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WATER QUALITY CONSTITUENTS

*Temperature**

TEMPERATURE is a prime regulator of natural processes within the water environment. It governs physiological functions in organisms and, acting directly or indirectly in combination with other water quality constituents, it affects aquatic life with each change. These effects include chemical reaction rates, enzymatic functions, molecular movements, molecular exchanges between membranes, etc., within and between the physiological systems and organs of an animal. Because of the complex interactions involved, and often because of the lack of specific knowledge or facts, temperature effects as they pertain to an animal or plant are most efficiently assessed on the basis of net influence on the organism. Depending on the extent of environmental temperature change, organisms can be activated, depressed, restricted, or killed.

Temperature determines those aquatic species that may be present; it controls spawning and the hatching of young, regulates their activity and stimulates or suppresses their growth and development; it can attract and kill when the water becomes heated or chilled too suddenly. Colder water generally suppresses development; warmer water generally accelerates activity.

Temperature regulates molecular movement and thus largely determines the rate of metabolism and activity of all organisms, both those with a relatively constant body temperature and those whose body temperature is identical to, or follows closely, the environmental temperature. Because of its capacity to determine metabolic rate, temperature may be the most important single environmental entity to life and life processes.

Variations in temperature of streams, lakes, estuaries, and oceans are normal results of climatic and geologic phenomena. Waters that support

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some form of aquatic life other than bacteria or viruses range in temperature from 26.6° F. in polar sea waters to 185° F. in thermal springs. Most aquatic organisms tolerate only those temperature changes that occur within a narrow range to which they are adapted, whether it be high, intermediate, or low on this temperature scale.

Within the same species, the effects of a given temperature may differ in separate populations, in various life cycle stages, or between the sexes, and such effects may depend on the temperature history of the individual tested, as well as on present or past effects of other environmental factors.

Freshwater has the greatest density at 38° F.; higher and lower temperatures result in waters with lower density. Seasonally induced temperature changes are greatest in the midlatitudes.

In lakes, insolation warms the surface waters in spring, reducing their densities compared to the deeper waters until eventually the density differences are sufficient to prevent the wind from mixing the body of water; thermal stratification then occurs. The warm upper layer (epilimnion) is well mixed to a depth determined by wave and other wind induced currents. The cool bottom waters (hypolimnion) become stagnant except for minor currents confined to this strata. A strata of sudden temperature changes (thermocline) separates these regions. In autumn, the lake radiates heat, surface temperatures decrease, surface water density increases, and water viscosity increases. Soon the wind, aided by reduced density differences between water layers, mixes the surface with the bottom waters resulting in a homogenous water mass. Depending on altitude and local climatic conditions, the lake continues to mix until the following spring in latitudes of less than about 40°. In latitudes north of about 40°, winter surface water temperatures are less than 38° F. and these are superimposed over the water mass until they are cooled to freezing. An ice cover eliminates wind induced mixing and stagnation occurs.

Thermal stratification in reservoirs may assume many patterns depending on geographical location, climatological conditions, depth, surface area, and type of dam structure, penstock locations, and hydropower use. In general, large, deep impoundments will cool downstream waters in the summer and warm them in winter when withdrawal ports are deep; shallow, unstratified impoundments with large surface areas will warm downstream waters in the summer; water drawn from the surface of a reservoir will warm downstream waters; a reduction in normal flow downstream from an impoundment will cause marked warming in summer; and "run-of-river" impoundments, where the surface area has not been increased markedly over the normal river area, will produce only small changes in downstream water temperatures.

In the deep, stagnant, summer bottom waters, as well as in ice covered waters, atmospheric reaeration is absent and oxygen from photosynthesis by plants is limited. Decomposing organisms (especially those settling to the bottom waters in summer) remove oxygen from the water and the gaseous byproducts of decomposition are trapped. Undesirable soluble phosphorus, carbon dioxide, iron, and manganese concentrations increase in these stagnant waters. Designed thermal discharges can reduce some of these problems. Ice cover can be limited, thus allowing wind and thermally induced currents to reduce winter stagnation. A deepwater summer discharge could warm hypolimnetic waters to decrease density and permit total water mass mixing where a cold water fishery would not be damaged by such action.

Stratification may occur in streams receiving heated effluents. There are three recognized forms of stream stratification: overflow, interflow, and underflow; the forms are determined by the relationship between the density of the influent and the density of the stream water.

Surface freshwaters in the United States vary from 32° to over 100° F. according to the latitude, altitude, season, time of day, duration of flow, depth, and many other variables. Agents affecting natural water temperature are so numerous that no two water bodies, even in the same latitude, are likely to have the same thermal characteristics. Fish and other aquatic life occurring naturally in each body of water are those that have become adapted to the temperature conditions existing there. The interrelationships of species, length of daylight and water temperature are so intimate that even a small change in temperature may have far-reaching effects. An insect nymph in an artifically warmed stream, for example, might emerge for its mating flight too early in the spring and be immobilized by the cold air temperature, or a fish might hatch too early in the spring to find its natural food organisms because the food chain depends ultimately on plants, and these in turn, upon length of daylight, as well as temperature. The inhabitants of a water body that seldom becomes warmer than 70° F. are placed under stress, if not killed outright, by 90° F. water. Even at 75° to 80° F., they may be unable to compete successfully with organisms for which 75° to 80° F. is favorable. Similarly, the inhabitants of warmer waters are at a competitive disadvantage in cool water.

An animal's occurrence in a given habitat does not mean that it can tolerate the seasonal temperature extremes of that habitat at one time. The habitat must be cooled gradually in the fall if the animal is to become acclimatized to the cold water of winter, and warmed gradually in the spring if it is to withstand summer heat.

Some organisms might endure a temperature of 92° to 95° F. for a few hours, but not for days. Gradual change of water temperature with the season is important for other reasons: an increasing or decreasing temperature often "triggers" spawning, metamorphosis, and migration. The eggs of some freshwater organisms must be chilled before they will hatch properly.

The temperature range tolerated by many species is narrow during very early development; it increases somewhat during maturity, and decreases

