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BIOLOGICAL EFFECTS OF ARTIFICIAL DESTRATIFICATION AND AERATION IN LAKES AND RESERVOIRS - ANALYSIS AND BIBLIOGRAPHY

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16. ABSTRACT

The state of the art of research concerning the biological effects of reaeration and destratification is described, with emphasis on lakes and reservoirs. Research needs are discussed, based on this review. Useful descriptions of methods and devices for reaeration and destratification and a comprehensive annotated bibliography of 337 references are included.

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UNITED STATES DEPARTMENT OF THE INTERIOR
Rogers C. B. Morton
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Commissioner

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We thank the scientists who responded to our request for literature. We are especially indebted to Drs. Heinz Bernhardt, Arlo Fast, Kenneth Malueg, Lowell Leach, James Symons, E. A. Thomas, and Thomas Wirth. We also thank the many individuals and publishers, who granted permission to use their figures.

The report was reviewed by the Reaeration Research Program Management Team of the Bureau of Reclamation. Minor editorial revisions were made.

FOREWORD

This report was developed through a professional services agreement with the authors, under the general direction of the Reaeration Research Program Management Team, Bureau of Reclamation.

This report represents one phase of a comprehensive program of research in reaeration and control of dissolved gases. The results and conclusions of this report will be used in designing biological monitoring programs for field applications of reaeration and destratification.

CITATION

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PURPOSE

The literature survey was conducted to summarize information on the virtual and potential impact of artificial destratification and/or aeration on the ecology of natural and manmade lakes and of rivers and streams.

ARTIFICIAL DESTRATIFICATION

Reasons

The main intent in destratifying a lake is to improve the water for beneficial use. One objective is to increase the quality of water discharged into streams and rivers from manmade lakes (Symons and Robeck, 1966). These discharges augment streamflow and increase the capability of the water to further assimilate wastes. Interest also exists in using aeration and destratification techniques to pretreat water ultimately used in waterworks by reducing tastes and odors, chlorine demand, and concentration of hydrogen sulfide, manganese, and iron (Teerink and Martin, 1969). Koberg and Ford (1965) used destratification techniques to reduce evaporation from a lake. Aeration may also be used to keep waters free of ice. This strategy may reduce winterkill of fish in shallow eutrophic lakes in North America that are frozen for several months a year (Wirth, 1970). Aeration may also reduce the effects of cultural eutrophication (Malueg et al., 1971).

Methods

Some efforts at artificial destratification merely mix the water and do not destroy the thermocline. Thus, it is necessary to set out three definitions.

1. Artificial destratification disrupts the stratification of a standing water body. Density differences between water masses are decreased sufficiently, such that the prevailing meteorological forces and convection currents will keep the density of the water uniform.

2. Aeration is any process which brings oxygen into a system. Bernhardt (1967) and Fast (1971) aerated the hypolimnion of a lake without destroying the thermocline. Mercier and Perret (1949) pumped hypolimnetic water to a shore station, aerated it there, and pumped it back into the hypolimnion. The term "lake aeration" commonly means artificial destratification by compressed air (Fast, 1968).

3. Mixing is a random intermingling of components which do not lose their individual identities.

Artificial destratification will usually bring about aeration and mixing. But, aeration and mixing may be induced in unstratified bodies of water as well. There are three basic techniques used to destratify a lake.

Mechanical pumping. — Water may be simply pumped from the bottom to the top (Hopper, Ball and Tanner, 1953; Anon, 1965-1966; Ridley, Cooley and Steel, 1966; and Irwin, Symons and Robeck, 1966) or *vice versa* (Grim, 1952). Figure 1 shows a side view of the mechanical pump used by Irwin et al. (1966) to bring water from the hypolimnion to the surface. A variant on mechanical pumping is the injection of river water into an impoundment in such a way as to induce turbulent mixing (Cooley and Harris, 1954).

Injection of diffused air. — Another method involves injecting diffused air, usually from perforated pipes on the bottom in the deepest part of the lake or from a point source near the bottom at the same location (Schmitz and Hasler, 1958; Nickerson, 1961; Ford, 1963; Koberg and Ford, 1965; Irwin et al., 1966; Johnson, 1966; Fast, 1968; Haynes, 1971; Lackey, 1971, and Barnett, 1971). This technique results in immediate aeration. Since the bubbles rise from a pipe, usually linearly set out on the bottom, whole screens of bubbles are created (Figure 2). Moreover, the rising bubbles tend to lift the lower layer of water to the surface and turbulent mixing is induced.

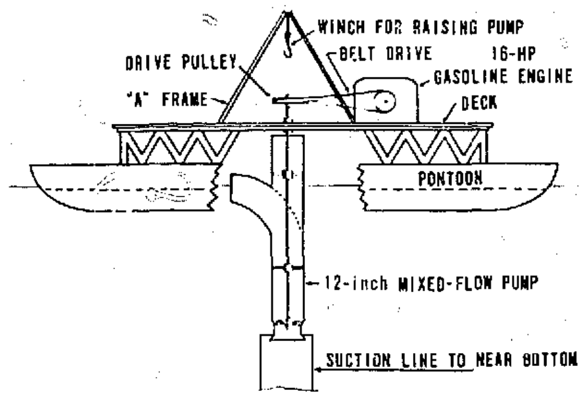

Figure 1. Design of pump, pontoon and engine of a mechanical pump used for artificial destratification by Irwin, et al. (1966). From J. Sanit. Eng. Div., Proc. ASCE 92 (SA6), p. 26. With permission of Am. Soc. Civil Engineers.

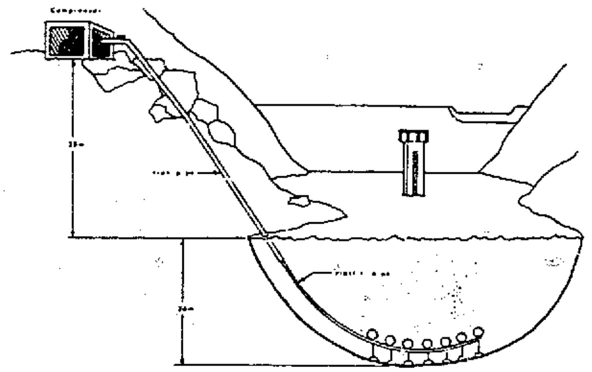

Figure 2. The diffuse air injection system at El Capitan Reservoir, California. El Capitan dam and control tower are in the background. From Fast (1968). With permission of author and editors of Fish Bulletin, California Department of Fish and Game.

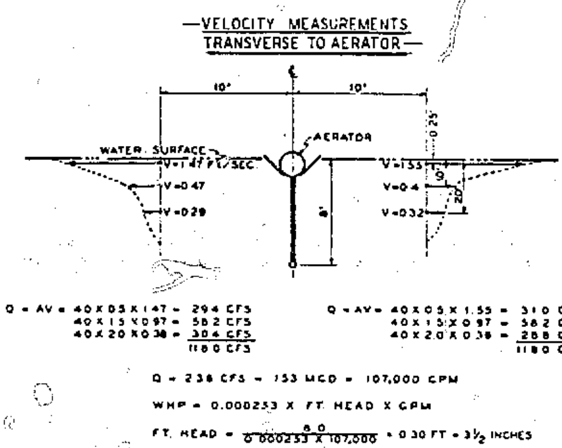

Figure 3. Side view of the floating aerator of Riddick (1957) showing velocities of upwelling water. Courtesy of Scranton Publishing Co.

Still other methods have been used to inject air into lakes. Riddick (1957) used a perforated iron pipe suspended from floats to force air into lake water at a depth of 2 m to prevent the onset of stratification and thus decrease pumping costs (Figure 3). If stratification never develops, a high resistance to mixing will not develop and an intermittent mixing will suffice to maintain destratification. Fast (1968) calls this apparatus a floating aerator. Nickerson (1961) used a blower to inject air to a 2.5-m depth. A number of workers have used diffuse air tubes (Fast, 1968) which are vertical tubes which extend from the bottom to the surface of the lake. Figure 4 shows a system used by Johnson (1966). Compressed air is introduced at the bottom. As the air rises, it entrains hypolimnetic water which is released at the surface.

Aero-Hydraulics gun. —The third technique involves the use of the Aero-Hydraulics gun (Laurie, 1961; Wirth and Dunst, 1967). This is a low-head, high volume, positive displacement pump (Figure 5). Periodically, air bubbles rise in a vertical tube to promote piston action. The rising bubble forces water above it upward out of the pipe and entrains a volume of water behind it in the vertical tube (Bryan, 1964). The bubble shatters when it reaches the top of the gun. The water "shot" from the top of the "gun" behaves as a narrow turbulent stream which entrains still further quantities of water along with it.

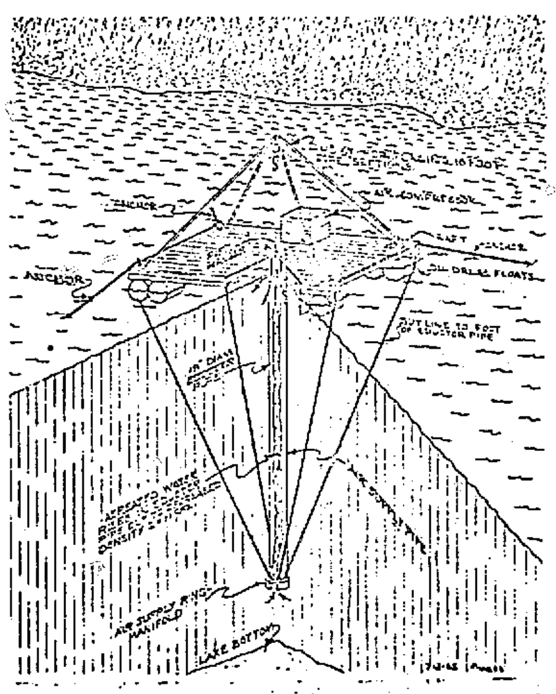

Figure 4. Aerator used at Erdman Lake by Johnson (1966). Courtesy of Washington Department of Fisheries, Olympia.

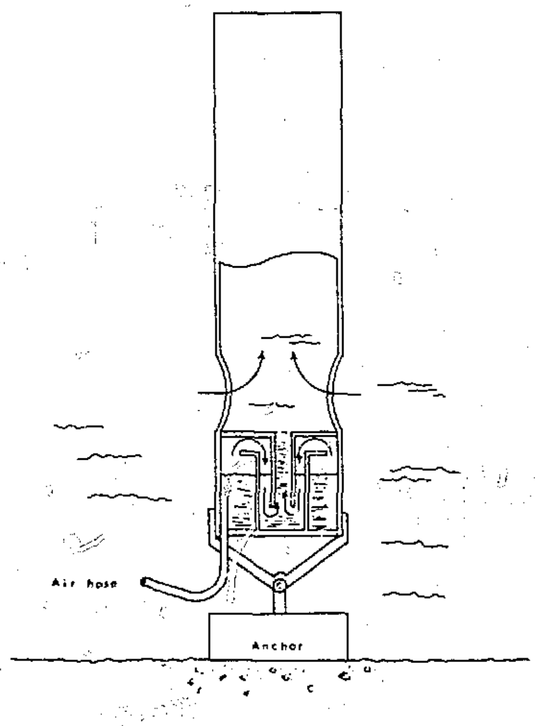

Figure 5. An Aero-Hydraulics cannon. The air chamber at the bottom of the barrel is being filled with air from a compressor on shore. From Fast (1968). With permission of author, editors of Fish Bulletin, California Department of Fish and Game and the manufacturer: Aero-Hydraulics Corporation, Lachine, Quebec, Canada.

AERATION DEVICES

It is not necessary to destratify an entire lake to achieve the desired changes in water quality in outflows from reservoirs, particularily in large reservoirs. Thackston and Speece (1966) outline the early techniques and Speece (1969 and 1970) describes recent methods.

Local Aeration of Lake

Aeration of Lake Eufuala, Oklahoma, in the vicinity of the penstocks has been shown to increase the concentration of O_2 in the water released (Leach, Duffer and Harlin, 1970).

Hypolimnetic Aeration

Speece (1971) recommends the use of a downflow bubble aerator to increase the concentration of oxygen in the hypolimnion. Bubbles of pure oxygen are diffused into a mass of water flowing downward in an inverted cone. During descent the oxygen diffuses into the water and nitrogen from the water diffuses into the bubble, (Speece, Madrid and Needham, 1970). The hypolimnetic aeration strategy of Mercier and Perret (1949) has already been described. Bernhardt (1967) and Fast (1971) used compressed air to successfully aerate the hypolimnion of a reservoir without changing the temperature profile; hence stratification (Figure 6). Water is drawn in behind a rising column of air bubbles in a vertical stack open at the surface and either leaves the stack at the top of the hypolimnion (Bernhardt, 1967) or is forced down again in the space between the stack and a jacket around the stack and out near the inlet (Fast, 1971).

Speece has designed a hypolimnetic aerator that pumps water to the surface through one vertical pipe and forces it down another, (the U-tube) (Speece and Orosco, 1970). Low pressure air is injected into the water before descent. Thus, the descending water becomes charged with oxygen under pressure. The injection of pure O_2 into the water as it descends has been attempted (Speece, 1971).

Spray on Ice

In lakes where winterkill of fishes occurs, water is pumped from the lake, spraying into the air and allowed to run back into the lake through holes in the ice (Flick, 1968).

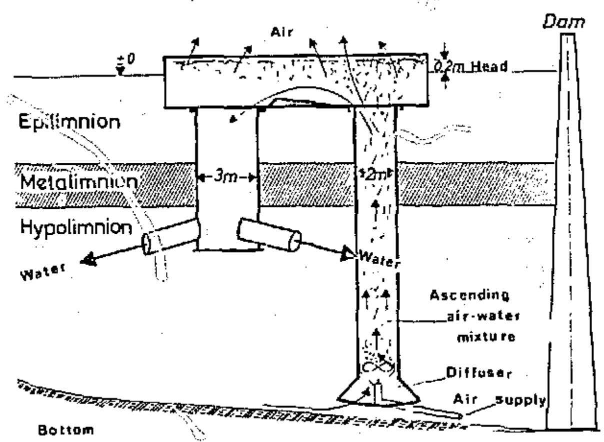

Figure 6. The new hypolimnetic aerator of Bernhardt. From Bernhardt, H. and F. Hotter. 1971. Die Kunstliche Beluftung von Oberflachengewassern. KFK-ATV-DVGW-Arbeitsblatt AW 161, 44 p. With permission of H. Bernhardt. German words translated by D. Toetz.

Submerged Weirs

Knight (1965) described a submerged weir of rock, built around the turbine intakes at the Roanoke Rapids hydroelectric station. The weir extended to within 7.5 m of the surface. It prevented the intake of hypolimnetic water into the penstocks.

Turbine Aeration

Wisniewski (1965) and Thackston and Speece (1966) describe the supplemental aeration of water as it moves through hydroelectric turbines.

Selective Withdrawal

Both hypolimnetic withdrawal and discharge from the surface could be managed to achieve a mix of the water masses downstream to manipulate temperature and dissolved gases.

The withdrawal of any stratum of reservoir water through multiple outlets is theoretically feasible. But, most existing dams do not have multiple outlets and they are costly to build. Olszewski (1961) describes a technique of hypolimnetic withdrawal from a natural lake. Others have described the tactic applied to reservoirs (Imberger and Fischer, 1970; and Fruh and Clay, 1971).

Aeration in Penstock

Aeration in the penstock with pure O_2 has been suggested by Speece (1971) in addition to aeration of the hypolimnion.

Other Methods

King (1970) lists Venturi aerators, air pressure injection and use of Howell-Bunger valves. Aeration may also be accomplished in free chutes, tunnels, baffled drops and energy dissipators such as stilling basins.

BIOLOGICAL EFFECTS OF ARTIFICIAL DESTRATIFICATION

Observations

Seasonal changes in the structure and function of communities in fresh waters are well known. These changes are accompanied by changes in the chemistry of the water caused by biological agents, as well as physical changes imposed by meteorological regimes. The cyclical changes induced by the biota are less predictable than those under physical control. For example, the annual cycle of water temperature is more predictable than the annual cycle of phytoplankton. Generally, artificial ecosystems such as reservoirs have less predictable changes than natural lakes, because of irregular perturbations, e.g., irregular outflows, water level decrease, etc.

Assessing the effect of artificial destratification involves comparing normal and perturbed stations. Previous studies have dealt with this problem in five ways. Baseline data may exist on lakes where prior limnological reconnaissance was made (Mercier and Perret, 1949; Anon, 1964-65; and Thomas, 1966). This approach may be unsatisfactory if data gathered previously are fragmentary or not recent. Sampling the year prior to artificial destratification may reveal the normal annual heat budget of the lake. If meteorological conditions are generally the same from year to year, these data may be very useful. Data of 1 year on biological cycles are of dubious value for comparative purposes because of great variability in the annual timing of microbiotic cycles, e. g. in reserviors in the southwestern United States (Silvey and Roach, 1964). The predictability of annual cycles becomes difficult in large reservoirs where inflow and outflow are irregular and background data would have to be extensive.

Another strategy is to choose two similar lakes in the same geographical area and to use one as a control (Irwin, Symons and Robeck, 1967). This strategy assumes that the lakes are really comparable. This affirmative decision is usually made in reference to a few parameters, which are of immediate interest such as dissolved oxygen, temperature and Mn. Knoppert et al. (1970) found that two contiguous reservoirs, used in an experiment of this sort, initially had populations of different species of algae.

Another approach is to divide the water body mechanically and use one part as a control (Malueg et al., 1971). This strategy is almost impossible to accomplish on anything but small ponds. But, it may be useful to answer questions with a high degree of resolution.

It is possible on extremely large bodies of water to use stations far removed from the perturbation as control stations if one assumes that no spatial differences exists between stations. Thus, since aeration at the damsite of Lake Eufaula, Oklahoma, produced a local destratification of the lake, Summerfelt (1972) was able to use upstream stations as controls.

Many workers have compared observations during artificial destratification to the conditions existing during the spring or early summer, before the perturbation was accomplished. These observations are of limited usefulness. Unfortunately, they often lead the worker to believe that the changes involved were caused by the perturbation, when they might be merely normal annual events.

Slack and Ehrlich (1967) suspended vertical cylinders of polyethylene from the surface to the bottom of a lake. Compressed air was allowed to rise from the bottom of one cylinder, while another, which was not mixed, served as a control. This approach may be useful for short term observations, but its applicability for productivity studies is controversial (Verduin, 1969 and Kemmerer, 1970). The failure of the experimental conditions to reflect the actual area of sediments: lake volume ratio is another major drawback.

Physical Factors and Biogeochemistry[1]

Biogeochemical cycling of elements implies both abiotic and biotic control of the direction and rate of chemical changes in the environment. Generally, only a few parameters are singled out as controlling these changes. In lakes the transparency of the water, the temperature regime, the turbulent mixing are probably the most important physical factors. All have important effects on the biota, which in turn affects the chemical milieu of lake water.

Chemical reactions in the lake environment involve (1) sorption and precipitation, (2) complexation, (3) oxidation and reduction, (4) acid-base reactions, and (5) biotic absorption and assimilation (Stumm and Morgan, 1970). If the biota had no role in the cycling of elements, then the form of elements and the rate and direction of chemical reactions should be predictable and involve largely thermodynamic considerations. However, since the biota profoundly alters the milieu in which chemical reactions can occur, it also has a large role in biogeochemistry of some elements that are seldom limiting to plant or animals in lacustrine environments. Two major alterations of the chemical environment by the biota involve consumption and production of oxygen and carbon dioxide, respectively, and the respective changes induced in redox potential and pH. These two parameters are major factors driving chemical reactions in natural waters. The biota also produces complex organic molecules which are involved in complexation and sorption reactions. It may also regulate concentration of certain elements by consumption or storage.

Artificial destratification ought to affect the rate and direction of mineral cycling by inducing a new chemical milieu. A case in point is the change in the oxidation state of Fe and Mn due to a change in the redox potential. In addition, Lee (1970) points out that the rate of waterflow over the sediments and turbulent mixing are important in controlling the speed of many chemical reactions involving the sediments. Thus, artificial destratification and lake mixing ought to set a new stage for chemical reactions by changing temperature, redox potential, pH, and mixing rates. Artificial destratification should also accelerate many of those reactions involving sorption with the sediments or particulate matter and complexation reactions.

Mixing effects. — The specific technique used to destratify a lake may have unique effects. The exact pathway of the water set in motion has seldom been followed in detail, however.

Mechanical pumping. — Hooper et al. (1953) pumped hypolimnetic water at 11.0°C and discharged it at the surface (24.5° C). The water moved 0.61 to 1.5 m horizontally from the outlet before its horizontal velocity decreased and vertical mixing began. Horizontal lenses of cold water, 0.30 — 0.61 m thick, were found 0.61 — 1.21 m below the surface at distances of 1.83 — 3.05 m from the outflow. At greater horizontal distances from the outlet, it was impossible to detect thermal differences.

Irwin et al. (1966) pumped hypolimnetic water to the surface and induced a turbulent discharge horizontally to mix the colder water completely with water at the surface.

Compressed air. — Fast (1968) describes the theoretical aspects of diffuse air injection. "Figure 7A (sic 2 A) illustrates a thermally stratified lake before air injection. It is characterized by horizontal, iso-density strata. These strata are thickest in the epilimnion and hypolimnion since these zones are almost uniform in temperature. The metalimnion is the zone of rapid change in density and is characterized by narrow iso-density strata.

"Although air may be injected at any level in a lake, destratification is generally most effective if air is injected at the deepest point (Figure 7 B) (sic 2 B). As the air is released and bubbles rise to the surface, vertical water currents are generated. The temperature and density of the upwelling water is about equal to that at the point of air release.

"Upon reaching the surface, the upwelled water diverges radially. The now horizontally flowing cold bottom water converges and sinks below the warm,

[1] This section was written by Dale W. Toetz.

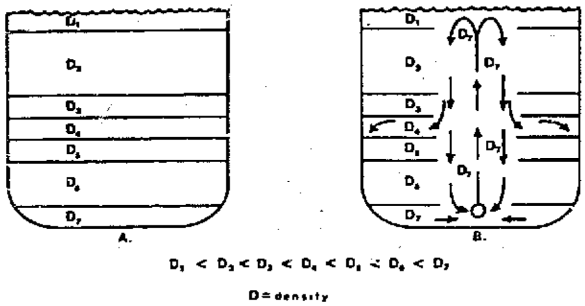

Figure 7. Hypothetical destratification patterns caused by a diffused aeration system. Figure A illustrates a stratified lake, and Figure B, a lake being destratified. With permission of author and editors of Fish Bulletin, California Department of Fish and Game. From Fast (1968).

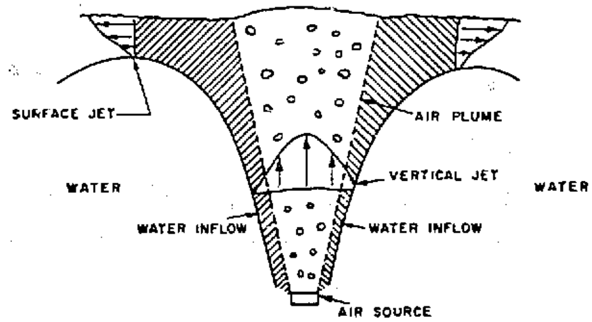

Figure 8. Cross section of a plume of water rising from a point source. From Zieminski and Whittemore (1970).

surface water. The vertical flow downward is perpetuated by density differences. Upon converging with the warm surface water and sinking, the cold water mixes with the epilimnion and metalimnion water along its periphery to form water of intermediate temperature and density. This mixed water now spreads out horizontally at levels of equal density. The depth of outflow depends on the degree of mixing and initially may be confined mostly to the metalimnion. As the mixing process progresses, the shape and number of the iso-density strata change. Concomitant with this change is a change in the rate of mixing. The rate of destratification is greatest when injection begins and approaches zero apparently an an exponential function as the lake approaches isothermy (Koberg and Ford, 1965)." Dye tracings by Johnson (1966) have confirmed some of these details.

