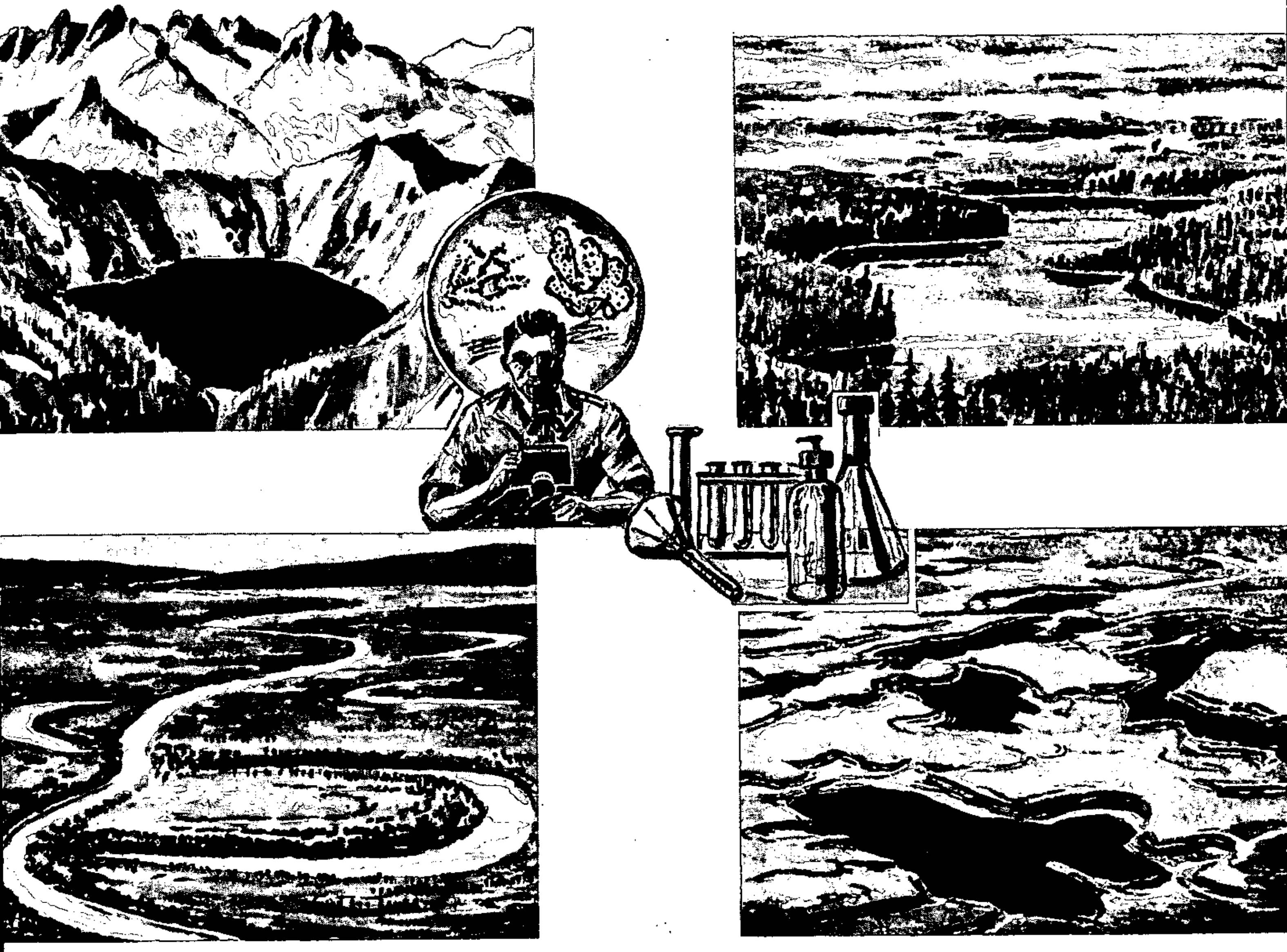
PRIMER ON LAKES IN WASHINGTON



STATE OF WASHINGTON
DIXY LEE RAY, Governor

DEPARTMENT OF ECOLOGY
WILBUR G. HALLAUER, Director

Water-Supply Bulletin 49

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United States Department of the Interior
Geological Survey • 1978

THE SEAL OF THE STATE OF WASHINGTON 1889

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PRIMER ON LAKES IN WASHINGTON

By

N. P. Dion

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1978

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WHY THIS REPORT WAS WRITTEN

This report was prepared to provide a nontechnical, "layreader" introduction to the many physical, chemical, and biological characteristics of lakes. The report includes a glossary of lake and geologic terms related to lakes of Washington State--and to lakes generally--and discusses the many characteristics involved in evaluation of lake-water quality. The report is intended not only as an entity in itself but as a contribution to a better understanding by the general reader of several other more technical and more detailed reports on lakes in Washington.

INTRODUCTION

"A lake is the landscape's most beautiful and expressive feature. It is earth's eye; looking into which the beholder measures the depth of his own nature" - Thoreau[1].

Whether we accept Webster's definition of a lake as "a considerable inland body of standing water," or prefer Thoreau's more poetic description as "earth's eye," most of us would agree that the landscape, and indeed the people, of Washington would be considerably poorer without the many ponds, lakes, and reservoirs within the State. For this paper we accept the definition by Walcott (1965) that a lake is a body of standing water an acre or more in size.

Lakes have been used as sources of water and food, as transportation routes, and as bases of recreation and esthetics. We have found it to our advantage to improve the condition of existing lakes and to build artificial lakes where nature has not provided them. We have also found it to our disadvantage to allow lakes to become polluted or choked with weeds.

Many of us do not realize, however, that freshwater lakes, even when completely uninfluenced by people, will undergo a very slow, natural process of aging that eventually results in the "death" of the lake. Over a period of thousands of years, a lake will become filled with sediment and covered with vegetation. Limnologists--scientists who study freshwater lakes-- call this evolutionary process lake succession. Man can hasten or retard the rate of succession with his ability to change the physical, chemical, and biological conditions within the lake. Limnology is thus a very broad and complex science, and one which is necessary for the proper understanding and management of the lake resource.

This primer describes some of the physical, chemical, and biological conditions that limnologists are studying in Washington lakes. Among the subjects discussed are lake formation and shape, the physical and chemical processes in lakes, lake biology and biological processes, human influence on lake conditions, and some of the steps that can be taken to rehabilitate lake conditions. Those readers wanting more information than that presented in this primer with respect to specific Washington lakes are referred to the reports of Bortleson and others (1975) and Dion and others (1975).

Limnological terms which the reader may not be familiar with are underlined and briefly defined where first used in the text, and are more fully defined in a special section near the end of the primer. A knowledge of limnological terms will be useful to those readers who continue reading about lakes in the selected references listed at the end of the primer.

Because this report is a general overview of many facets of the field of limnology, it incorporates considerable material from previously published reports, in particular Born and Yanggen (1972), Britton and others (1975), Lee (1970), and Reid and Wood (1976).

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[1] The quotations beneath the section titles are taken from Walden, by Henry David Thoreau (1854).

LAKE ORIGIN AND FORM

Lake Formation

"It is very certain, at any rate, that once there was no pond here, and now there is one."

There are nearly 8,000 lakes in Washington, but the number of lakes differs widely among the counties (fig. 1). All lakes consist fundamentally of an accumulation of water in a basin. Lake basins originate in a variety of ways and their geographic distribution is dictated in large part by their manner of origin.

Most of Washington's lakes are the result of glacial and fluviatile (river or stream) action. In the Puget Sound lowland of western Washington and the lowland areas of northeastern Washington, many lakes occupy depressions in the surface of glacial drift--the gravel, sand, silt, and clay laid down by the continental glacier during the ice age. These depressions are generally either long troughs cut into drift plains by the passing ice sheet (fig. 2) or are more circular kettles left by the melting of huge blocks of glacial ice (fig. 3). Still others are simply shallow depressions left on an irregular surface of glacial deposits.

Lakes in the foothills of the Cascade and Olympic Mountains and in lower mountains occupy either kettle depressions in glacial drift or depressions cut into bedrock by the continental glacier. Lakes in the higher mountains of Washington occur in basins cut by local alpine glaciers (fig. 4). Where such lakes occupy cirques--deep basins formed by glacial erosion in the side of a mountain--they are called cirque lakes, and small cirque lakes are called tarns. Lake Chelan in Chelan County, the State's largest and longest natural lake, occupies a mountainous troughlike basin more than 1,600 feet deep which was probably eroded to that depth by alpine and continental glacial ice.

Many lakes were formed by river processes. One well known type is the oxbow (or "horseshoe") lake, formed by the cutoff and isolation of a river meander (fig. 5). Several lakes along the Yakima River, near Sunnyside in Yakima County, were formed in this way. In the semiarid Columbia Basin, underlain by lava, most lakes occupy the more deeply cut parts of some coulees of the channeled scablands (fig. 6). Most of these coulees were cut by gigantic, catastrophic floods resulting from the breaking of dams of glacial ice and the rapid emptying of large glacial lakes.

Figure 7 shows generally the areas of Washington where one can expect to find lakes that owe their origin to the foregoing described geologic processes.

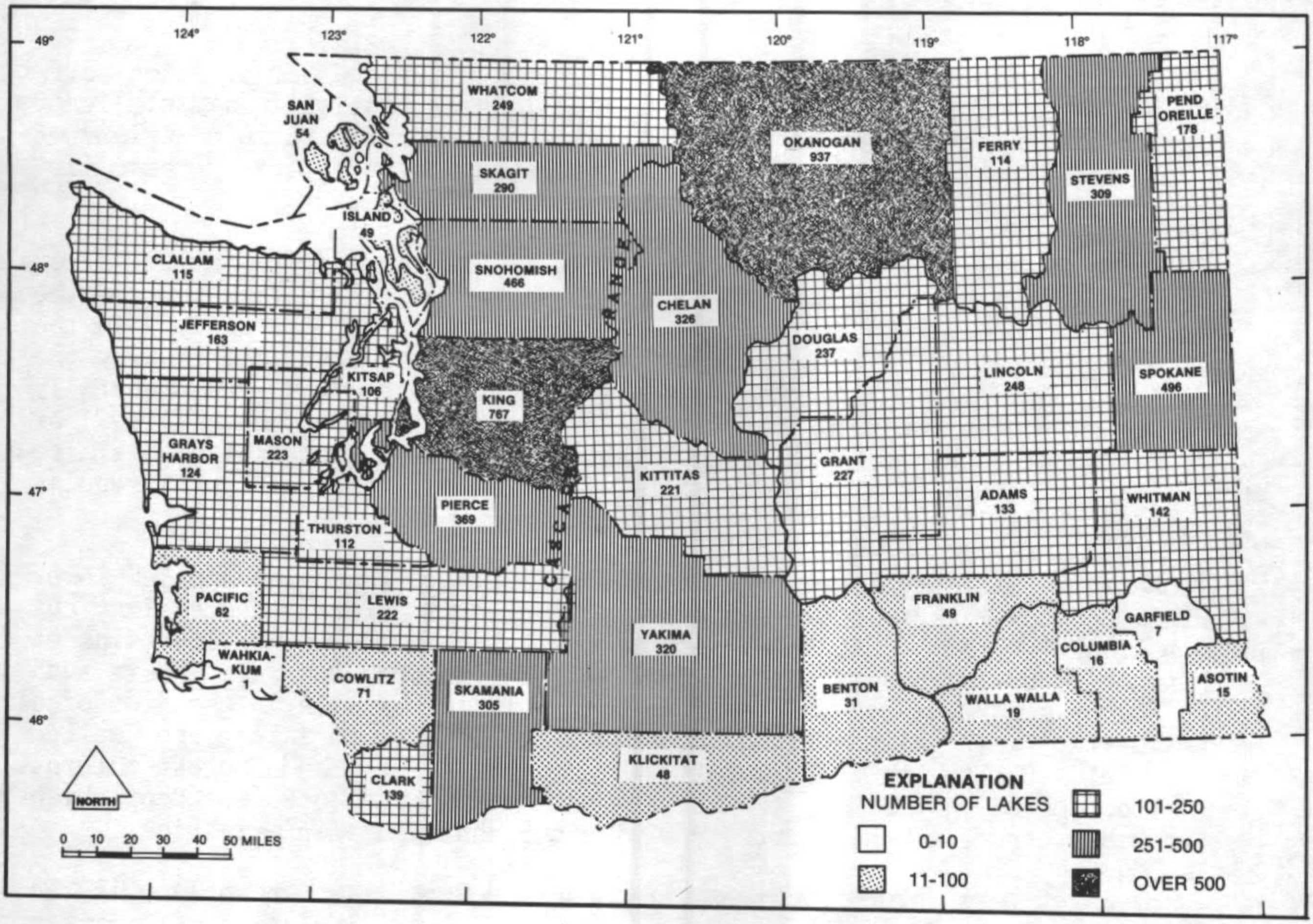
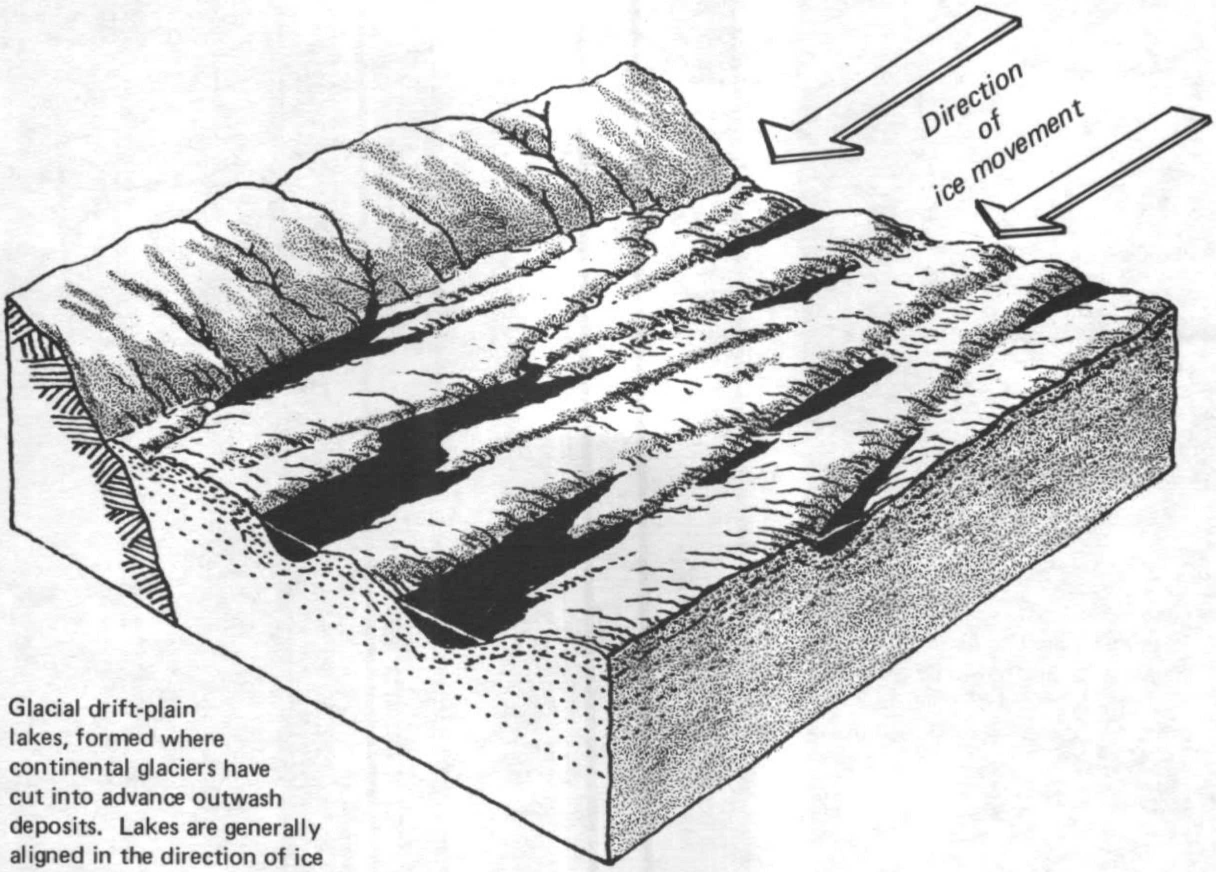


FIGURE 1.--Distribution of lakes in Washington, by county. (Based on data from Wolcott, 1964 and 1965.)