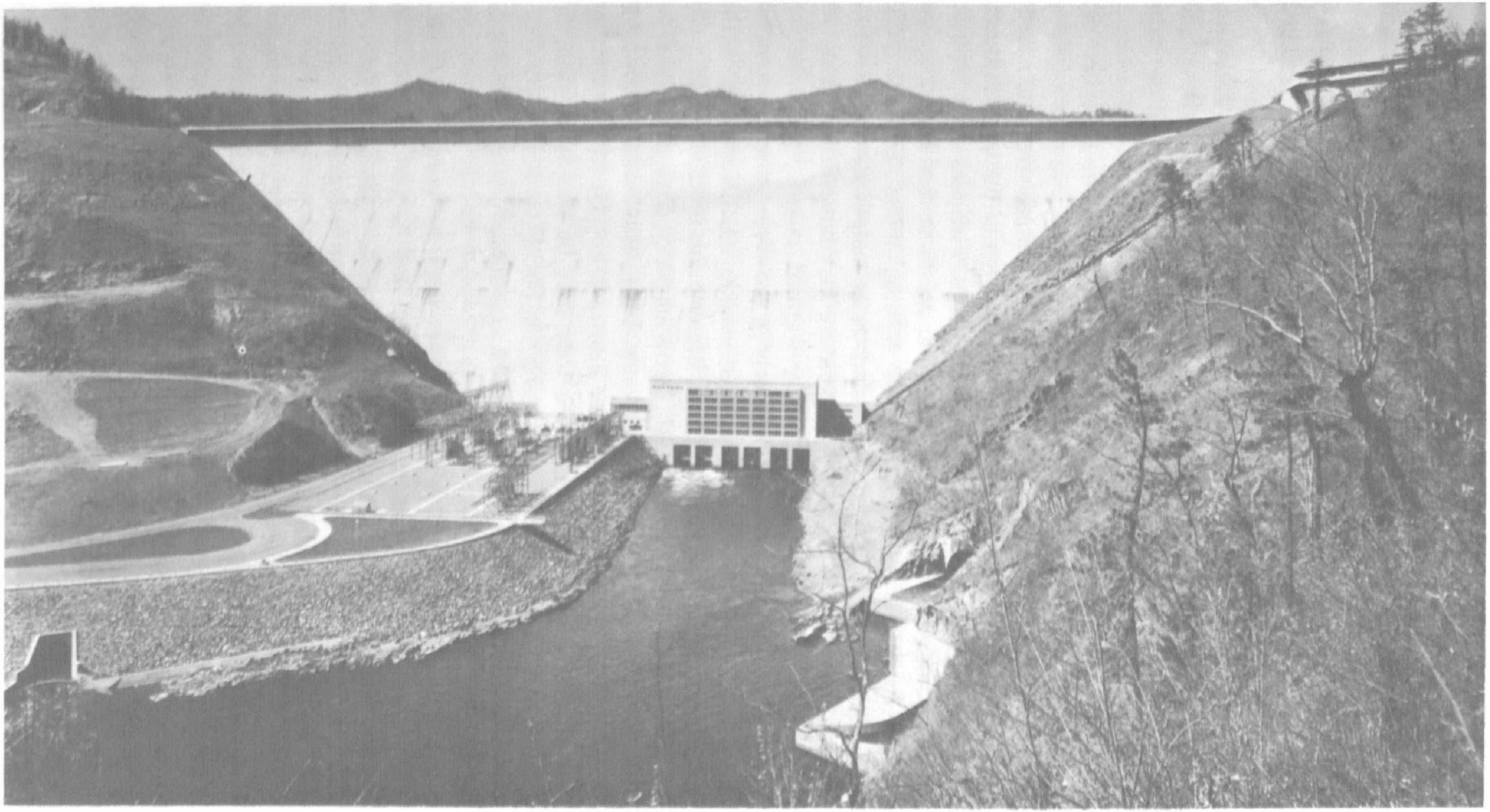

Figure 8. Fontana Project, Tennessee Valley Authority

again in the old adult. Similarly, the tolerable temperature range is often more restrictive during the reproductive period that at other times during maturity. Upper lethal temperatures may be lower for animals from cold water than for closely related species from warm water. Many motile organisms such as fish, some zooplankton, certain algae, and some associated animals can avoid critical temperatures by vertical and horizontal migration into more suitable areas. However, some organisms may be attracted to areas with critical temperatures, and, upon arrival, succumb.

Changes in fish populations can result from many types of artificial cooling and heating of natural waters. These changes result from the discharge of condenser cooling water from thermal electric generating plants, industrial waste cooling waters, and other heated effluents, and irrigation waters. Streams are warmed also by the sun when the shade from stream bank trees and other vegetation is eliminated. The discharge of cold water from stratified impoundments may provide an ideal habitat for trout and other cold water fish, when sufficient dissolved oxygen is present, but not for the warm water fish that inhabited the stream before impoundment.

For every 18° F. increase in temperature, the chemical reaction rate is approximately doubled in an organism or in an environment. Life processes in the water are accelerated with temperature increases and slowed as the water cools.

The solubility of gases, including oxygen, in water varies inversely with temperature. In fresh water, the solubility of atmospheric oxygen is decreased by about 55 percent as the temperature rises from 32° to 104° F. under 1 atmosphere of pressure (760 mm. Hg.). Because all desirable living things are dependent on oxygen in one form or another to maintain the life processes that produce energy for growth and reproduction, dissolved oxygen is of imposing significance in the aquatic environment.

When organism metabolism increases because of higher temperatures, organism development is speeded, and more dissolved oxygen is required to maintain existence. But, bacterial action in the natural purification process to break down organic materials is also accelerated with increased temperatures, thus reducing the oxygen that could be available in the warmer water. When organisms use larger amounts of oxygen, and when oxygen has been reduced by temperature action and interaction, organisms may perish. Life stages that are especially vulnerable are the eggs and larvae. At higher temperatures, phytoplankton have been found to need greater amounts of certain growth factors such as vitamin B_{12}. Between 96.8° and 98.2° F., for example, the vitamin requirement has been found to increase over 300 times for some species.

Fish and other motile organisms seek a preferred temperature at which they can best survive, which is several degrees below a temperature that is lethal. Larger individuals tend to move out of areas that are too hot, but larvae and juveniles cannot often move fast enough to avoid a sudden temperature increase. Large fish and fish in schools avoid heated areas in summer but may be attracted to such areas in winter. This phenomenon may result in good fishing during the cooler months, but an absence of this sport at other times.

Reproduction cycles may be changed significantly by increased temperature because this function takes place under restricted temperature ranges. Spawning may not occur at all because temperatures are too high. Thus, a fish population may exist in a heated area only by continued immigration. Disregarding the decreased reproductive potential, water temperatures need not reach lethal levels to wipe out a species. Temperatures that favor competitors, predators, parasites, and disease can destroy a species at levels far below those that are lethal.

Fish food organisms are altered severely when temperatures approach or exceed 90° F. Predominant algal species change, primary production is decreased, and bottom associated organisms may be depleted or altered drastically in numbers and distribution. Increased water temperatures may cause aquatic plant nuisances when other environmental factors are favorable.

Synergistic actions of pollutants are more severe at higher water temperatures. Given amounts of domestic sewage, refinery wastes, oils, tars, insecticides, detergents, and fertilizers more rapidly deplete oxygen in water at higher temperatures, and the respective toxicities are likewise increased.

The National Technical Advisory Committee on Water Quality Criteria (Anon., 1968), composed in part of the nation's leading fishery experts, recommended that to maintain a well-rounded population of warm water fishes, heat added to a freshwater stream not exceed that which would raise the water temperature more then 5° F. at the expected minimum daily flow for the month involved. In lakes, the temperature of the upper waters should not be raised more than 3° F. above that which existed before heat was added. The increase should be based on the monthly average of the maximum daily temperatures. Temperature should be measured in those areas where important organisms are most likely to be affected adversely.

The Committee recommended provisional maximum temperatures as compatible with the well-being of various fish species and their associated biota as follows:

93° F.: Growth of catfish, gar, white or yellow bass, spotted bass, buffalo, carpsucker, threadfin shad, and gizzard shad.
90° F.: Growth of largemouth bass, drum, bluegill, and crappie.
84° F.: Growth of pike, perch, walleye, smallmouth bass, and sauger.
80° F.: Spawning and egg development of catfish, buffalo, threadfin shad, and gizzard shad.
75° F.: Spawning and egg development of largemouth bass, white and yellow bass and spotted bass.

68° F.: Growth or migration routes of salmonids and for egg development of perch and smallmouth bass.

55° F.: Spawning and egg development of salmon and trout (other than lake trout).

48° F.: Spawning and egg development of lake trout, walleye, northern pike, and sauger.

Because of the large number of trout and salmon waters that have been destroyed, made marginal or nonproductive, remaining trout and salmon waters must be protected if these resources are to be preserved. The Committee further recommended that inland trout streams, headwaters of salmon streams, trout and salmon lakes and the deeper waters of lakes that contain salmonids not be warmed. No heated effluents should be discharged in the vicinity of spawning areas.

Little work has been done regarding thermal addition effects in subtropical estuarine ecosystems. In the subtropical environment, optimum temperatures for many forms are only a few degrees lower than maximum lethal temperatures. Organisms may be existing under stress with naturally occurring summer temperatures. Great care should be exercised to prevent harmful temperature increases.

In general, marine water temperatures do not change as rapidly or range as widely as those of freshwaters. Marine and estuarine fishes, therefore, are less tolerant of temperature variation. Although this limited tolerance is greater in the estuarine than in the open water marine species, temperature changes are more important to those fishes in estuaries and bays than to those in open marine areas.

Marine surf-zone discharge from large-scale coastal power plants may be expected to significantly alter the shore environment for species of invertebrates and fish that are commonly found there.