Zieminski and Whittemore (1970) have studied small scale models of lake aeration (Figure 8). The width of the plume is about 5 percent of the depth. The water containing air bubbles rises because it is more bouyant. It also entrains water inflowing from the sides. Strong surface currents spread radially at the surface, their velocity being inversely related to the distance from the plume. At the same time bottom water flows as a strong current toward the disperser.

The upwelling water rising above an aerator apparently spreads out horizontally and uniformally mixes with the upper water masses such that the lowering of the thermocline occurs simultaneously in all parts of the lake (Irwin et al., 1966 and Knoppert et al., 1970). The rapid and uniform distribution of water brought to the surface has also demonstrated by observations of dye injection (Nickerson, 1961). The conceptual model of the air diffuser system of the latter workers has been confirmed in general by Riddick (1957), who aerated a small reservoir by forcing air through sections of a perforated pipe about 10 m long suspended about 2 m below a float. Water was reported to be upwelling from immediately below the spargers. When the upwelling water reached the surface, it moved out laterally at high velocity (Figure 3). Float tests indicated that the water traveled from the aerator to the end of the lake and then fanned out and returned partly at the sides of the reservoir.

The Aero-Hydraulics guns (Bryan, 1964) ought to move water in an analogous manner. However guns can be positioned at variable depths, thereby affecting the height and width of the plume. Also, the bottom inlet will be positioned at variable depths as the height of the stack can be different.

Fast (1971) aerated the hypolimnion of a small, bowl-shaped Michigan lake. His aeration device was positioned above the greatest depth. Aerated water flowed out at a distance of about 1 m above the bottom. When isopleths of the concentration of dissolved oxygen were plotted on a cross section of the lake, lenses of oxygen rich water could be seen penetrating horizontally from the bottom of the device (Figure 9).

Temperature

Basic studies. — The classical pattern of thermal stratification in lakes is discussed by numerous authors (Hutchinson, 1957; Ruttner, 1963; and Kittrell, 1965). After ice leaves the lake in early spring, the lake is isothermal from top to bottom, usually close to 4° C (Figure 10). Solar radiation is largely absorbed in the first meter and wind-driven currents distribute the heat evenly through the water column. This period of mixing is called spring turnover. As the season advances, the increase in temperature of the surface

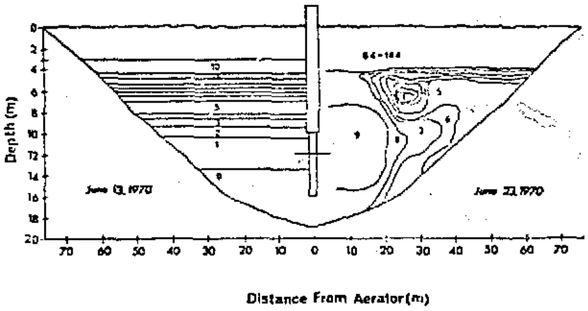

Figure 9. Before and after effect of hypolimnetic aeration on distribution of dissolved oxygen. From Fast (1971) with permission.

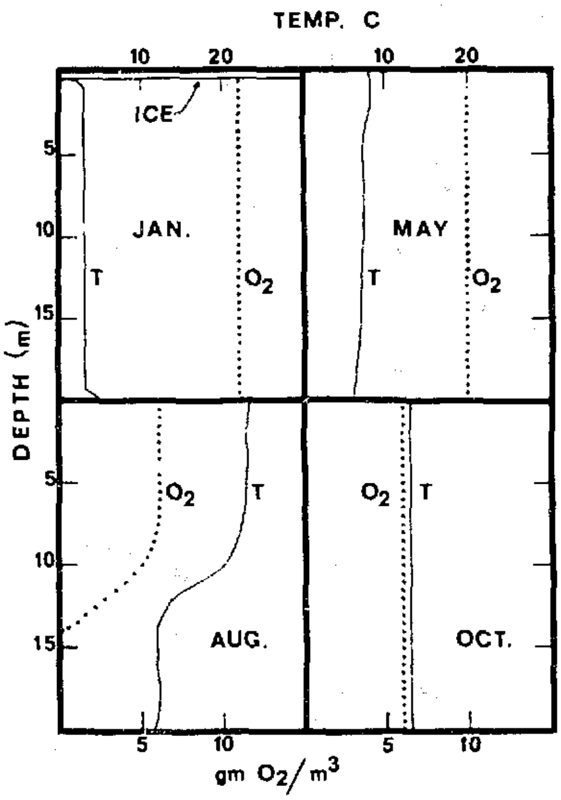

Figure 10. Generalized seasonal profiles of temperature and oxygen in a dimictic lake.

waters proceeds faster than the increase at greater depths. If the temperature gradient in the boundary between the two layers of the lake is steep, the water in the layers have different densities. If the density differences are great enough, the bottom layer (hypolimnion) will be effectively cut off from the upper layer (epilimnion). The probability of this event becomes greater at higher water temperatures since density changes are greater. The layer of discontinuity between is called the thermocline and may be operationally defined as the layer where the temperature change is 1° C or more per meter. The epilimnion may range in thickness from 2 to 18 m depending upon the effectiveness of wind-induced circulation. The more effective the latter, the thicker the epilimnion. The effectiveness of the wind is inversely related to mean depth and directly related to wind speed and the site and orientation of the basin of the lake.

During the summer the epilimnion circulates continuously. It is isothermal vertically and increases in temperature as air temperatures increase. Vertical movement in the hypolimnion is slow, but horizontal currents are not uncommon (Lathbury, Bryson, and Lettau, 1960). The temperature of hypolimnetic water remains essentially the same as at the outset of stratification. This stage is called summer stagnation.

When the heat balance of the lake becomes negative in late summer, water temperatures in the epilimnion decrease. The epilimnion, however, remains isothermal vertically. When epilimnetic waters have cooled to a point where the denisty is nearly the same as that of hypolimnetic waters, the two water masses begin to mix and stratification is broken. The water of the lake circulates completely. This stage is known as fall turnover. The lake remains isothermal vertically, and the water temperature progressively decreases with time. If ice forms on the lake, minor vertical gradients in temperature can be observed: a slight increase in temperature between the bottom of the ice and the water surface of the sediments. A lake which has two mixing periods, spring turnover and autumnal turnover, a period of summer stagnation, and an ice cover in winter, is said to be dimictic. The lake is said to be monomictic, if summer stagnation occurs, but ice cover does not form and the lake circulates continuously between autumn and spring.

The normal pattern of temperature distribution may be confused in reservoirs because of seiches and density currents (Churchill, 1965 and Kittrell, 1965). Seiches, standing waves set in motion by differential pressure on the lake surface, are particularily common on large bodies of water. Density currents are caused by inflowing water masses moving into a like density stratum in the lake. The density of the inflow may be greater, for example, than the surface waters because of a higher mineral content or lower temperature. These water masses sink under the surface and flow along on the bottom (underflows) or along some stratum (interflow).

Large flows of colder water generate turbulence and effectively decrease the vertical extent of the thermocline, thus *making the temperature gradient more* gradual. The influence of inflow can be seen in comparing the temperature curves for the Hallstättersee and Altausseersee (Figure 11).

Applied studies. — Artificial destratification causes dramatic changes in the thermal profile of a stratified lake. The general changes are common to mixing lakes with diffused air, with Aero-Hydraulics guns and with mechanical pumps. In all cases, the first effect is lowering of the thermocline. Bryan (1964) lowered it about 4 m in 7 days; Hooper et al. (1953) 3.8 m in 10 days. Sometimes, mixing is so intense that lowering of the thermocline and destratification occurs within a day (Irwin et al., 1966). Artificial destratification of the lake will eventually occur with continual mixing or aeration. The time needed is a function of the volume, stability of stratification, the energy supplied, and other factors.

Artificial destratification results in isothermy (Ford, 1963; Bryan, 1964; Irwin et al., 1966; Bernhardt, 1967; Fast, 1966 & 1971; and Malueg et al., 1971) (Figure 12). In general, a slight decrease in water temperature occurs near the surface and a sharp increase occurs at those depths which were formally below the thermocline. For example, aeration of Blelham Tarn, Ireland, resulted in a decrease from about 15° to 14° C in the first 6 m and an increase from about 8.9° to 13.5° C at 10 m (Bryan, 1964). Thus, within a few days or weeks the heat budget of the lake is abruptly increased, although surface temperatures may be lower.

The heat budget of mixed lakes is also higher on a seasonal basis than unmixed ones. For lakes mixed from early spring to late autumn, the deeper waters are usually warmer than when they are not mixed (Johnson, 1966; Thomas, 1966; Hedman and Tyley, 1967; Irwin et al., 1967; Fast, 1968; and Fast, 1971). Compared to previous years, Hedman and Tyley (1967) found the surface waters were cooler as did Koberg and Ford (1965) and Thomas (1966). But, Johnson (1966) reports higher temperatures in surface *waters during aeration.* Generally, surface temperatures are cooler by only a few degrees, while temperatures near the bottom may be as much as 15° C higher (Fast, 1971).

The mixing process prevents insulation of the water at lower depths from temperature changes in the

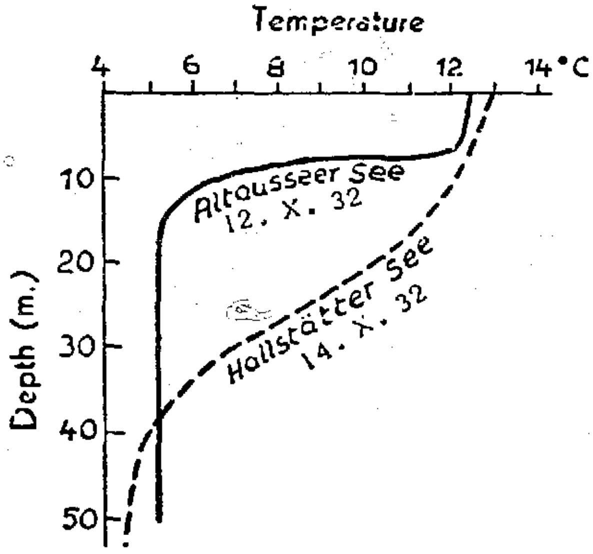

Figure 11. Influence of inflow— outflow relations on the extent of the thermocline in two adjacent lakes. From Ruttner (1963). Translated by D. G. Frey and F. E. J. Fry. Courtesy of the University of Toronto Press. Hallstattersee has a high rate of water exchange, while Altaussersee has a low rate of water exchange.

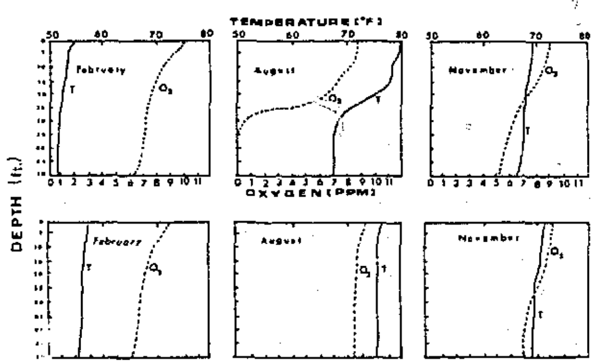

Figure 12. Vertical distribution of temperature and oxygen in Lake Wohlford, California, before (upper panel) and after (lower panel) lake aeration. Legend for upper panel applies also to lower panel. From Fast (1966).

atmosphere, because it negates the effect of quiescent conditions brought about by calm weather or ice cover. Thus, Johnson (1966) reported aeration during the winter actually depressed water temperatures 1.7° C compared to the year before when the lake was not aerated. Schmitz and Hasler (1958) report water temperatures as low as 0.7° C, during winter aeration of a lake in Wisconsin. If mixing is initiated when the lake is covered by ice, the slightly warmer bottom water may be brought to the surface (Patriarche, 1961), and temperature gradients are eliminated (Figure 13). Further, Patriarche (1961) reports a decrease in the temperature of the ooze. Winter aeration of Cox Hollow Lake, Wisconsin, during the winter, decreased the overall temperature of the lake by about 1.6° C, but did not reduce the temperature below freezing (Wirth, 1970). The changes caused by aeration of ice-covered lakes may not be completely uniform throughout the lake (Patriarche, 1967; Brezonik, Delfino and Lee, 1969).

In spite of the possibility that thermal conditions in the lake are more responsive to changes in atmospheric temperature, the time required for the lake water to cool to 4° C in autumn is usually longer if the lake has been mixed. Thus, the increased heat absorbed in summer because of mixing, generally retards the rate of autumnal cooling (Johnson, 1966 and Fast, 1968). But, surface temperatures in spring are not higher or lower during years when mixing occurs compared to years when the lake is unmixed.

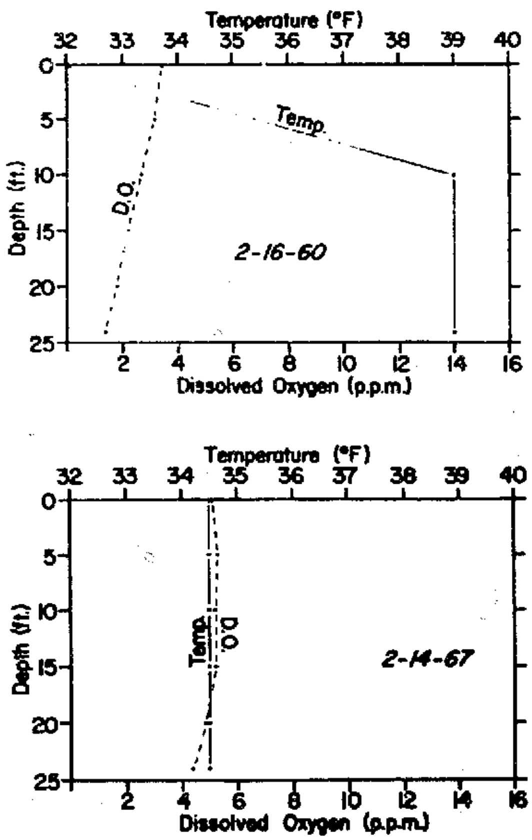

Figure 13. Vertical distribution of temperature and dissolved oxygen in an ice covered lake (Cox Hollow, Wis.). During 1960 there was no mixing aeration; during 1967 the lake was aerated. From Wirth (1970) with permission.

Mixing of lake waters generally results in uniform horizontal changes in isothermal strata if the lake is sufficiently small. But, Leach et al. (1970) only lowered the thermocline in a small area, when they tried to destratify Lake Eufaula, Oklahoma, a large reservoir. Thus, most mixing efforts have apparently resulted in uniform horizontal changes in heat content, because the lakes were relatively small. Seiches (Anon, 1964-65) and density currents (Churchill, 1965) also complicate the interpretation of the data on the effect of lake aeration in large reservoirs. Withdrawal from reservoirs may affect the vertical profile of temperature, especially near the dam. The models proposed by Bohan and Grace (1969) and Grace (1971) are of interest in this respect. A mixing cell formed in Cox Hollow Lake, Wisconsin, during the 1967 aeration effort (Uttormark, 1968). Aero-Hydraulic guns were used and apparently under certain meteorological conditions uniform horizontal mixing will not occur.

Slack and Ehrlich (1967) report that aeration of lake water in plastic enclosures resulted in an increase in temperatures of bottom water and isothermy above the point of air injection, but not below. The exact depth at which the spargers are placed is critical in determining the vertical extent of isothermy.

Flick (1968) pumped water from below the ice, sprayed it into the air, and allowed it to run back into the lake through holes in the ice. This caused only mild vertical turbulence in the lake. Dye tracing revealed that the water running back into the lake spread out horizontally just under the ice.

When hypolimnetic water is aerated, the thermocline is generally maintained and thus, epilimnetic temperatures are not greatly affected. Bernhardt (1967) reports that the depth of the thermocline increased after hypolimnetic aeration. Turbulence in the hypolimnion is apparently greater when it is aerated than when it is not. But, the hypolimnion is not mixed uniformily and the effect of aeration is best seen in the vicinity of the downflowing water. In cross section, tongues of warmer water can be seen spreading out horizontally from the point of reentry. A tendency exists for heating to occur near the sediments before it does near the boundary layer of the thermocline (Fast, 1971). Bernhardt (1967) observed that the temperature of the hypolimnion of a German lake increased from about 6° to 10° C.

Oxygen

Basic studies. — The concentration of dissolved oxygen (DO) in lake water represents the balance between input and use. Typically, the input occurs through photosynthesis and diffusion. Both events occur at or near the surface. Use occurs at all depths, but is particularily intense over the sediments. Oxygen is used in biological respiration or abiotic chemical oxidation. If biological respiration is not greatly accelerated by exogenous influx of organic matter, then oxygen will usually be near or at saturation in the entire water column when the lake circulates completely.

Temperature, rate of photosynthesis, rate of aeration, respiration rate and rate of chemical demand affect the oxygen balance in lakes. Each variable is also affected by a host of conditions, some of which become crucial in accelerating oxygen recharge or use.

Typically, DO disappears from the hypolimnion of lakes during summer stagnation (Figure 10), because of no input from the epilimnion and low light energy limits photosynthesis. The supply of DO existing at the outset of stagnation is depleted if biological respiration is sufficiently intense. Lakes developing stratification but no depletion of DO are called oligotrophic; those that do develop DO depletion are called eutrophic. Respiration in the hypolimnion is chiefly microbial and probably directly related to the mass of dead material raining from the epilimnion or stored in the sediments. Upon destratification in autumn, the distribution of DO becomes isochemical with respect to depth and remains so until summer stagnation occurs the next year (Figure 10).

Other factors besides the magnitude of the mass of organic matter capable of decomposition may create observed profiles of dissolved oxygen. Temperature affects the rate of microbial activity and thus the magnitude of oxygen consumption. All other factors being equal, an increase in hypolimnetic temperature should accelerate use of oxygen there.

Ordinarily, low temperature depresses respiration sufficiently that the standing quantity of DO in the water under an ice-covered lake at the time of freezeup is adequate for organisms with aerobic respiration until spring. But, sometimes in shallow fertile lakes with deep snow cover this does not occur and a winter fish kill results.

The solubility of DO in water is inversely related to temperature. The solubility is also affected similarly by the concentration of dissolved solids, but the magnitude of the effect is much lower (Hutchinson, 1957). Over the normal range of temperature encountered by aquatic organisms, the relative change in the absolute mass of DO/unit volume is much greater than the relative change in partial pressure of the gas in water. Hence, it is most useful for physiological purposes to learn the mass of DO/unit volume when making comparisons. Limnologists may report data on DO as mass/unit volume or percent saturation. If the temperature is known, nomographs can enable calculating one from the other. For ecological purposes it would be desirable to know both the total mass of DO and its percent saturation.

Ruttner (1963) discusses how the bottom profile and the depth of the lake can play an important role in determining the magnitude of oxygen consumption in lake waters. Particularily acute in this respect is the relationship between the surface area of the sediments and lake volume. Lee (1970) emphasizes the importance of the sediments in the oxygen budget of a lake.

During stagnation, the vertical distribution of DO may assume other forms depending upon the intensity of production or consumption of oxygen in the lake. If algae are concentrated in layers and the rate of eddy diffusion is low, then the concentration of DO in this layer may be much higher than that above or below (oxygen maxima). This produces a heterograde curve (Figure 14). When eddy diffusion is low and a layer contains large masses of decomposing organic matter, the concentration of dissolved oxygen in the layer may be much lower than that above or below (oxygen minima). This also produces a heterograde curve (Figure 14). Thus, the shape of the oxygen curve will be determined by the interplay of many factors. But, if no mixing and turbulent eddy diffusion occurs, respiration will be most important.

Applied studies. -- In most cases, the immediate effect of artificial destratification is an increase in the concentration of DO in the former hypolimnion (Figure 12) (Hooper et al., 1953; Bryan, 1964; Hedman and Tyley, 1966; Irwin et al., 1966; Leach

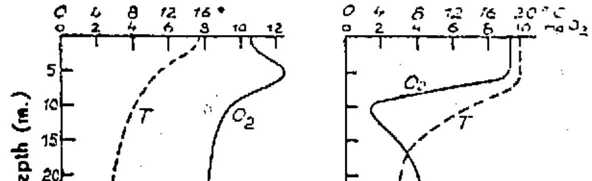

Figure 14. Heterograde type distributions of dissolved oxygen illustrating (A) an oxygen maximum (B) an oxygen minimum. From Ruttner (1963). Translated by D. G. Frey and F. E. J. Fry. Courtesy of the University of Toronto Press.

and Harlin, 1970; Lackey, 1971; Malueg et al., 1971; and Haynes, 1971). The concentration of DO in the former epilimnion may decrease slightly (Bryan, 1964; Johnson, 1966; Irwin et al., 1967; and Haynes, 1971). Ridley et al. (1966) showed that the concentration of DO at the surface decreased from 20 to 7.5 mg/l in about a week. Mixing may depress the concentration of DO at the surface to critical limits for the survival of fish (Thomas, 1966). This decrease at the surface is usually attributed to mixing waters with a high biological oxygen demand. But, Haynes (1971) believes it is associated with a reduction in the rate of photosynthesis. Woods (1961) failed to increase the standing quantity of oxygen by aerating a shallow ice-covered lake in Minnesota, which contained vast quantities of *Ceratophyllum*. Apparently, the respiratory demand for oxygen by plants and sediments vastly exceeded the input via aeration. This was also shown by Patriarche (1961). Aeration of eutrophic lakes during the winter may not increase the oxygen concentration in the water because the amount of oxygen exchange with the atmosphere is too low to satisfy respiratory demands. Aeration may eliminate supersaturation of oxygen at the surface of lakes which contain surface scums of blue-green algae (Haynes, 1971).

No one has apparently measured diel changes in the concentration of DO in a mixed lake, so the magnitudes of these changes are not known. The concentration of DO at night is apt to be a better measure of the suitability of the environment for survival of aquatic life than the concentration of DO during the day. The concentration of DO at 3 m in Cox Hollow Lake increased after aeration from 0.0 to 3.9 mg/l during the first week, but declined thereafter to less than 1.0 mg/l a few weeks later (Brezonik et al., 1969). Kolbe (1964) and Malueg et al. (1971) report similar observations.

Leach and Harlin (1970) initiated aeration of Lake Roberts, New Mexico, twice after the onset of stratification. As a result of the first effort, the concentration of DO increased in the deep water and the vertical distribution was orthograde when aeration ceased. When aeration was attempted about a week later, the concentration of DO rose initially but then fell rapidly and was essentially depleted at all depths a few days later. Cloudy weather and a decomposing mass of dead or dying algae were apparently responsible for an unusually high rate of oxygen depletion.

