thus, heated water should be cooled before its introduction into lakes and reservoirs. There are several cooling devices used in thermal industrial plants. The most effective is the dry-cooling tower. Cooling and spray ponds, although not as effective, are more economical and are used more frequently (Linsley and Franzini, 1964).

LAKE MANAGEMENT

Although lake water-quality problems are best controlled by effective management of the watershed area, some within-the-lake management tools are often necessary. Multipenstock release systems on a reservoir allow for greater flexibility in releasing water from various depths, and hence reducing potential water-quality problems. For example, domestic wastewater containing undesirable chemical constituents, such as manganese and iron, can be passed through the lake by regulating the release of water at the dam. Mechanical aeration can be used to increase the oxygen in the water, to prevent the buildup of hydrogen sulfide concentrations (see p. 46), and to depress high levels of manganese or iron before the water enters the distribution system. Regulating recreation on the lake may help prevent accelerated eutrophication. Many recreational lake areas do not have adequate sanitary facilities, and drainage of human wastes into the lake may cause bacterial contamination.

WATER-QUALITY CONTROL

Although preventive measures for water-quality control are always preferable, it is often necessary to manage a lake system to control after-the-fact water-quality problems. These problems generally arise as part of the eutrophication process, and are often accelerated by man.

ALGAL BLOOMS

Algal blooms are a troublesome problem in lakes. An algal bloom is an excessive amount of phytoplankton production which usually occurs during the spring and summer in nutrient-enriched lakes. Minimum conditions for an algal bloom are a sufficient concentration of plant nutrients in the water, adequate sunlight, and a water temperature suitable for growth. The concentration of algae that constitutes a bloom is not precise, and it depends upon the type of algae. Lee (1970) proposed that a concentration of ½ million to 1 million cells per litre indicates a bloom condition.

When minimum conditions for algal growth are met, the growth of algae takes place at a more or less constant rate (fig. 6). If no property is limiting, the algae grows rapidly, causing a bloom. At some point, an essential condition becomes limiting and restricts further algal growth. The cell density may remain stable for a few days, but because of limiting materials for growth and tissue repair, the cells begin to die. As the algal cells die, they sink and are decomposed by bacteria, which results in the uptake of dissolved oxygen and release of cellular materials back to the water or lake sediment.

Although algae are essential for other organisms to live, algal blooms may cause coloration or fouling of the lake water. Algae may clog sand filters at water treatment plants. Recreational activities, such as boating and fishing, may be hindered by mats of floating algae, and water sports may prove harmful because of the presence of toxic algae (Mackenthun and Ingram, 1967, p. 157–166).

Effective treatment and control of algae requires some knowledge of the number, kind, and distribution of algae in the water. The application of an algicide is the most frequent method of control. Copper sulfate is the most common and effective algicide used today, because it is toxic to many algae at comparatively low concentrations, has a relatively low toxicity to man and other animals, and is inexpensive (Gratteau, 1970, p. 25). The concentration of copper sulfate which is toxic to a particular type of algae varies with the abundance of the algae, the temperature, pH, alkalinity, and amount of organic matter in the water. Mackenthun and Ingram (1967, p. 258–260) present application rates for copper sulfate based on these variables. The most effective time for the application of an algicide is at the junction of the initial growth phase and the rapid growth phase. To determine the growth-phase junction, several algal-growth curves are needed. These can be prepared by frequently collecting water samples and counting the algal cells. Once several growth curves are established for the algal species of the lake, it will be possible to predict with some reliability the growth-phase junction, and hence the best time to apply an algicide. Mechanical removal of algae may be an alternative control, especially in water where localized blooms occur (Thomas, 1965). The harvested material is usually hauled to shore and burned, or removed to a disposal site (Gratteau, 1970, p. 25).

Higher aquatic plants may be killed with herbicides or removed by mechanical means. Livermore and Wunderlich (1969, p. 498–512) and Mackenthun and Ingram (1967, p. 264–273) discuss the removal of both submersed and emersed aquatic plants. If the plants are removed mechanically, they are usually hauled out of the watershed area so that their contained nutrients will not reenter the lake upon decomposition.