Some investigators have becomed alarmed over the loss in organisms contained in the water pumped across condensers and through a generating plant. These are subject to thermal shock, physical damage, and perhaps commercial additives. These organisms include phytoplankton, crustaceans, zooplankton, and shellfish larvae, such as clams and oysters that have stages of drift in the water column for a few weeks before they settle to the bottom. Studies have shown a 95 percent mortality of these organisms when they are subjected to the rise in temperature in crossing the condenser.

Available data indicate that commercial and key food-chain estuarine animals cannot tolerate temperatures greater than approximately 90° F. regardless of the temperature to which they have been acclimated. Thus, natural peak summer water temperatures in a subtropical or tropical estuary may be near the tolerance threshold for a number of desirable marine organisms.

In subtropical waters, organisms that find the environment undesirable are not replaced by organisms of greater temperature tolerance, as so often happens in northern latitudes.

The National Technical Advisory Committee on Water Quality Criteria, in reporting to the Secretary of the Interior, recommended that the discharge of any heated materials into coastal waters be closely managed. This Committee stipulated that any rise owing to such discharges should be restricted to 1.5° F. during the critical summer months, outside of established mixing zones. To make water quality standards more meaningful, mixing zones must have definition. The National Technical Advisory Committee suggested only that adequate passageways be provided at all times for the movement or drift of organisms, and that mixing areas must not be used for, or considered as, a substitute for waste treatment, or as an extension of, or substitute for, a waste treatment facility.

Dissolved Oxygen

Dissolved oxygen (D.O.) is a water quality constituent that, in appropriate concentrations, is essential not only to keep organisms living but also to sustain species reproduction, vigor, and the development of populations. Organisms undergo stress at reduced D.O. concentrations that make them less competitive to sustain their species within the aquatic environment. For example, D.O. concentrations around 3 milligrams per liter (mg/l) or less have been shown to interfere with fish populations through delayed hatching of eggs (Silver et al., 1963), reduced size and vigor of embryos (Silver et al., 1963; Van Horn and Balch, 1957), production of monstrosities in young (Alderdice et al., 1958), interference with food digestion and acceleration of blood clotting (Bouck & Ball, 1965), decreased tolerance to certain toxicants (Cairns and Scheier, 1957), reduced food efficiency and growth rate (Chiba, 1966; Herrman et al., 1962), and reduced maximum sustained swimming speed (Davis et al., 1963).

Oxygen enters the water by absorption directly from the atmosphere or by plant photosynthesis, and is removed by respiration of organisms and by decomposition. That derived from the atmosphere may be by direct diffusion or by surface water agitation by wind and waves, which may also release dissolved oxygen under conditions of supersaturation.

In photosynthesis, aquatic plants utilize carbon dioxide and liberate dissolved and free-gaseous oxygen at times of supersaturation. Since energy is required in the form of light, photosynthesis is limited to the photic zone were light is sufficient to facilitate this process. According to Dice (1952), ". . . the ultimate limit of productivity of a given ecosystem is governed by the total effective solar energy falling annually on the area, by the efficiency with which the plants in the ecosystem are able to transform this energy into organic compounds, and by those physical factors of the environment which affect the rate of photosynthesis." Verduin (1956) summarized the literature on primary production in lakes; based on computations of photosynthetic oxygen production, he found that the yields of several lakes were mostly between 42 and 57 pounds of dissolved oxygen per acre per day. A year-round study under completely natural conditions in western Lake Erie showed winter yields of about 11 pounds of dissolved oxygen production per acre per day, and summer maxima of about 85 pounds per acre per day. The annual oxygen production curve closely followed the solar radiation curve. The net oxygen production rate for East Okoboji Lake in Iowa, a producer of large plankton populations, was 79 pounds per acre per day, with production largely confined to the first 2 meters (Weber, 1958). Whipple et al. (1948) noted that supersaturation in the upper waters is not cumulative to a great extent because circulation is maintained by wind action and convection currents both of which promote contact of the water and the air with a consequent loss of oxygen. Higher saturation is frequently found in the upper region of the thermocline in infertile oligotrophic lakes. Wind action seldom disturbs the waters of this zone, convection currents are absent, and diffusion is a slow process. Plants find an abundant supply of carbon dioxide and sufficient light in this area to stimulate photosynthesis, resulting in supersaturation values that may exceed 300 percent.

During respiration and decomposition, animals and plants consume dissolved oxygen and liberate carbon dioxide at all depths where they occur. Because excreted and secreted products and dead animals and plants sink, most of the decomposition takes place in the hypolimnion; thus, during lake stratification there is a gradual decrease of dissolved oxygen in this zone. After the dissolved oxygen is depleted, anaerobic decomposition continues with evolution of methane and hydrogen sulfide.

In the epilimnion, during thermal stratification, dissolved oxygen is usually abundant and is supplied by atmospheric aeration and photosynthesis. Phytoplankton are plentiful in fertile lakes and are responsible for most of the photosynthetic oxygen. The thermocline is a transition zone from the standpoint of dissolved oxygen, as well as temperature. The water rapidly cools in this region, incident light is much reduced, and photosynthesis is usually decreased; if sufficient dissolved oxygen is present, some cold water fish abound. As dead organisms that sink into the hypolimnion decompose, oxygen is utilized; consequently, the hypolimnion in fertile lakes may become devoid of dissolved oxygen following a spring overturn, and this zone may be unavailable to fish and most benthic invertebrates at this time. During the two brief periods in spring and fall when lake water circulates, temperature and dissolved oxygen are the same from top to bottom and fish can use the entire water depth.

The National Technical Advisory Committee (Anon., 1968) recommended that D.O. concentrations be above 5 mg/l assuming normal seasonal and daily variations for a diversified warm water biota. The Committee stated that under extreme conditions concentrations may range between 5 and 4 mg/l for short periods during any 24-hour period, providing that the water quality is favorable in all other respects. For cold water biota, it is desirable that D.O. concentrations be at or near saturation especially in spawning areas. D.O. levels in the hypolimnion of lakes should not be lowered below 6 mg/l at any time because of the addition of oxygen demanding wastes. The Committee further specified that D.O. concentrations in surface coastal waters should be greater than 5.0 mg/l, except when upwellings and other phenomena may cause this value to be depressed. D.O. concentrations in estuaries and tidal tributaries should not be less than 4.0 mg/l at any time or place, except in naturally dystrophic waters or where natural conditions cause D.O. to be depressed.

pH

The world's literature on pH published prior to about 1950 has been critically evaluated by Doudoroff and Katz (1950). They concluded that ". . . under otherwise favorable conditions, pH values above 5.0 and ranging upward to pH 9.0, at least, are not lethal for most fully developed freshwater fishes. Much more extreme pH values, perhaps below 4.0 and well above 10.0, also can be tolerated indefinitely by resistant species. However, regardless of the nature of acid or alkaline wastes responsible, such extreme conditions, associated with industrial pollution, are evidently undesirable and hazardous for fish life in waters which are not naturally so acid or alkaline."

Lloyd (1968) summarized the conclusions of the European Inland Fisheries Advisory Commission, Food and Agricultural Organization of the United Nations, with the statement:

> "There is no definite pH range within which a fishery is unharmed and outside which it is damaged, but rather there is a gradual deterioration as the pH values are further removed from the normal range. The pH range which is not directly lethal to fish is 5–9; however, the toxicity of several common pollutants is markedly affected by pH changes within this range; and increasing acidity or alkalinity may make these poisons more toxic. Also, an acid discharge may liberate sufficient carbon dioxide from bicarbonate in the water either to be directly toxic, or to cause the pH range 5–6 to become lethal.
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> "Below a pH value of 5.0 fish mortalities may be expected, although some species may become acclimated to values as low as 3.7. However, the productivity of the aquatic ecosystem is considerably reduced below a pH value of 5.0, so that the yield from a fishery would also become less. Some acid waters may contain precipitated ferric hydroxide which may also act as a lethal factor."

The National Technical Advisory Committee (Anon., 1968) recommended for fish and other aquatic life that:

(1) No highly dissociated materials should be added in quantities sufficient to lower the pH below 6.0 or to raise the pH above 9.0.

(2) To protect the carbonate system and thus the productivity of the water, acid should not be added in sufficient quantity to lower the total alkalinity to less than 20 mg/l.