In many cases, aeration produces an orthograde distribution (Figure 12) in the concentration of DO (Ridley et al., 1966; Fast, 1968; and Leach and Harlin, 1970). In some cases aeration may abolish the thermocline as it is usually defined, but density differences between strata may remain sufficiently high that DO remains stratified. The data of Johnson (1966) and Slack and Ehrlich (1967) may be interpreted this way. Upon cessation of mixing, during the period wherein thermal stratification usually occurs, DO usually restratifies (Leach et al., 1970).

Isoclines of the concentration of DO may be depressed deepest in the vicinity of the aerator. Thus, the depth of equal concentration of DO may not be uniform throughout the basin (Bernhardt and Hotter, 1967; and Wirth and Dunst, 1967). This is particularily true in reservoirs when the aerator is placed near the dam (Laverty and Nielsen, 1970). Johnson (1966) eliminated metalimnic maxima in the concentration of DO.

The concentration of DO in lakes may decrease during the course of the summer (Thomas, 1966; and Symons et al., 1967). Evidence exists that mixing accelerates this decrease (Johnson, 1966 and Haynes, 1971). The data of Bernhardt (1967) suggest that aeration arrested the decline in the percent saturation of water 0.5 m above the bottom of Wahnbach reservoir.

Mixing of a lake may produce serious deficiencies in DO in the first year or so of mixing. Thomas (1966) aerated Lake Pepper, Canton Zurich, Switzerland. The normal rate of decline in the concentration of DO in the first 5 m during the summer and autumn was generally the same prior to lake aeration as it was during the 4 years the lake was continually mixed. But, during autumn the decline was faster. The concentration of DO between 5 and 35 m was always higher during the years of aeration than before, but the rate of decline during the summer and autumn was about the same during the years of aeration as before. Data taken in the 3 years following the mixing show that the rate of change in the mass of DO above 5 m during summer and autumn was irregular, but that the rate of change in the interval 5 to 35 m during the same period was about the same as the rate during lake aeration. The absolute mass of DO in all strata was generally much lower after aeration than during or before. This suggests that either the lake became more eutrophic as a result of lake aeration and/or the loading of organic matter had been accelerated.

During hypolimnetic aeration of Wahnbach reservoir, the concentration of DO in hypolimnetic water increased from 5 to 12 mg/l. Oxygen saturation in water over the sediments was above 30 percent throughout the period of aeration (Bernhardt, 1967). Fast (1971) describes a rapid increase in the concentration of DO after hypolimnetic aeration. At the outset, DO was depleted in the hypolimnion, but 1 day after aeration a tongue of water containing 1.0 to 4.0 mg O_2/l extended horizontally from the vicinity of the apparatus (Figure 9). After 9 days of aeration most of the hypolimnetic water had a concentration of over 8 mg O_2l. The concentration remained high for the duration of the summer. Heterograde curves (oxygen maxima) were still observed during hypolimnetic aeration and surface concentrations were generally higher than the control year (Fast, 1971).

Fast (1971) also used diffused air to aerate and destratify an oligotrophic lake. Aeration brought about isochemical conditions in respect to oxygen. The concentration of DO near the bottom increased from 4.5 to 7.0 mg/l and oxygen maxima at intermediate depths were not observed.

Artificial aeration of ice-covered lakes abolished any steep gradients in the concentration of DO which may exist because of intense rates of photosynthesis just below the ice or high rates of respiration near the sediments. (Figure 13). It arrests the usual decline of DO during late winter (Wirth 1970).

Mixing and aeration under ice cover at one point was reported to affect the whole basin uniformly (Wirth, 1970). The data of Flick (1968) suggest that spraying lake water onto the surface of the ice and allowing it to run back into a lake, does not allow for turbulent mixing in the lake. Consequently, the oxygen rich water spreads out horizontally under the ice. In Cox Hollow Lake aeration increased the concentration of DO by 2 to 4 mg/l. The concentration of DO in a Canadian lake, which did not have a complete turnover in autumn, was increased during the winter with lake aeration just prior to ice formation (Halsey, 1968).

Greenbank (1945) concluded that snow depth was a primary variable affecting the rate of depletion of DO in lakes which are subject to the winterkill of fishes. Deep snow reduces the rate of oxygen production by autotrophs. A prime difficulty in assessing the effect of aeration in these lakes is that snow depth and duration of snow cover on ice can vary from year to year. Data from several years are needed to obtain a reasonable picture of changes in DO concentrations during a control year. Wirth (1970) compares the concentration of DO in lake water in a winter when aeration was accomplished to data in a winter when aeration was not. During both winters there was a comparable snow cover. In an undisturbed ice-covered lake there is a gradual decrease in the concentration of DO with depth (Halsey, 1968; and Wirth, 1970). The stratification of DO in Cox Hollow Lake was more intense when the ice was not covered by snow, as photosynthesis just under the ice apparently increased the mass of DO. As expected, the absolute quantity of DO in an unaerated lake was higher when the ice did not have extensive snow cover (Wirth, 1970). But, regardless of the extent of aeration or snow cover, the concentration of DO declined with the advance of the winter in all years (Wirth, 1970).

Oxidation and Organic Matter

Changes in the concentration of organic matter in lake water as a result of lake aeration have seldom been followed. Knoppert et al. (1970) report a decrease in organic matter ($KMnO_4$ consumption) as a result of lake aeration. Symons et al. (1967) report no difference in the concentration of organic nitrogen between a mixed and a control lake.

Fast, Moss and Wetzel (1972) describe changes in dissolved organic carbon (DOC) as a result of hypolimnetic aeration. There was rapid oxidation and utilization of DOC as a result of hypolimnetic aeration. The concentration of particulate organic carbon (POC) was also partly removed in the same way. After aeration of an oligotrophic lake, DOC concentrations became uniform with depth, having been moderately stratified at the outset (Fast et al., 1972). Concentrations of POC were uniform with depth and higher by more than a factor of two, suggesting moderate disturbance of sediments. The concentration of POC returned to levels observed the year before after 1 month of aeration, but the concentrations of DOC increased to over 6 mg C/l. High concentrations of DOC were correlated with increased densities of phytoplankton.

No one has followed detailed changes in the structure or chemistry of the sediments after lake aeration. Fast et al. (1972) report that profundal sediments were gelatinous and adhesive before aeration, but loose and nonadhesive afterwards, apparently the result of changes from anaerobic to aerobic decomposers and invasion by macrobenthos.

The role of the sediments as a sink for oxygen has been stressed by Lee (1970) and the effects of resuspension have been explored by Seattle University (1970) and others. Mercier (1954) reports the gradual decrease in sediment thickness as the result of artificial maintenance of aerobic conditions over a period of years in the bottom waters of Lake Bret.

The results of the destratification work described above should direct attention to the need for careful inventory of the source of unusually large masses of organic matter. After aeration of lakes with heavy blooms of algae the concentration of DO is unpredictable. Timing the onset of aeration seems to be particularily acute.

Alkalinity, CO_2 and pH

Basic studies. — In most lakes the bicarbonate buffer system controls pH. Ruttner (1963) and Hutchinson (1957) describe the relationship between alkalinity, pH, and free CO_2. This gas has a large role in changing pH and, hence, the different forms of alkalinity. Carbon dioxide is exchanged between the atmosphere and the water and is produced through respiration and used in photosynthesis as a source of carbon. The carbon in bicarbonate may be similarily used. The net result is that CO_2, alkalinity, and pH are under strong biological control, but are also strongly influenced by physical phenomenon such as mixing and diffusion at the air-water and sediment-water interface.

During stagnation, free CO_2 and bicarbonate depletion in the epilimnion by autotrophs leads to an increase in pH and a decrease in alkalinity. Conversely, in the hypolimnion respiration exceeds photosynthesis ($P/R < 1.0$) producing an increase in free CO_2, a decrease in pH, and an increase in alkalinity. The vertical distribution of pH and alkalinity in a lake may take other forms, depending on the intensity of mixing, respiration and/or photosynthesis (Figure 15).

Applied studies. — The immediate effect of artificial destratification of a lake is a decrease in pH in surface waters (Haynes, 1971) and an increase in pH near the bottom (Leach and Harlin, 1970; and Malueg et al., 1971). The latter two papers also report isochemical conditions in respect to pH with depth. As might be expected, the alkalinity of the epilimnion increases. However, not all the results are the same. While Irwin et al. (1966) observed that values of pH became uniform with depth, they also observed that pH decreased both at the surface and near the bottom (6.1 to 5.2) after the onset of mixing. Symons, Irwin and Robeck (1967) also observed decreases only at the surface.

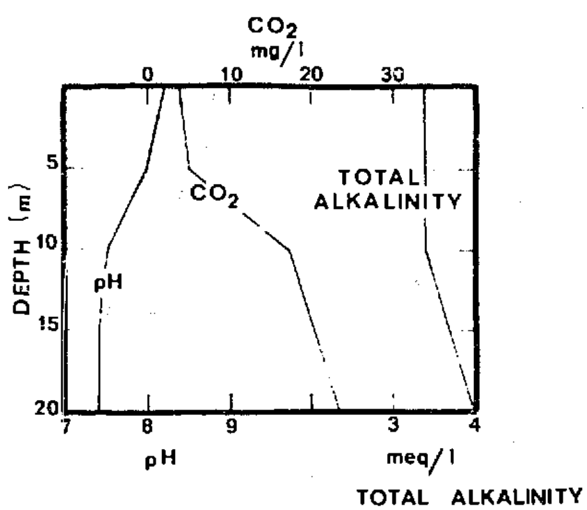

Figure 15. Generalized profiles of pH, carbon dioxide and alkalinity in a stratified lake.

Irwin et al. (1966) also observed the water became isochemical with respect to CO_2. The concentration at the surface increased slightly, while that near the bottom decreased. Haynes (1971) states that increases in CO_2 at the surface and decreases in pH can be attributed to a decreased rate of CO_2 uptake by blue-green algae at the surface because mixing prevents formation of surface scums. He also suggests that large volumes of CO_2 can be lost to the atmosphere during the period when CO_2-rich bottom water is brought to the surface. The data of Mercier (1955) can also be interpreted in this way.

Slack and Erhlich (1967) report abolishment of gradients of pH, CO_2 and alkalinity in an aerated vertical cylinder. Haynes (1971) observed stratification of pH and CO_2 in Lake Kezar, New Hampshire, in spite of mixing with diffused air. This eutrophic lake contained immense blooms of algae during mixing. Photosynthesis at the surface was intense enough to often produce carbonate alkalinity, while respiration in deeper water was high enough to maintain high concentrations of CO_2. At the other extreme, aeration of an oligotrophic lake in Michigan produced a uniform distribution in pH with a value of 7.9 (Fast, 1971).

The data of Fast (1968) suggest that the concentration of CO_2 during August and September at 17 m in El Capitan Reservoir, California, was lower during the 2 years of aeration, than the year before and after aeration. But, this was not reflected in a tendency for pH to decrease and may be due to the way in which the water was buffered.

McNall (1971) reports that pH in Lake Roberts, New Mexico, was stratified before the onset of lake aeration, decreasing from over 9 to about 8.7 at 4.6 m and then to 7.5 at 7.6 m. After 21 hours of mixing, pH decreased linearily from 8.7 at the surface to 7.7 at 11.6 m. Thereafter, pH rose in the surface waters and decreased in deep waters, until it was isochemical with respect to depth, after 144 hours of mixing at a value of about 8.7.

Lackey (1971) found little difference between the pH of lake water during aeration as compared to the year before. Malueg et al. (1971) report wider extremes of pH (6.2 to 9.6) in an unaerated side of a pond than on the aerated side where the range was 6.4 to 7.2.

Transparency

Basic studies. — The quantity of radiation passing through lake water is largely affected by the abundance of particulate matter and suspended organic material. In natural lakes, algae and organic detritus make up the bulk of the particulate fraction and the degree of transparency is related directly to their abundance. In impounded waters and in natural lakes, disturbed by carp or fed by glacial streams, particulate matter suspended in the water may be more important than algae in extinguishing incoming radiation. The magnitude of this effect is difficult to predict with great precision. It is known, however, that there will be longitudinal and seasonal variations in the transparency of water in reservoirs. Water entering an impoundment drops its silt load at the head of the lake and becomes progressively clearer as it moves downstream. At times of high flow, reservoir water will tend to be less transparent than at times of low flow. If heavy inflows correspond to seasonal meteorological events (spring rains, snowmelt, etc.), there will be pronounced seasonal changes in the transparency of the water.

Resuspension of bottom materials in shallow reservoirs not subject to high rates of water turnover may also create turbid water (Norton, 1968). Changes in the seasonal transparency of pond water is predictable within limits (Epperson and Toetz, unpublished) and is probably related to wind speed and mean depth.

The factors affecting the transmission of various wavelengths of radiation, as well as the change in solar flux with the seasons are discussed by Hutchinson (1957) and Ruttner (1963). The literature examined on the aeration and mixing of lakes contained little reference to the subject of changes in wavelength extinction with depth after artificial destratification.

Applied studies. — When aeration and mixing are initiated during a bloom of blue-green algae, there is an immediate increase in the transparency of the water due to the decrease in shading by algae which tend to float on the surface (Haynes, 1971). Malueg et al. (1971) found a twofold increase in the dpeth of the Secchi disc in the side of the pond they aerated, compared to the side not aerated. Wirth, Dunst, Uttormark and Hilsenhoff (1970) report clearer water during years when aeration was practiced. Wirth (1970) reports a decrease in the depth of Secchi disc under the ice of Fox Lake, Wisconsin, during the winter season because of a bloom of algae. In all cases above, light penetration was influenced predominantly by the density of algae.

Hooper et al. (1953) report no measureable decrease in the transparency of the water during mixing of West Lost Lake, Michigan, even though turbidity was stratified in the undisturbed lake. Before the outset of mechanical pumping, turbidity increased from 2 to 12 mg/l below 11 m and was always less than 3 mg/l above. After mixing turbidity became isochemical at 3 mg/l. Decreases in transparency of water were attributed to an increase in the density of algae following the onset of mixing. Fast (1971) reports a bloom of algae occurred in the epilimnion during hypolimnetic aeration. The year before, when the hypolimnion was not aerated, this bloom did not occur. Total solids were more evenly distributed in a mixed lake than in a nearby lake, which was not mixed (Irwin et al., 1967).

Aeration of an oligotrophic lake (Fast, 1971) decreased the transparency of the water, due to suspension of detritus, sediment and other materials. Continued turbulence caused by jet-type inlet systems in Queen Elizabeth II Reservoir, United Kingdom, apparently reduced the rate of sedimentation of silt and organic debris (Ridley et al., 1966). Sediment and detritus only become important in influencing transparency in certain cases. Unfortunately, the concentration of particulate organic matter and the concentration of particulate inorganic matter are rarely reported together so it is impossible to assess the relative effect of each on water transparency. This would seem to be mandatory in studies of destratification of turbid reservoirs. Rapoza (1971) reports a decrease in specific color after lake aeration, but little work has been done on the effect of artificial destratification on the spectral quality of lake water.

Conductivity and Major Cations and Anions

Basic studies. — Conductivity is generally viewed as an indirect measure of the mineral content of water. In fresh waters it is useful in identifying water masses where mineral content may be vastly different. In waters where the calcium bicarbonate buffer system dominates, alkalinity and conductivity are directly related such that nomographs can be used to learn one from the other.

The major cations in fresh water are Ca, Na, Mg and K, while the major anions are HCO_3, SO_4 and Cl. The bicarbonate ion has been discussed and SO_4 will be dealt with below. The rest of the ions are not thought to limit phytoplankton growth in the Liebig sense, but are necessary elements for growth of plants and animals. Since these forms are rarely limiting, their biogeochemical cycling is not dominated by organisms as is the case with P or N. An exception is Ca and to some extent Mg, which are precipitated when autotrophs withdraw C from the bicarbonate buffer system.

These ions also have charges and may have importance in regulating ion permeability. The work of Wetzel (1965) on marl lakes shows how important the monovalent:divalent ratio of cations can be to primary productivity.

Applied studies. — The data of McNall (1971) show a linear decrease in specific conductance with depth before lake aeration from 220 to 440 microhms/cm^2 at 25° C. After aeration the specific conductance increased at the surface and decreased at the bottom until 144 hours later it was isochemical with respect to depth at 300 microhms/cm^2 at 25° C. Apparently, mixing uniformily redistributed ions responsible for conductance in the water. In some cases, the onset of mixing and/or aeration has little apparent effect on the vertical distribution of specific conductance (Irwin et al., 1967; Slack and Ehrlich, 1967; and Malueg et al., 1971).

In natural lakes the changes in specific conductance follow similar changes in alkalinity, probably because the major cations are Ca and Mg in these lakes and are involved in the bicarbonate buffer system. Thus, both bicarbonate alkalinity and specific conductance increased at 8.8 and 11 m, respectively, after the onset of mechanical pumping (Hooper et al., 1953).

During aeration of an oligotrophic lake, alkalinity and specific conductance decreased sharply at the bottom and then gradually increased (Fast, 1971). Both increased gradually at the surface. Aeration of hypolimnetic water of a lake also produced a sharp decrease in bicarbonate alkalinity and conductivity. The decrease may be attributed to the precipitation of Ca and Mg as CO_2 is lost from solution. Lake aeration abolished the usual vertical stratification of specific conductance (Lackey, 1971).

Calcium appears to be one of the major cations influenced by aeration and mixing. Thus, Fast (1971) reports a slight decrease in Ca after aeration of an oligotrophic lake and Symons, Irwin and Robeck (1968) show Ca to increase at 1.5 m after aeration, although similar changes were not observed in deeper waters. Fast et al. (1972) attribute a decrease in Ca to precipitation of Ca as $CaCO_3$. Lackey (1971) reports a slight increase in the concentration of Ca during the year of aeration compared to the year before, but Hedman and Tyley (1967) report no significant change after aeration in a plastic cylinder. Lake aeration or mixing has no apparent effect on the concentrations of other cations (Hedman and Tyley, 1967; Irwin et al., 1967; Fast, 1968; Fast (Section 4 Lake) 1971; and Lackey, 1971).

Sulfur

Basic studies. — This element has a biogeochemical cycle involving oxidation-reduction reactions between the two forms ordinarily measured by limnologists. The inorganic form, H_2S, will usually occur under reducing conditions and the repugnant odor of the gas is a sign that the water mass is anoxic. The other form, SO_4, will occur with dissolved oxygen in the epilimnion. It can be converted to H_2S by microorganisms that use it as an election acceptor when oxygen is lacking. Another group of microorganisms can oxidize H_2S to SO_4. These exist at the temporary boundary between an oxygen rich epilimnion and an H_2S rich hypolimnion. Thus, microorganisms plus physical and chemical factors can lead to clinograde distributions of H_2S, and/or maxima of SO_4 at mid depths (Figure 16).

Applied studies. — Upon aeration of a stratified lake with a clinograde distribution of H_2S, this compound will begin to disappear from the hypolimnion (Irwin et

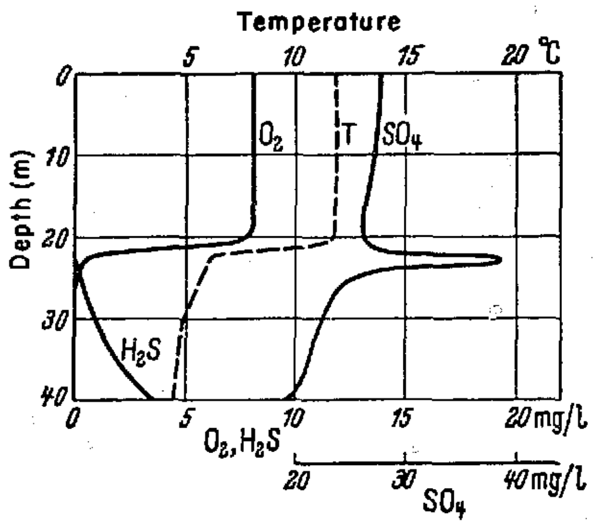

Figure 16. Vertical distribution of temperature, oxygen, sulfate and hydrogen sulfide in a stratified lake. Note the maximum of sulfate at the thermocline, due to the activity of microorganisms capable of oxidizing hydrogen sulfide. From Ohle, W. 1954. Sulfat als "Katalysator" des limnischen Stoff Kreislaufes der Gewasser. Vom Wasser 21:10. Reprinted by Ruttner (1963). Translated by D. G. Fry and F. E. J. Fry. Courtesy of the University of Toronto Press.

al., 1966; and Leach and Harlin, 1970). It may increase in concentration slightly in the epilimnion (Irwin et al., 1966). Leach and Harlin (1970) report temporary increases in surface water following aeration. They also report venting of large volumes of H_2S to the atmosphere. Upon cessation of aeration, H_2S stratified again.

Little data exist to show the effect of aeration on an annual basis. But, the data of Irwin et al. (1967) suggest the concentration of H_2S in Boltz Lake was lower during the second year of mixing.

The concentration of SO_4 generally shows little or no change, after mixing begins (Fast, 1968; Hedman and Tyley, 1967; and Symons et al., 1968). This may be because H_2S is vented to the atmosphere allowing little time for oxidation to SO_4 (Leach and Harlin, 1970). No one has measured both H_2S and SO_4 at the same time, however, in an effort to follow changes in the sulfur cycle as the result of aeration or mixing. The concentration of SO_4 was significantly lower in an aerated lake than in the same nonaerated lake the year before (Lackey, 1971).

Manganese and Iron

Basic studies. — Both Mn and Fe are somewhat alike in their chemical properties, so it is convenient to consider them together. Both react similarily to changes in the concentration of DO and pH. Typically, Fe and Mn exist as free ions only in the near absence of oxygen, where they exist as divalent ions (Ruttner, 1963). When they exist as trivalent ions, they are almost instantly precipitated from solution in the presence of oxygen, although at acid pH, the rate of precipitation will be slower than at alkaline pH (Ruttner, 1963). Both are important trace elements. Iron may have a stimulatory effect on photosynthesis when added to lake water in a chelated form. In an epilimnion with oxygen, much of the Fe exists as a chelated complex with dissolved organic matter. Manganese is more readily reduced and less readily oxidized than is Fe. Therefore, it is apt to occur at somwhat higher concentration of dissolved oxygen than will Fe.

Applied studies. — After the onset of lake aeration of a stratified lake, Mn and Fe, respectively, became isochemical with respect to depth and gradually decreased in concentration (Haynes, 1971; and Wirth and Dunst, 1967). This was also the experience of Leach and Harlin (1970) with respect to Mn, but not Fe.

The vertical distribution of Mn in Cox Hollow Lake before and during lake aeration is shown in Figure 17. Increasing the saturation of DO depressed the percent

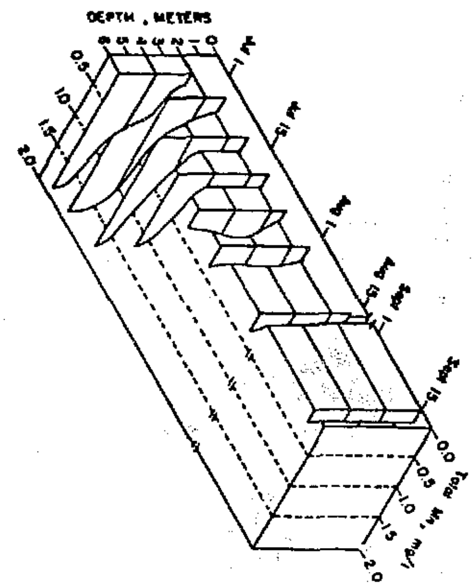

Figure 17. Vertical distribution of Mn in Cox Hollow Lake, Wisconsin, during 1966. Lake aeration began on July 1. From Brezonik, et al. (1969). J. Sanit. Eng. Div., Proc. ASCE (SA5), p. 931. With permission of Am. Soc. Civil Engineers.

saturation Mn 0.5 m over the bottom of Wahnback Reservoir (Bernhardt and Hotter, 1967). Manganese concentrations decreased in deep waters following artificial destratification (Symons et al., 1967).