Glacial drift-plain lakes, formed where continental glaciers have cut into advance outwash deposits. Lakes are generally aligned in the direction of ice movement.

FIGURE 2.--Sketch and photograph showing geologic origin and example of typical drift-plain lakes.

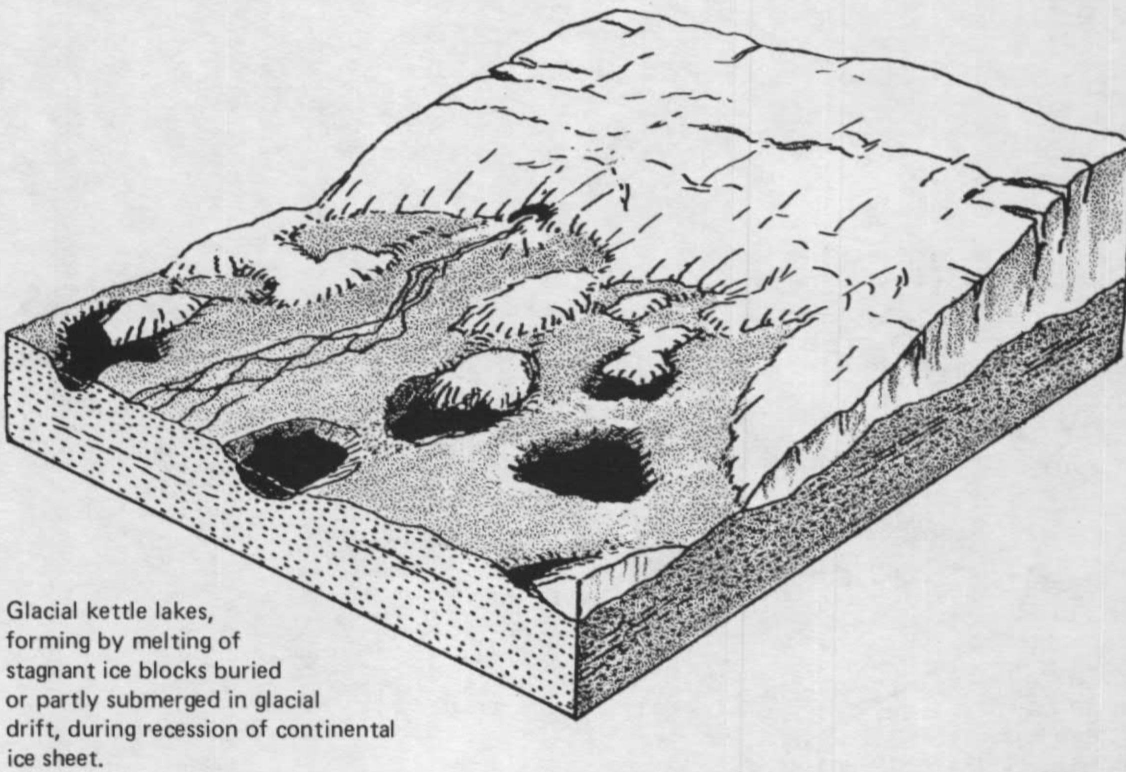


FIGURE 3.--Sketch and photograph showing geologic origin and examples of typical kettle lakes.

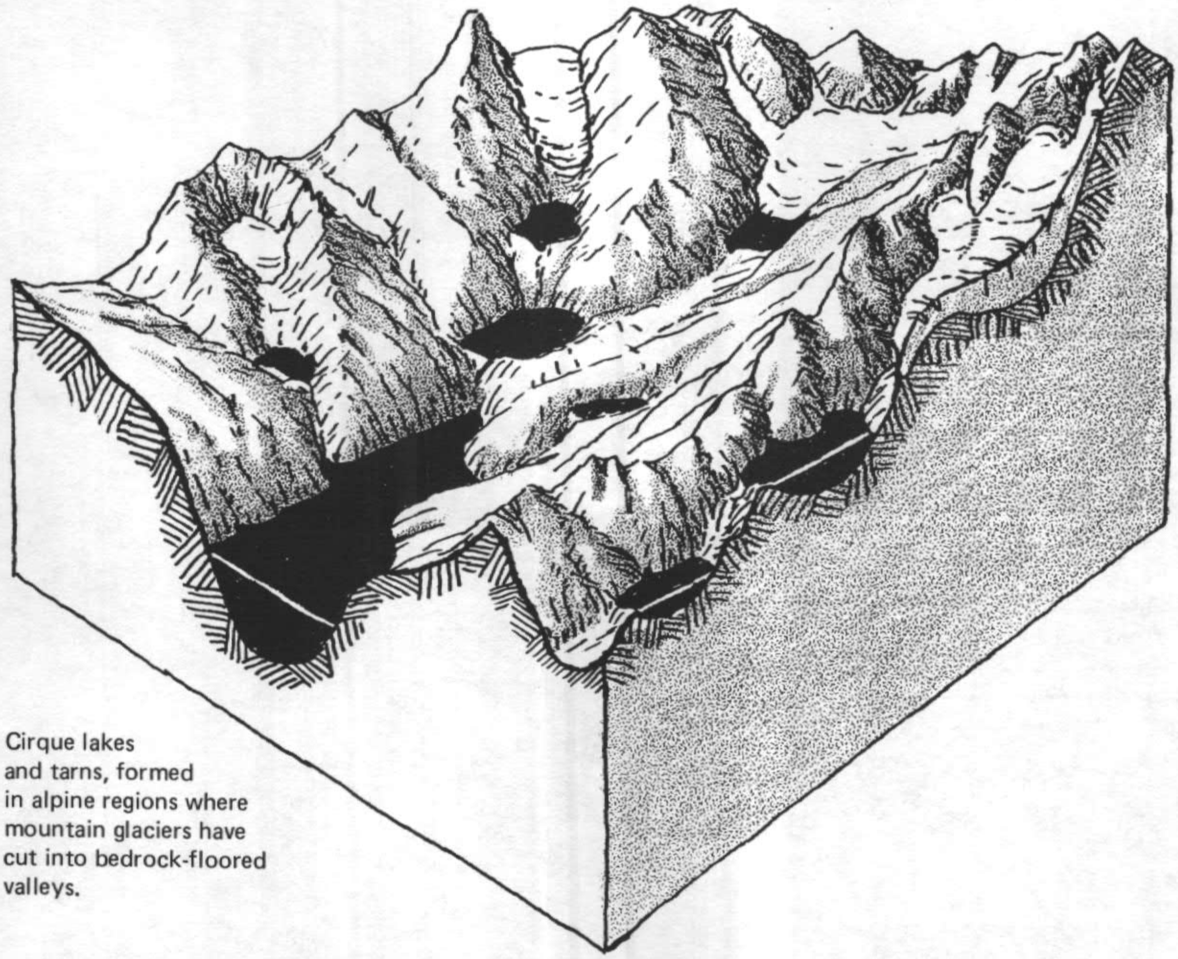


FIGURE 4.--Sketch and photograph showing geologic origin and examples of typical cirque lakes and tarns.

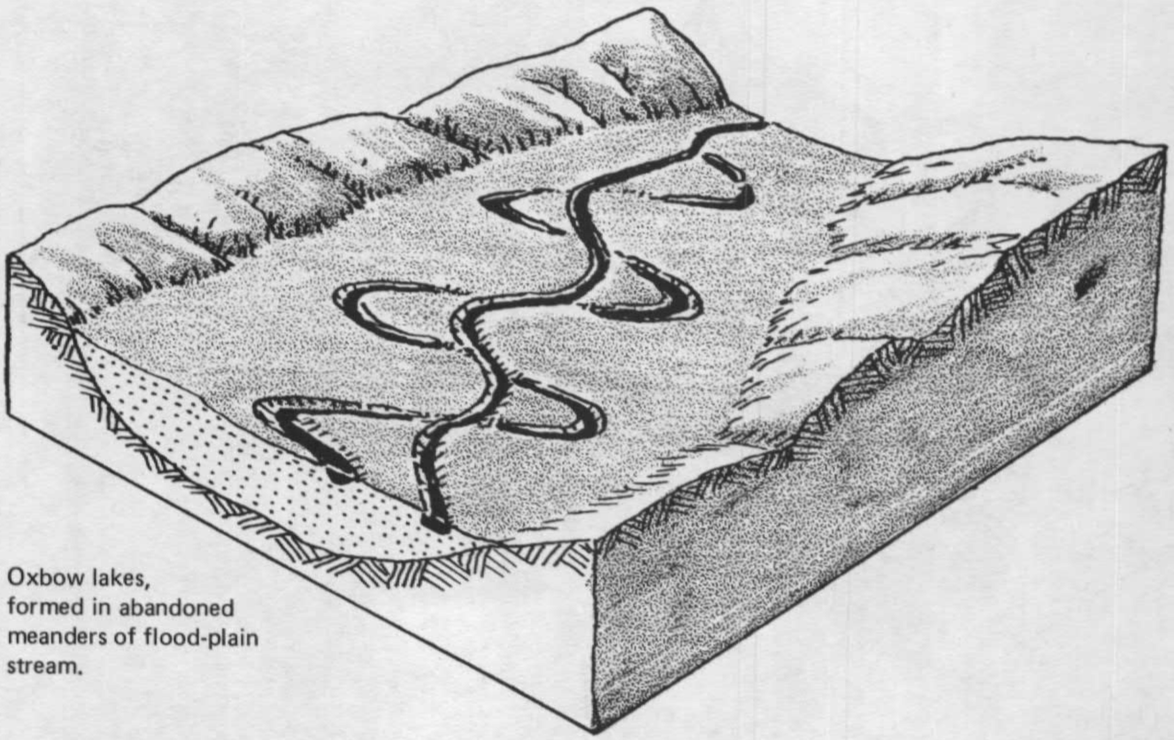


FIGURE 5.--Sketch and photograph showing geologic origin and example of typical oxbow lakes.

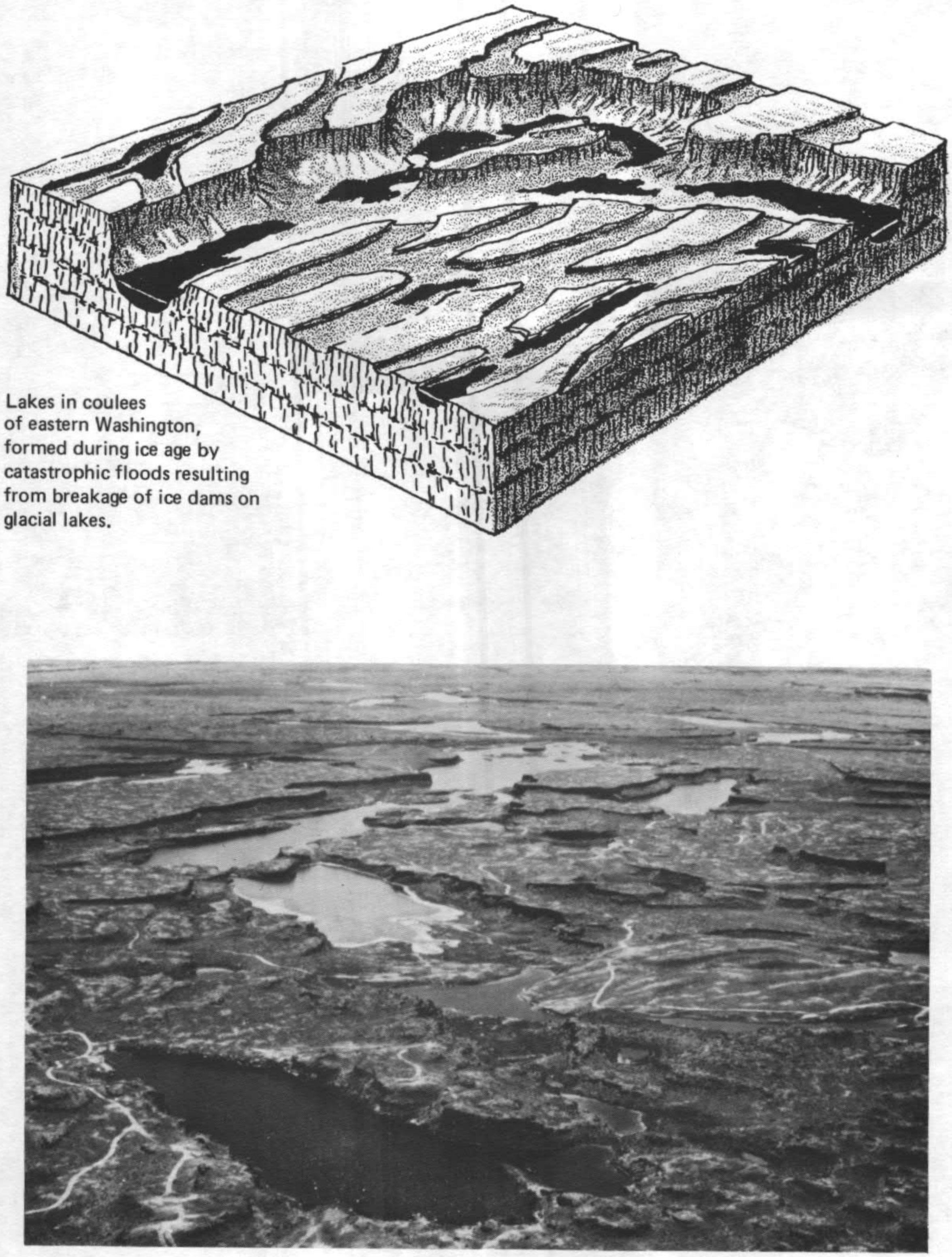


FIGURE 6.--Sketch and photograph showing geologic origin and examples of typical coulee lakes.