(3) The addition of weakly dissociated acids and alkalies should be regulated in terms of their own toxicities as established by bioassay procedures.

Neel et al. (1961), in studying raw-sewage stabilization ponds, found that pH values above 8.0 are produced by a photosynthetic rate that demands more carbon dioxide than the quantities furnished by respiration and decomposition; pH levels below 8.0 indicate failure of photosynthesis to utilize completely the amounts of carbon dioxide so produced. "In general practice, pH values above 8.0 are assumed to denote the presence of carbonate; a level of 8.0 indicates bicarbonate alone; and values below 8.0 show the occurrence of free carbon dioxide. Carbon dioxide, usually produced by decomposition and respiration, will react with any carbonate present to form bicarbonate and water. Photosynthesis by aquatic plants utilizes carbon dioxide, removing it from bicarbonate and producing carbonate when no free CO_2 exists. Carbonates of calcium and magnesium are but weakly soluble and quantities of them leave solution. Decomposition and/or respiration thus tends to reduce pH and increase bicarbonates, whereas the tendency of photosynthesis is to raise pH and reduce bicarbonate" (Neel et al., 1963).

Light

Rooted, suspended, and floating aquatic plants require light for photosynthesis. Light penetration into waters is exceedingly variable in different lakes. Clarke (1939) pointed out that the diminution of the intensity of light in its passage through water follows a definite mathematical formula. The relationship between the depth of water and the amount of light penetrating to that depth can be plotted as a straight line on semilogarithmic paper. Even the clearest waters impede the passage of light to some extent; light passed through 100 meters of distilled water is reduced to 1 or 2 percent of its incident value.

The principal factors affecting the depth of light penetration in natural waters include suspended microscopic plants and animals, suspended mineral particles such as mineral silt, stains that impart a color, detergent foams, dense mats of floating and suspended debris or a combination of these. The region in which light intensity is adequate for photosynthesis is often referred to as the trophogenic zone, the layer that encompasses 99 percent of the incident light. The depth of the trophogenic zone may vary from less than 5 to greater than 90 feet.

The length of daylight in water varies inversely with the depth of the water. The seasonal variation in the intensity of solar radiation influences the potential rate of photosynthesis. In winter the presence of ice with an over layer of snow further limits the amount of relatively poor incident light energy that reaches the water. The work of Birge, reported by Neess and Bunge (1957), indicates that the absorptive quality of clear ice is very similar to that of water, although the addition of air bubbles or particulate matter reduces the transmission of light. Snow further reduces light penetration through ice. Greenbank (1945) found 84 percent light transmission through 7½ inches of very clear ice, and 22 percent through 7½ inches of very cloudy ice. A 1-inch snow cover permitted only 7 percent light transmission through the ice and snow; 2 inches of snow permitted only 1 percent light transmission. Bartsch and Allum (1957), studying sewage stabilization ponds, found that in the absence of snow 20 to 55 percent of the incident light passed through 10 to 12 inches of ice, whereas, with a 1- to 3- inch snow cover 93 to 99 percent of the incident light was absorbed by ice and snow, when the ice was 1 to 2 feet thick. Mackenthun and McNabb (1961) found less than 1 percent of light passing through 16 inches of ice covered by 2 inches of snow.

Beeton (1958) made 57 paired photometer and Secchi disc measurements at 18 stations in Saginaw Bay in Lake Huron. He found that the average percentage transmission of surface light intensity, at the Secchi disc depth, was 14.7 percent. Verduin (1956) made simultaneous determinations with the Secchi disc and submarine photometer during August, 1955, on Lake Erie. The Secchi disc readings in meters were plotted against the depth associated with 1 percent of the surface light. A line drawn by inspection through the scatter diagram, suggests that an approximate estimation of the depth of the euphotic zone can be obtained by multiplying the Secchi disc readings by 5. Riley (1941) used a factor of 3. Verduin (1956) computed a factor of 2.5 using the data of Bursche (1955). Rawson (1950) listed a factor of 4.3 for a Secchi disc reading of about 1 meter.

Tyler (1968), after extensive experimentation, concluded that Secchi disc readings could be used to plot the depth of the euphotic zone for a particular body of water provided that calibrations had been made against a photometer for that particular water. Tyler further concluded that if modern instruments were available for measuring precise light penetration, that it would probably be better not to undertake such a calibration.

The maximum Secchi disc reading reported for Lake Tahoe, California-Nevada, was 136 feet at one station on April 4, 1962 (McGauhey et al., 1963). A minimum Secchi disc reading of 49 feet was recorded in Emerald Bay of Lake Tahoe on May 21, 1962. In contrast, the Secchi disc disappeared in 3 feet in Lake Sebasticook, Maine, during a July, 1965, study. In areas with less dense algal growths, the readings were increased to 8 feet. Beeton (1965) records the average Secchi disc depth for Lake Superior as 32.5 feet; Lake Michigan, 19.6 feet; and Lake Erie, 14.6 feet.

Flow

The velocity of water movement is extremely important to aquatic organisms in a number of ways including the transport of nutrients and organic food past those organisms attached to stationary surfaces; the transport of plankton and benthos as drift, which in turn serve as food for higher organisms; and the addition of oxygen to the water through surface aeration. Silts are moved downstream and sediments may be transported as bed load. These in turn are often associated with major nutrients, such as nitrogen and phosphorus, which may be released at some point downstream from their introduction.

The determination of flow is necessary to compute pounds of materials passing a given point. Computations are often made on pounds of nitrogen, phosphorus, or other elements of concern, on amounts of plankton and benthos as drift, on amounts of pollutants, such as wool, fibers, or other microscopical identifiable materials that may be associated with a point source.

Flow determines those species of stream bed organisms that may be present in a particular stream reach. Some of these, such as the black fly larva, require fast water. Others, such as the immature forms of caddisflies and mayflies, will develop to large populations in more sluggish water. Among many invertebrate genera there are those particular species that are adapted for life not only under the two extremes of flow but also under its many variations.

Silt

The deposition of sediments in streams can and often does destroy insect and mussel populations. Ellis (1931), in studying the Mississippi, Tennessee, and Ohio Rivers, reported that erosion silts had destroyed a large portion of the mussel population in various streams by directly smothering the animals in localities where a thick deposit of mud was formed, and by smothering young mussels even where the adults could maintain themselves. Ziebell (1957) reported a marked reduction in organisms 100 yards downstream from the discharge of a gravel washing operation entering the South Fork Chehalis River in Washington. Ziebell and Knox (1957) investigated the effects of yet another gravel washing operation on the Wynooche River in Washington. The results of bottom samples collected downstream from the operation revealed reductions of 75 to 85 percent at distances exceeding 1 mile. Silt from a gravel washing plant located on Cold Creek and the Truckee River, Calif. reduced bottom organisms over 75 percent for a distance of more than 10 miles downstream (Cordone and Pennoyer, 1960). Reports published by the Oregon State Game Commission summarized the results of extensive collections of bottom organisms upstream and downstream from gold dredge operations on the Powder River (Anon., 1955). During siltation, production of fish food organisms decreased to nearly zero in the zone of heaviest pollution and the effect of siltation extended for a distance of 20 miles. In about 1 year after the dredge closed operations, the silt was flushed from the pools and riffles by freshets and bottom organisms increased 8 to 10 fold in weight per unit of bottom area.

Few data are available regarding the direct harm of sediments to fish. In most cases indirect damage to the fish population through destruction of the food supply, eggs, or changes in the habitat probably occur long before adult fish are harmed directly. Ellis (1944) stated that particulate matter of a hardness greater than one, if held in suspension by current action or otherwise, will injure the gills and other delicate exposed structures of fishes, mollusks, and insects when the particles are large enough. Kemp (1949) stated that mud or silt in suspension will clog or cut the gills of many fish and mollusks, and he considered 3,000 p.p.m. dangerous when maintained for a period of 10 days. Wallen (1951) conducted controlled aquarium investigations on the direct effects of turbidity on warm water fishes; he found that observable behavioral reactions that appeared as a turbidity effect did not develop until concentrations of turbidity neared 20,000 p.p.m. and in one species reactions did not appear until turbidities reached 100,000 parts per million (p.p.m.).