Iron and Mn were not stratified in El Capitan Reservoir during the summer when the lake was aerated, but both elements were stratified the year before when the lake was not aerated (Fast, 1968). Aeration of Cox Hollow Lake reduced the Mn concentration from 2.0 to 0.2 mg/l in 10 weeks (Brezonik et al., 1969). They also studied the forms of Mn in the lake. Virtually all of the soluble Mn in the epilimnetic waters was in the soluble form. A small part of the particulate fraction was oxidized Mn. This form of Mn was not detected in the hypolimnion until after aeration, although 40 — 50 percent was in particulate form. The authors speculate on the removal of Mn through the processes of oxidation, sorption, and complexation reactions.

Silicon

Basic studies. — Silicon is an important constituent of the skeletal elements of many organisms, e. g. the frustules of diatoms, the spicules of certain Heliozoa and siliceaus sponges. Because of its use by diatoms in the epilimnion it may be stratified and limiting in the Liebig sense (Lund, 1950). Silicon may increase in the hypolimnion after the diatom maxima of late summer because of release from the sediments (Ruttner, 1963).

Applied studies. — After the onset of aeration and mixing of a stratified lake, the stratification of Si is broken and it is mixed uniformly throughout the water column (Anon, 1965-66; Ridley et al., 1966; and Hedman and Tyley, 1967). After the onset of mixing a water supply lake in the United Kingdom, the concentration of Si rose from 0.5 to 1.0 mg/l only to decrease after 3 weeks to 0.5 mg/l, presumably because of uptake by a bloom of *Asterionella formosa* (Anon, 1965-66). After additional pumping, the concentration rose again to 2.5 mg/l and then fell again to 0.6 mg/l. During the last period when the concentration of Si was decreasing, the diatom bloom was in decline and, therefore, the decrease in concentration was not thought to be related to uptake by diatoms.

Other workers have reported little or no change in the concentration of silica due to lake aeration (Johnson, 1966; Fast, 1968; and Haynes, 1971).

Other Elements

The onset of artificial destratification apparently causes little change in the vertical distribution of elements such as B, Fl, and Al (Hedman and Tyley, 1967; and Fast, 1968). Zinc remained unstratified before and after the onset of lake aeration (Haynes, 1971). But, Leach and Harlin (1970) report concentration of B, Fe, Mn, and Al increased markedly in the surface water after the onset of lake aeration. The concentration of Sr at the surface also increased. Analyses were apparently performed on unfiltered water. The metals were apparently extracted from the bottom muds by bottom currents moving toward the base of the air plume. The metals reaching the surface were held in suspension near the aerator and not dispersed great distances radially.

Copper sulfate has been used routinely as an algacide. Haynes (1971) reports that after destratification of Kezar Lake, New Hampshire, which had received many copper sulfate treatments, the concentration of Cu increased slightly from about 2 μg Cu/l to 6 to 7 μg Cu/l. Copper concentrations were always isochemical with respect to depth.

Nitrogen

Basic studies. — Limnologists generally measure four or five forms of nitrogen: nitrate (NO_3), nitrite (NO_2), ammonia (NH_4), particulate nitrogen (PN) and Kjeldahl nitrogen (KN). PN is a measure of sestonic N of a size which cannot pass an arbitrary pore size of a filter. KN measures both particulate and most forms of dissolved nitrogen. Inorganic nitrogen, *i. e.*, NO_3, NO_2, and NH_4 are used by producers. These forms are extensively monitored to describe increases or decreases as related to the process of primary production. Low concentrations indicate the producers are N limited. But, this interpretation is not realistic because a high turnover rate may keep the supply rate correspondingly high.

Nitrogen is mineralized from organic matter and appears in the form of amino acids, NH_4, etc. Ammonia is usually measured by limnoligists, but not the organic N compounds, even though they can be used by autotrophs. Under aerobic conditions, NH_4 is also oxidized to NO_2; and NO_2 is oxidized to NO_3 (nitrification). But under anoxic conditions, mineralization proceeds no further than NH_4. If lake water containing NO_3 becomes anoxic, denitrification will occur. This is an important step for it represents an exit of N from the control of the biota, just as N_2 fixation represents the entrance of N into the control of the biota. Under nonanoxic conditions, it must be assumed that uptake, mineralization and nitrification occur simultaneously. The net direction of these processes can only be learned from changes in the concentration of inorganic N, when it is reasonable to believe that uptake by autotrophs is negligible, *i. e.*,during winter.

In a stratified eutrophic lake, NH_4 will have a negative clinograde distribution; NO_3 will be nearly absent from the hypolimnion and negligible in the epilimnion and NO_2 will occur in the narrow strata between O_2-rich water and O_2-poor water. Keeney (1972) reviews recent literature on nitrogen cycling.

Applied studies. — Upon artificial destratification, the clinograde distribution in the concentration of NH_4 is disrupted and the concentration of NH_4 near the bottom decreases (Symons et al., 1967; Brezonik et al., 1969; Leach and Harlin, 1970; and Haynes, 1971). The NH_4 brought to the surface may be vented to the atmosphere as H_2S is vented (Leach and Harlin, 1970). The concentration of NH_4 at the surface may rise after aeration but it is notoriously upredictable, rising during the death of a population of algae or plunging to zero because of intense uptake. But, generally the concentration becomes isochemical with depth (Irwin et al., 1966; and Haynes, 1971) or it may exhibit a mild clinograde distribution (Wirth and Dunst, 1967).

Brezonik et al. (1969) present evidence that after NH_4 stratification is broken, nitrification of NH_4 to NO_3 occurs (Figure 18). The data of Anon (1965-66),

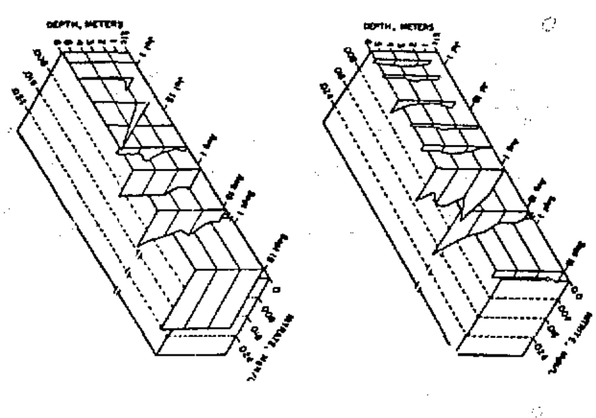

Figure 18. Vertical distribution of nitrite (right) and nitrate (left) in Cox Hollow Lake, Wisconsin, during 1966. Lake aeration began on July 1. From Brezonik, et al. (1969). J. Sanit. Eng. Div., Proc. ASCE 95 (SA5), p. 934 and 935. With permission of Am. Soc. Civil Engineers.

Johnson (1966) and Symons et al. (1968) may be *similarily interpreted.*

The inverse clinograde distributions of NO_3 and NO_2 are disturbed upon destratification and the distribution becomes isochemical with depth (Brezonik et al., 1969; and Haynes, 1971). No one has studied inducing artificial denitrification by lake aeration and subsequent restratification. Brezonik et al. (1969) report that a net loss of N occurred from Cox Hollow Lake, after aeration and speculate that the sediments acted as a sink for PN, which settled out of the water column.

Phosphorus

Basic studies. — Typically, limnoligists measure three forms of dissolved phosphorus: inorganic phosphorus or orthophosphate (PO_4-P); total dissolved phosphate (tot-P_{diss}); and hydrolysable phosphate (Tot-P_{diss}less PO_4-P) in addition to particulate phosphate (Part-P) (Golterman, 1969). Total phosphate (TP) represents (Tot-P_{diss}) + (Part-P). Each category must be *operationally defined, since it is impossible to clearly* separate dissolved and suspended matter and since a technique for a particular fraction might also measure part of another at the same time. For example, the molybdate method for PO_4-P measures part of the dissolved organic fraction. The phosphorus thus measured is called soluble reactive phosphorus by Strickland and Parsons (1968). Given these complications and the fact that phosphorus has a turnover rate, it is not surprising that nutrient limitation is not readily detectable by measuring the standing quantity of phosphorus. Moreover, changes in concentration are often meaningless without some knowledge of the nature of the change since phosphorus can undergo complicated chemical reactions in lake water such as precipitation, sorption, and redox reactions (Lee, 1970).

Typically, TP and PO_4-P exhibit clinograde distributions in stratified lakes which have clinograde distributions of oxygen. The TP in the hypolimnion is thought to originate from the Part-P, which has rained down from the photic zone (Hutchinson, 1957). Generally, most of the TP there is in soluble form, thus accounting for the large fraction of PO_4-P often measured. In the epilimnion PO_4-P is often very low in concentration because of intense competition for this substrate among autotrophs. The turnover rate, however, may be very high. Also, PO_4-P may be in low concentration because of chemical reactions, e.g., precipitation, which carries it out of the photic zone. Almost all workers believe Fe is implicated in this reaction but the exact nature of the precipitate is questionable (Lee, 1970). Lee (1970) reports that many workers believe the bulk of nonoccluded phosphorus is held in the sediments by a sorption reaction by hydrous oxides of Fe, Al and Mn. In an anoxic hypolimnion the ferric iron of the precipitate with phosphorus is reduced to ferrous iron and becomes soluble, thus releasing phosphorus. According to Hasler and Einsele (1948), if reduced sulphur is present, ferrous iron will be precipitated to the sediments as FeS, thus freeing phosphorus to be available at overturn. If this does happen, then venting H_2S to the atmosphere during artificial destratification should lower the concentration of soluble phosphorus in the water column, if artificial destratification is not continued from year to year.

Redox reactions are also believed to control the release of phosphorus from sediments. The classical work of Mortimer (1941-42) is often cited as evidence of the redox potentials associated with release of phosphorus. Generally, it is believed that an oxidized microzone above the sediments inhibits the release of phosphorus, but recently Lee (1970) cites papers which show that phosphorus is released from even these sediments and emphasizes the importance of mixing in the exchange rate. Fitzgerald (1970) and others have shown how aerobic sediments can strip phosphorus from lake water.

Artificial destratification changes a host of factors that are important in determining the rate and direction of chemical reactions. Since all change simultaneously, it is difficult to predict the exact course of events. Artificial destratification should promote precipitation and/or sorption of phosphorus and also prevent the release of phosphorus from sediments. But, lake aeration might accelerate rates of release by increasing the temperature of the sediments.

Applied studies. — The immediate effect of aerating a stratified lake may result in breaking the stratification of TP and PO_4-P and redistributing these forms evenly throughout the water column (Hooper, et al., 1953 only for TP; Wirth and Dunset, 1967; and Leach and Harlin, 1970). When the concentration of PO_4-P is high, mixing merely redistributes PO_4-P evenly throught the water column (Ridley, et al., 1966) without a decrease in the bottom waters. Some workers do report a decrease in TP (Haynes, 1971) and in PO_4-P in bottom waters (Bernhardt and Hotter, 1967; Hedman and Tyley, 1967; Leach and Harlin, 1970; and Haynes, 1971). Usually, Part-P shows a corresponding increase in surface waters (Hooper et al., 1953) and so may PO_4-P (Hedman and Tyley, 1967; and Leach and Harlin, 1970). The data of Symons et al. (1967) for hydrolysable phosphate may be interpreted similarily. Malueg et al. (1971) report little difference in the concentration of TP and PO_4-P between control and experimental sections of the pond they aerated.

Changes in TP and PO_4-P in the surface waters following the onset of mixing are determined by the biota and are often unpredictable. For example, if a bloom of algae dies at the surface, more (Tot-P_{diss}) will be found there than deeper. Haynes (1971) reported PO_4-P decreased to undetectable concentrations after aeration, possibly because of more repid uptake by algae. There is evidence that bringing phosphorus to the epilimnion will stimulate algal production, but in these cases, vertical mixing was relatively incomplete (Hooper et al., 1953; and Fast, 1971 for Hemlock Lake).

It is apparent that the data are scanty in regard to phosphorus. Without efforts to draw up mass balance budgets, it will be extremely difficult to draw conclusions regarding the overall flux of this nutrient.

Conclusions on Physical Factors and Biogeochemistry

Artificial destratification, like natural destratification, causes changes in physical and chemical parameters in lakes. There are important differences, however. The heat budget of the lake is increased and mixing may be intense enough to resuspend sediments.

Elements with a strong tendency toward biological control may assume unpredictable distributions as a result of artificial destratification, while those with little biotic control assume distributions influenced by strong physical and/or chemical control.

Sudden artificial destratification leads to loss of CO_2, H_2S, and NH_4 to the atmosphere. These losses represent an artificial sink for these elements. But, it might be also possible to speculate that those losses are balanced by compensatory mechanisms in the ecosystem, e. g. higher rates of turnover. A paucity of data exists on the turnover of elements and the behavior of pollutants during artificial destratification.

Algae[2]

Basic studies. — Most studies on the biological effects of artificial destratification deal with changes in the composition, density, and productivity of the phytoplankton and do not consider aquatic macrophytes and periphyton. Fogg (1966) sets out the principle factors which affect fluctuations of planktonic algae in temperate waters. The rate of increase of a population depends upon a genetically fixed capacity for multiplication of cells and a host of environmental parameters. Primary emphasis by limnologists in the past has been to correlate temperature, light, or nutrient concentrations with periods of population density increase (Hutchinson, 1967). For example, an increase in the density of certain blue-green algae is always associated with warm temperatures. Factors affecting the rate of population decrease are light limitation by self shading, nutrient limitation, or limitation by lack of organic growth factors, by autoinhibition, and by loss through sinking, grazing, outflow and parasitism (Fogg, 1966). It must be recognized that all of the above factors can operate at any time.

Applied studies. — One immediate effect of artificial destratification is elimination of species of algae which have unique distributions in stratified lakes. Thus, Bernhardt (1967) reports the elimination of maxima of *Oscillatoria rubescens* in the metalimnion, its completely random vertical distribution in the whole lake, and then its eventual demise after the onset of lake aeration. Fast (1971) also gives a similar account for a small unidentified bacterium after aeration of the hypolimnion. Other species which have lesser known requirements are similarily eliminated, e. g. *Mallomonas,* (Lackey, 1971).

After the onset of artificial destratification, dramatic decreases in the abundance of scum forming blue-green algae are best attributed to uniform mixing of the trichomes (Haynes, 1971) rather than a destruction or

[2] This section was written by Dale W. Toetz.

death of cells. A real decrease in the biomass of blue-green algae as a result of artificial destratification is reported in qualitative and quantitative terms (Anon, 1971 and Malueg et al., 1971). Partial mixing of a highly eutrophic lake may be inadequate to decrease substantially the biomass of blue-green algae. (Ambuhl, 1967).

One of the major characteristics of a lake during artificial destratification is thought to be high turbulence. This may have the effect of selecting against certain blue-green algae which move vertically in lakes via buoyancy changes (Fogg and Walsby, 1971). It may also affect diatoms (Lund, 1971 and Ridley, 1971). Anon (1965-66) and Johnson (1966) suggest that mechanical mixing eliminated well established populations of green algae and cryptomonads. The abundance of green algae also declined during artificial destratification even though some species had flagella and could presumably adjust their position with respect to depth (Lackey, 1971).

Hooper et al. (1953) report an increase in the population of *Chroococcus* and an apparent increase in the growth of periphyton, shortly after the onset of mechanical mixing. However, these data are difficult to interpret since a description of the usual annual cycle of phytoplankton for this lake was not given. After the onset of artificial destratification, the subsequent occurrence of other species is not easy to predict. Haynes (1971) suggests that lake aeration had little to do with the demise of a bloom of *Aphanizomenon flos-aquae,* but once the density of this species did decrease, green algae dominated the species composition of the flora. A bloom of *Asterionella formosa* occurred some 4 months later than usual in the Thames Valley after the onset of mixing (Anon, 1965-66). Blue-green algae increased in abundance in late August, but not to the "usual" immense densities.

When density of various species are compared among years before and during lake aeration, certain taxa appear to be favored. Robinson, Irwin, and Symons (1969) report a relative decline in numbers of blue-green algae and an increase in green algae and flagellates in small Kentucky reservoirs. In Parvin Lake, Colorado, certain species of algae were more abundant during lake aeration than in a comparable period the year before when no aeration was practiced (Lackey, 1971). Four species of green algae declined in abundance. The most dramatic event was a wholesale decline in the density of winter diatoms, notably *Asterionella formosa.* The periodicity of *Anabaena flos-aquae* was reduced from spring to autumn to merely the months of summer.

During artificial destratification the density of *Anabaena* may increase (Ridley, et al., 1966; and Lackey, 1971). Both *Aphanizomenon* and *Gomphosphaeria* may also increase in density (Lackey, 1971; and Knoppert et al., 1970).

Malueg et al. (1971) aerated one side of a pond which had been divided with polyethylene. The control side developed usual obnoxious blooms of algae dominated by *Anabaena* and *Trachelomonas.* In the aerated side *Trachelomonas* dominated, and *Anabaena* persisted in trace numbers. The difference in total numbers of cells between the control side and the treatment side was small due to the method of counting, but the difference in chlorophyll *a* was great.

Trachelomonas is a flagellate, and some motile organisms have an advantage over nonmotile forms in highly turbulent water. *Ceratium* becomes more abundant during lake aeration (Lackey, 1971). The data of Robinson et al. (1969) suggest that the flagellated forms, which were dominant species in an unmixed lake, were also dominant species in nearby mixed lakes. Chlorophytan flagellates were relatively abundant in Section Four Lake (Fast et al., 1972). There was no dramatic difference in the number of algal species between mixed and unmixed lakes (Robinson et al., 1969).

Data on primary productivity are confined to recent work by Fast (1971) and Haynes (1971). Unfortunately, Haynes has no control data, and Fast's observations on primary productivity during hypolimnetic aeration are complicated because of leakage of hypolimnetic water into the epilimnion. In Kezar Lake the initial effect of artificial aeration is a sharp decrease in primary production near the surface when the blue-green algae were distributed deeper (Haynes, 1971). As a result of better light penetration, primary production at 1.5 and 2.5 m increased. Chlorophyll *a* was stratified near the surface before mixing and was distributed evenly in the water column afterwards.

Fast (1971) measured primary productivity and algal density in Section Four Lake during lake aeration and also the year before when it was not aerated. Changes in density of algae were erratic, but trends with time were approximately parallel in both years (Figure 19). But, productivity (mg C fixed/m^3/4 hours) and productivity per cell were always about three times higher during the year of lake aeration than the year before. Fast (1971) believed that nutrients were more available during aeration and the reduction in standing crop of phytoplankton was caused by increased mixing rates and the increased volume of the lake which was

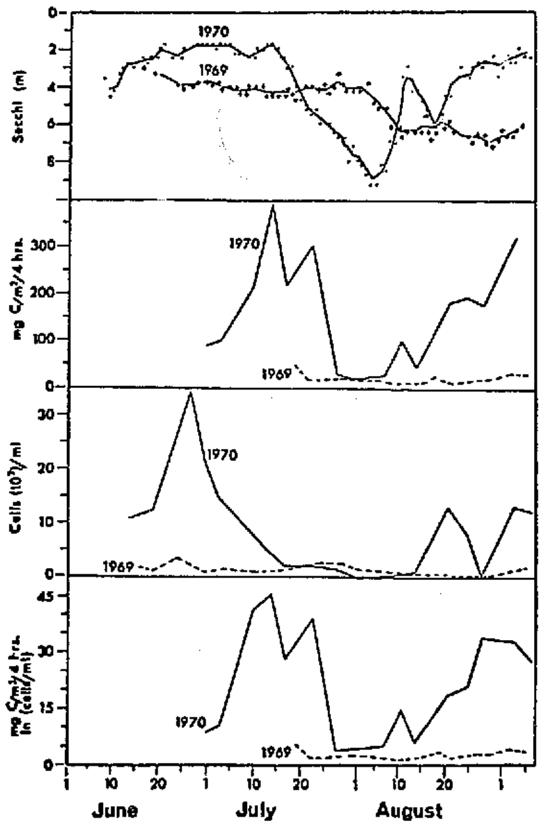

Figure 19. Transparency, biomass and ^{14}C productivity in Section Four Lake, Michigan, before lake aeration (1969) and during lake aeration (1970). From Fast (1971) with permission.

mixed. Uptake of ^{14}C in water from a pump-storage reservoir was also lower during mixing (Simmons and Neff, 1969).

Fast (1971) also observed the short-term and the long-term rate of periphyton growth in the epilimnion. Short-term colonization rates on glass slides were higher during the year of lake aeration than during the control year. Rates of colonization during the entire summer were not markedly different from rates during the control year.

Artificial destratification may produce dramatic decreases in standing crop as measured by total numbers of cells (or filaments) (Lackey, 1971 and Robinson et al., 1969), or chlorophyll *a* (Malueg et al., 1971). But, other workers report the opposite (Hooper et al., 1953; Johnson, 1966; and Fast et al., 1972). These contradictory conclusions are not surprising in view of the fact that the lakes were different and the intensity and duration of mixing was different. Ridley (1971) summarizes the situation as follows: "For this reason, "mixing" must be defined in terms of the amount, and length of time, necessary to produce vertical and horizontal movements within the lake to solve the particular problem. At the present state of knowledge, there is no single system of mixing which can be applied to all situations. In the United Kingdom there are multiple systems within reservoirs so that horizontal and vertical movements within the water mass can be arranged at high, and also low, velocities. This enables the amount of mixing energy to be varied, and then applied to particular biotic changes in the ecosystem. At lakes where recreational facilities are paramount, the problems usually apply for only a few months each year, but even so, each project should be evaluated according to the natural sequences of the lake biota.

"It is an over-simplification to assume that continuous mixing at a constant energy input from spring through fall will always achieve consistent and low-level rates of primary production. There will be times when mixing energy levels require increasing or decreasing, thus using the installation as an aid to in-lake quality control, and not as a panacea."

Fast (1971) shows an increase in $^{14}CO_2$ fixation and an increase in photosynthetic efficiency as a result of artificial destratification. From an ecological viewpoint, these data are interesting because they suggest that lake aeration may increase turnover rates. Data on community respiration, rate of energy flow from producers to other trophic levels, rate of nutrient cycling, etc. are needed. These data might well show an increase in primary productivity as a result of lake aeration results also in an increase in respiration leaving the ratio between the two variables about the same.

Evidence exists, both empirical (Talling, 1971) and theoretical (Murphy, 1962), that increasing the depth of mixing will reduce standing crop of algae by artifically increasing the depth of the zone of mixing to well below the compensation point. Talling (1971) suggests that this is an explanation for the annual spring pulse of phytoplankton to occur earlier in shallow Esthwaite Water than in nearby Windermere, which has a greater mean depth. Oskam (1971) has developed a mathematical model which predicts the outcome of mixing on algal biomass in a light-limited, homogeneously mixed body of water. The main intent is to use the model to predict a critical mixing depth which will allow algal control by mixing. Bella (1970) has developed a similar model. Both authors recognize that the unpredictable effect of grazing, sinking, outflow, parasitism, and situations where nutrients are not limiting, complicate the application of the model. This means that mixing depth should not be over emphasized in developing theories on the effects of artificial destratification on the phytoplankton. The paper by Uhlmann (1971), however, shows how some of these interactions could be reconciled.