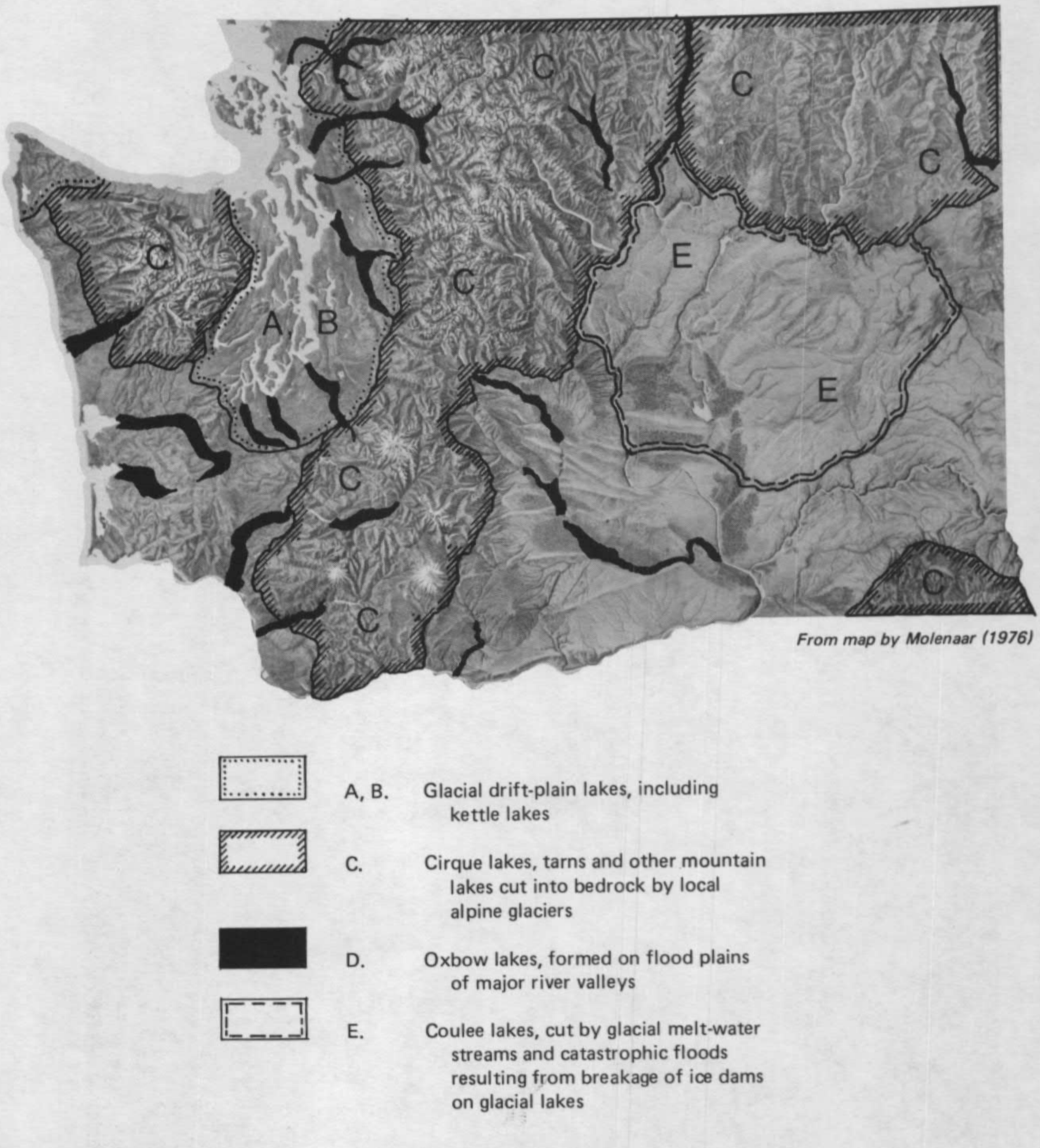


FIGURE 7.--Generalized areas of Washington characterized by lakes of various geologic origins, as shown diagrammatically in figures 2 through 6.

A smaller number of lakes in Washington owe their formation to less common geologic actions and the building activities of animals. Some lake basins were formed by the deformation of the earth's crust through warping or faulting. A few lakes, such as Battleground Lake in Clark County, occupy the craters of extinct volcanoes; such lakes are referred to as crater lakes. Still other lakes were formed when landslides or lava flows blocked streams flowing in natural valleys or canyons. A few Washington lakes, chiefly in Okanogan County, owe their formation to the solution, and eventual collapse, of limestone formations.

Beavers play an important role in lake formation. Using logs, sticks, and mud, beavers are capable of building dams that are not only structurally sound, but also large enough to impound several acres of standing water. But people are the ultimate builders of dams. Artificial lakes range in size from small stock ponds to the mighty hydroelectric and irrigation reservoirs on the Columbia River.

Lakes have also formed as an indirect result of human activities. In the lower Columbia Basin area, irrigation seepage and runoff have created numerous ponds and lakes in depressions and rocky coulees that previously were dry. Also in this category are the quarries, pits, and other excavations which people have abandoned and which have subsequently filled with water to form lakes.

The manner of lake origin affects many of the physical, chemical, and biological events that occur within the lake, and imparts distinctive characteristics to the lake.

Lake Shape

"It is a clear and deep green well, half a mile long and a mile and three quarters in circumference, and contains about sixty-one and a half acres...."

The shape of a lake depends partly on the forces that produced the basin and partly on the events that occur in and near the lake after it has been formed. Lake shape is best portrayed by a detailed bathymetric (depth) map such as the one shown in figure 8. These maps are usually made by combining land surveying or photography, for the shore outline, with depth soundings made from a boat.

The measurement of the shape of geographic features of the earth is termed morphometry. From the bathymetric map can be obtained a number of morphomeric parameters which express certain aspects of the lake shape in numerical terms and which allow quantitative comparisons between lakes. Only the most commonly used morphometric parameters are discussed in this primer. A more complete and rigorous discussion is presented by Hutchinson (1957).

The area of a lake is the size of its surface as determined on a map or aerial photograph of known scale. On a bathymetric map the area is enclosed within the shoreline or zero-depth contour. For lakes with sloping bottoms the area decreases as the stage, or water level, falls and increases as the stage rises.

Determining the volume of a lake, as shown in figure 9, involves deriving and summing the volumes of each layer of water bounded by depth contours on the bathymetric map. The volume of each layer is derived by multiplying the depth of the layer by the average of the areas of the upper and lower surfaces of the layer. The volume of a lake is usually reported in acre-feet--the amount of water required to cover 1 acre to a depth of 1 foot.

The maximum depth of a lake is, as the term implies, the greatest depth sounded; sedimentation, erosion, and lake-stage fluctuations, however, can rapidly alter the depth of a lake. The mean depth (in feet) of a lake is obtained by dividing lake volume (in acre-ft) by lake area (in acres). Given two lakes of equal surface areas and maximum depths (lakes A and B in figure 10) the lake with the greater volume (lake A) will have the greater mean depth. Most Washington lakes (72 percent) have mean depths of less than 26 feet; only 7 percent have mean depths of greater than 66 feet. Mean and maximum depth obviously change with changes in lake stage.

The relative depth of a lake is the ratio of the maximum depth to the mean lake diameter, in percent. Lakes A and B in figure 11 have the same maximum depth, but the diameter (and area) of lake B is larger than that of lake A. Consequently, the relative depth of lake A (1.9 percent) is greater than that of lake B (1.0 percent). Most lakes in Washington are large and shallow and have relative depths of less than 2 percent. A few lakes are small and deep and have relative depths greater than 4 percent.

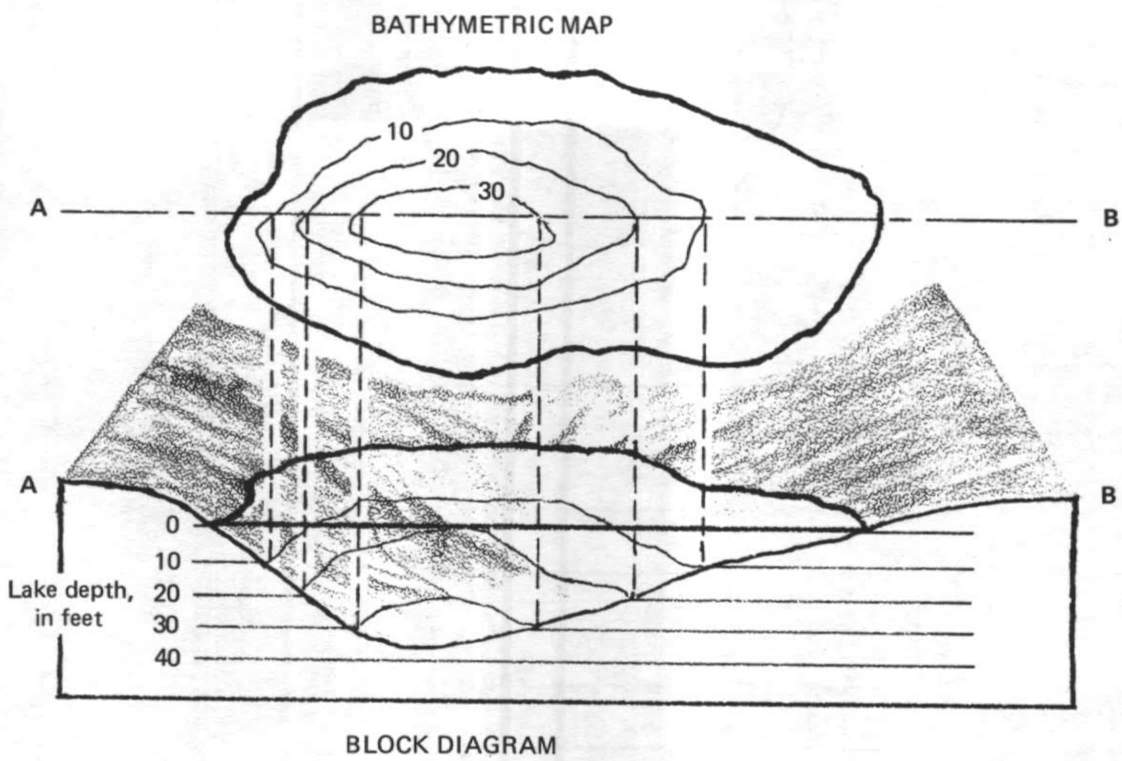
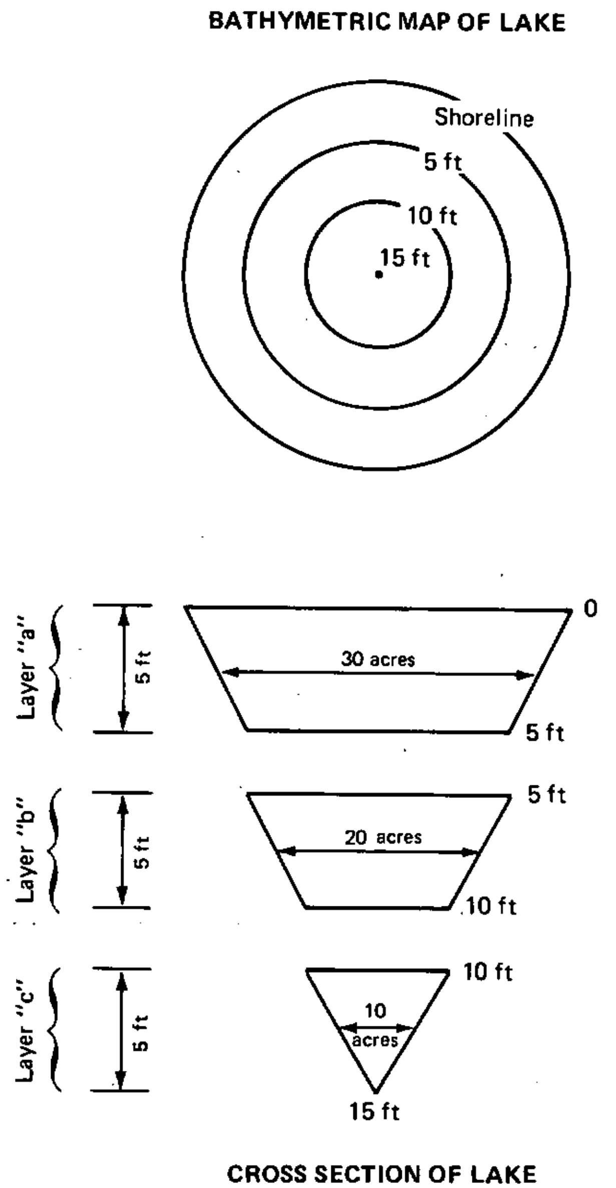


FIGURE 8.--A bathymetric map and the lake it represents.



Volume of lake = (volume of layer "a") + (volume of layer "b") + (Volume of layer "c")

Volume of lake = (5 feet x 30 acres) + (5 feet x 20 acres) + (5 feet x 10 acres)

Volume of lake = (150 acre - feet) + (100 acre - feet) + (50 acre - feet)

Volume of lake = 300 acre - feet

FIGURE 9.--Determination of volume.

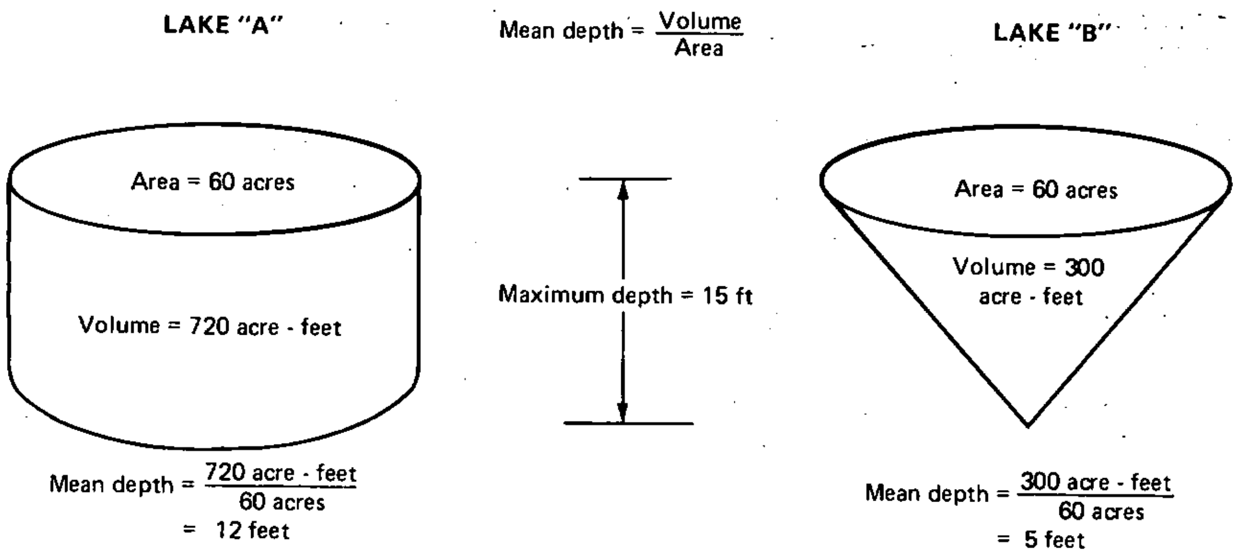


FIGURE 10.--Determination of mean depth.