The effects of silt upon fish eggs and the developing fry has received greater attention. Stuart (1953) concluded that silt is not very dangerous in the normal streams if excess occurs only at intervals; however, the character of such normal streams can be drastically altered by allowing the washings of quarries, gravel pits, and mines to flow into the streams untreated. In many cases the quantities allowed to enter the stream may be small and the materials in suspension may in itself be of a nontoxic character, but continous application of small quantities over the reeds may by much more detrimental to the welfare of very young fish than sudden flushes of large quantities. Others who have noted the detrimental effects of silt upon the eggs and developing fry of fish include Campbell (1954), Snyder (1959), and Shapovalov and Berrian (1940). Shapovalov and Taft (1954) in discussing mining silt concluded that from a practical standpoint the damage to spawning beds would occur when mining silt enters a stream at times other than storm periods when the water velocity is insufficient to carry the sediment in suspension.

Turbidity reduces the enjoyment of fishing and may limit fishing success. This effect has been determined in expressable data for Fork Lake in Illinois where it was found that the fish caught per man-hour decreased from 6.53 to 2.04 when the transparency in feet as measured by the Secchi disc was likewise reduced from an average of 4.0 to 1.3 (Bennett, Thompson, and Parr, 1940).

Buck (1956) in a study of 39 farm ponds, rotenoned and then stocked with largemouth bass and bluegill or largemouth bass and redear sunfish were classified into clear ponds-turbidities less than 25 p.p.m., intermediate ponds-turbidities from 25 to 100 p.p.m., and muddy ponds-turbidities in excess of 100 p.p.m. At the end of two seasons, the average total weight of all fish in clear ponds was about 1.7 times greater than in intermediate ponds and 5.5 times greater than in muddy ponds. Largemouth bass were harmed the most by turbidity in both growth and reproduction. Average volume of net plankton in surface waters of clear ponds was 8 times greater than in intermediate ponds and 12.8 times greater than in muddy ponds.

Sediment is believed to destroy algae by molar action, by simply covering the bottom of the stream with a blanket of silt, or by shutting off the light needed for photosynthesis. Tarzwell and Gaufin (1953) found that turbid waters may transport the byproducts of bacterial action on organic wastes and the effluent of sewage treatment plants considerable distances before they are utilized. When water clears as a result of impoundment so that phytoplankton can grow, fertilizing materials are utilized and may produce troublesome blooms far from the source of pollution. Corfitzen (1939) found that the greatest loss in light intensity was due to light absorption by silt with some additional loss by reflection and refraction.

Attached algae and vegetation are affected by silt principally by: (1) Covering bottom materials with a layer of sediment, (2) reducing light transparency and preventing light penetration, and (3) grinding algae by action of abrasive particles. A reduction of plant food is accompanied by a reduction in the poundage of plant feeding animals that can be supported, and this in turn limits the production of carnivorous animals including fish.

The European Inland Fisheries Advisory Commission, Food and Agricultural Organization of the United Nations, prepared water quality criteria on finely divided solids (Anon., 1965). With respect to chemically inert solids and to waters that are otherwise satisfactory for the maintenance of freshwater fishes they made the following conclusions:

> "(a) There is no evidence that concentrations of suspended solids less than 25 p.p.m. have any harmful effects on fisheries.
>
> (b) It should usually be possible to maintain good or moderate fisheries in waters which normally contain 25 to 80 p.p.m. suspended solids. Other factors being equal, however, the yield of fish from such waters might be somewhat lower than from those in category (a).
>
> (c) Waters normally containing from 80 to 400 p.p.m. suspended solids are unlikely to support good freshwater fisheries, although fisheries may sometimes be found at the lower concentrations within this range.
>
> (d) At the best, only poor fisheries are likely to be found in waters which normally contain more than 400 p.p.m. suspended solids."

"In addition although several thousand p.p.m. solids may not kill fish during several hours or days exposure, such temporary high concentrations should be prevented in rivers where good fisheries are to be maintained. The spawning grounds of salmon and trout require special consideration and should be kept as free as possible from finely divided solids."

Oil

McKee (1956) in summarizing the effects of oil substances on aquatic life in freshwater, stated that:

"(1) free oil and emulsions may coat and destroy algae and other plankton;

(2) heavy coatings of free oil on the surface may interfere with the natural processes of reaeration and photosynthesis, while light coatings would be less detrimental because wave action and other turbulence would maintain adequate reaeration; and

(3) water soluble principles may exert a direct toxic action."

The deleterious effect of crude oil and lubricating oils on fish is due to a film formed over the gill filaments of fish, which prevents the exchange of gasses and results in suffocation (Klinke, 1962).

The effects of oils on marine animals may include the tainting of fish and shellfish flesh, poisoning by ingestion of oil or soluble fractions, such as phenol, ammonia, and sulfides, disturbances of marine food chains, physical fouling of animals with heavy coats of oil, and repellent effects (Hawkes, 1961).

Many thousands of waterfowl have been destroyed by the effects of oil pollution. This wasteful loss has deprived nature lovers, waterfowl hunters, and bird watchers of immeasurable enjoyment. The destruction of many duck species, such as the canvasback, redhead, and scaups, comes at a critical period for these species that are fighting for survival against the forces of nature. In future years additional waterfowl will be destroyed if oil dumping is continued, especially in late winter. In this modern age of technical development, the discharge of oil into a river system indicates man's lack of responsibility for the preservation of our natural resources.

Erickson (1965) pointed out that the effects of oil on birds depend upon a variety of factors including the type of oil, extent of contamination of plumage, temperature of the air and water, and the quantity of oil ingested. He found that migratory birds are affected indirectly by deposits of oil on the bottom, in shallow water, or along the shore that reduces the available food supply of both plants and animals. Elements within the food chain are eliminated by chemical or physical properties of the oils and food for waterfowl may become unavailable by being overlayed or embedded in the oily materials. Accumulation of petroleum sludge may also prevent germination and growth of plants and the production of invertebrates important as food, either by smothering or by toxic effects.

Oil causes matting of the duck feathers so that ducks become waterlogged, lose their ability to fly and drown if they cannot get out of the water soon enough. It breaks down the insulating power of the feathers; body heat and stored reserves of energy are rapidly lost. Diving ducks may starve, and, following the preening of oil from contaminated feathers, bleeding ulcers may be produced in the digestive tract causing mortality.

Major Nutrients

Eutrophication is a term meaning enrichment of waters by nutrients through either man-created or natural means. Present knowledge indicates that the fertilizing elements most responsible for lake eutrophication are phosphorus and nitrogen. Iron and certain "trace" elements are also important. Sewage and sewage effluents contain a generous amount of those nutrients necessary for algal development.

Lake eutrophication results in an increase in algal and weed nuisances and an increase in midge larvae, whose adult stage has plagued man in Clear Lake, Calif., Lake Winnebago, Wis., and several lakes in Florida. Dense algal growths form surface water scums and algal-littered beaches. Water may become foul-smelling. Filter-clogging problems at municipal water installations can result from abundant suspended algae. When algal cells die, oxygen is used in decomposition, and fish kills have resulted. Rapid decomposition of dense algal scums, with associated organisms and debris, gives rise to odors and hydrogen sulfide gas that creates strong citizen disapproval; the gas often stains the white lead paint on residences adjacent to the shore.

Nitrogen and phosphorus are necessary components of an environment in which excessive aquatic growths arise. Algal growth is influenced by many varied factors: vitamins, trace metals, hormones, auxins, extracellular metabolites, autointoxicants, viruses and predation and grazing by aquatic animals. Several vitamins in small quantities are requisite to growth in certain species of algae. In a freshwater environment, algal requirements are met by vitamins supplied in soil runoff, lake and stream bed sediments, solutes in the water, and metabolites produced by actinomycetes, fungi, bacteria, and several algae.