Conclusions. — The species composition and density of algae may change in an unpredictable manner during artificial destratification. Those plankters with requirements unique to stratified waters may be reduced in density. The impact of these changes on other trophic levels is not clear. The standing crop of algae as measured by total numbers of cells and chlorophyll *a* may decrease, but the amount, duration, and timing of mixing to achieve a low standing crop of algae in any given lake is not clear. One study suggests that primary productivity and the efficiency of primary productivity increases. I speculate that artificial destratification [illegible]rates both the rate of energy flow and the rate of [illegible]nt cycling in the ecosystem.

Other Microorganisms[3]

The effects of artificial destratification on the abundance of microorganisms other than algae have not been intensely studied. Laverty and Nielsen (1970) and Rogers et al. (1971) report that the density of coliform bacteria did not appear to change as a result of lake aeration. Anon (1971) describes the results of a survey of operators of waterworks, who used lake aeration to improve the quality of water in their storage reservoirs. Insufficient data were apparently provided for a sound conclusion regarding the effect of artificial destratification on the density of coliform and fecal coliform bacteria. No data were provided regarding the occurence of *Salmonella.*

Gravel et al. (1969) have demonstrated that the density of coliform bacteria is higher in the hypolimnion than in the epilimnion of certain Texas reservoirs. They suggest that the rate of mortality of coliform bacteria is lower in the hypolimnion, than in the epilimnion. If so, lake aeration should result in lower densities of coliform bacteria for the lake as a whole. But, the immediate effect of mixing a lake with a high density of coliform bacteria in the hypolimnion might be to increase their density temporarily in the epilimnion. Anon (1971) points out that although most water treatment plants can overcome any increase in density of bacteria in raw water entering the treatment facility, waterworks operators ought to know what to expect in terms of changes in the denisty of bacteria and the public ought to be assured that water-based recreation on aerated lakes poses no threat to human health.

Zooplankton

Basic studies. — Zooplankters are subjected to a wide spectrum of spatial and temporal environmental extremes in a stratified lake. During artificial mixing the environmental extremes are less, but currents may move zooplankters in unusual ways, e. g. from the profundal to the littoral. Those organisms possessing sufficient movement to overcome artificial currents have a vertical distribution reflecting species preferences for environmental regualting factors. Those species not possessing an ability for short-term adaptation may have a vertical distribution pattern related to changes in population density.

Environmental variables affecting zooplankters may be classified as biotic and abiotic. Abiotic includes temperature, dissolved gases, dissolved solids, light, etc. Biotic includes predation, coactions, food abundance and distribution, and competition. For more complete discussions on limiting factors of zooplankton see Pennak (1946), Ruttner (1963), and Hutchinson (1967).

Applied studies. — Lackey (1971) found that vertical distribution patterns of zooplankters were not affected and that copepod and rotifer abundance was altered in a small artificially destratified mountain lake. After aeration *Daphnia schleri,* which prefers the littoral, was less abundant. *D. galeata mendotae* was present during the year of treatment, but not during the control year. The density of rotifers *(Filnia, Keratella* and *Polyarthra)* was less during the winter of treatment year than during the winter of the control year. The periodicity of population maxima of *Filina* was changed from winter and spring to spring and summer. All except *Keratella* are believed to be food gatherers and perhaps an abundance of microseston during the winter enables them to expand their numbers. McNall (1971) found that zooplankton density increased during one period of aeration of a small trout lake in southwestern New Mexico.

Fast (1971) found that artificial destratification extended the vertical distribution of zooplankton to depths which they did not occupy during stratification. He noted also a high vulnerability of zooplankton to predators at the site of upwelling in El Capitan Reservoir.

Copepods and cladocera were generally distributed more toward the surface during profundal aeration in

[3] This section was written by Dale W. Toetz.

Lake Bret, Switzerland, than in a prior year without aeration (Linder and Mercier, 1954). The difference in depth distribution was attributed to a higher rate of light extinction during aeration. During the control year the density of cladocera and copepods was higher than during the year when aeration was practiced. In both years the density of cladocera and copepods decreased during autumn, but the rate of decrease was much greater during the year the profundal was aerated.

Linder and Mercier (1954) report the apparent elimination of *Corethra plumicornis* and *Synchaeta pectinata* which had been present before aeration. But, the denisty of *Diaphanosoma brachyurum* increased. This copepod had apparently become rare due to the cultural eutrophication of Lake Bret between 1900 and 1943. Its appearance may reflect the amelioration of septic conditions. The rotifer, *Notholca longispina,* found in low numbers in Lake Bret in 1902-03 and 1943 had expanded its density markedly by the fifth year of aeration. It too was considered a representative of an oligosaprobic community.

Conclusions. — Artificial destratification alters the species composition and density of phytoplankton and zooplankton. The standing crop of zooplankton may decrease and species that are characteristic of oligotrophic waters may appear. Insufficient data exist to accurately predict the effect of these coupled changes on the structure and function of lacustrine ecosystems.

Benthic Macroinvertebrates[4]

The sediments of a lake or reservoir exhibit considerable longitudinal variation in chemical composition and texture. The littoral zone extends from the shoreline to the limit of rooted vegetation and its sediments contain terrestrial materials that have been modified by water action, drift materials, and autochthonous organic matter (Welch 1952). The sublittoral zone extends from the limit of rooted vegetation down to about the upper level of the hypolimnion. The sediments of this zone contain materials which had their origin in the littoral zone as well as materials deposited from the pelagic zone. The profundal zone includes the bottom bounding the hypolimnion and its sediments are largely finely divided, soft oozes. These zones grade into each other and lines of demarcation are usually not distinct. Since the extent of the hypolimnion varies seasonally, the extent of the profundal area as defined above is not permanent. Shallow lakes may contain the upper two zones or perhaps only the littoral zone. In addition to differences in bottom materials, considerable variation also exists in physicochemical conditions of the water over the sediments of each zone especially when the lake is stratified.

Due to the variation in environmental parameters in and over the sediments of a lake from the shore to the depths, considerable longitudinal variation exists in diversity and abundance of benthic macroinvertebrates. The littoral zone generally supports a much greater diversity than the sublittoral and profundal zones. Although caution should be used in specifying any single factor as the sole condition limiting the distribution of benthic macroinvertebrates, almost all discussions of limiting factors stress the importance of dissolved oxygen (DO). Ruttner (1964) stated that a limiting factor of major importance to the benthic animals of the ooze is the oxygen content of the water adjacent to the bottom. Limited benthic fauna in streams below some storage impoundments has been attributed to seasonally low tension of DO (Isom 1971). Because of the importance of DO as a limiting factor and since this parameter is changed considerably by artificial aeration, the relationship betweeen DO concentration and distribution of benthic macroinvertebrates will be discussed. Because of the relationship between temperature and oxygen, temperature will also be discussed.

Basic studies. — Considerable variation exists in species composition of populations of benthic macroinvertebrates with respect to lake depth. The greatest diversity occurred roughly in the region of 0.5 to 3.0 m in Lake Mendota (Muttkowski 1918) and in Lake Oneida (Baker 1918). In a survey of benthic macroinvertebrates in a highly productive impoundment, 52 percent of the organisms by number and 76 percent by weight were collected between 0 and 3 m in depth (Peterka 1970). The 3 to 8 m zone had 42 percent by number and 21 percent by weight of the total, while 6 and 3 percent respectively, were taken from the 8 to 12 m zone. Ephemeropthera, Gastropoda, and Amphipoda were not taken from depths exceeding 10 m by Saether (1970). Trichoptera was not collected below 5 m. Oligochaetes and chironomids were more abundant at shallower depths but were taken from all depths including the maximum of 117 m.

Depth distribution is closely associated with concentration of DO. Saether (1970) collected 209 individuals belonging to seven species from a station 44.5 m deep where the concentration of DO was 2.6 mg/l. However, only 52 individuals in three species were

[4] This section was written by Jerry Wilhm.

taken from a station 28 m deep where the concentration of DO was 0.8 mg/l. The profundal zone of second order lakes (i.e. temperature of bottom water near 4 C; two circulation periods, one in spring and one in autumn (Welch 1952) is especially limiting during summer stagnation. Few kinds of animals are able to thrive in the anoxic profundal zone (Eggleton 1931). Chironomid larva were abundant in the profundal area in a lake studied by McLachlan and McLachlan (1971) during most of the year; however, no organisms were collected from the profundal area during summer months. The fauna is more evenly distributed in third order lakes (i.e. temperature of bottom water similar to surface water, circulation continuous). Although *Tanytarsus* has been reported to be extremely sensitive to low oxygen concentrations, the organism has been taken from profundal waters of oligotrophic lakes (Brundin 1958) and in oligotrophic conditions in northern and eastern sections of Lake Erie (Brinkhurst 1969).

Although populations of benthic macroinvertebrates are limited quantitatively in deeper waters, they may attain great numbers (Eggleton 1931). Sublette (1957) explained that the summer benthic fauna of a second order lake attains large numbers of individuals in the upper profundal or lower littoral zones during stagnation. Fauna are sparse in the profundal zone during this time.

Dispersal of benthic macroinvertebrates has been reported to be induced by anoxic conditions. Bay, Ingram, and Anderson (1966) noted that when oxygen at the mud-water interface becomes depleted, chironomid larvae become limnetic. Chironomid larvae developing in unfavorable subtrates may disperse to more favorable areas (Hilsenhoff 1966). The large number of individuals in the upper part of the profundal zone of a second order lake in summer has been explained as a migration upward by the animals to escape the DO depletion in the hypolimnion.

Species of benthic macroinvertebrates differ considerably in rate of oxygen consumption. Olson and Rueger (1968) measured oxygen metabolism of 11 species of benthic macroinvertebrates and reported a range in oxygen consumption from 0.0505 ml O_2 (g hr)$^{-1}$ in dipteran *Tipula* sp. to 0.04004 in the mayfly *Leptophlebia* sp. Smaller specimens usually had higher rates than larger specimens of the same species. Berg, Jonasson, and Ockelmann (1962) studied the oxygen consumption of some profundal benthic invertebrates and reported that the rate of respiration had three main types of relations to oxygen content of the water:

1) Linear oxygen consumption from air saturation down to about 1.5 to 5.0% oxygen and below this a marked decrease of consumption *(Tubifex tubifex, Chironomus anthracinus, Ilyodrilus hammoniensis)*;

(2) A decreasing rate of consumption from air saturation down to 4 to 6% oxygen and a still more marked decrease below this *(Lumbricillis rivalis, Procladius, Pisidium casertanum)*;

(3) Oxygen consumption decreases gradually to the minimum values *(Corethra flavicans)*.

Benthic populations differ considerably in their ability to withstand anoxic conditions. Walshe (1947a) compared ability to live under anaerobic conditions in ten different species. *Chironomus paganus* was the most resistant and *Tanytarsus brunnipes* the most sensitive. Organisms tested from streams were less resistant than those from still water. Thienemann (1928) also noted that *Tanytarsus* larvae were sensitive to poorly aerated water. *Chironomus thummi*, however, can withstand low and rapidly changing oxygen concentrations, but not completely anoxic conditions for over a few hours at a time (Augenfeld, 1967). *Chironomus plumosus* may inhabit areas completely devoid of oxygen for several weeks or more. Most of the true aquatic species of oligochaetes are able to thrive in low concentrations of dissolved oxygen (Pennack 1953). Some are able to withstand the complete absence of oxygen for extended periods and thus endure summer and winter stagnation in lakes. However, populations cannot be maintained indefinitely in the absence of oxygen (Dausend 1931). Many additional examples are given by Thienemann (1954). Low oxygen concentration would thus reduce species diversity of the benthic community. Prolonged anoxic conditions would severely reduce or eliminate populations of benthic macroinvertebrates.

The ability of many invertebrates to withstand anoxia has been correlated with possession of glycogen stores. Glycolytic enzyme systems have been reported in the tissues of *C. plumosus* (Zebe and McShan 1957, Augenfeld and Neess 1961). The anaerobic breakdown of glycogen provides less than 10 percent of the energy per molecule than that yielded by complete oxidation. An animal relying on anaerobic respiration would require either a reduction in energy requirements or an increase in the rate of use of carbohydrates. Harnisch (1938) reported that larvae of *C. thummi* used the second method. He found the body weight of these animals was about 14 percent glycogen and that they lost approximately 10 times more glycogen in anoxia water than in aerated water. However, Augenfeld

(1967) suggested that larva of *Chironomus plumosus* use both alternatives. He found that larvae were composed of 13.1 percent glycogen and exhibited a twofold rate of increase in use in oxygen-free water while reducing activity. *Tanytarsus* sp. had only 2 percent glycogen and was unable to survive anoxic conditions.

Oxygen concentration also influences activity. Bloodworms use body undulations to draw water through their burrows and the amount of food ingested is probably proportional to the activity of the larvae. Walshe (1953) found that two subspecies of *Chironomus plumosus* differed in the minimum oxygen concentration threshold for undulating motions. Augenfeld (1967) dredged *C. plumosus* from the hypolimnion of Lake Mendota in late summer and observed that they were inactive until placed in aerated water for a few minutes. Walshe (1947b) reported a sudden increase in activity and therefore in oxygen consumption in *Chironomus plumosus* in aerated water after a period of anaerobiosis. Berg et al. (1962) noted that the rate of activity of *Corethra flavicans* increased as oxygen consumption increased. Oxygen consumption was proportional to the oxygen content of the water. Thus, low oxygen concentrations may reduce activity and thus energy requirements of benthic macroinvertebrates.

Since many functional parameters are related to temperature, methods of reaeration inducing temperature changes may have pronounced effects on the benthic system. Increased oxygen consumption at higher temperatures has been reported by many authors. A curve relating oxygen consumption to a gradually increased temperature was found to be less steep than Krogh's curve in *Chironomus anthracinus* and similar to Krogh's curve in *Lumbricus rivalis and Pisidium casertanum.* The slope was steeper than Korgh's curve in *Tubifex tubifex, Tubifex barbatus, Ilyodrilus hammoniensis, Corethra flavicans,* and *Procladius* (Berg et al. 1962).

Temperature may also influence changes in glycogen content. Tressler and Domogalla (1931) found that glycogen concentrations were lowest when temperatures were highest. Augenfeld (1967) stated that since the rate of use of glycogen is positively correlated with temperaure even in the presence of oxygen, it is possible that the larvae were unable to take in food rapidly enough to meet the higher metablic demands.

An increase in temperature in a lake resulting from destratification procedures may decrease the length of the life cycle of certain benthic macroinvertebrates. Hilsenhoff (1966) reported an inverse relationship between temperature and hatching time of eggs in laboratory populations of *Chironomus plumosus.* Eggs held at 24° C hatched in 3 days, those at 16° C in 6.5 days, and those at 9° C in 14 days. Eggs held at 8° did not hatch and eventually decomposed. Pupation is also influenced by temperature. The pupal stage of laboratory populations of *Chironomus plumosus* lasted 1 day at 24 ° C. A pupal stage of 6 to 10 days was normal when mud temperatures were 10° C.

In addition to being limited by low oxygen concentrations, feeding rates are also influenced by temperature. Larvae collected from the field during winter when the mud temperature was 5° C or lower never had food in their digestive tract (Hilsenhoff 1966). At temperatures of 12° C and above, larvae fed actively. Hilsenhoff (1967) showed that a feeding stimulus is necessary for emergence. He suggested that this stimulus was provided in Lake Winnebago, Wisconsin, by diatom blooms which were initiated by nutrients flowing into the lake in runoff water. No emergence occurred in May following a winter with virtually no runoff. Thus, anoxic conditions may influence feeding and therefore prevent emergence.

Applied studies. — Several reaeration studies have included observations of benthic macroinvertebrates. Fast (1971) compared changes in benthic populations in a eutrophic lake with an oligotrophic lake. The hypolimnion was aerated in the eutrophic lake while thermal stratification was maintained. Oxygen concentrations increased from 0.0 to over 10.0 mg/l. The three most important benthic taxa in the eutrophic lake were *Chironomidae, Anisoptera,* and *Chaoborinae.* The oligotrophic lake was completely destratified. Unlike the eutrophic lake, the sediments were well oxidized and contained sparse amounts of organic matter prior to aeration. The concentration of dissolved oxygen was always high over the sediments. Oligochaetes and chironomids dominated the benthic assemblage.

Changes in the benthic populations resulting from artificial destratification were observed in a sharply stratified reservoir (Inland Fisheries Branch 1970). Artificial destratification made temperature and oxygen concentration relatively uniform. A rise in water level of 10 m influenced changes in the littoral zone, but did not mask the broad changes in the profundal zone caused by destratification. The bottom fauna consisted mainly of chironomids, tubificids, clams, and nematodes.

Lackey (1971) observed benthic populations in a Colorado montane lake maintained in a thermally destratified condition year around. Prior to aeration dissolved oxygen depletion normally developed in the hypolimnion in summer and winter. The lake was not completely destratified by aeration. The most abundant benthic macroinvertebrates in the montane lake were *Chironomidae, Lumbricus,* and *Asellus.*

Chironomids. — Chironomid larvae increased greatly after aeration in the eutrophic lake studied by Fast (1971). Total numbers of chironomid larvae increased 65 percent after aeration, while biomass increased 52 percent. Chironomid larvae were mostly restricted to depths less than 9 m prior to aeration. No larvae were collected from depths exceeding 15 m and few adults emerged from depths exceeding 7 m. After aeration larvae gradually extended their depth distribution into the profundal zone and capitalized on the rich supply of organic matter. Dispersal was probably caused by dispersion of eggs and active emigration of late instars. Dugdale (1955) noted mature larvae leaving their burrows and swimming between the surface and bottom shortly after sunset. Chironomid emergence also gradually extended into deeper water and total emergence from the lake almost doubled. Total numbers of pupae also increased. Fast suggested that aeration and increased temperature accelerated decomposition. The increased bacterial production may lead to increased production of macroinvertebrates such as chironomids that feed on microorganisms.

Fast (1971) measured a 54 percent decrease in numbers of chironomid larvae after destratifying the oilgotrophic lake and a 73 percent decrease in biomass. Chironomid larvae were less abundant during the entire summer after aeration than the summer before aeration. He observed that the pattern of larvae being more abundant in shallow water during June and more abundant in deeper water by September was not changed by aeration. Density of chironomid pupae was greater in early summer before aeration than after; however, numbers in late summer were approximately equal. Pupae showed the same numerical shift from shallow to deep water during the summer before and after aeration. Total adult emergence reflected the decrease in larval and pupal standing crop. Before treatment almost all emergence was from less than 4 m and no midges emerged below 12 m. As aeration continued a more uniform emergence by depth occurred. Fast suggested that reduction in standing crop of chironomids could be due to emergence. Spring temperatures were warmer after aeration and this could have promoted a greater emergence rate prior to early summer sampling.

The midge fauna was limited in the reservoir observed by the Inland Fisheries Branch (1970). Midge larvae were almost absent below 10 m under stratified conditions. After the fall overturn, they were more abundant in deeper water although few occurred below 15 m. During the following summer when the lake was aerated, chironomid larvae increased in abundance and were present at all depths. During the summer following aeration, the reservoir stratified again and midge larvae disappeared from deeper waters. Midge pupae distribution pattern was similar to larval distribution. Although several midges capable of tolerating anaerobic conditions were present in the reservoir, they were virtually absent below 10 m during stratification. It was stated that a combination of toxic chemical conditions rather than anoxia alone probably limits distribution of midges.

Midge larvae are an important component in the montane lake studied by Lackey (1971). This lake was not completely destratified and the density of midge larvae did not change much during destratification except for lower abundance in the profundal zone.

Chaoborinae. — In the eutrophic lake studied by Fast (1971), total numbers of *Chaoborus* larvae increased 250 percent after aeration, but total weight decreased 22 percent. This resulted from a large increase in *Chaoborus punctipennis* after aeration, a midge much smaller than *C. flavicans. Chaoborus* was most abundant in the 8 to 12 m depth interval prior to treatment and were most abundant from 4 to 8 m after aeration. Aeration of the profundal area may decrease predation of *Chaoborus* by fish. *Chaoborus* avoids highly anoxic conditions. Fourth instar larva may remain in deep water during the day in summer rather than nestle in deep profundal muds presumably because of highly anaerobic conditions (Teraquchi and Northcote 1966). Under aerobic conditions a large percentage may have nestled in the mud and thus reduced their vulnerability to predation. Fast (1971) observed that *Chaoborus* was the most important trout food item prior to aeration of the eutrophic lake and *Daphnia pulex* was the most important after aeration.

In contrast to the changes in *Chaoborus* following aeration observed by Fast, Lackey (1971) reported that this group was not greatly affected by destratification except for somewhat lower densities at two stations. A distinct summer decline in abundance occurred in both the year preceding treatment and during treatment.

Ephemeroptera. — Standing crops of mayflies did not change significantly after aeration in the eutrophic lake and these organisms did not invade the hypolimnion after aeration (Fast 1971). Most individuals were collected between 0 and 4 m and no individuals were taken below 11 m. The depth distribution was not changed by aeration. Other limiting factors such as temperature, food, or sediment compostion may have restricted their distribution. Although standing crops were similar before and after treatment, more mayflies emerged after aeration began. Emergence prior to aeration was mostly between 4 to 8 m and all mayflies emerged from less than 4 m after aeration. The time of maximum emergence was not changed by aeration.

Four species of mayflies were collected in the oligotrophic lake observed by Fast (1971). Although numbers taken were similar before and after treatment, biomass decreased 55 percent after aeration. Nymphs were seldom collected below 11 m and were never taken below 14.5 m prior to aeration. Although depth distribution of the nymphs was not altered significantly by aeration, adult emergence patterns differed greatly after treatment. Peak emergence before aeration occurred in early July and adults never emerged below 8 m. Peak emergence after aeration occurred during August and emergence occurred between 0 and 12 m.

Oligochaeta. — The number of oligochaetes increased after aeration in the eutrophic lake (Fast 1971). These worms were more abundant at intermediate depths, but no persistent pattern was observed. Total biomass and numbers of oligochaete microdriles decreased considerably after aeration in the oligotrophic lake (Fast 1971). Aeration did not significantly change depth distribution. Oligochaetes were especially abundant at depths below 14 m before and after aeration. The author suggested that the most likely reason for the observed reduction was a decrease in primary production and an increased heat budget. An increased heat budget would have caused accelerated metablic rates. Temperature increases may have caused increased respiration, while protein synthesis remained the same or decreased due to a decreased food supply.

Oligochaetes were the most abundant benthic organism in the reservoir studied by the Inland Fisheries Branch (1970). Following prolonged stagnation, numbers were low below 10 m. Aeration induced an oligochaete population explosion and the animals invaded the profundal zone. After a full year of destratification, the normal summer distribution pattern was reversed and highest numbers occurred in the deeper areas. It was suggested that several factors such as higher temperature, ample oxygen and food, and disappearance of the toxic conditions associated with stratification may have influenced the dramatic increase in the worm population after aeration.

Lumbricus inconstans was common in the montane lake studied by Lackey (1971), but highly variable in abundance. One station had higher densities of this species following aeration, while two stations had approximately the same standing crop before and after treatment.

Other benthic macroinvertebrates. — Nematodes increased rapidly after destratification of a reservoir (Inland Fisheries Branch 1970). Sparse populations existed in shallow areas prior to treatment. After destratification the population exploded dramatically and organisms were taken from the profundal zone. After a year of destratification the population decreased and a year later when the lake stratified again, nematodes virtually disappeared. The authors stated that the population explosion in this species is not surprising considering the importance of food and oxygen as limiting factors and the short generation time. They were unable to explain the virtual elimination of the species a year after destratification ceased.