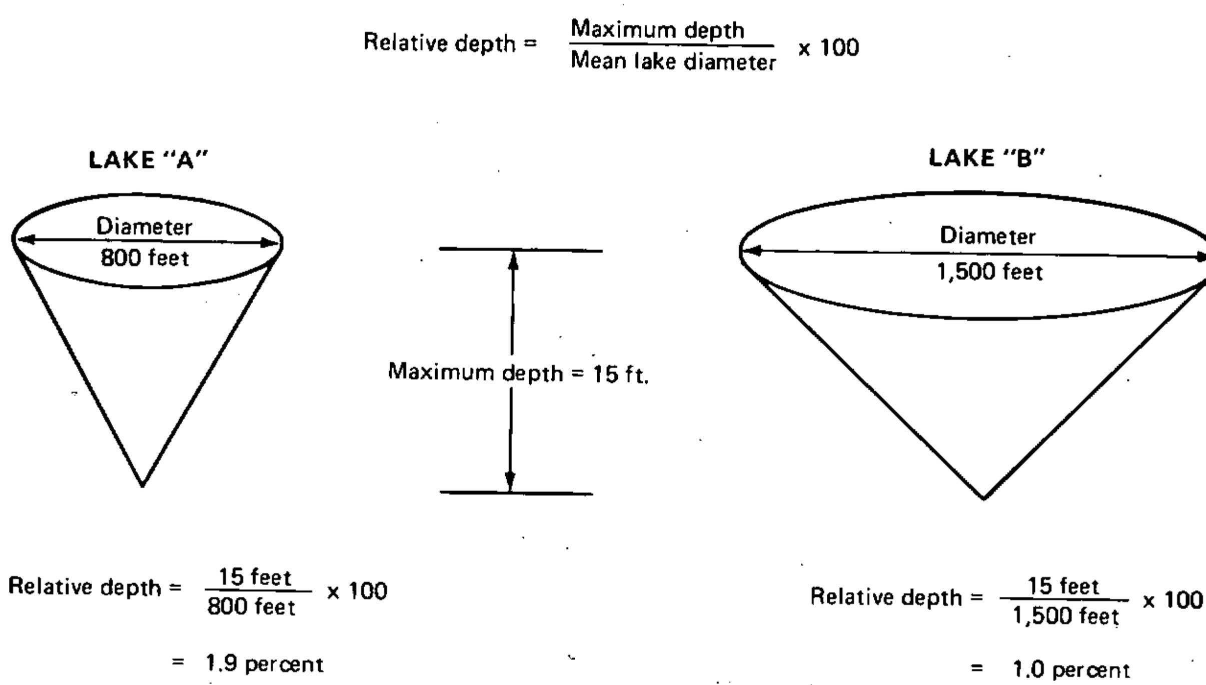
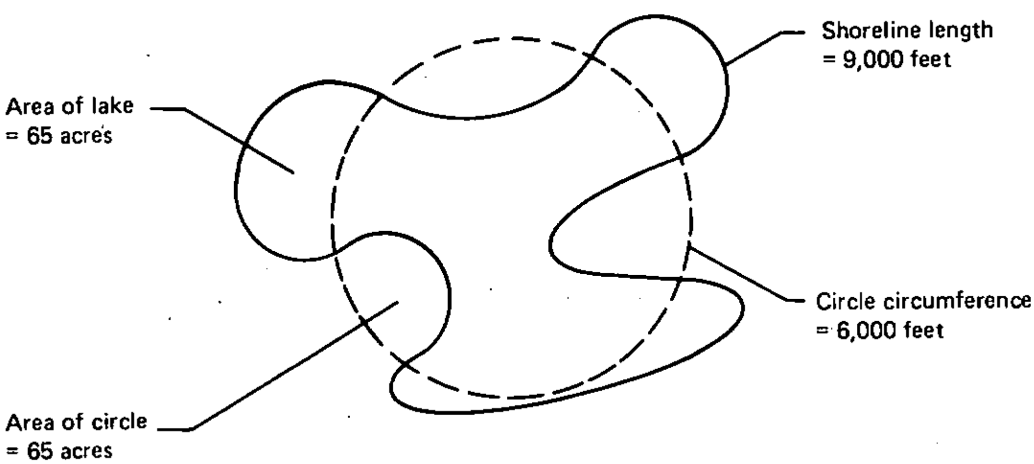


FIGURE 11.--Determination of relative depth.

The shoreline length of a lake is measured along the water's edge on a photo or map of known scale. The shoreline configuration of a lake is the dimensionless ratio of the shoreline length to the circumference of a circle having the same area as the lake. For example, the lake in figure 12 has an area of 65 acres and a shoreline length of 9,000 feet. A true circle having an area of 65 acres would have a circumference of only 6,000 feet. The shoreline configuration of the lake, therefore, would be 9,000/6,000, or 1.5. The shoreline configuration value is usually greater than unity. Nearly circular lakes have values near unity, irregularly shaped lakes have higher values, and long, narrow lakes have the highest values. About one-half (49 percent) of Washington's lakes have shoreline configuration values between 1.5 and 3.0. Only 4 percent have values above 3.0.

All of the variables described above have been found to be useful in comparisons or explanations of differences in the physical, chemical, and biological processes of different lakes.

$$\text{Shoreline configuration} = \frac{\text{length of lake shoreline}}{\text{circumference of circle}}$$



$$\text{Shoreline configuration} = \frac{\text{9,000 feet}}{\text{6,000 feet}} = 1.5$$

FIGURE 12.--Determination of shoreline configuration.

PHYSICAL PROCESSES

Hydrology

"The pond rises and falls, but whether regularly or not, and within what period, nobody knows, though, as usual, many pretend to know."

The water supply of a lake is governed by the hydrologic cycle, the system in which water evaporates into the atmosphere from the earth's surface and then condenses to return to earth as precipitation to replenish the surface and underground supplies of water. The cycle, portrayed in figure 13, is driven chiefly by solar energy and gravity. Even though water may be temporarily detained or stored in such places as glaciers, lakes, snowpacks, oceans, or ground-water aquifers, the hydrologic cycle is in continuous motion. Lakes may gain water from precipitation, from surface inflows such as rivers and streams, and from the subsurface inflow of ground water through seeps and springs. Lakes may also lose water by evaporation (including transpiration from aquatic plants), and by surface and subsurface outflow.

The general pattern of lake-level fluctuations of most Washington lakes (fig. 14) is a rising stage in spring and early summer and a decline in the fall and winter. The lake levels rise when inflow from snowmelt and precipitation on the watershed exceeds the losses by outflow and evaporation. After the early summer peak is reached, the stage declines gradually to the winter low because of the reduction in precipitation and the increase in evaporation during late summer and early autumn.

The general pattern described above is different in the lowland areas of western Washington where winter temperatures are generally above freezing. In this region, lake stages begin rising in autumn in response to greater rainfall and a lower rate of evaporation. After peaking in mid- to late winter, lake stages decline to a late-summer low in response to decreased rainfall and increased evaporation.

Most Washington lakes possess some form of outlet and are termed open lakes. Open lakes catch sediments introduced by inflowing streams, but substances dissolved in water generally move through without accumulating. The relationships of inflow, outflow, evaporation, and seepage (in and out) determine the stage of an open lake. Water-level fluctuations of open lakes usually occur rapidly in response to changes in inflow, and may be of large magnitude in small lakes fed by large rivers. In forested areas or other regions where the soil in the drainage basin can store large amounts of water, the magnitude of water-level fluctuations is reduced significantly.

In the semiarid regions of Washington, such as the Columbia Basin, some streams do not find their way to the sea, but end in lakes without outlets. In those regions evaporation usually exceeds precipitation, and such lakes seldom fill to overflowing and may even dry completely in summer. These lakes are termed closed lakes and are typically saline, that is, high in salt content. As do open lakes, closed lakes tend to trap sediment; but unlike open

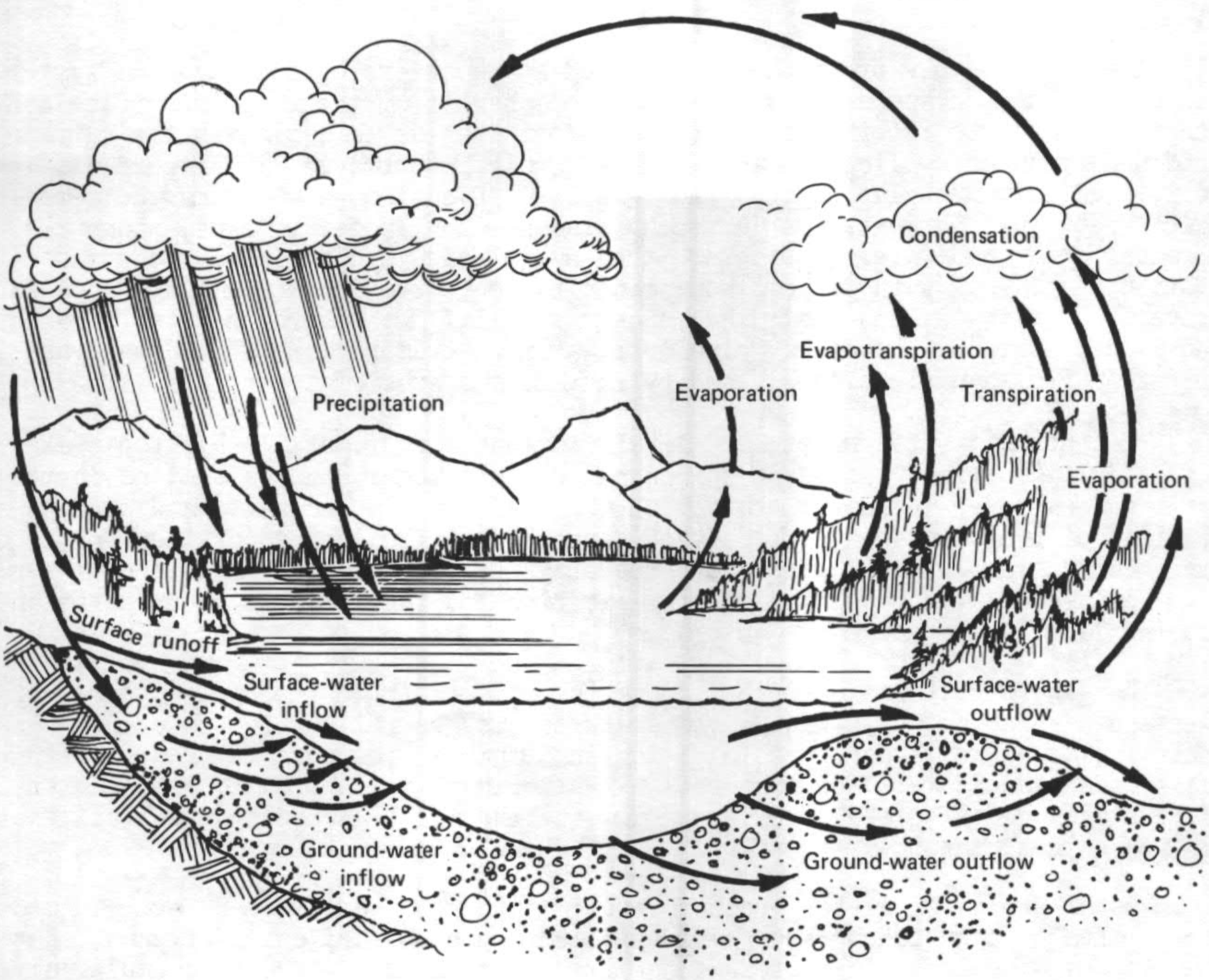


FIGURE 13.--The hydrologic cycle.

lakes, the absence of an outlet and the high rate of evaporation create deposits of mineral salts which would otherwise have remained in solution and been carried to sea. Water-level fluctuations of closed lakes may be rapid or slow, depending on the type and size of inflow. It should be pointed out that truly closed lakes occur only rarely because most lakes have at least some outflow seepage to ground water.

One of the hydrologic variables sometimes used in comparing lakes is the water renewal time. It is the time needed to replace the entire volume of a lake under average conditions of inflow and outflow, and it is usually longer for closed lakes than for open lakes.

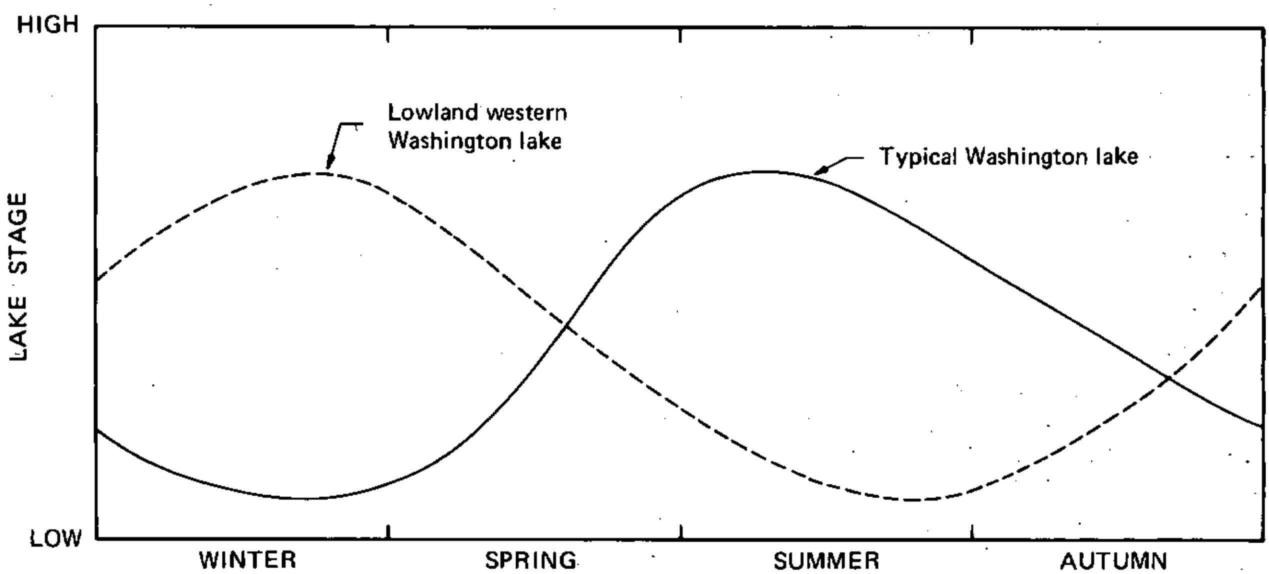


FIGURE 14.--Lake stage fluctuations in Washington lakes.

Temperature

"Moreover in summer, Walden never becomes so warm as most water which is exposed to the sun, on account of its depth."

Most liquids, including water, contract and become more dense as they cool. Water is unique, however, in that it is one of only two known compounds (the other being cesium chloride) that reaches its maximum density above, rather than at, the freezing point. As shown in figure 15, fresh water reaches its maximum density (at sea level) in the liquid state at about 4°C (degrees Celsius), a few degrees above the freezing point. Because ice is less dense than water at near-freezing temperatures, ice floats. If the maximum density of water were at the freezing point, ice would sink and lakes would freeze from the bottom up. In severe winters lakes would freeze solid and most aquatic plants and animals would be killed. These seemingly simple facts help explain the complex thermal phenomena that are observed in lakes.

The annual temperature cycle of moderately deep and deep lakes in temperate climates is illustrated in figure 16. In winter, a temperate-region lake is typically covered with ice. With the arrival of spring, warmer air temperatures and increased day length bring about the melting of the ice and a rise in the temperature of the upper water of the lake. As this water warms to 4°C, it becomes more dense than underlying water, sinks, and is replaced by less dense (and colder) water from below. This convective circulation, aided by the stirring of the wind, eventually produces a water body of uniform temperature (4°C) and maximum density. This mixing process has been termed the spring overturn. As the upper water warms above 4°C, it becomes less dense and no longer mixes with the underlying water. With increased heating the resistance to mixing between layers of different densities increases and thermal stratification develops.