Evidence indicates that: (1) High phosphorus concentrations are associated with accelerated eutrophication of waters, when other growth promoting factors are present; (2) aquatic plant problems develop in reservoirs or other standing waters at phosphorus values lower than those critical in flowing streams; (3) reservoirs and other standing waters collect phosphates from influent streams and store a portion of these within consolidated sediments; and (4) phosphorus concentrations critical to noxious plant growths vary, and they produce such growths in one geographical area, but not in another. Potential contributions of phosphorus to the aquatic environment have been indicated in the literature (table 2).

Keup (1968) in flowing water studies found that phosphorus is temporarily stored in bottom sediments or transported as a portion of the stream's bed-load after its removal from the flowing water. Long-term storage is affected when the phosphorus is pooled in deltas or deposited on flood plains. Keup reviewed the literature on phosphorus discharges by specific streams (table 3).

Once nutrients are combined within the ecosystem of the receiving waters, their removal is tedious and expensive; removal must be compared to inflowing quantities to evaluate accomplishment. In a lake, reservoir, or pond, phosphorus is removed naturally only by outflow, by insects that hatch and fly out of the drainage basin, by harvesting a crop, such as fish, and by combination with consolidated bottom sediments. Even should adequate harvesting methods be available, the expected standing crop of algae per acre exceeds 2 tons and contains only about 1.5 lbs of phosphorus. Similarly, submerged aquatic plants could approach at least 7 tons/acre (wet weight) and contain 3.2 lbs/acre of phosphorus. Probably only half of the standing crop of submerged aquatic plants can be considered harvestable. The harvestable fish population (500 lbs.) from 3 acres of water would contain only 1 lb. of phosphorus.

Dredging has often been suggested as a means of removing the storehouse of nutrients contained within the lake bed sediments. These sediments are usually rich in nitrogen and phosphorus, for they represent the accumulation of years of settled organic materials. Some of these nutrients are recirculated within the water mass and furnish food for a new crop of organic growth.

Hasler (1957) found that, in an undisturbed mud-water system, the percentage of nutrients, as well as the amount of phosphorus that is released to the superimposed water, is very small. In laboratory experiments, when P^{32} is placed at various depths in the mud, the diffusion into the overlying noncirculating water is negligible, if the phosphorus is

Table 2. Pounds of Phosphorus Contributed to Aquatic Ecosystems

Major Contributors:

Sewage and Sewage Effluents: 3 lbs. per capita per year.*
Some industries, e.g., potato processing: 1.7 lb. per ton processed.
Phosphate rock from 23 States (Mackenthun and Ingram, 1967).
Cultivated agricultural drainage: 0.35–0.39 lb. per acre drained per year (Engelbrecht and Morgan, 1961) (Sawyer ,1947) (Weibel, 1965).
Surface irrigation returns, Yakima River Basin: 0.9–3.9 lbs. per acre per year (Sylvester, 1961).
Benthic Sediment Releases.

Minor Contributors:

Domestic duck: 0.9 lb. per year (Sanderson, 1953).
Sawdust: 0.9 lb. per ton (Donahue, 1961).
Rainwater.**
Groundwater, Wis.: 1 lb. per 9 million gals. (Juday and Birge, 1931).
Wild duck: 0.45 lb. per year (Paloumpis and Starrett, 1960).
Tree leaves: 1.8–3.3 lb. per acre of trees per year (Chandler, 1943).
Dead Organisms; animal excretions.

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*Various researchers have recorded the annual per capita contribution of phosphorus in pounds from domestic sewage as 2 to 4 (Bush & Mulford, 1954), 2, 3 (Mentzler et al., 1958), 1.9 (Owen, 1953), and 3.5 (Sawyer, 1965).

**Influenced by pollution present in atmosphere "washed out" by rainfall.

Table 3. Phosphorus Discharged by Selected North American Streams (from Keup, 1968)

Principal land use	River	Number of analyses	Season of sampling	Drainage area (mile^2)	P—P (lb/annum/ mile^2)	Population density mile^2	Reference *
Forested	West Branch Sturgeon R, Mich	27+	July	14	37	Sparse	A.
	Pigeon, Minn	4	Aug. and Sept	600	28	Sparse	B, C, D.
	Poplar, Minn	4	Aug. and Sept	114	21	Sparse	B, C, D.
	Baptism, Minn	4	Aug. and Sept	140	42	Sparse	B, C, D.
	St. Louis, Minn	4	Aug. and Sept	3430	58	Sparse	B, C, D.
	Bois Brule, Wis	4	Aug. and Sept	113	97	Sparse	B, C, D.
	Bad, Wis	4	Aug. and Sept	611	78	Sparse	B, C, D.
	Montreal, Wis	4	Aug. and Sept	281	98	Sparse	B, C, D.
	Black, Mich	4	Aug. and Sept	202	65	Sparse	B, C, D.
	Presque Isle, Mich	4	Aug. and Sept	260	39	Sparse	B, C, D.
	Ontonagon, Mich	4	Aug. and Sept	1290	44	Sparce	B, C, D.
	Yakima, Wash	?	Annual	182	473	Sparse	E.
	Tieton, Wash	?	7 months	237	492	Sparse	E.
	Cedar, Wash	?	Annual	125	204	Sparse	E.
	Mulligan, Maine	12	4 seasons	21	4	Sparse	F.
	Stetson, Maine	19	4 seasons	29	20	Sparse	F.
	East Branch Sebasticook, Maine	56	4 seasons	56	128†	> 63‡	F.
Agricultural	Ellerslie, Prince Edward Island	≈44	April-Dec	10	113	Sparse	G.
	Pigeon, N. C	18	July	133	97	Light	This article.
	Johnathans, N. C	5	July	65	201	Light	This article.
	Kankakee, Ind. and Ill	6	June-Sept	5280	139	28	H, I.
	Vermillion, Ill	8	June-Sept	1230	179	36	H, I.
	Fox, Ill. and Wis	7	June-Sept	2570	489	145	H, I.
	Kaskaskia, Ill	100	April-Dec	5220	225	>174‡	J.
	Streams near Madison, Wis	?	?	?	235-262	?	K.
Urban	Du Page, Ill	5	June-Sept	325	18	380	H, I.
	Des Plaines, Ill. and Wis						
	Above confluence with Chicago River	5	June-Sept	635	570	1270	H, I.
	Total basin (includes Chicago River)	19	June-Sept	2180	4020	2570	H, I.
	Chicago, Ill	16	June-Sept	810	6540	5650	H, I.

*Data given, or computed from data in the refernces. A. Ball and Hooper (1963), B. Putnam and Olson (1959), C. Putnam and Olson (1960), D. Anon. (1964), E. Sylvester (1961), F. Anon. (1966), G. Smith (1959), H. Hurwitz, et al. (1965), I. Anon. (1963), J. Engelbrecht and Morgan (1961), K. Sawyer (1947).

†One seasonal (9 months) industry contributes approximately 75 per cent. ‡Only sewered population known.

placed more than 1 c.m. in the mud. Application of lime to the water or mud reduces the amount of soluble phosphorus released. Acidification of previously alkalized mud will, upon agitation, increase the amount of phosphorus entering solution. In an aquarium experiment, circulation of the water above phosphorus-rich mud, with the aid of air bubbles, increased the phosphorus in solution.

Zicker et al. (1956) found in laboratory experiments that the percentage of phosphorus released to water from radioactive superphosphate fertilizer placed in an undisturbed mud-water system was very small, with virtually no release of phosphorus from fertilizer placed at depths greater than ¼ inch below the mud surface. Radiophosphorus placed ½ inch below the mud surface showed only a very slight tendency to diffuse into the water, while the radiophosphorus placed at a 1-inch depth did not diffuse into the water at all.

Dredging deepens an area within a lake and can be beneficial if the increased depth is sufficient to prevent growth of larger nuisance plants. Dredging uncovers yet another soil strata that will contain phosphorus in some quantity, subject to solution in water. The newly dredged area immediately begins to receive organic fallout from waters above, and forms a new interface at which nutrient exchange is substantial. Sediments disturbed during a dredging operation liberate nutrients at a rate more rapid than sediments left undisturbed and all of these factors must be considered when recommending dredging for nutrient removal. Based entirely on nutrient considerations, dredging can be advantageous only when it removes sediments that contain a higher concentration of nutrients than the interface likely to be formed by fallout.