ANAEROBIC CONDITIONS

The quantity of available dissolved oxygen in a lake is often a limiting factor to productivity. When thermal stratification occurs in a lake, the lighter water at the surface forms a density barrier which prevents reaeration

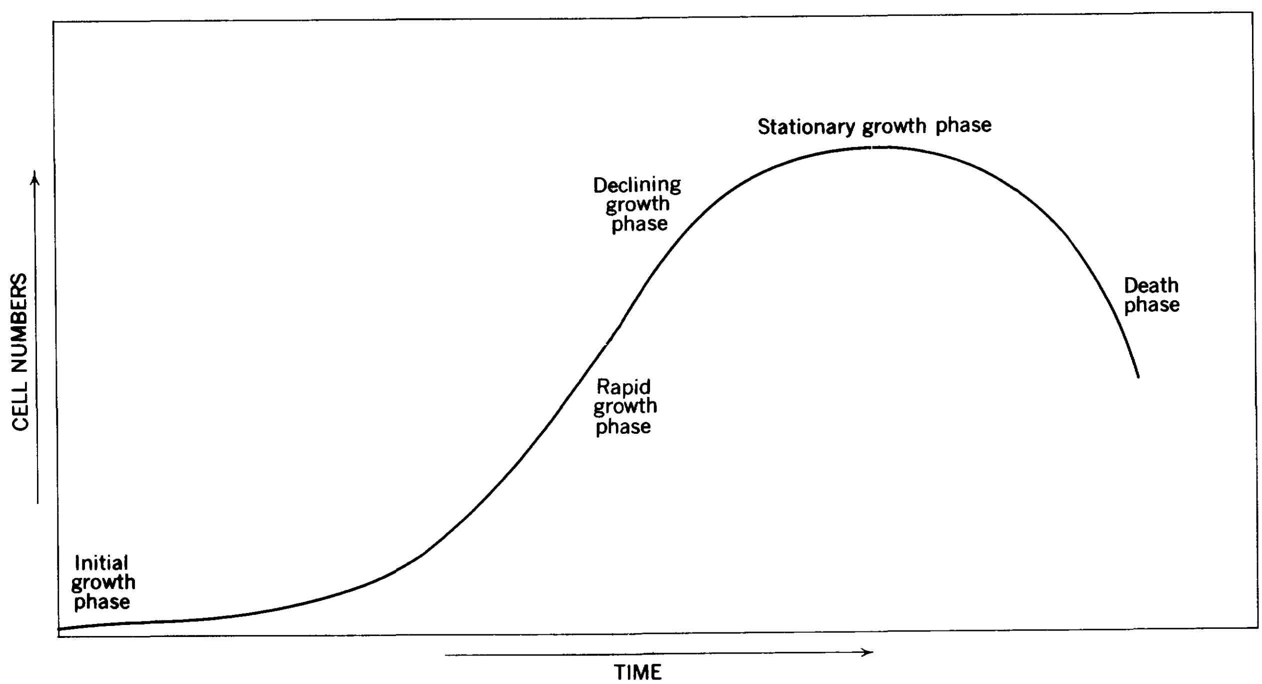

Figure 6.—Typical growth pattern of blooming unicellular algae.

by atmospheric oxygen in the bottom waters. The sinking and decomposition of algae following a bloom may add to the depletion of dissolved oxygen in the lower water. The introduction of large amounts of other oxygen-demanding materials, such as organic wastes, raises the BOD (biochemical oxygen demand) of the water, and thus depletes the oxygen supply.

Under anaerobic conditions, water quality often depreciates. For example, concentrations of hydrogen sulfide, soluble manganese, and iron may increase in the bottom water. Anaerobic conditions also can result in undesirable taste and odor from hydrogen sulfide buildup. Obviously, aquatic life will be adversely affected.

Mechanical aeration of lakes has become a useful management tool in reducing anaerobic conditions. Pumping or drawing off the deoxygenated water, combined with recirculation of oxygenated water from the surface, will help to relieve hypolimnetic oxygen depletion (Thomas, 1962, p. 303; Irwin and others, 1969).

FISH KILLS

Fish kills may become an important problem in some lakes. Fish are killed by exposure to toxins in waste discharges and by some algicides. Anaerobic conditions may suffocate fish. Rapidly changing or excessively high water temperatures may kill fish, or cause an increase in fish respiration. This means that more water passes through their gills, and hence introduces more toxins into their bloodstream.