Summer thermal stratification is characterized by (1) an upper zone of uniformly warm water; (2) an intermediate zone of transition where temperature decreases rapidly with depth; and (3) a lower zone of uniformly cold water. Limnologists call these three zones the epilimnion, the metalimnion (sometimes called the "thermocline"), and the hypolimnion, respectively. The condition of thermal stratification is a stable one; the transition zone acts as a barrier between the upper warm-water zone and the lower cold-water zone, preventing the exchange of heat and dissolved substances. In addition to acting as a physical barrier by restricting the movement of water masses, the transition zone also acts as a biological barrier that affects the movement and dispersal of many aquatic organisms.

In autumn, cooler air temperatures and decreased day length cool the upper water of the lake. This cooled water, being more dense, settles and is replaced by warmer (and less dense) water from below. As cooling approaches 4°C, the cooled upper water approaches maximum density and sinks all the way to the bottom. This process of fall overturn again produces a water body of uniform temperature (4°C) and maximum density. At this time there is a complete mixing of dissolved gases and chemicals that had accumulated in the warm and cold zones during summer thermal stratification, thereby producing uniform chemical conditions throughout the lake.

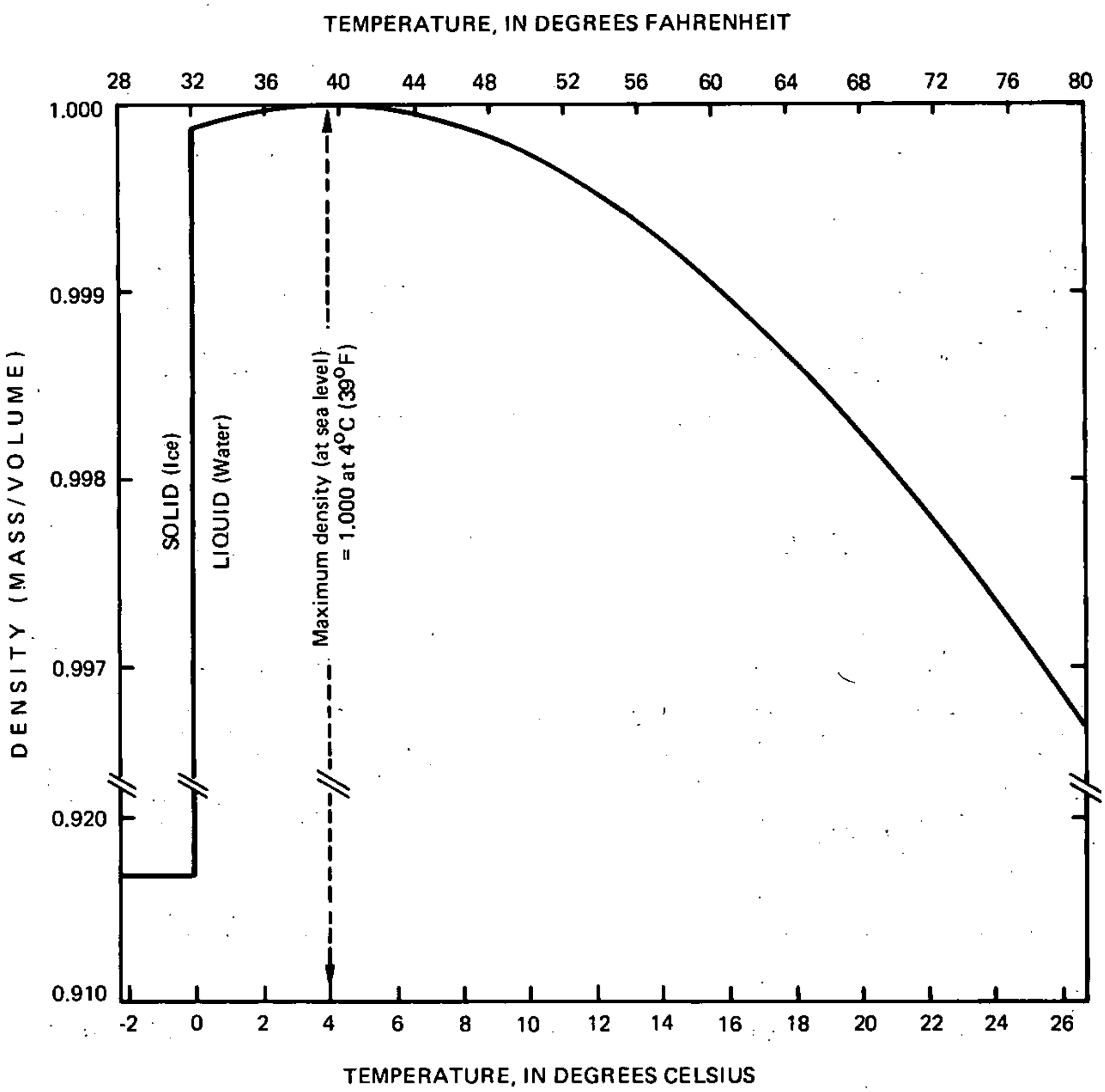


FIGURE 15.--The temperature-density relationship of fresh water.

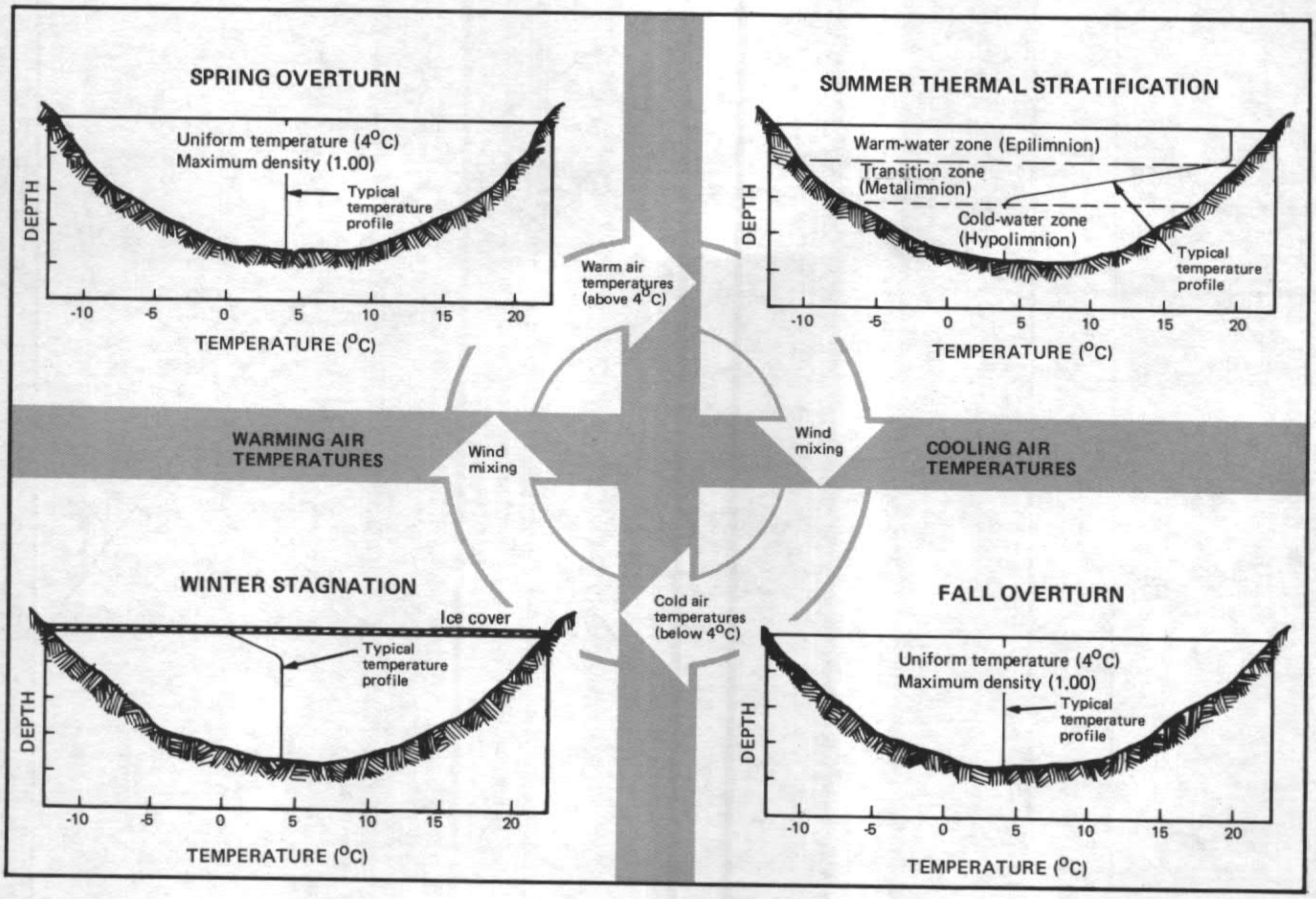


FIGURE 16.--The annual temperature cycle of a temperate-region lake.

Continued cooling during autumn lowers the upper-water temperature below 4°C, and an inverse temperature stratification develops, with water at about 4°C on the bottom and slightly colder, less dense, water above. This inverse stratification is most pronounced following the formation of the ice cover. Below the ice (0°C), the temperature of the water rises to near 4°C. The period of winter stagnation now exists.

Spring warming results in the melting of the ice cover, a spring overturn, and the continuation of the annual temperature cycle. Lakes that undergo this twice-yearly process of thermal overturn are referred to as dimictic.

Many lakes throughout Washington are too shallow to stratify thermally. Water temperatures in these lakes are practically constant from top to bottom, indicating that the waters are well mixed throughout.

Water density is not determined solely by temperature; it is also a function of salinity, or the amount of salts dissolved in the water. As salinity increases, water density also increases. In some lakes in eastern Washington the salinity of the bottom waters has increased the density of the water sufficiently to prevent vertical mixing. Such lakes do not undergo complete overturn regardless of air temperature or depth and are called meromictic. Some examples of meromictic lakes in Washington include Hot, Soap, and Wannacutt Lakes.

Light Penetration

"The water is so transparent that the bottom can easily be discerned at the depth of twenty-five or thirty feet."

An important physical property of water is its transparency, its capacity to transmit light. Not all solar radiation (sunlight) reaching the surface of a lake penetrates the water; a significant portion is reflected from the water surface back to the atmosphere. Turbidity is the principal factor affecting the depth of light penetration in lake water, and results from high concentrations of plankton (small, free-drifting organisms) and suspended organic and inorganic substances. The depth of light penetration through clear, colorless ice is similar to that through water, but is greatly decreased if the ice is stained with organic matter, clouded with air bubbles, or formed in irregular crystals. Snow cover further reduces or prevents light transmission through ice.

A very simple device for measuring the transparency of lake water is the Secchi disc, a disc 8 inches in diameter and painted white and black in alternating quadrants. Its use is depicted in figure 17. The depth at which the disc disappears from view is termed the "Secchi-disc transparency" of the lake. Lakes in Washington vary greatly in transparency. The Secchi-disc transparency of Summit Lake in Pierce County was 79 feet (the highest measured thus far in Washington) on July 17, 1973. In contrast, the transparency for Artesian Lake in Grant County was only 0.1 foot on June 10, 1974. Where small Secchi-disc readings are caused by plankton only, the readings provide an index of a lake's productivity (yield of organic matter) relative to other lakes at that same time.

Sunlight is required by aquatic plants for the basic metabolic process of photosynthesis, in which chlorophyll-containing plants convert carbon dioxide and water into sugar and oxygen. The sugar is used by aquatic plants and animals to build tissue. The oxygen is vital to plant and animal respiration and is also necessary for the decomposition of organic and inorganic substances.

As shown in figure 17, the lake zone that has sufficient light for photosynthesis is called the euphotic zone and, in summer, it often corresponds closely with the warm-water zone of many lakes. The lower limit of the euphotic zone occurs at a level where oxygen is consumed at the same rate as it is produced. This is the compensation level, and it is approximately 3 to 5 times the Secchi-disc depth. Below the compensation level is the aphotic zone where there is insufficient light to maintain photosynthesis. As with Secchi-disc transparency, the depth of the compensation level varies with time of day and season of the year.

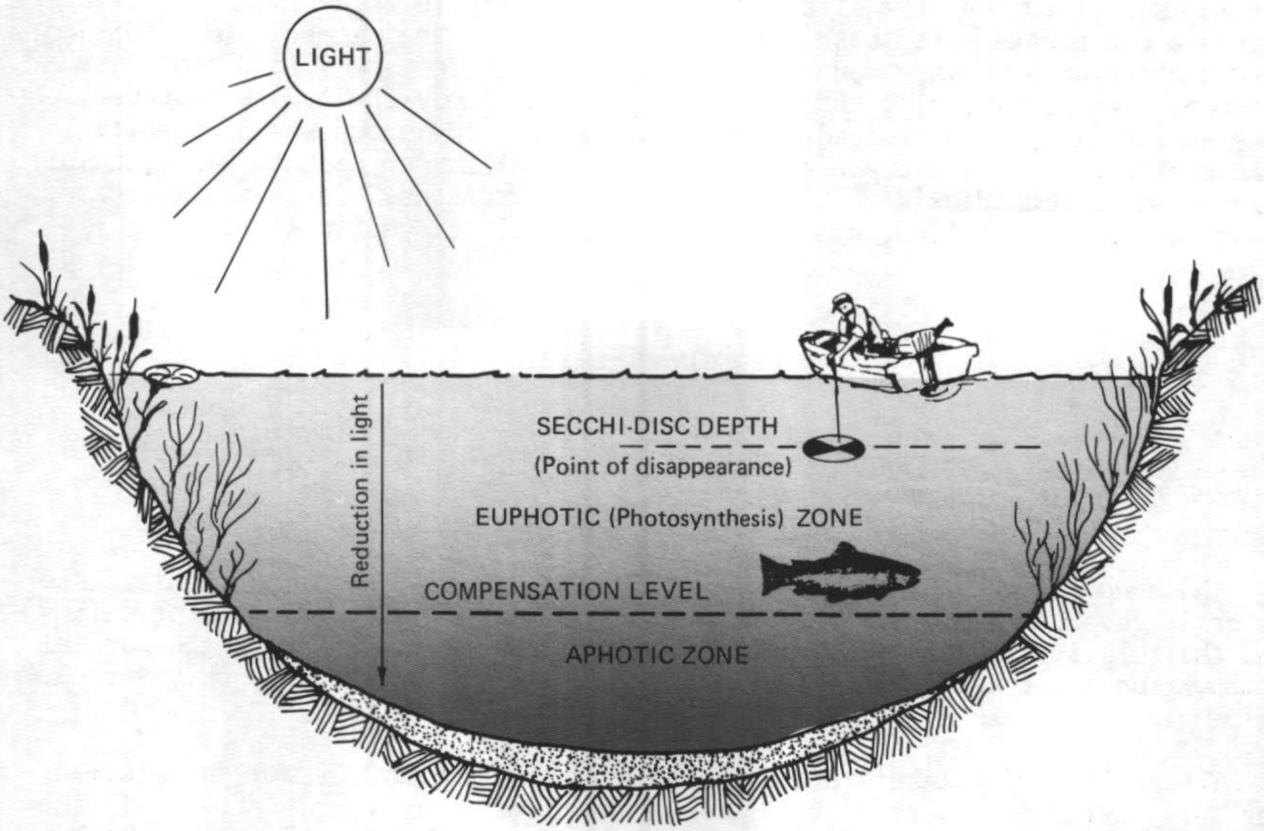


FIGURE 17.--Light zones and transparency measurements in lakes.