Three species of Odonata were collected by Fast (1971) from the eutrophic lake and six species from the oligotrophic lake. Odonata were most abundant between 0 and 4 m in the eutrophic lake and did not invade the hypolimnion after aeration. Odonata numbers and biomass were about the same before and after treatment in the oligotrophic lake.

Crayfish increased depth distribution following aeration (Fast 1971). Before aeration in the eutrophic lake, 95 percent of the crayfish were in the 0 to 4 m depth. After aeration crayfish rapidly became distributed to maximum depth in the oligotrophic lake. The average depth for males increased from 4.4 to 11.8 m after aeration, while mean depth of females increased from 8.8 to 9.5 m.

Lackey (1971) observed that maintaining the thermally destratified conditions year around did not alter significantly the standing crop nor the annual cycle of the isopod *Asellus intermedium*. However, he noted an increase in abundance of the amphipod *Hyalella azteca* during stratification.

Conclusions. — The zoobenthos populations in the eutrophic lake were mostly restricted to the epilimnion prior to aeration (Fast 1971). Much of the lake was uninhabited and underexploited. After aeration certain species invaded the hypolimnion (especially midges). Total numbers of benthic macroinvertebrates almost doubled. In contrast, destratification resulted in a reduction in standing crop in the oligotrophic lake. Oligochaete microdiles and chironomid larvae had especially large decreases in standing crop. The organisms in the sharply stratified reservoir exhibited increases in density and rapidly invaded the profundal zone (Inland Fisheries Branch 1970). Maintaining a montane lake in a destratified condition the year around did not cause large changes in the benthic populations (Lackey 1971).

Fish[5,6]

Physicochemical changes ensuing with the annual cycle of stratification, described above by Toetz, have a significant ecological impact on the production, survival and distribution of the entrie biotic community. Vertical variation in temperature and dissolved oxygen (DO) of stratified lakes are especially important variables effecting the species composition, growth and distribution of fish populations.

Aeration is a tool which can be used to artificially destratify standing water or aerate oxygen depleted hypolimnetic waters. The value to lake and stream fisheries of manipulating the environment is seemingly great, and where it has been installed as an operational device, it points to a variety of benefits compatible with multipurpose uses. Artificial destratification and hypolimnetic aeration produce different physicochemical perturbations which undoubtedly have different ecological impacts. Cases will undoubtedly arise where artificial destratification which would provide optimal benefits for warm-water fishes would create conditions intolerable for cold-water fishes. The review of basic research below points out the impact which stratification has on survival, distribution and growth of fishes, while the section on applied studies describe effects on fish of artificial aeration under experimental conditions. Applied studies relating aeration to fish ecology represent a small percentage of all investigations dealing with aeration. Artificial destratification for the explicit purpose of improving fish habitat has been attempted by Grim (1952), Hooper, Ball and Tanner (1953), Johnson (1966), Van Ray (1967), and Fast and St. Amant (1971). Aeration studies that include observation or discussions of fish population response include: Fast (1966, 1971); Irwin, Symons and Robeck (1967); Wirth, Dunst, Uttormark and Hilsenoff (1967); Lackey (1971); and Summerfelt and Hover (1971).

Basic studies

Fish distribution. – As long as physicochemical factors are not limiting, fish will distribute themselves according to the distribution of their food (Fast, 1971; Summerfelt, 1971). For example, Horak and Tanner (1964) found adult rainbow trout *(Salmo gairdneri)* in Horsetooth Reservoir, Colorado, most numerous between 18.9 to 21.1 C even though DO in the hypolimnion was not limiting. The distribution was apparently related to food selection for Cladocera which were most abundant in the epilimnion. Other fishes have been noted to exhibit vertical migrations with their prey (Galligan, 1962).

Fishes are often detrimentally affected because of the reduced volume of fish habitat when lake strata of desirable temperature and DO becomes limiting. Habitat of cold-water fishes, such as the cisco *(Leucicthyes artedi)*, may be compressed to a narrow stratum of the thermocline which is overlaid with thermally lethal water and bounded on the lower side by cool but anoxic water (Hile, 1936). Tanner (1960) reported a 20 to 40 percent reduction in volume of "liveable" trout water in stratified lakes. Fast (1971) defined suitable rainbow trout habitat as having 7.5 mg/l DO and $< 24^{o}$ C temperatures. In Hemlock Lake, a eutrophic lake in northern Michigan, trout were restricted to levels above 8 m because of hypolimnetic oxygen depletion and high concentrations of CO_2, H_2S, and NH_4. Their upper limit was related to the 21° C isotherm. Data of Lackey (1971) show that depth distribution of trout in Parvin Lake, Colorado, was similarly raised by hypolimnetic DO depletion. Mortality of cold-water fishes has been reported when hypolimnetic DO depletion forced fish into epilimnetic water where their temperature tolerance was exceeded (Colby and Brooke, 1969).

Under conditions of summer stratification, some lakes (natural) and reservoirs (manmade) are capable of maintaining a warm-water fishery in the epilimnion more or less vertically separated from trout living in the "winter-stored" hypolimnetic water. Stratified lakes with warm-water fishes in the epilimnion and salmonids in the hypolimnion create two types of fisheries, i.e., "two-story fisheries". This situation occurs in many northern and western natural lakes and reservoirs which have epilimnetic temperatures $< 21°$ C and a relatively large hypolimnion. It occurs in southern reservoirs which have epilimnetic waters much warmer than 21° C but at least small hypolimnetic areas with suitable oxygen.

[5]This section was written by Robert C. Summerfelt, Leader, Oklahoma Cooperative Fishery Unit, Oklahoma State University, Stillwater 74074

[6]Categorization of fishes as warm-water or cold-water fishes is commonplace as it gives basic recognition of species differences in tolerance to water quality (Water Quality Criteria, 1968). Warm-water fishes include species such as largemouth *(Micropterus salmoides)*, bluegill *(Lepomis macrochirus)*, gizzard shad *(Dorosoma cepedianum)*, and channel catfish *(Ictalurus punctatus)*; cold-water fishes refer to the various trouts and salmon *(salmonids)*, white-fishes, and ciscoes whose original distribution was basically limited to the glaciated areas of North America.

Reservoirs suitable for two-story fisheries have been defined as having hypolimnetic waters with temperatures of $< 21^\circ$ C and DO > 3 mg/l (Kirkland and Bowling, 1966; Wilkins, Kirkland and Hulsey, 1967).[7] DO concentration of 3 mg/l or less used by Kirkland and Bowling (1966) as criteria for determining the suitability of reservoirs for two-story fisheries in Tennessee and Georgia is only one-half the 6 mg/l recommended by Water Quality Criteria (1968) for the hypolimnion of oligotrophic lakes. DO concentrations lethal to trout acclimatized to low oxygen may be only one-half the DO concentration lethal to trout acclimatized to air-saturated water (Fry, 1960). Even without acclimatization to low oxygen, minimal DO concentrations are 3.4 mg/l for brook trout *(Salvelinus fontinalis)*, 2.8 mg/l for brown trout *(Salmo trutta)* and 2.5 mg/l for rainbow trout at ca. 21° C (Burdick et al., 1954). Hatching, survival and growth of young salmonids, said to be among the most sensitive of fishes, have been observed repeatedly in the laboratory at near 3 mg/l DO (Doudoroff and Shumway, 1967). DO concentrations lethal to fish are sharply lowered by increased concentrations of CO_2 (Black, Fry and Black, 1954) and NH_4 (Water Quality Criteria, 1968).

Eutrophication of stratified waters leads to a hypolimnetic oxygen deficit. Anoxia and anaerobic decomposition results in the accumulation in the hypolimnion of compounds toxic to fish (e.g., CO_2, H_2S, NH_4). Levels of many of these compounds exceed water quality criteria[8] for fish and other aquatic life (Water Quality Criteria, 1968). Even aeration, however, may not remove all toxic components. Irwin et al. (1967) demonstrated in bioassay studies that hypolimnetic waters, though aerated in tanks to 4 to 5 mg/l DO, contained sulfides that were lethal to fish.

Studies by Spurgel (1951), Mayhew (1963), Eley, Carter and Dorris (1967), and MacCallum and Regier (1970) show that vertical distribution of fish is deeper before stratification and during fall overturn than during summer stratification. Where epilimnetic water temperatures are suitable for warm-water fishes, stratification with complete hypolimnetic DO depletion (i.e., anoxia) will generally limit fish to the epipelagic and limnetic areas of the epilimnion (Spurgel, 1951; Byrd, 1952; Mayhew, 1963; Rael, 1966; Eley et al., 1967; MacCallum and Regier, 1970). A decrease in fishing success has been reported to coincide with stratification when fisherman fish below the metalimnion (Mayhew, 1963). In TVA reservoirs, fishing success decreased with occurrence of oxygen depleted density currents (Eschemeyer and Tarzwell, 1941). Fish make excursions into an anoxic hypolimnion (Pearce and Achtenber, 1920; Spurgel, 1951; Mayhew, 1963; Rael, 1966). For example, Pearce and Achtenberg (1920) report perch *(Perca flavescens)* could survive anoxic hypolimnetic water for 2 hours and make occasional short-term movements into the hypolimnion from the thermocline where they concentrate to feed on chironomid larvae. Behavorial response of fishes to gradients of DO, CO_2, and NH_4 are conflicting and show variations due to prior conditioning, temperature and interspecies variations (Powers and Clark, 1943; Whitmore, Warren and Danderoff, 1960; Summerfelt and Lewis, 1967). I believe that fish are not repelled by low DO but move out of water with low DO, or high CO_2 and NH_4 only after they begin to sense respiratory discomfort.

In Keystone Reservoir, Oklahoma, during periods of chemical and thermal stratification, temperature and DO were the most important variables affecting vertical distribution of fish (Eley et al., 1967). Species specific differences occurred but captures in vertical gill nets were generally above depths containing <2 mg/l DO. Heimer (1964) and Horak and Tanner (1964) found water temperature to be more important that the DO in the distribution of trout where DO was not limiting. Temperature was also given as the most important factor influencing the distribution of fish in Norris Reservoir, Tennessee (Dendy, 1945).

Thermal stratification also affects fisheries management by interfering with the dispersal and detoxification of some types of fish toxicants (Clemens and Martin, 1953; Turner, 1959; Foye, 1964) thereby reducing the success of efforts in lake reclamation to obtain a complete kill of undesirable fish populations. In certain stratified lakes containing a two-story fishery, warm-water fishes have been eradicated by chemical treatment of the epilimnion. Stratification prevented the fish toxicant from penetrating the hypolimnion and affecting the trout (Greenback, 1941; Hayes and Livingston, 1955).

Summerkills. - Fish mortality associated with summer thermal stratification has been related to: 1) mixing of anoxic hypolimnetic waters with the surface waters; 2) reduced photosynthesis because

[7] Fast (1971) defined adequate DO and temperature as 5.0 mg/l and temperatures less than 24° C.

[8] "A criterion is a characteristic of a physicochemical biological nature that is required to support a designated use" (Water Quality Criteria, 1968).

of climatic conditions; 3) algae toxins; and 4) disease, sometimes brought on because of oxygen stress. Fish kills due to DO depletion in stratified eutrophic lakes and reservoirs with warm-water fish populations may occur because of turnover and mixing of a large volume of anoxic hypolimnetic water with a smaller volume of epilimnetic water. Surface withdrawals can thin the epilimnion over a thickened hypolimnion which has a large biological oxygen demand (BOD) (Wiebe, 1940; Eley et al., 1967). Meterologic conditions causing an upwelling of oxygen depleted waters can cause a fish kill. Development of dense phytoplankton blooms in the epilimnion when followed by several days of warm, cloudy weather create an oxygen depletion because *in situ* oxygen production and wind agitation is insufficient to meet the BOD. Summerkills can be caused by dense surface "blooms" of bluegreen algae which shade out algae below the bloom and depress DO levels (Swingle, 1966). Release of algal toxins is associated with decay of large blooms of bluegreen algae (Mackenthun and Herman, 1948).

Summer stagnation conditions may indirectly cause fish kills by producing stressful conditions which precipitate epizootics among fish populations (Rock and Nelson, 1964). The role of stress in the resistance of disease is discussed by Wedemeyer (1970).

Eley et al. (1967) described thermal and chemical stratification which resulted in a summer fish kill within and downstream from an Oklahoma reservoir. They reported winter current into Keystone Reservoir, Oklahoma, which eventually caused a fish kill. In the winter, a chemical stratification of highly conductive waters occurred when dense, mineralized waters accumulated because the discharge at 1.2 m sub-surface was of less saline surface waters. Below 12 m DO was < 2 mg/l, whereas the lighter, less conductive water above 12 m had DO > 10 mg/l. Chemical stratification prevented spring overturn, and summer thermal stratification was superimposed on the chemical stratification. By July 1966 a thermocline was located at 5.6 m and anoxia in the Cimarron River arm of the reservoir occurred below 4.6 m. A fish kill occurred although oxygen in the surface waters were generally > 5 mg/l. Release of the denser, anoxic hypolimnetic waters at 20.1 m below the surface commenced in July. The discharge was well aerated and saturated with oxygen downstream from the dam, but it had a high BOD which reduced stream oxygen content as the water flowed downstream. Ammonia, however, was not eliminated by aeration. Concentrations of 12.4 mg/l ammonia 46 m below the dam were assumed to be responsible for a fish kill which coincided with the release. The low level discharge did reduce chemical stratification and fall overturn occurred.

Although a voluminous literature shows that activity, growth and production of both cold-water and warm-water fishes can be restricted by the lack of suitable levels of DO (Doudoroff and Shumway, 1967), the impact of stratification is largely limited to descriptions of vertical distribution. Mayhew (1963), however, observed growth checks and retarded growth of bluegill *(Lepomis macrochirus)* associated with the period of stratification in Red Haw Lake, Iowa.

Stratification with concurrent DO depletion removes a substantial portion of the lake basin from use by fish in the season when most of the annual fish growth occurs. Loss of habitat would appear to be a critical factor affecting annual fish production (Spurgel, 1951; Mayhew, 1963). Both intra- and interspecific competition between profundal and limnetic feeders would be increased as a result of diminution of habitat.

Age and growth of rainbow trout in three areas (canyon, open hills, and inflow) of Flaming Gorge Reservoir, located on the Green River in northwestern Utah and southwestern Wyoming, were described for 1965-1968 by Varley, Regenthal and Wiley (1971). Distinctive horizontal variation and limnological features of the reservoir varying from the inflow site to the damsite affected growth. Significant first and second year growth differences occurred: poorest growth occurred in the deeper canyon area nearest the dam, best growth in the inflow area. But, in 1969, filling of Flaming Gorge and inflow conditions, affected by discharges from Fontenelle Reservoir, forced the trout to avoid the inflow area and now their summer distribution is mostly limited to the hypolimnetic waters of the canyon area where growth was initially the poorest (Varley, personal communication[9]).

Norris Reservoir, a Tennessee Valley Authority (TVA) impoundment in Tennessee, lacked mayflies, dragon flies, caddisflies and beetle larvae but contained abundance of Diptera, *Chironomus* and *Coretha* larvae (Wiebe, 1938). Species diversity, represented by d is most commonly > 2 in oxygenated hypolimnetic areas of lakes or reservoirs (Wilhm, personal communication), but generally less

[9] John D. Varley, Division of Wildlife Resources, Utah State Department of Natural Resources, Salt Lake City, Utah.

than 1.0 in an anoxic hypolimnion indicating a stress similar to that found in streams receiving pollution (Wilhm, 1972). Ewing (1971) found very low diversity (d = 1.46 to 1.92) of the benthic macroinvertebrate community in Eufaula Reservoir, Oklahoma with frequent occurrences of monospecific communities (d = 0.0).

Perhaps, because of low macrobenthos diversity, observations on stomach contents of reservoir game fishes led some investigators to conclude that benthic invertebrates were of little importance in the reservoir food chains (Dendy, 1946; Eschmeyer, 1950), and that a plankton-to-fish food chain with plankton-gizzard shad-game fishes was the major basis for the sport fishery (Isom, 1971). This view of reservoir trophic interrelationship is an over simplification which fails to account for the important observations by Darnell (1958) and Baker and Schmitz (1971) which show that gizzard shad *(Dorosoma cepedianum)* are primarily bottom feeders and that organic detritus is their major food item. Although threadfin shad *(Dorosoma petenense)* are mainly limnetic feeders, organic detritus can represent a "significant addendum" to their diet (Baker and Schmitz, 1971). In Oklahoma, few reservoirs have threadfin shad, and the bulk of the diet of piscivorous fishes (white bass, *Morone chrysops;* gar, *Lepisosteus spp;* largemouth bass, *Micropteus salmoides;* and flathead catfish, *Pylodictis olivaris)* is gizzard shad (Moser, 1968; Turner and Summerfelt, 1970; Zweiacker, 1970; Summerfelt, 1971). The major portion of the volume of gut content of carp *(Cyprinus carpio)*, smallmouth buffalo *(Ictiobus bubalus)* and river carpsucker *(Carpiodes carpio)* was organic detritus (Summerfelt, Mauch and Mensinger, 1970; Tafanelli, Mauck and Mensinger, 1970; Summerfelt, Mauck and Mensinger, 1972). These fishes along with gizzard shad comprised a large percentage of the standing crop of many southeastern reservoirs.

Considerable quantities of organic allochtonous inflow enters the food chain (McConnell, 1968), however, Lind (1971) found that the major source of input in the organic matter budget of a central Texas reservoir was from *in situ* primary production. Oxidation rates of organic matter and primary productivity are likely to be altered by artificial destratification and aeration (Fast, 1971). Fundamental alterations in productivity and turnover rates will likely affect fish production, however, the outcome will have to be ascertained empirically as theoretical models of reservoir trophic interrelationships to predict these impacts are presently unavailable.

Applied studies

Artificial destratification. – Benefits, some only speculative, of artificial destratification include prevention of summer fish kills, enhanced production of fish food organisms, increased rates of organic matter decomposition, reversal of natural eutrophication process, and enhancement of favorable trophic conditions for fish by expanding fish habitat (Fast, 1966, 1968, 1971; Inland Fisheries Branch, 1970). As a tool for fisheries managers, it can facilitate mixing fish toxicants and herbicides, and detoxification after chemical treatment (Fast, 1966).

Artificial destratification can produce homiothermy, increase DO concentrations, and vent accumulation of CO_2 and H_2S and certain other compounds toxic to fish. Destratification experiments by Irwin et al. (1967) indicate that accumulation of toxic sulfides may not be vented to the surface in toxic concentrations if artificial mixing is slow. Fast (1966b) obtained reduction in algae blooms which reduced organic accumulation and hypolimnetic oxygen depletion by artificial destratification. Lackey (1971), however, found that numbers of blue-green algae increased with artificial destratification of a Colorado reservoir.

Hooper et al. (1963) lowered the epilimnion of a 1.46 h, limestone sink lake in northern Michigan by 4 m by pumping hypolimnetic water to the surface. This increased the volume of the epilimnion by 49.9 percent. Although the lake did not contain fish during their study, they concluded that the habitat for trout was greatly expanded. Total phosphorus in the epilimnion was increased temporarily but the increase was of small magnitude relative to equivalancy in commercial fertilizer. The authors speculated that the treatment increased the carrying capacity for trout beyond that which could be "safely achieved by artificial fertilization".

Johnson (1966) obtained greatly increased survival and production of coho salmon, *Oncorhynchus kisutch*, in a Washington lake by artificial destratification. In 3 years prior to artificial destratification, epilimnetic warming above 25° C and hypolimnetic DO concentrations $<$ 5 mg/l accompanying stratification, limited the water habitable by young coho salmon to 15 percent of the total volume. Compressed air mixing lowered surface temperatures and added oxygen to the hypolimnion. Total living space was increased greatly and coho salmon survival from fry to smolt stage was increased from 12.9 to 42.1 percent, although average size decreased slightly from 15.4 to 14.2 g. My computations from Johnson's data show that during 3 years of artificial destratification, annual smolt migrant biomass was 328 percent greater than the 3-year average biomass prior to artificial destratification. Johnson's report represents one of the most significant positive impacts of artificial destratification on a fish population; however, costs relative to increased production were not given.

Fast (1971) destratified an oligotrophic lake to examine its effect on distribution and survival of rainbow trout and other biota in limesink lakes in northern Michigan. Although zoobenthos and surface phytoplankton standing crop were reduced, destratification had little apparent effect on the biota. Midges emerged from greater depths during aeration but depth distribution of most organisms, other than crayfish, were not greatly altered. Riddick (1957), however, found a four-fold increase in *Cyclope* and *Diaptomus* following summer destratification.

Leach and Harlin (1970) accomplished complete thermal destratification of Lake Roberts in southwestern New Mexico in 3 days of aeration.[10] Lake Roberts, 28.3 ha at 1840 m mean sea level, had a history of summer fish kills which occurred because of hypolimnetic oxygen depletion and lethal surface temperatures. In the year of the study fish were restricted to the upper 3.6 m level where temperature was 18° C; the hypolimnion was 14° C and anoxic. After complete mixing, the entire water column was 18° C with a minimum DO of 6.0 mg/l. Aeration was stopped in 7 days and the lake restratified in 17 days. An anoxic hypolimnion again formed below 3.6 m. The lake was artificially destratified again for 40 days during which time the lake went completely anoxic from surface to bottom, causing a nearly complete fish kill. The anoxia was thought to arise from discharge over the lake's spillway of surface algae following a heavy rain, and from a high BOD caused by heavy algae mortality and circulation of bottom organic matter into the water column. Aeration was continued and fish were restocked when DO was partially restored but the lake became anoxic again, presumably as a result of decomposition of fish which died from temperature shock during stocking. After fall overturn the lake was restocked without further incident.

Wirth et al. (1966) studied the effects of a compressed air gun system on a small fertile Wisconsin impoundment. DO depletion was prevented at the bottom of the lake during the first summer of operation. Although DO concentration became temporarily low during the early part of summer, the fish habitat had been expanded and the numbers of bottom organisms had been increased. Midge larvae were present in significant numbers for the first time in March of the following year.

An unsuccessful attempt to modify environmental conditions of an eutrophic lake by aeration was made by Van Ray (1967). An aeration system consisting of three, 0.5 h.p. air compressors with plastic air lines, was operated 24 hours a day for a period of nearly 1 year. Heavy mortality of rainbow trout occurred in mid-July and limnological conditions during winter months were little changed from preaeration years. The failure of the aeration system to produce any beneficial effects on the lake environment was probably due to the advanced state of eutrophication and the small size of the aeration system.

Fast and St. Amant (1971) artificially destratified a southern California reservoir by nocturnal air injection. Their objective was to obtain mixing without increasing surface temperatures to create conditions suitable for maintaining rainbow trout throughout the year. During artificial mixing, suitable DO concentrations were maintained but surface temperatures increased above maximum levels tolerable by rainbow trout. They suggested hypolimnetic aeration, as used by Bernhardt (1967) and Fast (1968, 1971), as an alternative procedure as it potentially can oxygenate the hypolimnion without disturbing stratification thereby maintaining the cool water suitable for trout.