Fish kills can be prevented only by treating the cause, which involves proper planning and management of the lake. Obviously there are no after-the-fact control measures for fish kills. However, immediate cleanup of dead fish along the shores of lakes will reduce odors and improve recreation and the esthetic value of beaches. Chemical tests for the investigation of fish kills can be used on distressed or dead fish. Any conditions at the site of the kill that might help identify the cause of death should be investigated, such as oxygen depletion or evidence of toxicity (Burdick, 1965; Slack and others, 1973, p. 158–159).

SEDIMENT DEPOSITION

Sediment deposition is one of the most prevalent problems with real-estate lakes (Rickert and Spieker, 1971), and it has become increasingly evident in all lakes. Reservoirs in particular are depositories for sediment. Accelerated sediment deposition usually results from soil disturbances in the watershed. Common causes of soil disturbances are logging, road construction, farming, and overgrazing. Sediment deposits may fill the lake, introduce nutrients, or reduce the esthetic value of the lake. Organic sediment may place an oxygen demand upon the lake water.

Once deposition has occurred, the life of the lake may be extended by dredging, or if the reservoir can be drained, the sediment can be removed with earthmoving equipment. Both sediment-removal techniques are expensive, and unless watershed-protection measures are undertaken, the success of these techniques may be shortlived.

SUMMARY OF MANAGEMENT OPTIONS

There are few management options available for reducing eutrophication once it occurs. The best management is prevention——choosing the reservoir site carefully, understanding the potential nutrient loads of the tributaries, and clearing the reservoir site completely and carefully. Most important, however, is the wise management of the watershed. The maintenance of a plant cover with a minimum of soil disturbance in the watershed is of prime importance. The removal or prevention of domestic and industrial waste is of course a desirable feature and a prerequisite for the reduction or prevention of eutrophication.

CONDUCTING LAKE STUDIES

Studies of lakes are conducted for a number of reasons. Frequently, lakes are studied to determine present or changing water-quality conditions. Water-quality measurements can be made to assess physical, chemical, and biological factors. Morphological studies of lakes are designed to determine the bottom configuration, sediment deposits, or erosional processes resulting from wave action.

For convenience and understanding, as well as for management direction, lake investigations can be separated into the three categories of reconnaissance, monitoring, and interpretative.

Reconnaissance investigations are somewhat encompassing in design. They are not intensive studies, but are of sufficient detail to determine the physical arrangement of a lake and the distribution and abundance of materials (chemical or biological) in the lake basin at a particular time. The results of a reconnaissance study may be the end product of a lake study, or they may point the way toward more intensive investigations. In any event, a reconnaissance study is a prerequisite to the design of a monitoring program or an interpretative study.

Monitoring studies or programs are designed to determine time-trend changes in a particular variable. Such studies usually determine the changes in abundance of materials in lakes, the distribution pattern having been determined during the reconnaissance study.

Usually, but not always, monitoring takes place at the same site on a lake, at predetermined time intervals.

Interpretative studies are designed to determine the processes that govern the distribution and abundance of materials in a lake. An effective interpretative study is usually designed after sufficient data are collected in a reconnaissance study. Interpretative studies are generally made to advance our knowledge of limnology, or to study a special type of lake or processes within a lake.

From the standpoint of lake management, a reconnaissance study is often sufficient, and the measurements discussed below are those frequently made during reconnaissance investigations.

MEASURING THE PROPERTIES OF LAKES

The number of sampling sites on a lake will vary with the size and shape of the basin. In shallow lakes, having a circular basin, a single site in the deepest part of the lake may be sufficient to describe the distribution and abundance of the constituents in solution. In natural lakes, the deepest point is generally near the lake center, and in reservoirs, the deepest area is near the dam. In lakes with irregular shape and with several arms and bays that are protected from the wind, additional sampling sites may be needed to adequately define the water quality. The investigator can determine this need by comparing the thermal and specific-conductance profiles in the bays with those in the deepest area of the lake. If a significant difference exists, then additional sampling sites may be needed.