WATER CHEMISTRY

Pure water does not occur in nature; all lake waters contain varying amounts and kinds of dissolved solids and gases. The substances in solution are critical to the continuation of aquatic life to the extent that the size and type of many aquatic communities are often determined by the amounts and kinds of dissolved substances available. For example, the only nutrients (chemicals required for life processes) available to algae (simple, usually microscopic plants) are those that are dissolved in the water. In addition, certain organisms may depend on the availability of specific dissolved substances; snails, mussels, and other animals with limey shells are dependent on the availability of dissolved calcium carbonate. The processes of respiration and photosynthesis are dependent on the availability of certain gases, namely oxygen and carbon dioxide, in the proper concentrations. Certain other gases, even in small quantities, are known to be harmful to aquatic life.

Dissolved Solids

".....the waves, I suspect, do not so much construct as wear down a material which has already acquired consistency."

The composition and content of dissolved solids in any particular lake water is governed by the lake's hydrology--the sources and amounts of inflow and the relative amounts of inflow and outflow. In many places the natural composition and content of solids is altered, either beneficially or adversely by people.

The geology of a lake's drainage basin is an important factor in determining the mineral load carried to a lake, particularly an open lake. If the drainage basin is underlain by volcanic or dense, highly crystalline rocks, which are relatively insoluble, the lake water is generally low in dissolved minerals. If, on the other hand, the drainage basin is underlain by sedimentary rocks which are relatively soluble, the lake water is apt to be high in dissolved minerals.

The atmosphere is also an important source of dissolved solids. Near coastlines, the sea supplies large amounts of sodium, chloride, magnesium, and sulfate to the atmosphere. This salinity can be carried inland for great distances, although most of it is precipitated with rainfall in the coastal regions. Windblown dust from the soil contributes calcium and potassium to lakes; in semiarid regions the fallout of these elements in dust often exceeds the amounts contributed through precipitation. Dissolved-solids concentrations are usually higher in closed lakes than in open lakes because in closed lakes the soluble salts remain in the lakes as evaporation proceeds.

The specific conductance of water--its capacity to conduct an electrical current--is an approximate measure of its total mineral content. Specific conductance is usually expressed as micromhos per centimeter (µmho/cm) at 25°C. The purer the water is, the greater its resistance to electrical flow will be, and the lower the specific conductance value. The specific conductance of water in western Washington lakes usually ranges from 25 to 100 µmho/cm and in eastern Washington lakes from 100 to 400 µmho/cm, except in the Columbia Basin, where the values range from 400 to 800 µmho/cm.

The chemical constituents commonly found in Washington lakes in the greatest concentrations are calcium, magnesium, sodium, potassium, bicarbonate, carbonate, sulfate, chloride, fluoride, and silica. In addition, measurable amounts of iron, aluminum, nitrogen, and phosphorus also occur, but typically in lower concentrations. Although many elements and compounds act as nutrients to nourish aquatic plants, nitrogen and phosphorus generally limit the extent of plant growth because they are needed in relatively large amounts and these needs often exceed available amounts. Measurements of nitrogen and phosphorus are thus often used by limnologists as indices of a lake's plant-producing potential.

Dissolved Gases

"How peaceful the phenomena of the lake!"

Of all the chemical substances dissolved in water, oxygen is by far the most important because it is required by aquatic plants and animals for life processes. The amount of oxygen in lake water is thus a good indicator of life-support conditions in the lake. Many of the compounds necessary for the continuation of aquatic life, such as proteins and carbohydrates, can be stored within an organism. They have no capacity, however, for the long-term internal storage of oxygen; oxygen deprivation for just a short time is usually harmful or fatal. As an indicator of lake conditions, limnologists generally agree that a series of oxygen determinations is probably more valuable than any other single series of measurements.

The oxygen available for biological processes in lake water is in solution, much like dissolved solids. Oxygen is absorbed directly from the atmosphere and is produced by plant photosynthesis; it is removed from solution by the respiration of organisms and by the oxidation of organic and inorganic matter.

The amount of oxygen dissolved in water at any given time is dependent on the temperature and the salinity of the water, and on the atmospheric pressure at the lake surface. The solubility of oxygen in water is decreased by (1) increased temperature, (2) increased salinity, and (3) decreased atmospheric pressure. Hence, all other factors being equal, cold water contains more oxygen than warm water, fresh water contains more oxygen than saline water, and a lake at low altitude contains more oxygen than one at high altitude.

Most of the oxygen produced by photosynthesis in the upper, lighted (euphotic) zone of a lake is produced by phytoplankton (the plant part of the plankton) which usually saturate that zone with oxygen. The oxygen content of the lower, dark (aphotic) zone is usually low because the small amount of oxygen produced there is consumed by the oxidation of decomposing organic and inorganic matter.

Aquatic plants and animals, especially fish, are adversely affected by oxygen depletion; certain minimum levels of oxygen are needed to maintain healthy conditions. A reduction of dissolved-oxygen concentration to less than 3 mg/L (milligrams per liter) has been shown to interfere with fish populations through delayed hatching of eggs, decreased tolerance to toxicants, and reduced growth rate. A dissolved-oxygen concentration greater than 5 mg/L is normally recommended for warm-water fish species; for cold-water fish species the concentration should not be less than 6 mg/L.

Another gas of importance in the aquatic environment is carbon dioxide, which is produced by respiration and by the decomposition of organic and inorganic matter, and which is absorbed from the atmosphere. Carbon dioxide is important because (1) it protects the water against rapid changes of acidity or alkalinity, (2) it regulates certain biological processes in aquatic organisms, and (3) it contains carbon, one of the critical building blocks of organic matter. Carbon dioxide is very soluble in water but, like oxygen, its solubility decreases with increasing temperature.

Although high concentrations of carbon dioxide interfere with the proper respiration of some fish species, the interference occurs at concentrations much higher than those usually found in natural situations. Because most fish species can acclimatize to widely changing concentrations of carbon dioxide, the presence of high concentrations of carbon dioxide cannot be considered a serious health hazard.

When all the oxygen in the cold, lower region (hypolimnion) of a lake has been depleted, the decomposition of organic matter may continue anaerobically (without oxygen), resulting in the production of the gases methane and hydrogen sulfide. Methane, also called "marsh gas," is odorless and in the concentrations found in nature, it does not apear to be toxic to aquatic organisms. Hydrogen sulfide can easily be detected, even in low concentrations, by its distinctive "rotten eggs" odor. It is a poisonous gas, and concentrations well below 1 mg/L are known to interfere with the growth of fish and the hatching of fish eggs.

LAKE INHABITANTS

Aquatic Plants

"A closer scrutiny does not detect a flag nor a bulrush, nor even a lily, yellow or white, but only a few small heartleaves and potamogeton, and perhaps a water target or two....."

Aquatic plants are found in most lakes but differ in type and quantity from lake to lake and with time. The composition and richness of a lake's plant growth is often a measure of the overall "health" of the lake.

Lake plants can be broadly divided into the simple, microscopic algae and the larger, more complex macrophytes. Most macrophytes have roots, stems, and leaves, and can readily be seen with the unaided eye. They are divided into those that are attached, or rooted, to the lake bottom and those that are freely floating. The rooted forms can be further subdivided into emersed, floating-leaved, and submersed plants. Some typical examples of each category which are common in Washington lakes are given below.

Aquatic Macrophytes

Manner of growth	Representative plants
Rooted	--
Emersed	Bulrush, cattail, sedge
Floating-leaved	Watershield, waterlilies, some pondweed
Submersed	Elodea, watermilfoil, most pondweed
Freely floating	Duckweed

Rooted plants are usually found attached in shallow areas where sunlight reaches the lake bottom. These plants provide bases of attachment for some forms of algae, provide shelter and protection for insects, birds, and fish, and contribute, as do all plants, to the oxygen supply of the lake. In addition, rooted plants draw nutrients from the soil; upon the death and decay of the plants the nutrients become available to nourish algae.

Algae contain chlorophyll but lack the roots, stems, and leaves characteristic of macrophytes. Most algae are planktonic--that is, they float passively in the water--but others are attached to submerged rocks, wood, concrete, and even larger plants. A few algae common to Washington lakes are shown in figure 18.

Algae occur in various shapes, sizes, and ecological roles. The most commonly encountered groups of algae are the greens, blue-greens, and diatoms. Green algae contain bright, grass-green pigments, have a well-defined nucleus, and are more abundant than all other groups combined. The cells of green algae may occur singly, as spherical colonies, or as filaments.

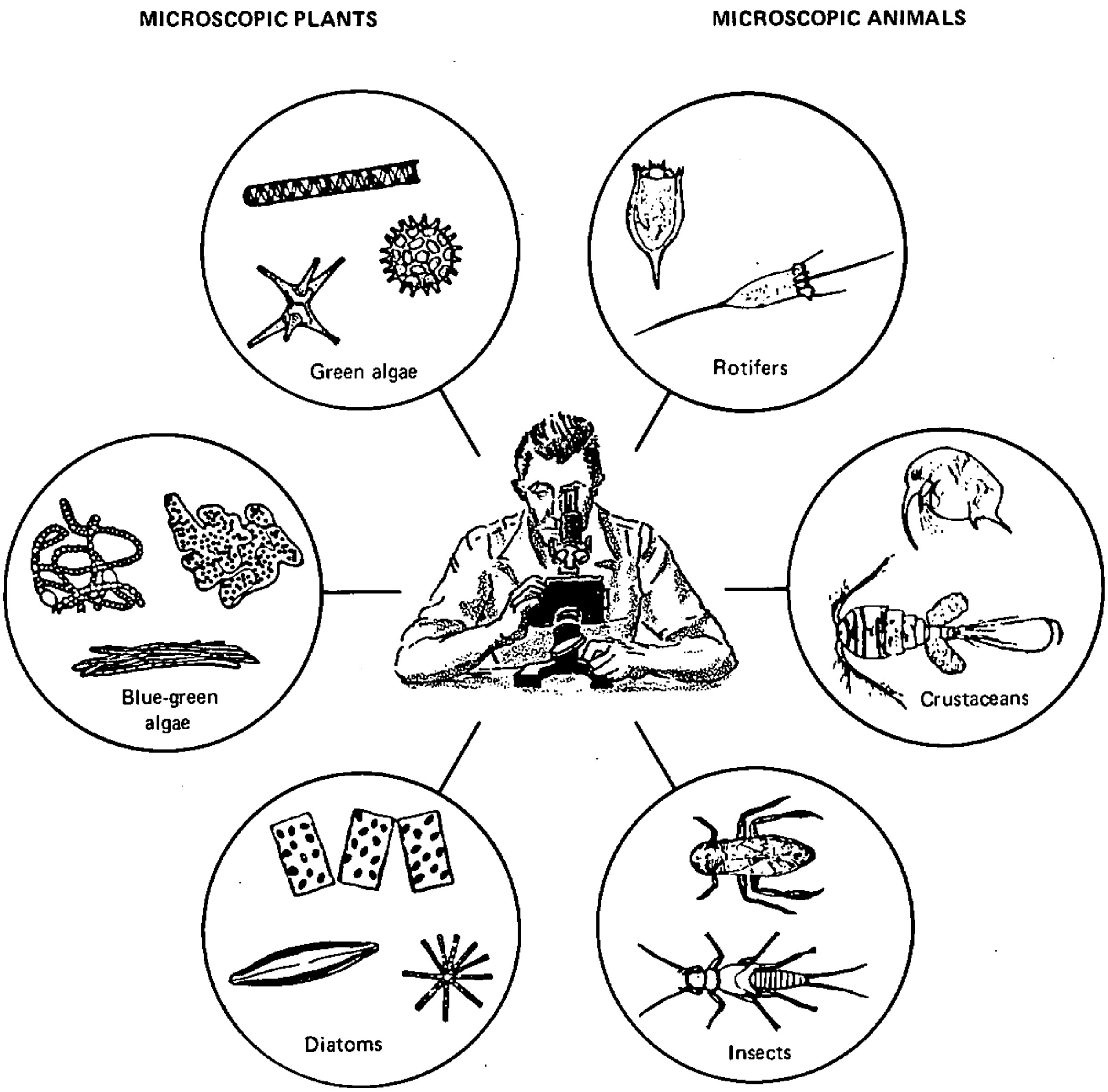


FIGURE 18.--Microscopic plants and animals typical of Washington lakes.

Blue-green algae lack the well-defined nucleus found in green algae and, in addition to green chlorophyll, contain blue, and often red, pigments. Most blue-green algae are filamentous and all occur in gelatinous sheaths. Blue-green algae are the most apt to produce the offensive algal blooms frequently seen on the surface of stagnant water bodies. When they become overabundant, blue-green algae may give water an unpleasant odor or taste and some, through the release of toxins, make the water poisonous to the animals that drink it. In addition, the gelatinous sheaths of blue-green algae make the algae difficult to filter in water-treatment operations.

Diatoms are yellow-green or yellow-brown algae that occur singly or, more rarely, in colonies. Their cells, the walls of which are made of hard silica, are composed of two overlapping halves, similar to a pillbox. In addition to being dependent on the same dissolved nutrients as other aquatic plants, diatoms also require an available supply of dissolved silica for the building of their cell walls.

Aquatic Animals

"Nevertheless, the pond is not very fertile in fish. Its pickerel, though not abundant, are its chief boast."

The aquatic animals commonly seen in Washington lakes range in size from microscopic, invertebrate (without backbone) animals to the larger, vertebrate animals such as fish. Some spend their entire life in water and can be called truly aquatic; others are aquatic only during part of their lives.

The aquatic vertebrates commonly seen in lakes are fishes, amphibians, reptiles, birds, and mammals. Because of their larger size, they are more conspicuous and generally of more interest to people than are the smaller animals without backbones. Numerically, however, the vertebrates constitute a relatively small part of a lake's animal population.

The most common and numerous animals in Washington lakes are the invertebrate rotifers, crustaceans, and insects, a few of which are shown in figure 18. Although they are usually present in large numbers, they are seldom noticed because of their small size. The smaller invertebrates that drift passively with the water currents are known collectively as zooplankton (the animal part of the plankton). Unlike the phytoplankton, however, many of the zooplankton are capable of limited locomotion. Zooplankton are important because they convert small food particles (chiefly algae) into forms large enough for larger, vertebrate animals.

Rotifers are among the most widely distributed and abundant of freshwater animals. They have a mouth which is surrounded by fine hairs and feed upon bacteria, algae, and small bits of organic matter. When feeding, the hairs beat in such a manner as to resemble a miniature pair of revolving wheels, hence the name "rotifer."

Crustaceans are shrimplike animals that have two pairs of antennae, one pair of appendages per segment, and gills. They eat algae and organic matter and are an important source of food for small fish and some large fish, such as Washington's sockeye and chum salmon. The two groups of crustaceans most commonly seen in Washington lakes are water fleas and copepods.

Literally thousands of species of insects spend part, or all, of their lives in fresh water. Many that spend their adult life out of water, such as mayflies and stoneflies, have immature stages--nymphs, larvae, and pupae--that develop beneath the water. All insects, especially in their immature stages, are important sources of food for vertebrates.

The Lake Ecosystem

"The perch swallows the grub-worm, the pickerel swallows the perch, and the fisherman swallows the pickerel...."

The ecosystem of a lake is the interaction of the biological communities of plants and animals with the physical and chemical environments of the lake. Even though most ecosystems can be regarded as stable--they persist as recognizable entities over the years--they are nonetheless continually changing in response to changes in their physical, chemical, or biological parts. The interdependence of these parts makes ecosystems complex; disruption of one part of a lake ecosystem affects numerous other parts.