Hypolimnetic aeration. — Aeration without destratification can increase DO without appreciably changing the heat budget or maximum temperatures. The latter is an advantage in regions where cold-water fishes are desired. Destratification may eliminate certain cold-water fishes when temperature becomes limiting. Bernhardt's (1967) aerator can accomplish hypolimnetic aeration without destratification, thus, potentially improving water quality for fishes without exceeding their temperature tolerance.

Fast (1971) aerated the hypolimnion of Hemlock Lake, Michigan, using a hypolimnetic aerator of a design different than that used by Bernhardt. Hypolimnetic DO values increased from 0.0 before

[10] Additional observations on the Lake Roberts study, including physicochemical conditions, and effects on fish and zooplankton are reported by McNall (1971).

aeration to over 11 mg/l after aeration. Thermal stratification was maintained during aeration. Rainbow trout, restricted to levels above 8 m before aeration, extended their distribution throughout the lake as hypolimnetic anoxia was eliminated.

Hypolimnetic aeration can have an important impact on southern impoundments because anoxic hypolimnetic waters with temperatures suitable for salmonids can be aerated and the lake transformed into a two-story fishery. This would permit the establishment of unique salmonid fisheries in southern waters where otherwise warm epilimnetic and anoxic hypolimnetic water prevent their existence.

Ice cover and winterkill. — Shallow, productive dimictic lakes of the northern tier states of the United States, and Canada often have conspicuous over-winter fish mortality. The cause of winterkill in these lakes is due to oxygen depletion occurring because BOD exceeds *in situ* DO production when the lake surface is ice covered and blanketed by heavy snow cover. (Greenbank, 1945; Cooper and Washburn, 1946; Welch, 1952; Hutchinson, 1957; Reid, 1961.) Typically, DO in the lakes is saturated during fall overturn but severe oxygen depletion occurs under snow-covered ice because of reduced *in situ* photosynthetic oxygen production (Greenbank, 1945). Municipal effluents and fertilization of oligotrophic lakes to enhance fish production contributes to undesirable eutrophication causing winterkills (Hasler, 1947; Tanner, 1960).

Several methods have been applied to correcting the problem of winterkill, each having varying degrees of success (Patriarche, 1961): (1) diverting a flow of water into the lake; (2) raising the water level; (3) cutting holes in the ice; (4) pumping air into the water; (5) vegetation removal before ice cover occurs; (6) snow removal. Aeration is used to circulate lake water to the surface to melt the ice cover. Aeration is used to circulate lake water to the surface to melt the ice cover. Aeration usually begins with a channel above the air line but wind action is an important factor in expanding the channel. Generally, the direct addition of oxygen to the water by the aeration apparatus is small and beneficial effects depend on melting the ice cover to facilitate *in situ* oxygen production by green plants and to exposure of water to the atmosphere. It has had wide application and in many cases has been fairly successfully applied to deicing lakes (Hemphill, 1954; Schmitz and Hasler, 1958; Burdick, 1959; Schmitz, 1959; Rasmussen, 1960) and also to fall aeration of lake water prior to development of ice cover (Halsey, 1968). As a secondary objective, aeration may be applied to popular fishing lakes to break up ice cover sooner than normal (Seaburg, 1966).

Hemphill (1954) reported successful application of aeration to prevent winter mortality in a 2.4 h. mountain lake (2745 m elevation, mean sea level) in Arizona. Schmitz and Hasler (1958) maintained water and DO levels > 2 mg/l throughout the winter with the use of small aerator systems. Burdick (1959) reported several Wisconsin applications such as maintaining an ice-free lagoon to provide open water for ducks; keeping a ditch free of ice to concentrate northern pike for a fish salvage operation in a lake which had frequent winterkills; keeping area water open in a large hatchery pond to facilitate feeding trout; application to a private lake for maintaining winter DO concentrations suitable for overwinter survival of trout. Burdick indicated a cost of $158 for equipment and operating costs to keep 242 m^2 area free of ice for 43 days.[11] Preliminary experiments were cited which showed the possibility of causing winterkill by reducing oxygen concentration before ice cover can be removed.

Tubb (1966) conducted a study to determine the effects of aeration on small eutrophic winterkill lakes in North Dakota. Aeration maintained winter DO levels above 1 mg/l. Tubb suggested that the higher DO content of the aerated lakes may be due to a combination of atmospheric diffusion and the stripping of reduced gases by bubble action.

Patriarche (1961), Woods (1961), and Seaburg (1966) were all unsuccessful in preventing winterkill with small scale aeration systems. In some cases, circulation of bottom water by aeration through perforated pipe mixes water containing a high BOD with surface waters which already have low DO. In this case, aeration can intensify a natural fish kill by removing more of the DO (Patriarche, 1961). Patriarche speculated that year-round mixing might facilitate oxidation of organic matter present in the summer months thereby avoiding summer accumulation of BOD. Obviously, control of allochtonous organic and nutrient input would also help. Fertilization of shallow northern lakes, considered a potentially effective procedure for enhancing fish production, has been discouraged because it builds up organic matter and BOD by autochtonous production (Hasler, 1947).

The Utah State Department of Fish and Game attempted to prevent a winterkill in a large, shallow

[11] Economic analysis are uncommon, however Carufel (1962) reported an operating cost of $400 for 27 weeks of operating two pumps for winter aeration of two North Dakota lakes.

lake with the use of a compressor and several hundred feet of perforated hose (Dotson, 1962). The system succeeded in opening a section in the ice but failed to prevent a substantial loss of trout.

Dotson (1962) took a pessimist view of efforts to prevent winterkill by aeration. He concluded that the only apparent cure for winterkill is the raising of the water level to create more volume of water for oxygen storage. Some failures to remove ice cover and effectively add oxygen to the water by aeration are attributable, in part, to small capacities of certain commercial equipment relative to water depth over the air lines and the thickness of the ice cover. There seems little doubt that large equipment as used in several lake studies by Leach (1968) and Symons, Carswell and Robeck (1970) employing air diffusion apparatus, rather than perforated hose, would, in most cases, melt the ice of shallow eutrophic lakes and oxygenate the water. However, the economic feasibility for managing winterkill lakes has not been established.

Effects of Impoundments on Stream Invertebrates and Fishes

Basic studies. — Detrimental effects of reservoir discharges on stream fishes occur because of the high volume and fluctuations of the discharge, temperature extremes, low DO, high BOD content, supersaturation with nitrogen, and presence of toxic substances such as hydrogen sulfide and ammonia. Although the normal fluctuation in streamflows are reduced, the daily fluctuations in volume are such as to scour the tailwaters and wash out food and cover. Detrimental effects of fluctuating volumes of water discharges are not going to be altered by aeration.

In the summer, low-level penstock outlets of a stratified reservoir discharge water much colder than would have been the case for the natural stream (King and Kinney, 1965): "During the period from 1946 to 1956, investigations conducted on the effects of bottom discharges from reservoirs in Arkansas, Tennessee, and Kentucky revealed that several downstream warm-water fisheries had been virtually eliminated by cold-water (i.e. hypolimnetic) discharges." King and Kinney report that summer water temperatures downstream from a damsite may average 5.5° to 11.0° C lower than preimpoundment temperatures. Even lower temperatures are not uncommon. Average summer water temperatures in the Clinch River, Tennessee, were reduced from 26.7° C under preimpoundment conditions to 8.9° C in Norris Reservoir discharge (Isom, 1971). Similar declines in river water temperatures were noted in the Green River below Flaming Gorge Reservoir (Vanicek, Kramer and Franklin, 1970). Prior to closing of the dam in 1962, monthly mean river water temperatures were 14.6°-21.1° C June-August, but after impoundment they ranged from 4.5°-10.0° C.

Comparison of pre- and post-impoundment of fish populations in the Green River indicated a highly detrimental impact on certain fish and benthos from high volume, low temperature discharges for 104.6 km downstream from the Flaming Gorge Dam (Pearson, Kramer, and Franklin, 1968; Vanicek and Kramer, 1969; Vanicek, Kramer and Franklin, 1970). Native fishes diappeared completely in the first 11.3 km below the dam, and a reduction in numbers of native fishes occurred up to 104.6 km downstream to the confluence of the Green and Yampa Rivers (Vanicek, Kramer and Franklin, 1970). No reproduction of any native fishes occurred in the Green River above the mouth of the Yampa River. Taxonomic diversity of bottom fauna increased but the density of bottom fauna decreased progressively downstream from the dam (Pearson, Kramer, and Franklin, 1968). Growth of the Colorado river squawfish, *Ptychocheilus lucius,* the largest native minnow in North America and classed as a rare and endangered species, and that of the Colorado chub, *Gila robusta,* have been reduced in an area 74 km downstream from Flaming Gorge dam on Green River compared with preimpoundment growth (Vanicek and Kramer, 1969). The squawfish were not found closer than 105.4 km downstream from the dam site whereas before impoundment, they were collected in that area of the Green River. The chub were not collected closer than 75.6 km from the dam site.

Some cold tailwaters have created cold-water zones that provide excellent trout fisheries in geographical areas where climate and natural springs are lacking natural trout population (Tarzwell, 1938; Baker, 1959). Although tailwater trout fisheries lack suitable spawning conditions and are maintained by stocking, growth and survival in certain tailwaters can be excellent. Biomass harvested can be several times the initial stocking weight (Parsons, 1957). Often overlooked, however, is the stream section too warm for trout but too cold for satisfactory growth and reproduction of warm-water fish (Funk, 1970).

Isom (1971) reviewed effects of TVA storage and mainstream reservoirs on stream biota. The review indicates detrimental effects of low temperature and low DO on commercially valuable pelecypods, stream invertebrates and fishes. Both the diversity and biomass of invertebrate fauna in tailwaters is generally reduced. Oxygen deficiency associated with hypolimnetic oxygen depletion eliminated most typical trout stream macroinvertebrates in reservoir tailwaters.

Epilimnetic discharges from reservoirs can warm the water excessively for trout. Hydroelectric discharges produce pronounced diel fluctuations in release which produce highly variable temperature and DO conditions. Anoxic hypolimnetic discharges can eliminate fish from the immediate tailrace. Potentially, serious losses of Columbia River salmonids due to a myxobacterial disease has been increased with increasing water temperatures associated with impoundments (Pacha and Ordal, 1970).

On the Columbia River, water falling over spillways of large dams into deep plunge basins entrains high levels of nitrogen gas (over 125 percent saturation). Gas bubble disease has caused high mortality to adult and juvenile salmonids (Beiningen and Ebel, 1970). The problem also occurred below impoundments on the Snake River and is said to be "an urgent management crisis" (Sport Fishing Institute, 1971).

Applied studies. — Corrective measures to remedy poor water quality from impoundments have been under study since the early 1940s (Hull, 1958). Controlling levels of discharge and mixing levels are methods whereby desirable temperature and oxygen can be obtained in tailwaters of thermally stratified reservoirs. Recent emphasis includes turbine and tailrace aeration (Wisniewski, 1965) and reservoir destratification or hypolimnetic aeration and mixing (Bryan, 1965; Leach, Duffer and Harlin, 1970). The Sport Fishing Institute (Stroud, 1970) has assisted in examining the effectiveness of penstock depth on aquatic life within multipurpose reservoirs. Hester (1965) encouraged use of multilevel intake gates on multipurpose reservoirs for better downstream water quality of stream fishery benefits.

Leach, Duffer and Harlin (1970) released pumped compressed air into the hypolimnion immediately upstream of the power penstock intakes in Eufaula Reservoir, Oklahoma. Although they initially desired to aerate only the hypolimnion, DO was increased 55 to 80 percent in downstream releases. Observations by Speece (1970) indicate potential application of an aerating technique for completely saturating releases in reservoir discharges with DO. Unfortunately, however, the procedure injects nitrogen in excess of 104 percent saturation which would likely cause gas bubbles disease in salmonids.

A downflow bubble system described by Speece (1969) has promise as an instream device which adds oxygen and removes excess nitrogen. This apparatus should receive immediate attention for tailwaters having problems with nitrogen supersaturation.

[12] This section was written by Dale W. Toetz.

CONCLUSIONS

Used alone or in combination with engineering modifications of penstock discharges, aeration portends opportunities for significant modification of reservoir and tailwater environments. However, biological reaction to physicochemical changes are presently not predictable because comprehensive ecological monitoring and modeling of perturbations produced by aeration have not been undertaken.

Artificial destratification has increased fish habitat, increased fish production, and production of macroinvertebrates used by fish. Some failures resulted in part because of inclement weather and inadequate equipment, however, in other cases, aeration, when there exists a large BOD, has caused fish kills. There is hope that in the latter cases, continuous year-around aeration would enhance aerobic biodegredation of organic matter, oxidize or vent toxic products prior to this accumulation thereby avoiding fish kills. Aeration may be used to manage water quality of reservoir discharges and certain instream devices may be used to remove nitrogen supersaturation.

Downstream Effects of Artificial Destratification [12]

To our knowledge there have been no studies on downstream effects of artificial destratification, except for the report of Wirth et al. (1970) on U-tube aeration at the dam, the paper by Leach et al. (1970) on induced hypolimnion aeration for water quality releases, and reports of workers who sought to increase DO in water releases through the use of weirs, turbine aeration, etc. (Knight, 1965; Wisniewski, 1965; and Susag, Robins, and Schroepfer, 1967).

Wirth et al. (1970) report that after U-tube aeration in a modified U-tube in the damsite, the concentration of DO in hypolimnetic water rose from zero to 7 mg/l. The concentration of DO fell to 4-5 mg/l after the first 304 m downstream, but then rose again. Dense stands of macrophytes grew in the stream so it is difficult to interpret effects far downstream.

Wirth et al. (1970) also monitored N and P plant nutrients. The data for inorganic N reveal a very high proportion of N in reduced form. Apparently, the hypolimnetic water can be easily recharged with DO in transit through the U-tube, but the period of transit is insufficient for oxidation of other reduced compounds. Perhaps, the decrease in the concentration of DO in the first 304 m of the stream was due to intense nitrification. When anoxic water from the hypolimnion was released, a fish kill occurred below Keystone Reservoir, Oklahoma. Fish mortality was caused, not by low concentrations of DO, but by toxic concentrations of ammonia (Eley, Carter, and Dorris, 1967).

The net effect of hypolimnetic discharge on temperature was to reduce the maximum temperatures in the stream during the summer, raise minimum temperatures during the winter and reduce the diel minimum temperatures (Wirth et al., 1970). These effects might be anticipated without U-tube aeration, if discharge was made from the hypolimnion.

Leach et al. (1970) aerated Lake Eufaula, Oklahoma, in the vicinity of the penstocks of the dam. Both the concentration of DO and the percent saturation of DO were higher in the water released during lake aeration than before. At low rates of discharge, the effect of aeration was less prounced than at high rates of discharge.

Water releases from the bottom of impoundments, that have been artificially destratified, ought to contain a higher concentration of DO, have a preponderance of compounds in the oxidized state, and have an alkaline pH. In general, this water ought to resemble water from the epilimnion. But, the water from the bottom of an artificially destratified reservoir ought to be warmer. This might have disastrous effects on a cold-water fishery in the receiving stream.

While the physical and chemical properties of released water will have ecological effects downstream, the rate of streamflow and changes in this rate may have an even greater impact on the stream biota. This ought to be taken into account when assessing the ecological effects of reservoir aeration on downstream reaches.

Effects of Instream Aeration[13]

Engineering methodology for instream aeration is relatively new in the United States. Papers by Hogan, Reed and Starbird (1970), JBF Scientific Corporation (1971) and Whipple and Yu (1971) give a good overview of the state of the art. Hunter and Whipple (1970) and Whipple, Coughlan and Yu (1970) describe results of field tests, but ecological data are difficult to glean from their papers.

It will be hard to use aeration techniques in streams and rivers to raise the concentration of DO above 4 mg/l without the use of supplemental oxygen (JBF Scientific Corporation, 1971). Therefore, it is likely that the technique will be employed where waters are severely polluted.

Instream aeration resembles a natural process in that the longitudinal turbulence induced is characteristic of free-flowing rivers. Artificial aeration, however, induces a mixing cell of various proportions in which the movement of water is not wholly longitudinal, e.g. there is quite strong lateral and vertical mixing. This mixing cell might be effective in generating currents from bank to bank in small rivers, where the aeration apparatus is installed in midchannel (Whipple and Hunter, 1970). In large rivers this gear will be placed near the bank, out of the main channel, especially if the river is used for navigation. The placement of this gear and the currents it generates might have an effect on the movement of fish, but such conclusions can only be speculative at this time.

The degree to which instream aeration is apt to resuspend riverine sediments is not clear. Since this gear will be used on severely polluted rivers, which often contain large loads of pollutants in their sediments (Mathis and Cummins, 1971), it would be desirable to investigate the effect of disturbing these sediments by aeration.

Aeration by U-tube has great potential, but when used with air injection it may cause supersaturation of nitrogen. This situation is undesirable for fish. With any aeration device there will be rapid changes in the mass and/or the percent saturation of dissolved gases in water. The impact of these changes on the biota is not entirely clear, although the problems of supersaturation of nitrogen are well known.

RESEARCH NEEDS

Greater emphasis must be placed on design and experimentation in studies involving artificial destratification. A team approach is necessary in assessing the effects of artificial destratification on lake ecology. Studies should include rigorous controls so that specific questions can be answered at least for small lakes. It is also useful to develop models to predict and quantitate the perturbation on the system in order to optimize engineering efforts. Long-term changes on a reservoir ecosystem ensuing from annual artificial destratification as compared with antecedent conditions should be analyzed and compared with previous findings derived from observations made in a single summer. A need exists for comparative analysis of the impact of artificial destratification on reservoir ecosystems in different geographical regions in North America. Efforts should involve a decade of sustained effort on one ecosystem. Artificial destratification or hypolimnetic aeration should be considered to be a

[13] This section was written by Dale W. Toetz.

scientific research project with data carefully recorded and deposited regularly in a central data bank to be available to all researchers. Greater effort must be made to develop aeration tactics in rivers which take advantage of the natural fall of water. These devices ought to require no input of fossil fuel or nuclear energy. There is a need to combine aeration with other engineering alternatives to optimize water quality within and downstream from reservoirs.

Additional effort is needed to study effects of artificial destratification on rates of mineral cycling. Nitrogen stripping using a downflow bubble contact system as described by Speece (1969) should be given immediate review as a possible means for stripping nitrogen from water to alleviate nitrogen supersaturation which causes salmonid mortality. Information on the impact of artifical destratification on cycling of heavy metals, pesticides, and other pollutants is limited. Some hold that since many pollutants (e.g. copper) are lost to the sediments in alkaline and oxygenated waters, artificial destratification and aeration may be a satisfactory means of improving water quality. However, sediment-water exchanges cannot be predicted for many elements and compounds at this time (Lee, 1970). Thus, potential pollutants must be monitored in the sediments before an artifical destratification attempt is made, especially if it is not known whether mixing will result in suspension of some sediment.

More research is needed on the effect of artificial destratification on structure and function of the biotic community. Information is needed on species diversity of the various groups, population dynamics, microbial ecology, especially human pathogens, and secondary productivity. Further testing of the hypothesis that continuous aeration will retard the process of eutrophication and development of blue-green algal blooms is needed. A need exists to test promising hypotheses of the impact of annual cycles of destratification on dynamics of reservoir fish populations, especially important vital statistics on density, growth, mortality, and recruitment. Careful evaluation of the impact of aeration using U-tubes on fish and other aquatic life needs to be accomplished. Continuous destratification of northern winterkill and southern eutrophic lakes with histories of winterkill should be achieved to evaluate the hypothesis that effective oxidation will reduce detrimental effects on distribution, density, and productivity of aquatic fauna. Downstream effects on aquatic life associated with reservoir aeration needs study.

Additional symposia on reservoir ecosystems are desirable as they produce useful compendia of data, highlight accomplishments, and research needs. A special symposium on aeration of natural and man-made lakes would be desirable. The authors encourage a greatly expanded program of funding of research by Federal agencies charged with responsibility for hydroelectric, water supply, flood control, and irrigation developments.

BIBLIOGRAPHY PREFACE

Most of the papers reviewed were in the English language. The authors of some abstracts are noted at the end of the text by abbreviations as follows:

Abbreviation	*Author*
SWRA	Selected Water Resources Abstracts
LB	Larry Bowles
JNJ	Jeffery N. Johnson
MM	Michael Mnich
RS	Robert Summerfelt
DWT	Dale W. Toetz
JW	Jerry Wilhm

A

Albrecht, D, 1968
THE AERATION OF RUHR RIVER AT THE SPILLENBURG WEIR
Wass Stuttg 58: 317-321

The authors report measurements to assess the efficiency of two special type of weirs providing aeration of the oxygen-deficient Ruhr water: a free-falling weir ("plunging weir") and a step weir ("shooting weir"). Factors affecting the aeration above and below the weirs are discussed —DWT

APPLIED
rivers
aeration
physical properties

Albrecht, D, 1969
ASSESSMENT OF OXYGEN SUPPLY THROUGH WEIRS AND CASCADES
Wass Stuttg 59: 321-323

The author reviews and discusses the results of studies on the assessment of artificial aeration to improve oxygen concentration in polluted rivers. He compares the effect of mechanical aeration (turbine or propeller type) with that of weirs and explores the usefulness of cascade aeration —DWT

APPLIED
rivers
aeration
physical properties

Amberg, H R, Wise, D W and Aspitarte, T R, 1969
AERATION OF STREAMS WITH AIR AND MOLECULAR OXYGEN
TAPPI 52: 1866-1871

Methods of increasing the dissolved-oxygen content of streams using air or molecular oxygen are described. Power turbines using molecular oxygen are efficient and inexpensive. Aeration by means of a gas diffuser placed on the stream bottom was less efficient than turbine venting but absorption efficiencies were higher. When a portion of the streamflow was oxygenated under pressure and returned to the stream by means of an underwater diffuser, oxygen absorption efficiencies of 55 percent were attained, and the concentration of the dissolved-oxygen of the combined stream was increased. Aeration with air is effective only when the oxygen deficit is relatively high —DWT

APPLIED
rivers
aeration
physical properties

Ambühl, H, 1962
DIE KÜNSTLICHE BËLUFTUNG DES PFÄFFIKERSEE (ORIENTIERUNG ÜBER DIE ERSTEN ERGEBNISSE)
—Verb Schweiz Abwasserfachleute, Verb ber Nr 77/3

Pfaeffikersee is a lake in Switzerland. It was the site of an experiment to learn the effects of artificial ventilation. The ventilating device, a cylindrical tube about 2 m in diameter, was installed from just above the bottom of the lake to just below the surface of the water. Water was circulated in it by the force of compressed air. The experiment, from July 1958-Fall 1962, was discontinued during the winters. The tube placed in three test positions produced no great differences in results. Ventilation caused the temperature and oxygen content of Lake Pfaefferiker to increase over that of nearby Lake Greifen, but anaerobic conditions developed in both lakes during the summers. The nitrate content rose and the ammonia content fell in Pfaeffiker but these contents were reversed in Greifen. Hydrogen sulfide was present in small amounts or not at all in Pfaeffiker, presumably an improvement in water quality resulting from ventilation. Effective ventilation requires that sewage influx be stopped —SWRA

APPLIED
lake
destratification
physical properties
chemical properties

Ambühl, H, 1967
discussion of "IMPOUNDMENT DESTRATIFICATION BY MECHANICAL PUMPING" by W H Irwin, J M Symons, and G G Robeck
J Sanit Eng Div, Proc Am Soc Civ Eng 93(SA4): 141-143 Republished in 1969, pp 287-290 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio 616 p