A variety of equipment is available for the measurement of lake variables. A discussion of all the equipment and its use would be voluminous. Only general guidelines will be given here, and the reader is referred to the cited literature for more details.

Many lake measurements are now made in-place with the use of sensor probes and automatic readout or recording devices. Single-parameter devices are available for measuring temperature, depth, pH, specific conductance, dissolved oxygen, chloride levels, light penetration, and turbidity. Recently, multiparameter units have become available for the in-place measurements of several of these at the same time. While expensive, such pieces of equipment are great timesavers if a number of surveys are to be made. Multiparameter units may be read directly, or attached to continuous recorders. As a rule, all surface-to-bottom (vertical) measurements made from a boat should be done while the craft is at anchor.

While a number of publications describe lake survey techniques and methods, there is no recent publication addressed solely to the subject. The book entitled *Limnological Methods* (Welch, 1948) is the most recent manual on the subject. While there have been advances in limnological equipment and techniques since Welch's book, many of the techniques he described are still commonly used. Other references useful for lake studies are Mackenthun and Ingram (1967), Committee on Oceanography, Biological Methods Panel (1969), Brown, Skougstad, and Fishman (1970), Edmondson and Winberg (1971), Holme and McIntyre (1971), Goerlitz and Brown (1972), and Slack and others (1973). Only the important considerations of common measurements—what, why, and where—are discussed in detail here. References are given for detailed instructions on how a particular measurement is made.

PHYSICAL MEASUREMENTS

Mapping

A map of the lake can be prepared from aerial photographs or topographic maps, or the lake can be surveyed using any of the methods given in Welch (1948, p. 3–24). Maps are an essential first step in designing a detailed lake study, and are quite useful when the bottom contours of the lake are included. Bottom configuration and depth of water are easily measured in large lakes with an echo sounder (Holme and McIntyre, 1971, p. 14–17). In small lakes, a sounding line and weight are sufficient. When a lake or reservoir is sounded, installation of a staff gage or other similar type marker, and recording of the water-surface elevation of the lake will make it possible to compute the estimated volume of the lake at any given surface elevation. A complete discussion of how to sound and plot lake contours and how to determine the volume of water is given in Welch (1948, p. 25–49, 77–98). In reservoirs, bottom contours and water depth may be estimated from topographic maps made before the reservoir was constructed. Many recent topographic maps give the depth contours of reservoirs. Shoreline configuration will point out areas where wind circulation is likely to be negligible (bays and arms); bottom contours will indicate the deepest part of the lake, the shallow and shoal areas, and areas of sediment deposition. When the map is complete, a survey of the lake can begin.

Temperature

The temperature profile of a lake is determined by measurements at the deepest part of the lake and preferably in one or more shallow areas and in protected bays and arms. A thermistor attached to a readout device in the boat, with a cable marked in feet or metres, is the easiest way to obtain a temperature profile of a lake. However, other methods, most of which are not as convenient, are available (Welch, 1948, p. 101–125).

The exact position of the metalimnion can be determined, and consequently the positions of the epilimnion and hypolimnion, when temperature measurements are made at intervals of 1 to 3 ft (0.3 to 0.9 m). The temperature profile is then used as a guide for the collection of other limnological data.

Light Penetration

In some instances, especially for productivity studies, it is important to measure light penetration. This parameter is often not measured directly, but is estimated with a Secchi disk, a plate about 12 in. (30 cm) in diameter, with alternate black and white markings (Welch, 1948, p. 159). If light measurement is critical for a particular study, the discussion in Welch (1948, p. 159–167) and Holme and McIntyre (1971, p. 53–58) should be consulted.

CHEMICAL MEASUREMENTS

Dissolved Oxygen

Dissolved oxygen is one of the most important variables measured during a lake investigation. A limnologist can tell more about the water quality and the well-being and activity of the biota in a lake with dissolved-oxygen data than with any other measurement (Hutchinson, 1957, p. 575). Measurements made at many depth intervals are needed because the dissolved-oxygen concentration may be altered locally. It is not unusual, for example, to find a subsurface oxygen maximum resulting from photosynthesis in the epilimnion of lakes and oxygen depletion due to bacterial decomposition of organic matter in the hypolimnion of enriched lakes in late summer.