Limnologists may divide the organisms that make up an ecosystem into different classes in several different ways. The organisms may be classified according to life zone, community, or ecological function.

The four principal life zones of a lake--the littoral, limnetic, profundal, and water-surface zones--are shown in figure 19a. The littoral zone is that part of a lake, usually along the shoreline, where light penetrates to the lake bottom. The limnetic zone is the lighted, open-water region that extends downward from the water surface to the depth of effective light penetration (the compensation level). The profundal zone includes the lake bottom and the dimly-lit, deep-water area below the compensation level. The water-surface zone is the habitat at, or immediately below, the surface film of water. Organisms may inhabit one or more life zones, but the littoral zone usually contains the greatest variety of organisms due to the unique combination of food, shelter, and light found there.

Five major biologic communities typically found in a lake are shown in figure 19b; these are the benthos, periphyton, plankton, nekton, and neuston communities. The benthos community includes organisms, such as snails and rooted plants, that crawl or rest on the lake bottom or in the bottom sediments. The periphyton community includes all organisms, such as filamentous algae and diatoms, that are attached or clinging to such submerged substrates as rocks, plants, and piers. Those organisms whose movements are dependent on water currents belong to the plankton community, which is composed chiefly of microscopic plants and animals such as algae, rotifers, water fleas, and copepods. Animal plankton can exist at virtually all depths, but plant plankton are generally restricted to the upper, lighted zones of the lake. The nekton community is composed of organisms, such as fish, amphibians, and certain insects, that are able to navigate at will and consequently are found in virtually all regions of the lake. The organisms of the neuston community, such as whirligig beetles and floating plants, rest or swim on the water surface.

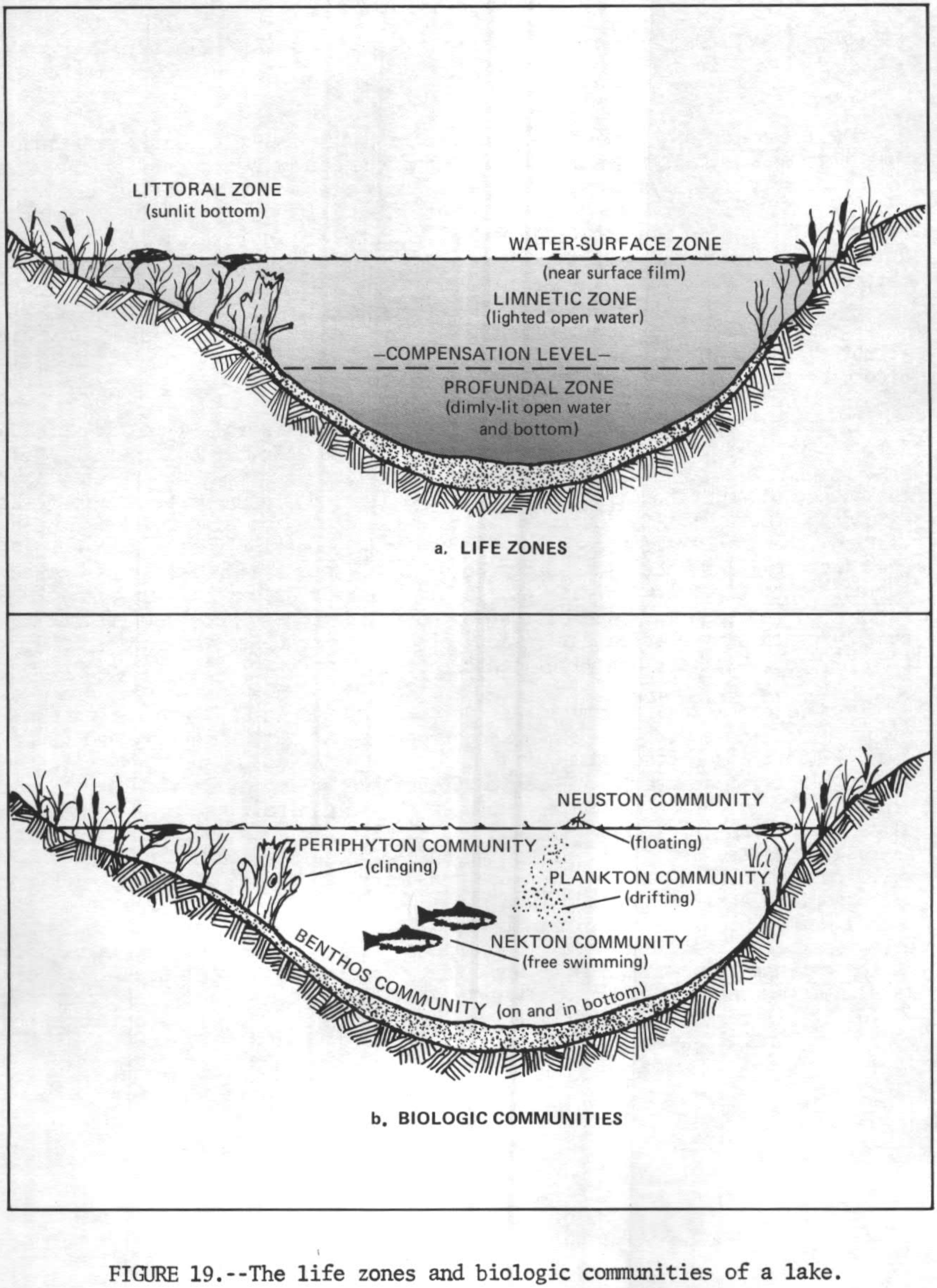


FIGURE 19.--The life zones and biologic communities of a lake.

From the previous discussion it is apparent that the communities differ in their degree of locomotion. Those communities that are mobile can usually escape from an adverse environment, provided it is only local in extent. Communities that are not mobile, however, must either adapt to the adverse environment or perish.

From an ecological viewpoint, perhaps the most important classification of organisms is by function within the ecosystem. The functional components of a lake ecosystem consist of producers, consumers, and decomposers. Producers are those organisms, chiefly algae, that produce organic tissue from inorganic substances dissolved in water. Consumers are the larger organisms that feed on the producers and smaller consumers. As producers and consumers die, decomposers, chiefly bacteria and fungi, break down the organic matter into its inorganic constituents. This continuous transfer of food energy, with repeated eating and being eaten, is referred to as the food chain (fig. 20).

Decomposers, in recycling materials used to build tissue, are an important link in the food chain. As bacteria and fungi decompose the complex organic substances produced in the lake, they liberate essential nutrients. Without decomposers, all of the available nutrients would soon be consumed, no oxygen would be produced by algae, and the lake would become barren of any life.

The producers, consumers, and decomposers within a lake ecosystem are usually in healthy balance, but remain so only under suitable water-quality conditions. This balance can be disrupted by the introduction of excessive amounts of organic or inorganic materials as a result of natural or man-caused activities. The lake ecosystem is capable of adjusting for such events, but the change often leads to lake conditions that are adverse to man's use and enjoyment of the water. Periodic evaluations of the ecosystems of Washington's lakes are important to ascertain the general health of the lakes and to determine if any adverse changes in lake conditions have occurred.

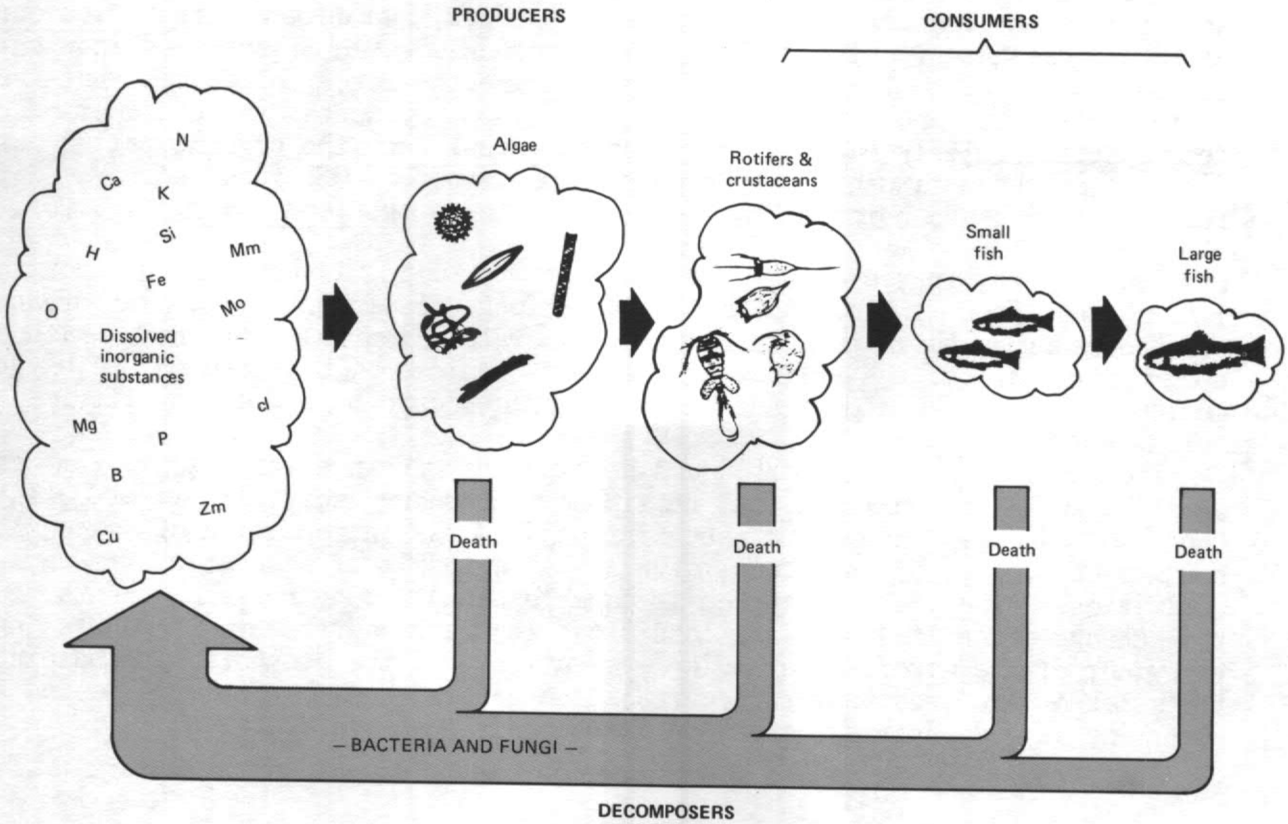


FIGURE 20.--A simplified food chain of a lake.

THE LIFESPAN OF A LAKE

Natural Succession and Eutrophication

"Perhaps on that spring morning when Adam and Eve were driven out of Eden Walden Pond was already in existence."

Lakes seldom exist more than a few thousands or tens of thousands of years--a relatively short period when considered in terms of geologic time. Because lakes are simply water-filled depressions in the earth's crust, they act as giant traps for organic and inorganic materials moved by water and wind. The ultimate fate of a lake basin is to become filled with sediment and to revert back to terrestrial vegetation. This natural evolutionary process is referred to as lake succession. As depicted in figure 21, the usual sequence of events in the succession process is: (1) Creation of a lake basin and its filling with water; (2) aging, or eutrophication, of the lake; (3) transformation of the lake to a marsh or swamp; and (4) the complete filling of the marsh or swamp with sediment and the growth of terrestrial vegetation.

The aging process of eutrophication is generally a natural one; it begins as soon as the lake is formed and continues as long as the lake exists as a body of water. As eutrophication progresses, lakes become smaller and more productive, primarily as a result of sedimentation and nutrient enrichment from numerous sources. In many lakes, only a fraction of the incoming sediments and nutrients is carried back out. Eventually, the lake reaches the eutrophic stage, characterized by frequent algal blooms, and seasonal deficiencies of dissolved oxygen. At this stage, sediments and plant debris have made the lake shallower and shoreline vegetation has invaded the lake. What was once sandy or gravelly shoreline is now silty or mucky wetland. With continued sedimentation, the lake is eventually transformed into a swamp or marsh; in time, trees and other dryland vegetation take over in the fertile soil.

In addition to increases in the numbers of plants and animals, the types of organisms may also change as eutrophication progresses. For instance, green algae and diatoms may be replaced by the more troublesome blue-green algae, and game fish such as salmon, trout, and bass may be replaced by carp, suckers, and catfish.

Sedimentation is a major cause of lake eutrophication. Most sediments are brought into a lake by tributary streams, storm runoff, and wind, but some originate within the lake from decaying vegetation and from shoreline erosion. Sedimentation increases the productivity of a lake because plant nutrients are usually attached to the incoming sediments and the newly deposited sediments provide additional rooting areas for aquatic plants. The turbidity caused by sedimentation somewhat compensates for the increased productivity, however, by reducing light penetration and, consequently, the amount of photosynthesis by plants.

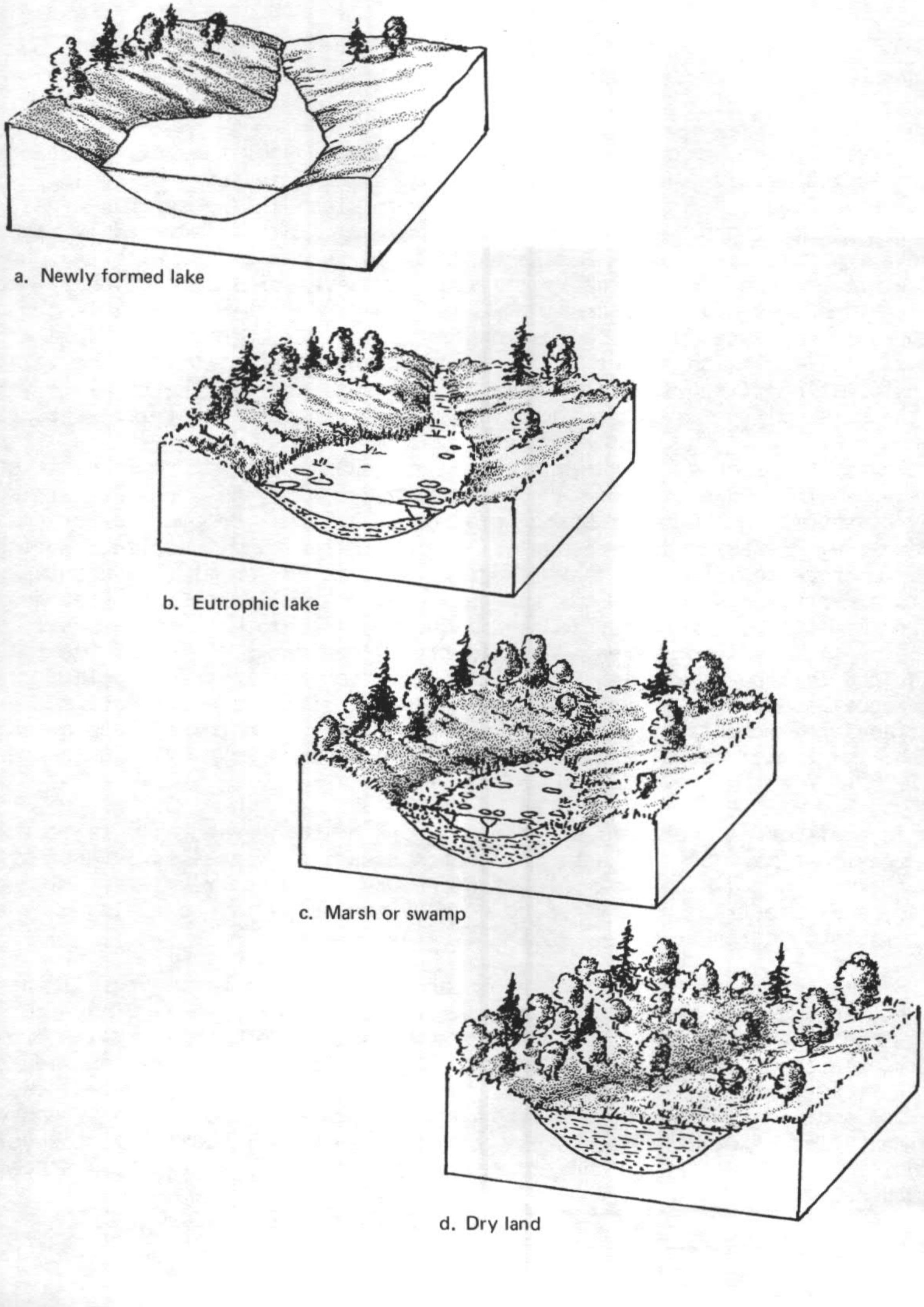


FIGURE 21.--The natural succession of a lake.