The total supply of an available nutrient depends on the total volume of water, as well as the concentration of the element in the water. Gerloff and Skoog (1957) in laboratory investigations determined that 5 units of nitrogen plus 0.08 unit of phosphorus (a ratio of 60:1) would produce 100 units of algae. The N–P ratio, as it naturally occurs in algae and submerged plants, is more nearly 10:1. Allen (1955) found that to obtain any appreciable increase it was necessary to supplement the sewage with nitrogen as well as carbon.

Sawyer (1947) studied the southeastern Wisconsin lakes and concluded that a 0.30 mg/l concentration of inorganic nitrogen (N) and a 0.01 mg/l concentration of soluble phosphorus (P) at the start of the active growing season could produce nuisance algal blooms. Nitrogen appears to be the more critical factor limiting algal production in natural waters (Gerloff and Skoog, 1957), since phosphorus is stored in plankton as excess and may exceed the actual need.

Sawyer (1954) discussed factors that influence the development of nuisance algal growths in lakes. The surface area is important since the accumulations of algae along the shoreline of a large lake under a given set of wind conditions could easily be much larger than on a small lake.

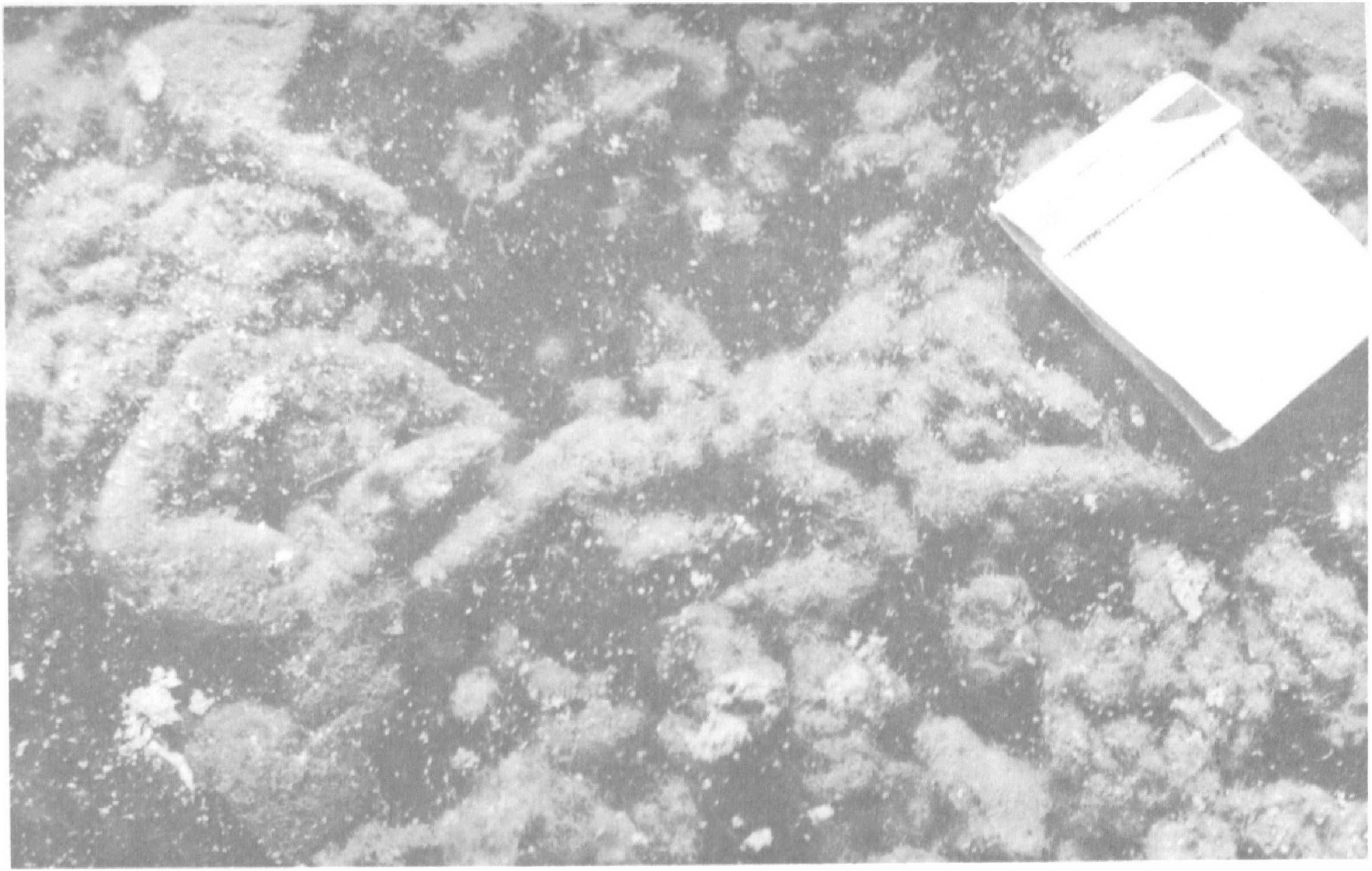

Figure 9. A Blue-green Algal Nuisance

under equal fertilization per acre. The shape of the lake determines to some degree the amount of fertilizing matter the lake can assimilate without algal nuisances since prevailing winds blowing along a long axis will concentrate the algal production from a large water mass into a relatively small area. The most offensive conditions develop during periods of very mild breezes that tend to skim the floating algae and push them toward shore. Shallow lakes, too, respond differently from deep stratified lakes in which the deeper waters are sealed off by a thermocline. In the nonstratified waters all the nutrients dissolved in the water are potentially available to support an algal bloom. In stratified waters, only the nutrients confined to the epilimnion are available except during those brief periods when complete circulation occurs.

Lund (1965) in his thorough literature review stated that "Nitrogen and phosphorus can still be considered as two of the major elements limiting primary production. In some tropical and highly eutrophic temperate lakes, nitrogen may be a more important limiting factor than phosphorus. In many other lakes phosphorus is present in very low concentrations and seems to be the major factor limiting production. Evidence from the addition of fertilizers to fish ponds and from what is known about the eutrophication of lakes by sewage supports the view that phosphorus plays a major role in production."

Chu (1943) found that optimum growth of all organisms studied in cultures can be obtained in nitrate-nitrogen concentrations from 0.9 to 3.5 mg/l and phosphorus concentrations from 0.09 to 1.8 mg/l, while a limiting effect on all organisms will occur in nitrogen concentrations from 0.1 mg/l downward and in phosphorus concentrations from 0.009 mg/l downward. The lower limit of optimum range of phosphorus concentration varies from about 0.018 to about 0.09 mg/l; and the upper limit from 8.9 to 17.8 mg/l when nitrate is the cource of nitrogen, while it lies at about 17.8 for all the planktons studied when ammonium is the source of nitrogen. Low phosphorus concentrations may, therefore, like low nitrogen concentrations, exert a selective limiting influence on a phytoplankton population. The nitrogen concentration determines to a large extent the amount of chlorophyll formed. Nitrogen concentrations beyond the optimum range inhibit the formation of chlorophyll in green algae.

Experiments by Ketchum (1939) with the diatom *Phaeodactylum*, showed a reduction in rate of cell division when phosphate present in the medium is less than 17 micrograms per liter (μg/l) P. Strickland (1965) stated that the limiting phosphorus concentration in some cultures has been found to be less than 5 μg/l. The problem is complicated because auxiliary compounds may affect the availability of phosphate to a plant cell. Sylvester (1961) found that nuisance algal blooms were observed in Seattle's Green Lake (a very soft-water lake) when nitrate nitrogen (N) levels were generally above 200 μg/l and soluble phosphorus (P) was greater than 10 μg/l.