To accurately define the distribution of dissolved oxygen, at least two dissolved oxygen measurements are needed in the epilimnion, one in the metalimnion, and at least two in the hypolimnion, one near its top and another near the lake bottom. Additional measurements may be necessary if the results show drastic changes in the dissolved oxygen concentration with depth. One advantage of measuring dissolved oxygen with a probe connected to a readout device is that measurements can be quickly made in-place at any depth in the lake. With the Winkler method (American Public Health Association and others, 1971, p. 474–488; Brown, Skougstad and Fishman, 1970, p. 126–129), the sample is collected at a particular depth with a sampling bottle, brought to the surface, and the dissolved oxygen level determined there. Regardless of how the dissolved-oxygen concentration is determined, its measurement is essential in a lake study.

Alkalinity and pH

Alkalinity is a measure of the capacity of water to resist a change in pH, and provides a measure of the carbon dioxide (CO_2), bicarbonate (HCO_3^-), and carbonate (CO_3^{-2}) in the water. The pH is a measure of the hydrogen ion (H^+) concentration (actually the activity of the hydrogen ion). Alkalinity is a function of pH and cannot be determined without measuring the pH. While pH can be measured with indicator dyes, or in-place with an instrument (often included on multiparameter units), alkalinity must still be measured on water samples collected in the lake. The pH value is logarithmic, ranging from 0 to 14. Alkalinity is expressed in mg/l of HCO_3^-, CO_3^{-2}, or as $CaCO_3$.

Both alkalinity and pH are altered by photosynthesis and respiration. As a result, they should be measured at depths similar to those used for dissolved-oxygen determinations. Instructions for alkalinity and pH measurements are given in American Public Health Association and others (1971, p. 52–56, and p. 370–376 for alkalinity, and p. 276–281 for pH) and Brown, Skougstad, and Fishman (1970, p. 41–44 for alkalinity, and p. 129–130 for pH).

Major Chemical Constituents and Specific Conductance

The major chemical constituents make up the bulk of the dissolved solids in water. Because most of these dissolved constituents are in the ionic state, they conduct electricity. Therefore, a correlation between the dissolved solids and the specific conductance of the water can be made (Hem, 1970, p. 96–103).

The major chemical constituents are important plant nutrients and are used in classifying water types and assessing enrichment (Beeton, 1969). Over short time periods and in the absence of outside influences, their concentrations change very little. Frequent measurement of the individual major constituents is usually not necessary, and concentration changes in dissolved solids (summation of the major dissolved constituents) can be detected by measuring the specific conductance of the water.

Water samples are collected with a standard water-sampling bottle, at the desired depth, and brought to the surface for filtering or other preanalysis treatment. General procedures for collection, preanalysis treatment, and analysis are found in Brown, Skougstad, and Fishman (1970, p. 4–18). Nonuniform vertical mixing of chemical constituents occurs because of wind and temperature changes, the shape of the lake basin, biological activity, and many other factors. Therefore, water samples for major chemical constituents collected at several depths in a lake will more accurately define the distribution of major chemical constituents than a single point sample. One sample taken in each of the epilimnion, metalimnion, and hypolimnion in the summer and winter is usually sufficient to describe the concentration of the major chemical constituents. Estimates of the dissolved solids concentration can be made during other times of the year with specific-conductance measurements.

Specific conductance is a measure of the ability of water to conduct an electrical current. It is usually expressed in micromhos per centimetre at 25°C, a micromho being the reciprocal of ohms X 10^6. Specific conductance may be measured in-place with a probe connected to a readout device, or it may be measured in a water sample collected at the desired depth in the lake. Wind movement of water masses often causes short-term changes in specific conductance. These changes are easily measured by towing a conductance probe behind a boat. Edmondson (1956) discusses the measurement of specific conductance.

Minor Chemical Constituents

The minor chemical constituents in water are often important plant nutrients and enzyme activators for both plants and animals. They are often transported with sediment. At times, particulary during rapid algal production, the minor chemical constituents in the water are effectively exhausted because of algal uptake. Too often, minor chemical constituents are not determined as a part of a lake-reconnaissance study. This is unfortunate because while their role in the ecosystem is not as well understood as that of the major chemical constituents, they are nonetheless important. More work on their specific relationships to algal production is needed.