Cultural Eutrophication

"It needs no fence. Nations come and go without defiling it."

Cultural eutrophication is lake aging in which the natural aging process is accelerated by human activities. In an undisturbed lake there is usually a healthy balance between the inflow of plant nutrients from natural sources, the number of algae, and their predators. People, however, can upset this balance and compress the aging process to a matter of just a few years by overenriching the lake water with nutrients, primarily the compounds of nitrogen and phosphorus. When that happens, algal populations "bloom" to concentrations too great to be consumed by their predators. Some typical sources of nitrogen and phosphorus are domestic, agricultural, and industrial wastes.

Most of the "symptoms" associated with cultural eutrophication, such as the decrease of light penetration through lake water, are the direct result of increased algal populations. As the algae die, they sink to the bottom of the lake where they are oxidized, thereby reducing the dissolved-oxygen concentration there.

The usual effects of cultural eutrophication are to impair the quality of the water and to increase the costs and complexities of water treatment for domestic, industrial, agricultural, and recreational uses. One of the more troublesome aspects of lake eutrophication is the increased frequency of taste and odor problems. Various species of algae smell or taste like fish, pigpens, cucumbers, geraniums, and grass. In the deep zone of an eutrophic lake, where algae cannot grow, the reduced oxygen concentration often causes the accumulation of large amounts of iron and manganese. Water supplies taken from this zone may have a "rusty" appearance and cause a reddish-brown stain on porcelain fixtures.

Eutrophic lakes have several other undesirable features. Certain blue-green algae release toxins (substances that are poisonous). Eutrophic waters are sometimes high in dissolved minerals, and excessive concentrations of certain minerals, such as sodium, could prevent use of the water for certain purposes, such as irrigation. Should sedimentation eliminate the cold, deep-water part of the lake, or if oxygen depletion occurs within that zone, only the warm, sunlit part remains with enough oxygen to support fish life and,as a result, the number and types of fish could decrease.

Not all cultural eutrophication is necessarily bad; much depends on the use of the water and the degree of eutrophication. Lakes that are used as water supplies or for contact recreation should be kept as oligotrophic (unproductive) as possible. Other lakes, however, may have to be artificially fertilized to increase the production of fish for sporting or commercial purposes.

Pollution

"....a mirror in which all impurity presented to it sinks...."

Pollution, which is broadly defined as the unfavorable alteration of a lake environment, can result in three general types of damage to a lake: (1) Ecological damage, such as harmful changes to the aquatic life; (2) economic damage, such as cleanup costs, reduced revenues, and depressed property values; and (3) esthetic damage, such as changes which make the lake less pleasing to use or to enjoy.

The presence of a pollutant is often difficult to detect. Some can be seen, tasted, or smelled; others are detectable only by their effects on plants or animals, or by chemical analysis of the lake water.

Pollutants that are potentially harmful to a lake may take several forms--organic materials (including petroleum products), poisons, radioactive materials, and thermal loads. However, pollution by organic materials from sewage, garbage, and animal wastes is the form that most frequently causes damage to lakes. Organic materials can degrade a lake by reducing or depleting the dissolved oxygen, by adding disease-carrying bacteria and viruses, and by adding plant nutrients that eventually lead to the cultural eutrophication of the lake. Organic pollution tends to suppress the development of some species of aquatic life and encourage the development of others. The normal, clean-water assemblage of plants and animals (for example, diatoms and stoneflies) is quickly replaced by pollution-tolerant species of plants and animals (for example, blue-green algae and sludge worms). The effects of organic pollution, therefore, are usually readily apparent, both to the eye and nose, and should be prevented whenever possible.

Poisons affect the metabolic efficiency of organisms. Common poisons include both organic materials, such as the pesticide DDT, and inorganic materials, such as the toxic metals cadmium, mercury, and zinc. Unlike pollution from sewage, poisons are usually difficult to detect and they affect all forms of life adversely. Some poisons, such as DDT, can be selectively concentrated in the tissues of organisms.

Radioactive materials can be particularly dangerous to the reproductive cells of both people and lower animals and, like DDT, certain types can be selectively concentrated in tissue. Fortunately, radioactive pollution of lakes is rarely encountered.

A more common, yet unconventional, type of pollution is thermal wastes or thermal loading, which causes raised water temperatures. Raised water temperatures adversely affect plants and animals by lowering the solubility of oxygen and increasing the rate of metabolism in the organism. In addition, warm water may stimulate the growth of algae, often leading to nuisance algal blooms.

Pollution may be introduced directly into the lake or it may be brought to the lake by tributary streams. Not all undesirable substances carried by tributaries necessarily enter lakes, however. Because of natural processes operating within streams, some polluting substances may dissipate before reaching a lake. For example, harmful bacteria may die, organic matter may be completely oxidized, or warm water may cool before reaching the lake. However, many polluting substances, such as toxic metals, remain intact regardless of the distance traveled.

ASSESSING LAKE CONDITIONS

"It is a gem of the first water which Concord wears in her coronet."

Assessing the condition of a lake is not an easy matter because there are so many different factors that can affect the condition, either adversely or beneficially. Lake condition cannot be determined by the measurement of a single characteristic; most limnologists measure many different physical, chemical, and biological characteristics and combine the results to arrive at the trophic level (degree of eutrophication) of a particular lake. Some that are usually measured include the amount of algae present, the dissolved substances in the water, the extent of light penetration, the concentration of oxygen in the hypolimnion (deep water) during thermal stratification, and the plant nutrient concentrations, in particular the compounds of nitrogen and phosphorus.

The indicators of lake eutrophication are best described by comparing the characteristics of both oligotrophic and eutrophic lakes, as presented in the table below (modified from Lee, 1970):

Characteristic	Oligotrophic (unproductive) lake	Eutrophic (productive) lake
Aquatic plant and animal production	Low	High
Dissolved substances in the water	Low	High
Light penetration through the water	Great	Small
Oxygen in the hypolimnion	Present	Absent
Water quality for most uses	Good	Poor

As might be expected, trophic conditions in Washington lakes range from highly oligotrophic to highly eutrophic. Of the lakes studied by the U.S. Geological Survey to date, Summit Lake in Pierce County is one of the most oligotrophic. Some of the more eutrophic lakes include Larsen Lake in King County, Stallard Lake in Douglas County, and West Medical Lake in Spokane County.

The trophic and water-quality conditions of Washington's lakes have been the object of reconnaissance- and intensive-level investigations by various agencies, colleges and universities, private consulting groups, and others. The results of most of these investigations have been published and the reports are included in those listed on pages 51-55. For descriptions of conditions in specific lakes, the reader is referred to one or more of the publications listed in these references.

LAKE-RESTORATION PROGRAMS IN WASHINGTON

"It is a mirror which no stone can crack, whose quicksilver will never wear off, whose gilding Nature continually repairs."

Although the best solution to lake problems is to prevent them from happening in the first place, that is not always feasible. In certain circumstances, problem lakes can and must be restored. Such projects are currently being conducted in Washington.

For many years the Washington Game Department has been using lake-restoration techniques as a fisheries-management tool in order to provide improved conditions for a particular fish species (for example, a replacement of scrapfish with trout). Recent undertakings by the Washington Department of Ecology, however, are much broader in scope. The objectives of the Department of Ecology's lake-restoration program are to restore to selected lakes those beneficial uses that have been lost or imparied in the recent past.

The ratification of Referendum 26 (Washington Future) in 1972 resulted in the appropriation of almost $7.5 million in fiscal years 1975-77 to the Department of Ecology for the purpose of rehabilitating highly eutrophic lakes. In 1973 the Department of Ecology, in cooperation with the U.S. Geological Survey, made a reconnaissance investigation of all lakes in the State covered under the Shoreline Management Act of 1971. The data obtained in that study were used to classify the lakes and identify those most in need of restoration. Using the results of the classification, the Department of Ecology selected 18 lakes for additional study, and restoration projects have now begun on some of these lakes.

The eligibility for funding of restoration projects under Referendum 26 is limited to such public bodies as local governments and municipal corporations. In operation, the Department of Ecology grants as much as 50 percent of the cost of any one project while the public body must make up the remaining 50 percent. However, a large part of the funds needed from the public body can be obtained from the Federal Government under Section 314 of Public law 92-500, the Water Pollution Control Act of 1972.

Although it is too early to determine how effective the lake-restoration projects in Washington will be, it is hoped that they will provide lake mangers with an effective tool in dealing with the problems of lake pollution and eutrophication.

TERMS COMMONLY USED IN LIMNOLOGY

Acre-foot. The volume of water required to cover 1 acre to a depth of 1 foot, and equal to 43,560 cubic feet, or 325,900 U.S. gallons.

Algae. Small, simple plants, usually aquatic, which contain chlorophyll but lack roots, stems, and leaves.

Algal bloom. A large number of a particular algal species. A condition in which the algae cloud the water noticeably.

Anaerobic. Conditions characterized by the absence of oxygen.

Aphotic zone. That part of a water body to which light does not penetrate with sufficient intensity to maintain photosynthesis.

Aquifer. A rock formation that is water bearing.

Bathymetric. Relating to the measurement of water depths, as for a lake.

Benthos community. The organisms living in or on the bottom of an aquatic environment.

Cirque. A deep, steep-walled basin in the side of a mountain, caused by glacial erosion.

Closed lake. A lake, usually in an arid or semiarid region, that does not have a surface outlet.

Compensation level. The depth at which oxygen production by photosynthesis balances oxygen uptake by respiration.

Consumers. Organisms that are unable to manufacture their food from nonliving matter and that feed upon other organisms.

Coulee. A short gulch or water channel.

Crater lake. A lake that occupies the crater of an inactive volcano.

Cultural eutrophication. The acceleration of the natural aging, or enrichment, process of a lake as a result of man's activities.

Decomposers. Organisms, mostly bacteria or fungi, that break down complex organic material into its inorganic constituents.

Dimictic. A term applied to a lake which undergoes two periods of thermal circulation, or overturn each year--in spring and fall.

Drainage basin. The area drained by, or contributing to, a stream, lake, or other water body.

Drift. Any rock material transported and deposited directly or indirectly by a glacier.

Ecosystem. The community of plants and animals interacting together within the physical and chemical environment.

Epilimnion. The upper, relatively warm, circulating zone of water in a thermally stratified lake.

Euphotic zone. That part of a water body where light penetration is sufficient to maintain photosynthesis.

Eutrophic. A term applied to a water body in which organic production is high as a result of a large supply of available nutrients.

Eutrophication. The natural process of enrichment and aging of a body of water.

Fall overturn. A natural mixing of thermally stratified waters that commonly occurs during early autumn. The sequence of events leading to fall overturn includes (1) cooling of surface water, (2) density change in surface water that produces convection currents from top to bottom, and (3) circulation of the total water volume by wind action. The overturn generally results in a uniformity of the physical and chemical properties of the water.

Fluviatile. Pertaining to a river or stream.

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

Hydrologic cycle. The cycling of water from the earth to the atmosphere, in the form of evaporation and transpiration, and back to earth in the form of precipitation.

Hypolimnion. The lower, relatively cold, non-circulating water zone in a thermally stratified lake.

Kettle. A basin formed by the melting of a detached mass of glacial ice buried or submerged in glacial drift.

Limnetic zone. The open-water part of a water body above the compensation level.

Limnologist. A specialist in the field of limnology.

Limnology. The science or study of inland bodies of water, such as lakes.

Littoral zone. The shallow part of a water body where light penetrates to the bottom.

Macrophyte. A plant that can be seen with the unaided eye.

Mean depth. A morphometric parameter of a lake obtained by dividing the volume by the area.

Meromictic. A term applied to a lake in which dissolved substances have increased the density of the bottom water sufficiently to prevent complete vertical mixing.

Metalimnion. The middle layer of water in a thermally stratified lake, in which temperature decreases rapidly with depth.

Morphometry. The measurement of the shape characteristics of lakes and lake basins.

Nekton community. Organisms that are able to navigate at will and consequently are found in virtually all regions of a lake.

Neuston community. Organisms that live on or just under the surface film of water.

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

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

Open lake. A lake, usually in a humid climate, that has a surface outlet.

Oxbow lake. A crescent-shaped lake formed in the abandoned meander of a river channel.

Periphyton community. Organisms that are attached to, or live upon, submerged surfaces.

Phytoplankton. The plant part of the plankton.

Plankton (community). Suspended or floating organisms that drift passively with water currents.

Producers. Organisms that can directly utilize dissolved minerals and gases to form organic matter.

Productivity. The total amount of living matter produced in an area per unit time regardless of the fate of the living matter.

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

Relative depth. A morphometric parameter of a lake defined as the ratio of the maximum depth to the mean lake diameter, in percent.

Scablands. Areas where erosion has removed the soil and the underlying rock is exposed or covered largely with its own coarse debris.

Secchi disc. A disc 8 inches in diameter and painted in white and black alternating quadrants, used to measure light transparency in lakes.

Shoreline configuration. A morphometric characteristic of a lake defined as the dimensionless ratio of the shoreline length to the circumference of a circle having the same area as the lake.

Specific conductance. The measure of a water's ability to conduct an electric current, usually expressed as micromhos per centimeter.

Spring overturn. A natural mixing of thermally stratified water that commonly occurs during the early spring. The sequence of events leading to spring overturn includes (1) melting of ice cover, if present, (2) warming of surface water, (3) temperature change in surface water that produces convection currents from top to bottom, and (4) circulation of the total water volume by wind action. The overturn generally results in a uniformity of the physical and chemical properties of the water.

Succession. The natural evolutionary process in which a lake eventually becomes filled with sediment and reverts back to terrestrial vegetation.

Tarn. A small mountain lake that occupies a basin gouged from rock by a glacier.

Thermal stratification. A temperature distribution characteristic of many lakes in which the water is separated into three horizontal layers: An epilimnion (warm water) at the top, a metalimnion in which the temperature changes rapidly with depth, and a hypolimnion (cold water) at the bottom.

Turbidity. Organic and inorganic materials suspended in water that reduce the pentration of light.

Water-renewal time. The time needed to replace the entire volume of a lake under average conditions of inflow and outflow.

Water-surface zone. That part of the lake at, or immediately below, the surface film of water.

Zooplankton. The animal part of the plankton.

SELECTED REFERENCES PERTAINING TO LAKES

Popular-nontechnical

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