Müller (1953) concluded that excessive growths of plants and algae in polluted waters can be avoided if the concentration of nitrate nitrogen is kept below about 0.3 mg/l and the concentration of total nitrogen is not allowed to rise much above 0.6 mg/l.

The question is sometimes asked, how much algae can be grown from a given amount of phosphorus? Allen (1955) found that the maximum that could be grown in the laboratory on sewage was 1 to 2 g/l (dry weight) and in the field in sewage oxidation ponds the maximum was 0.5 g/l. Thus, assuming optimum growth conditions and maximum phosphate utilization, the maximum algal crop that could be grown from 1 pound of phosphorus would be 1,000 pounds of wet algae under laboratory conditions or 250 pounds of wet algae under field conditions. Considering a phosphorus (P) content of 0.7 percent, 1 pound of phosphorus could be distributed among 1,450 pounds of algae on a wet weight basis.

A considered judgment suggests that to prevent biological nuisances, total phosphorus should not exceed 100 μg/l P at any point within the flowing stream, nor should 50 μg/l be exceeded where waters enter a lake, reservoir, or other standing water body. Those waters now containing less phosphorus should not be degraded (Mackenthun, 1968). Adequate phosphorus controls must now be directed toward treatment of nutrient point sources and to wastewater diversion around the lake or dilution within the lake, where feasible.

Micronutrients

It is generally conceded that abundant major nutrients in the form of available nitrogen and phosphorus are an important and a necessary component of an environment in which excessive aquatic growths arise. Algae, however, are influenced by many and varied factors. Vitamins, trace metals, hormones and auxins, extracellular metabolites, autointoxicants, viruses, and predation and grazing by aquatic animals are factors that stimulate or reduce algal growths. Some of these may be of equal importance to the major nutrients in influencing nuisance algal bloom production.

Harder, in 1917, is credited with first connecting growth inhibiting substances with algae. As early as 1931, autoinhibiting substances were recognized (Akehurst, 1931). These papers gave rise to a common belief that a plant can create its self-destruction through the production of growth inhibiting substances that it cannot tolerate but which may, in turn, stimulate other growths. Natural waters contain these active agents that are secreted and excreted by freshwater algae. The toxicity of these agents to other algae and bacteria and to fish varies constantly and is not well understood in the natural aquatic environment. It has been postulated that algae secrete not just one substance but several, some antibiotic, others stimulating. The amount secreted and the net result of the secretions would be determined by the prevelence of one group of substances over the other. Thus, sequences of algal blooms may be expected to occur under conditions of a nutrient supply far in excess of critical values.

In man's quest to reduce major nutrients enriching waters, such as nitrogen and phosphorus, and thereby restore such waters to a greater water use potential without attendant algal pests, other algal population-influencing factors will have a role in the ultimate success of the restoration efforts. This role is presently neither clearly defined nor understood. It does seem clear that the constant progression of the geologic clock cannot be substantially altered. Despite man's most ardent dreams, lakes now fertile and abundantly productive of algae will never again attain their crystal-clear, pristine appearance so well imprinted in the minds of long-time local residents. The old-swimmin-hole lingers on in local folklore. Recently defiled waters can be improved substantially, however, by reducing or removing the varying causes of algal productivity. By placing all known algal population influencing factors in their proper perspective and by intensifying investigative efforts directed towards the interrelationships of factors most likely to effect population controls, knowledge and nuisance reducing efforts will be enhanced. Lakes, reservoirs, ponds, flowing streams, estuaries, and bays will be improved, and the using public will be benefited.

Eyster (1964) divided the elements required by green plants into macronutrients and micronutrients. Macronutrients include carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, potassium, magnesium, calcium (except for algae where it is a micronutrient), and sodium. Micronutrients include iron, manganese, copper, zinc, molybdenum, vanadium, boron, chlorine, cobalt, and silicon.

Manganese is one of the key elements in photosynthesis and manganese-deficient cells have a reduced level of photosynthesis and a reduction in chlorophyll. Iron is associated with nitrogen metabolism. Arnon (1958) confirmed that chloride is a coenzyme of photosynthesis specifically concerned with oxygen evolution. Vanadium and zinc appear to be involved in photosynthesis. Calcium and boron are involved in nitrogen fixation. Molybdenum is necessary for nitrate utilization and nitrogen fixation. Cobalt is associated with the nutritional functions of vitamin B_{12}.

Fitzgerald (1964) discussed the sequences of algal blooms that occur under conditions of nutrient supply in sewage stabilization ponds far in excess of those found in natural lakes. He also reviews some of the factors other than nutrition that might influence the algal population. These factors include grazing and the production of inhibiting extracellular products. It is pointed out that there is evidence that an inverse relationship frequently exists between the density of phytoplankton and zooplankton. This might be the result of over-grazing in specific areas and a lack of grazing in adjoining areas or it may be due to an "exclusion" effect on zooplankton produces by extracellular plant metabolites. Gibor (1957) has shown evidence that algae can at times pass through the zooplankton without being affected by digestive processes.

In situations where the algae are so abundant that their control may be required by chemical means, it appears that animal predation or attacks by micro-organisms are not enough to cause a shift in the dominant species. Once the dominant species is eliminated, however, other species increase in numbers and become dominant. Factors thought to contribute to species dominance include secreted or excreted inhibiting extracellular products (Rice, 1954).

Léfevre (1964) stated that when an algal species develops extensively in standing waters causing waterblooms, it eventually becomes intoxicated by its own accumulated excretion products and dies. When the water is renewed slowly, this phenomenon does not occur because the extracellular products are constantly removed. Also, when one species of algae predominates in standing water, other species appear only sporadically and the number of bacterial species decreases. Léfevre et al. (1952) suggested that this phenomenon is due to antagonistic substances produced by the prodominant species. Léfevre (1964) stated that the production of extracellular active agents is conditioned by: (1) Nature of strain; (2) composition of culture medium; (3) nature and size of inoculum; (4) temperature; (5) illumination; (6) agitation of medium; (7)duration of culture; and (8) season of the year.

Of 154 algal species, 56 require no vitamins and 98 species require vitamin B_{12}, thiamin and biotin, alone or in various combination (Provasoli, 1961). Those blue-green algae not requiring B_{12} employ it readily as a cobalt source; since cobalt is generally scarse in water, even organisms not requiring B_{12} may compete for it. A great part of the vitamins in freshwaters and in the littoral zone of the sea can be assumed to come from any soil run-off especially during the spring floods. Muds are another source of vitamins. A third source is the vitamins present as solutes in water.

Vitamins are synthesized by several organisms. *Chorella* has been found to produce as much as 6.3 μg B_{12} per 100 g. of dry algae and *Anabaena* as much as 63 to 110 per 100 g. of dry algae (Brown et al., 1955). Burkholder (1959) studied the production of B vitamins by 344 bacteria isolated from waters and muds from Long Island Sound and found that 27 percent of these gave off vitamins B_{12}, 50 percent gave off biotin, 60 percent thiamine, and 11 percent nicotinic acid. Sixty-five percent of the actinomycetes studied were found by Burton and Lockhead (1951) to produce vitamin B_{12}. Robbins et al. (1950) reported that fungi and many bacteria, isolated from the water and mud of a pond in which *Euglena* blooms, produces B_{12}; they demonstrated also that these bacteria, grown with *Euglena* on agar plates of a medium deprived of B_{12}, diffused sufficient vitamin to support growths of *Euglena*. And Robbins and Kavanagh (1942) stated that the ability of a fungus to synthesize vitamins essential for their metabolic processes may be complete, incomplete, or absent.

Toxic Substances

Many pesticides and heavy metals are toxic to aquatic life in low concentrations. Many studies have related these toxicities to specific organisms and to specific dilution waters. The toxicity of a particular substance is dependent to a large extent on other water quality characteristics associated with the toxicant, such as temperature, pH, alkalinity, etc. The National Technical Advisory Committee (Anon., 1968) presented criteria for many of these elements and compounds based upon the present state of the art. In many instances it is necessary to determine through bioassay the toxicity to fish or other aquatic organisms by testing the particular effluent discharged with the particular water quality that receives the discharge.