As is the case with major chemical constituents, water samples for minor chemical constituents should be collected from the epilimnion, metalimnion, and the lower hypolimnion. The chemical species to analyze for, and the frequency of collection, will depend upon the enrichment status and particular suspected problems of the lake. Iron, aluminum, copper, manganese, molybdenum, and zinc are the minor chemical elements that are commonly measured. In appropriate cases, mercury and lead levels should be determined as well.

Water samples for minor chemical constituents are collected with a sampling bottle, using the procedures given in Brown, Skougstad, and Fishman (1970, p. 4–18). This publication also presents procedures for their determination. Because minor elements occur in small or trace quantities, care must be taken in the collection and handling of water samples. Nonmetallic bottles must be used, and preanalysis procedures, including filtering and acidification, must be followed carefully (Brown, Skougstad, and Fishman, 1970; American Public Health Association and others, 1971).

Major Plant Nutrients

Nitrogen, phosphorus, and carbon are the so-called major plant nutrients. Because they may limit the growth of phytoplankton and other plants, their measurement is important in lake surveys. The concentrations of these nutrients are readily altered by biological activity, and even short-term storage of the water samples before analysis may result in drastic concentration changes. The total nitrogen concentration can be estimated by analyzing for nitrate and total Kjeldahl nitrogen (ammonia plus organic nitrogen) and summing the results. Usually nitrite, the transitory oxidized form, is not present in significant quantities and can be ignored. Summing the concentrations of nitrate and total Kjeldahl nitrogen still has an inherent error in that some ammonia may escape from the sample container before analysis. Thus the sum of these two forms may represent an underestimation of the true nitrogen concentration. A discussion of analytical methods for the several forms of nitrogen is given in Brown, Skougstad, and Fishman (1970, p. 116–124) and American Public Health Association and others (1971, p. 221–248 and p. 453–470).

Phosphorus may be analyzed as a number of forms but is generally analyzed either as inorganic orthophosphate or total phosphorus (inorganic and organic). Usually a measure of the total phosphorus concentration is sufficient for reconnaissance studies. If the sample is to be filtered, care should be taken to rinse the filter with distilled water before collecting the sample. This is necessary because many commercial filters contain appreciable amounts of phosphorus. The analysis of phosphorus is described in Brown, Skougstad, and Fishman (1970, p. 130–133) and American Public Health Association and others (1971, p. 283 and p. 518–534).

Analysis of water for soluble and particulate carbon is a relatively new measurement. Some results and their significance can be found in Helms (1970) and Emery, Welch, and Christman (1971). Methods of collection and preanalysis treatment, as well as analytical techniques are given in Goerlitz and Brown (1972, p. 2–6). Silver filters are required for carbon analysis.

The frequency, depth, and location for collection of water samples for nitrogen, phosphorus, and carbon analysis depend upon a number of factors. Usually, it is wise to collect some samples in the winter before algal production, and some during the growing season. It is often advantageous to collect nutrient samples just after the spring overturn in order to estimate the maximum concentrations that may be available for the summer production period. However, relations between plant nutrient concentrations and algal growth are difficult to evaluate, and the investigator should not always expect definitive results. It is often useful to collect a water sample for algal cell counts at the same time a measurement of major plant nutrient concentration is made. Much of the nitrogen, phosphorus, and carbon in a lake may be in or sorbed by the sediment, thus becoming a potential nutrient source for plants. However, measuring the nutrient concentration in the bottom material to evaluate potential sources for plant production is a difficult task, and is not a routine lake-reconnaissance measurement. As a rule, water samples for nitrogen, phosphorus, and carbon are collected at several depths in the euphotic zone because this is the zone of active biological uptake of plant nutrients. A single surface sample and several more in the zone of light penetration are usually sufficient.

BIOLOGICAL MEASUREMENTS

The biological measurements made on lakes commonly include phytoplankton and periphyton types, their population density, and biomass (dry and ash weights per unit volume or area). Plant pigments such as chlorophyll are often used to estimate the biomass of phytoplankton and periphyton. In addition, the primary production (carbon assimilation) of these organisms can be determined by measuring oxygen output or the uptake of carbon-14. Other important biological measurements include types and numbers of zooplankton and benthic invertebrates.

Phytoplankton and Periphyton

The most commonly made biological measurements are those of the phytoplankton and periphyton. Phytoplankton are the one-celled plants responsible for most biologically or biochemically caused water-quality problems. Blue-green algae are usually responsible for nuisance conditions in lakes. Periphyton are the attached algae of lakes, reservoirs, and streams. Periphyton may also have a profound effect upon water quality, and may cause tastes and odors, as well as coloration. A number of techniques for collecting phytoplankton and periphyton have been published. Mackenthun and Ingram (1967, p. 149–173) present an excellent discussion on the role of algae in the aquatic environment.

Phytoplankton are collected with a water-sampling bottle. If the cells are to be kept alive for production studies, then a water bottle made of polyvinyl chloride (PVC) is recommended (Vollenweider, 1969, p. 5; Slack and others, 1973, p. 70). If a plankton net is used for collecting phytoplankton, then the mesh size (aperture of the net), diameter of the net orifice, and the amount of water passed through the net (length of tow) are needed with the results so that the number of organisms per unit volume can be calculated. Many small phytoplankton pass through the mesh; hence the use of nets for collecting phytoplankton is usually discouraged. In most studies concerned with phytoplankton types and abundance, samples are collected at various depths in the euphotic zone. Generally the samples are collected at the same depths as dissolved-oxygen samples because phytoplankton production is directly related to the dissolved-oxygen concentration.

After collection the samples are preserved in a dilute formaldehyde solution or Lugol's solution, or if analysis begins within 2 or 3 hours, the samples may be chilled at 3–4°C (Slack and others, 1973, p. 71). In the laboratory, the samples can be examined for types and numbers of phytoplankton, using the Sedgwick-Rafter, inverted microscope, or membrane filter method. These are described in detail in American Public Health Association and others (1971, p. 729–737) and Slack and others (1973, p. 70–78).

Usually periphyton is collected on artificial substrates (made of glass or Plexiglas) which have been placed in the lake. Measurements may also be made on periphyton attached to natural substrates. After sufficient time for colonization (4–6 weeks), the substrates are removed and the periphyton within a given area, for example 25 cm^2 (3.9 in^2) is scraped off. If the samples are to be examined within 2 or 3 hours, no special treatment is necessary. Periphyton samples may be maintained for 24 hours at 3–4°C. For extended storage of samples being examined for species identification and cell counts, the samples should be preserved with a dilute formaldehyde solution or Lugol's solution. Samples for biomass measurements should be air dried or frozen if oven drying cannot begin immediately after collection.

Samples are examined for types and numbers in the laboratory, using a Sedgwick-Rafter counting cell or an inverted microscope. Biomass measurements may also be made in the laboratory. Slack and others (1973, p. 86–93) discusses procedures, instructions and technique limitations.

Several taxonomic keys are available for identifying the phytoplankton and periphyton of a given area. In the absence of keys to local forms, the publications by Edmondson (1959), Needham and Needham (1962), and Prescott (1962) are useful. Algal taxonomy is best done by someone with training and experience in the science. However, in a given body of water, an untrained observer can often identify the common species with little trouble.

Biomass.—Both phytoplankton and periphyton biomass may be estimated by measuring the amount of cellular chlorophyll extract. Chlorophyll is the green plant pigment essential to the photosynthetic process. The technique is particularly valuable since samples can be easily collected and inexpensively analyzed.

A water sample containing phytoplankton or periphyton is filtered through a membrane filter, and the cells and filter placed in acetone or another extracting solvent. The chlorophyll content is determined spectrographically. A description of the method and a discussion of its limitations are found in Strickland (1960, p. 49–53), Vollenweider (1969, p. 21–40), American Public Health Association and others (1971, p. 746–747) and Slack and others (1973, p. 57–64).

Primary production.—While not a common measurement in routine lake surveys, primary production is useful in classifying lakes and describing their enrichment status. In enriched lakes, the oxygen light- and dark-bottle test is often used, but in unenriched lakes, the method is frequently not sensitive enough, and the carbon-14 method is used.

Samples of the water and associated phytoplankton or periphyton are collected at a given depth and put in suitable containers (usually 300-millilitre glass-stoppered bottles) for suspension at various depths. Before suspension, each sample container is either inoculated with radioactive carbon, in the carbon-14 method, or its initial oxygen concentration determined, in the oxygen light- and dark-bottle method. After being suspended at different depths for given periods of time, the sample is returned to the surface, and the amount of radioactive carbon taken up, or the change in oxygen concentration is measured. The techniques of primary production measurements are thoroughly discussed in Strickland (1960), Vollenweider (1969, p. 41–127), American Public Health Association and others (1971, p. 738–742), Janzer and others (1973), and Slack and others (1973, p. 93–122).

Zooplankton

Zooplankton, the animal part of the plankton, are an important part of the lake fauna. Some zooplankton are strong swimmers while others have weak powers of locomotion. A daily vertical migration of zooplankton is common. Zooplankton feed upon bacteria and algae, and under normal conditions may keep some algal populations under control. They are also an important food source for many fish. Because of their role in the aquatic environment, zooplankton types, numbers, and biomass are often measured in lake surveys.

Zooplankton may be collected with a water-sampling bottle; usually, however, zooplankton are collected with a net (usually a 202-micrometre mesh). If a water bottle is used, the samples should be collected at the same depths as phytoplankton samples, because zooplankton feed on phytoplankton. If a net is used, the aperture of the net, diameter of net orifice, and the length and depth of tow should be recorded so the population density can be calculated. Zooplankton samples to be examined for species identification and counts are preserved with a dilute formaldehyde solution, and those for biomass determinations are preserved by freezing with dry ice.

Methods for the collection and analysis of zooplankton are described in detail in Committee on Oceanography, Biological Methods Panel (1969, p. 47–59), Edmondson and Winberg (1971, p. 1–20 and 127–137), and Slack and others (1973, p. 78–86). Useful taxonomic keys for the identification of zooplankton are found in Edmondson (1959) and Needham and Needham (1962). These publications also provide lists of references to the literature on zooplankton.

Benthic Invertebrates

Benthic invertebrates are organisms that live on or within the bottom substrate of lakes and reservoirs. Many are permanent residents, completing their life history in the water. Others (insects such as mayflies, caddisflies, and damselflies) spend their immature stages in the aquatic environment but when near sexual maturity emerge from the water. After leaving the water, they mate, and the females lay their eggs over the water. The eggs then hatch in the water, and the cycle is repeated. Benthic invertebrates are important as a source of fish food and as consumers of algae and detritus. Some types (mayflies, gnats, and mosquitoes) may become nuisances around the lake or reservoir. When this occurs, chemical control is often necessary. Benthic invertebrates are also important indicators of the quality of the water. However, in their use as water-quality indicators, the type of substrate as well as the species must be considered (Mackenthun and Ingram, 1967, p. 38–42).

The collection of benthic invertebrates in a lake can be made with a variety of devices. Usually a grab, lowered into the water, which closes upon contact with the bottom or is tripped with a messenger, is used for collection. In the soft mud or detritus of lake bottoms, a spring-loaded Ekman grab can be used. For hard bottoms, a weighted Peterson grab may be required. Artificial substrates are also used for collection of benthic invertebrates. After collection, the samples are preserved in 40-percent isopropyl alcohol or similar preservative. Benthic invertebrate samples may be analyzed as to types, numbers per unit area, biomass (dry weight), or for diversity. Detailed instructions for the collection and analysis of benthic invertebrates are found in American Public Health Association and others (1971, p. 761–771), Edmondson and Winberg (1971, p. 25–65), Holme and McIntyre (1971, p. 80–168), and Slack and others (1973, p. 126–151).

The physical, chemical, and biological measurements given above are not complete, but cover most aspects of a reconnaissance study of a lake or reservoir. Other types of measurements are given in the cited references. For example, it may be desirable to survey the types of fish inhabiting a lake. Suggestions and references are given in American Public Health Association and others (1971, p. 771–779) and Slack and others (1973, p. 151–160). For extensive interpretative lake studies, consultation of a limnologist, as well as other experts on lakes and water quality, may be required. Many State, Federal, and private agencies can provide such assistance.

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