APPLIED
lake
destratification
microorganisms
physical properties

Ambühl describes an unsuccessful attempt to improve the water quality of Lake Pfäffekon, near Zurich, Switzerland. Despite aeration, mammoth growths of *Aphanizomenon* and *Peridinium* are reported. Stratification of dissolved oxygen was reported to remain undisturbed. Thermal stratification was not completely destroyed —DWT

chemical
properties

Anon 1960
NEW LIFE FOR POLLUTED SWEDISH LAKES
Water Wast Treat J 8: 65

The beneficial effects of aerating Swedish lakes are described

APPLIED
lake
destratification
physical
properties
chemical
properties

Anon 1962
DESTRATIFICATION OF IMPOUNDMENT WATER
Water and Water Eng 66: 112-115

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Anon 1963-64
FURTHER STUDIES OF PHYSICAL, CHEMICAL AND BIOLOGICAL CONDITIONS IN THE THAMES VALLEY STORAGE RESERVOIRS
Ext Forty-First Report, Director of Water Examination, Metropolitan Water Board 110 p

The jet type inlet systems in Queen Elizabeth II reservoir, United Kingdom, are described as well heir function in mixing the reservoir. Reservoir seiches are described for King George VI reservoir. The problem with fixed outlets on reservoirs with seiches is discussed —DWT

APPLIED
reservoirs
physical
properties
chemical
properties

Anon 1965-66
FURTHER STUDIES OF THE PHYSICAL, CHEMICAL AND BIOLOGICAL CONDITIONS IN RIVERS, STORAGE RESERVOIRS AND FILTER BEDS.
Ext Forty-Second Report, Director Water Examination, 1965 and 1966, Section X, Metropolitan Water Board 106 p

This paper reports the 1966 destratification of King George VI reservoir, United Kingdom. The observations on water chemistry during this effort are compared to a single "statistical control year." The epilimnion was lowered 6.5 m in 1 month by mechanical suction pumping. The 100 percent saturation isopleth for dissolved oxygen decreased from about 8.5 m to 13.0 m. The concentration of silica in the epilimnion increased after the onset of pumping from 0.5 to 3.0 mg/l, only to decrease afterward, apparently due to uptake by *Asterionella formosa.* This diatom increased in numbers after pumping began and reached bloom proportions during late July (about 4 months later in the year than when it ordinarily reaches maximum density in the Thames Valley) and decreased markedly during early August. Coincident with the onset of pumping, blue-green algae increased in density but the population did not reach "bloom" proportions. The first mixing in July eliminated a well-established population of green algae and Crytomonads —DWT

APPLIED
reservoir
destratification
microorganisms
physical
properties
chemical
properties

Anon 1966
THE AIR-BUBBLES SYSTEM, A NEW LIFE FOR POLLUTED WATER
Techq Eau Assain No 237, pp 43-47 Not seen

APPLIED
lakes
destratification
physical
properties
chemical
properties

Anon 1968
MANIPULATION OF RESERVOIR WATER FOR IMPROVED QUALITY AND FISH POPULATION RESPONSE
Wis Nat Resour Dept, Water Resour Res Section

A project was undertaken to test the effect of several water management techniques on the water quality and fish populations in artificial lakes and their discharge waters. Two small lakes in steep-sided wooded valleys in Governor Dodge State Park in southwest Wisconsin were studied. During summer, algae are a nuisance, surface temperatures are too high, nutrient concentrations are too high, and dissolved oxygen is absent in the bottom layer. In winter, the oxygen level under ice is critically low for fish. Bottom water discharge and air-gun induced circulation were studied as means of alleviating the nutrient and stratification problems. Preliminary results were good. In the circulation program, severe stratification was broken down, temperatures were reduced 5°–10°, dissolved oxygen was restored at the bottom, water clarity was improved, nutrient concentrations were lowered, snails populated the bottom, and complete freeze-over was prevented. In the bottom-discharge program, water was aerated in the outlet works and downstream water quality was greatly improved –SWRA

APPLIED
reservoir
destratification
reservoir
releases
benthos
physical
properties
chemical
properties

Anon 1970
9.5 MGD OF HOMOGENOUS GOOD QUALITY ODOR-FREE WATER
Air-Aqua Case History 3639 San Clemente Raw Water Storage Reservoir, Monterey, Calif Hinde Engineering Company, Highland Park, Ill

APPLIED
reservoirs

Anon 1970
ALGAE CONTROL BY MIXING, STAFF REPORT ON KEZAR LAKE IN SUTTON, NH
New Hampshire Water Supply and Pollut Control Comm, Concord Final Rept NERCOM-EP-71-01 109 p

The report concerns a project conducted to demonstrate the control of algae by destratification. The results obtained during the first 2 years of the demonstration (1968-69) are reported herein. The test lake was the 182-acre Kezar Lake in North Sutton, New Hampshire. Homogenizing, mixing or destratifying Kezar Lake was accomplished by forcing compressed air, from shore-located compressors, through PVC, 2-inch-diameter piping to the deepest portion of the lake where it was released through the water column. Clarity of the water was visibly and measureably improved; the populations of noxious algae, so objectionable to reaction interests, were decreased in number; and no harmful effects were detected. Operating pressures for the compressors are low. The equipment is convenient for necessary maintenance, and the operating and study budget is modest –Author (See also Haynes 1971)

APPLIED
lake
destratification
micro-organisms
physical
properties
chemical
properties

Anon 1971
ARTIFICIAL DESTRATIFICATION IN RESERVOIRS, A COMMITTEE REPORT
J Am Water Works Assoc 63(9): 597-604

This paper is a report of the American Water Works Association's Committee on Quality Control in Reservoirs. The paper describes the results of a questionnaire survey of the directors of waterworks, who used reservoir aeration to improve water quality. Information sought was (1) data on the reservoir (2) raw-water quality problems (3) reservoir mixing equipment (4) operation of mixing equipment (5) operating and initial costs (6) evaluation of the project (7) quality problems and (8) future plans. The conclusion of the committee was as follows: "Not all of the factors related to the use of artificial destratification as a method for water-quality control are known. The results of this survey, however, are sufficiently widespread and encouraging for the

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properties

committee to recommend this relatively inexpensive technique to water suppliers who are experiencing raw-water quality deterioration in their reservoirs as a result of anaerobic conditions in the hypolimnion caused by thermal stratification" —DWT

Anon 1971a
ALGAE CONTROL BY MIXING
Staff Report on Kezar Lake in Sutton, N H, prepared for the New England Regional Commission by New Hampshire Water Supply and Pollut Control Commission April 1971

During summers 1968 and 1969, Kezar Lake, New Hampshire, was aerated with a compressed air system. The effects of aeration are compared to conditions existing just before aeration began or during previous years. The effect of aeration on water temperature, water chemistry, transparency, and phytoplankton density is described. See Haynes (1971) for a thorough evaluation of the effects —DWT

APPLIED
lake
destratification
microorganisms
physical properties
chemical properties

Anon 1971b
AERATION SYSTEM REVITALIZES LAKES
Civil Eng May 1971

This article describes two "benefits" of aeration of lakes by compressed air: preventing ice cover from forming and increasing the recreational utility of a wastewater disposal pond for sport fishing —DWT

APPLIED
lakes
ponds
reservoirs
aeration

Anthony, M and Drummond, G 1971
RESERVOIR WATER QUALITY CONTROL
Presented at the International Symposium on Man-Made Lakes, Knoxville, Tenn, May 3-7, 1971 7 p

Cause and effect relationships involving the impoundment size and shape and the topographic, geologic, hydrologic, and land use characteristics of the watershed vary significantly. To evolve effective design and regulating procedures, it is necessary to evaluate and predict a number of specific impoundment properties including thermal stratification, the aspects which are described by the term "eutrophication," and the many aerobic and anaerobic reactions created by a spectrum of inflowing chemical constituents. While control of reservoir storage and release quality is extremely complicated, specific goals can be achieved. A fundamental consideration is the design of the reservoir outlet works. Experience with existing structures, model studies, and increasingly sophisticated predictive techniques has enhanced design approaches for selective withdrawal outlets. These outlets, along with adequate control of watershed pollution and appropriate wastes quality data acquisition, promise a much greater degree of control —Authors

APPLIED
reservoirs
reservoir releases
chemical properties
physical properties

Applegate, Richard L and Mullan, James W 1967
ZOOPLANKTON STANDING CROPS IN A NEW AND AN OLD OZARK RESERVOIR
Limnol Oceanog, 12: 592-599

The zooplankton populations (April 1964 through June 1966) of Beaver Reservoir before full impoundment are compared with those of 14-year-old Bull Shoals Reservoir, both on the White River in the Arkansas-Missouri Ozarks. Seasonal standing crop estimates show a unimodal curve in the old reservoir and a bimodal curve in the new reservoir. Significant seasonal differences between the reservoirs occurred in densities, species composition of cladoceran communities, and horizontal distribution. An increase in the standing crop in the new reservoir in spring 1966 was associated with species changes within the genus *Daphnia*. Mean annual standing crops of entomostracans and rotifers were similar in the two impoundments —Authors

BASIC
reservoir
zooplankton
biological communities

Augenfeld, J M 1960
A STUDY OF THE ECOLOGICAL PHYSIOLOGY AND THE RESPIRATORY ENZYMES OF SEVERAL DIPTERA
Diss Abs 21(3): 704-705

BASIC
benthos

Augenfeld, J M 1967
EFFECTS OF OXYGEN DEPRIVATION ON AQUATIC MIDGE LARVAE UNDER NATURAL AND LABORATORY CONDITIONS
Physiol Zool 40: 145-158

Starved larvae of two chironomid species in oxygen-saturated water lost 0.56 percent *of their dry weight in glycogen per day while larvae in* oxygen-free water lost 0.96 percent. The glycogen content of larvae supplied with food but without oxygen and of larvae of *C. plumosus* collected from an anaerobic hypolimnion is described and discussed —DWT

BASIC
lake
benthos

Augenfeld, J M and Neess, J C 1961
OBSERVATIONS ON THE RESPIRATORY ENZYMES OF VARIOUS LIFE-STAGES OF *CHIRONOMUS PLUMOSUS, CHIRONOMUS STAEGERI,* AND *AEDES AEGYPTI*
Biol Bull 120 (2): 129-139

Larvae of *Chironomus plumosus* and *Chironomus staegeri,* (Chironomidae: Diptera), have an active glycolytic system. The succinoxidase and cytochrome oxidase systems of *C. plumosus, C. staegeri,* and *Aedes aegypti* are least active in the larval stage, more active in the pupal stage, and most active in the adult stage —Authors

BASIC STUDIES
benthos
chemical
properties

B

Baker, C D and Schmitz, E H, 1971
FOOD HABITS OF ADULT GIZZARD AND THREADFIN SHAD IN TWO OZARK RESERVOIRS
In G E Hall (ed), Reservoir Fisheries and Limnology Spec Publ No. 8, Amer Fish Soc, Washington, DC, pp 3-11.

Organic detritus was the major food item of gizzard shad and it was a large portion of the diet of threadfin shad. The role of organic detritus in the diet of gizzard shad was stressed —RS

BASIC
reservoir
microorganisms
zooplankton
fish

Baker, D B and Kramer, J W, 1971
WATER QUALITY CONTROL THROUGH FLOW AUGMENTATION
Water Pollut Contr Res Series 16080 DFO0 1/71 EPA/WQO 156, p

To evaluate effects of augmentation from upground reservoirs on water quality, studies of the relationship between water quality and riverflow were undertaken in a 60-mile section of the Sandusky River in north-central Ohio. Oxygen concentrations were near saturation at medium and high flows but varied widely above and below saturation at low flows. In most river sections, algal respiration rather than BOD was responsible for low DO. It is predicted that flow augmentation will significantly reduce algal growth in the stream, with increased flow velocity being more important than dilution of algal nutrients —Authors

APPLIED
river
microorganisms
physical properties
chemical properties

Baker, F C, 1918
THE PRODUCTIVITY OF INVERTEBRATE FISH FOOD ON THE BOTTOM OF ONEIDA LAKE, WITH SPECIAL REFERENCE TO MOLLUSKS
New York State Coll Forestry, Tech Publ 9, 264 p (Not seen)

BASIC
lake
benthos

Baker, R F, 1959
HISTORICAL REVIEW OF THE BULL SHOALS DAM AND NORFORK DAM TAILWATER TROUT FISHERY
Proc S E Assoc Game and Fish Comm 13: 229-236

An example of papers describing trout fisheries developed in cold-water tailwaters below stratified southern impoundments —RS

REVIEW
river
reservoir
releases
fish

Barnett, Richard H, 1971
RESERVOIR DESTRATIFICATION IMPROVES WATER QUALITY
Public Works June: 60-65, 120

Aeration has provided an economically feasible and effective means of controlling domestic water quality problems due to taste and odor, high organic content, higher (sic) than desired dissolved oxygen content, warm water and higher than desired pH which normally occur in water served from Lake Casitas (California) during the spring and summer months. These problems are controlled through aeration by increasing the depth of usable water during the summer from 20 to 100 feet through addition of dissolved oxygen which eliminates manganese and hydrogen sulfide accumulation in the deeper water. The diffusers should be kept well above the reservoir bottom to avoid bringing manganese and other bottom constituents into solution. Aeration will become a permanent part of this Districts water quality control program. Experiments will be continued in an effort to increase the efficiency of the system and to determine the long-term effects on water quality parameters. A special effort will be made to gauge the effect on a number of types of algae blooms —Author

APPLIED
reservoir
aeration
physical properties
chemical properties

Bay, E C, Ingram, A A and Anderson, L D, 1966
PHYSICAL FACTORS INFLUENCING CHIRONOMID INFESTATION OF WATER-SPREADING BASINS
Ann Entomol Soc Am 59: 714-717
Chironomid larvae were found to occur among the seston deposited in water-spreading basins used for aquifer recharge. Larvae, which were more active in open water before sunrise than during midafternoon, settled most densely in those basins having the highest infiltration rates, unless the basins were arranged in series —Authors

BASIC STUDIES
benthos

Beiningen, K T and Ebel, W J, 1970
EFFECT OF JOHN DAY DAM ON DISSOLVED NITROGEN CONCENTRATIONS AND SALMON IN THE COLUMBIA RIVER, 1968
Trans Amer Fish Soc 99(4): 664-671
Concentrations of dissolved nitrogen gas were measured in the lower 640 km of the Columbia River from April to September 1968 to determine the effect of newly constructed John Day Dam on nitrogen saturation downstream. Observations were also made of symptoms of gas bubble disease and mortality in juvenile and adult salmon —Authors

BASIC
river
fish
physical properties
chemical properties

Bell, R K and Ward, F J, 1971
INCORPORATION OF ORGANIC CARBON BY *DAPHNIA PULEX*
Limnol Oceanogr 70: 713-726
In situ and laboratory studies have been carried out on the rate of incorporation of organic carbon by *Daphnia pulex* from various concentrations of carbon-14-labelled phytoplankton and artifical detritus. The estimated contribution of detrital carbon to total daily intake of *Daphnia pulex* was much less than the phytoplankton contribution, but it was significant. The rate of intake was independent of dissolved oxygen concentration down to 2.8 mg O_2/l, but intake was affected by temperature —DWT

BASIC
laboratory
zooplankton
cycling
nutrients

Bella, D A, 1970
DISSOLVED-OSYGEN VARIATIONS IN STRATIFIED LAKES
J Sanit Eng Div Am Soc Civ Eng 96(SA5): 1129-1146
A mathematical model for the distribution of dissolved oxygen in lakes is described. It was used to analyze data from Lake Sammamish, Washington. In stratified lakes like Lake Sammamish, both vertical dispersion and hypolimnetic respiration have a greater effect on the hypolimnetic oxygen change during the summer than does either photosynthetic oxygenation or aeration —DWT

APPLIED
lakes
aeration
physical properties
chemical properties

Bella, D A, 1970a
SIMULATING THE EFFECT OF SINKING AND VERTICAL MIXING ON ALGAL POPULATION DYNAMICS
J Water Poll Control Fed 42: R140-152
A simplified mathematical model is described which predicts the combined effects of growth, sinking, and vertical mixing on algal population dynamics in a lake —DWT

BASIC
microorganisms
biological communities

Berg, K, Jonasson, P M and Ocklemann, K W, 1962
THE RESPIRATION OF SOME ANIMALS FROM THE PROFUNDAL ZONE OF A LAKE
Hydrobiologia 19: 1-39
The oxygen consumption of some profundal and other mud-dwelling animals was studied in relation to varying periods of starvation, varying temperatures, and varying oxygen content of the water —JW

BASIC
lake
benthos

Bernhardt, H, 1963
ERSTE ERGEBNISSE ÜBER DIE BELÜFTUNGVERSUCHE DER WAHNBACHTAL-SPERRE
Vom Wasser 30: 11-49

This paper describes the first results of research on the aeration of Wahnbach Reservoir, West Germany. The general problems of using eutrophic reservoirs as water supply lakes is discussed. An effort to withdraw a large volume of hypolimnetic water (600,000 m^3) in contact with the bottom did not materially result in better water quality in the hypolimnion. Lake aeration was then attempted using compressed air released at the bottom. Aeration during 1961 and 1962 disrupted stratification and increased the temperature of deep waters. The oxygen concentration below 30 m was increased, compared to control years, but was not made isochemical. During mixing, the period wherein oxygen poor conditions occurred was shortened from 5 to 6 months to 1 to 2 months. During mixing, the concentration of Mn 50 cm above the bottom was over 1 mg/l for about 1 month, while during the control year it exceeded 1 mg/l over 5 months. Oxygen saturation and Mn concentrations were higher in the deep water in the vicinity of the aeration equipment than further away from the installation. The thermal properties of the rising column of water are described. Phosphate concentrations are reported during mixing, revealing isochemical conditions for dissolved phosphate —DWT

APPLIED
reservoir
destratification
physical properties
chemical properties

Bernhardt, H, 1967
AERATION OF WAHNBACH RESERVOIR WITHOUT CHANGING THE TEMPERATURE PROFILE
J Am Water Works Assoc 59(8): 943-964

This paper describes lake aeration and hypolimnetic aeration in Wahnbach Reservoir. Both methods of aeration improved water quality, but aeration of the hypolimnion had an additional advantage of maintaining a quantity of cold water for use as drinking water. The population of *Oscillatoria rubescens* declined after aeration —DWT

APPLIED
reservoir
hypolimnetic aeration
physical properties
chemical properties

Bernhardt, H 1969
DIE AUSWIRKUNGEN DER EUTROPHIERUNG AUF DIE TRINKWASSERGEWINNUNG AUS TALSPERREN
Stadehygiene 20: 161-166

This paper describes the problem that divalent Mn causes in floculation of drinking water with alum and the resultant benefits of preventing the formation of divalent Mn by artificial mixing —DWT

APPLIED
reservoir
destratification
chemical reactions

Bernhardt, H and Hötter, G, 1967
MÖGLICHKEITEN DER VERHINDERUNG ANAEROBER VERHÄLTNISSE IN EINER TRINKWASSERTALSPERRE WÄHREND DER SOMMER—STAGNATION
Archiv Hydrobiol 63: 404-428

The results of the aeration tests are described being carried out between 1964 and 1966 in the Wahnbachtalsperre. As in previous years the water of the reservoir was completely aerated and circulated in 1963 by introducing 6 m^3/min air bubbling up in the deepest area of the reservoir near the dam. However, the complete circulation of the whole reservoir water in summertime resulted in a warming of the whole watermass up to 16° C. This had a negative effect on the quality of drinking water and for industrial purposes as well. An aerobic condition was maintained even near the bottom of the reservoir. The complete circulation evidently hindered the development of *Oscillatoria rubescens* in summer. An intermittent removal of large quantities of water from the bottom outlet in 1965 was to compensate the extensive oxygen

APPLIED
reservoir
destratification
hypolimnetic aeration
microorganisms
physical properties
chemical properties
chemical reactions

consumption in the deeper water zones by sucking watermasses of higher oxygen content down to deeper water levels. Despite the removal of 9 hm^3, i.e. 55 percent of the reservoir inflow within the same time interval this procedure did not at all produce satisfactory results. —Author (The results of the 1966 hypolimnetic aeration effort are also described. The thermocline remained intact but sank from 10-15 m to 15-20 m after the onset of mixing. The oxygen concentration of the hypolimnetic water was prevented from falling below 40 percent near the dam, but the effect was less marked at the upstream stations —DWT

Bernhardt, H and Hötter, F, 1971
DIE KÜNSTLICHE BELUFTUNG VON OBERFLACHENGEWASSERN
KFK-ATV-DVGW-Arbeitsblatt AW 161, 44 p (Not seen)

APPLIED
lake
hypolimnetic
aeration

Black, E E, Fry, E J and Black, V, 1954
THE INFLUENCE OF CO_2 ON THE UTILIZATION OF OXYGEN BY SOME FRESHWATER FISH
Can J Zool 32: 408-420
CO_2 sharply inhibited oxygen utilization by fishes —RS

BASIC
fish
physical
properties
chemical
properties

Bishop, J W, 1966
ZOOPLANKTON METABOLISM: ADAPTION IN A THERMALLY STRATIFIED LAKE
PhD Thesis Cornell Univ, Ithaca, N Y, 50
The metabolism of migrating zooplankton in Lake Cayuga, New York, was less affected than that of nonmigrating organisms by changes in depth. Depth changes within the organism's normal migratory range had less impact on metabolism than changes outside this range. Combined changes in temperature and pressure had less affect on metabolism than changes in temperature alone —DWT

BASIC
lake
zooplankton
chemical
reactions
biological
community

Björk, S, 1970
THE LAKE RESTORATION RESEARCH PROGRAMME
International Biological Programme Section PF Sweden 2 p (mimeographed)

Bohan, J P and Grace, Jr, J L, 1969
MECHANICS OF FLOW FROM STRATIFIED RESERVOIRS IN THE INTEREST OF WATER QUALITY
U S Army Engineer Waterways Experiment Station Technical Rept H-69-10 Corp of Engineers, Vicksburg, Mississippi
Investigations were conducted to determine the characteristics of the withdrawal zone resulting from the release of flow through an orifice from a randomly stratified reservoir in experimental facilities for the purpose of developing means of predicting the quality of water discharged through similar openings in prototype intake structures —Authors

APPLIED
reservoir
reservoir
releases
physical
properties
chemical
properties

Boulier, Gary, 1971
ARTIFICIAL CIRCULATION ENHANCES MULTIPLE USAGE OF RECLAIMED WASTE WATER AT SOUTH LAKE TAHOE
International Symposium on Man-Made Lakes, Knoxville, Tenn, May 3-7, 1971
Sewage effluents given tertiary treatment in the Lake Tahoe basin are being pumped into Indian Creek Reservoir to avoid cultural eutrophication of Lake Tahoe. Indian Creek Reservoir is very eutrophic and typically has oxygen depletion in the

APPLIED
reservoir
aeration
fish
chemical
properties

hypolimnion in summer and in the whole lake under ice cover. The paper presents data to show how a compressed air aeration unit improved water quality and allowed the maintenance of a put-and-take fishery for rainbow trout —DWT

Bowles, L, 1972
VERTICAL DISTRIBUTION OF PLANKTON
In R C Summerfelt (Principal Investigator) Influence of artificial destratification on distribution of fishes and fish food organisms and primary productivity Oklahoma State University, Stillwater Dingell-Johnson Final Report, Oklahoma Proj F-24-R-2, Job No 3 35 p

The vertical distribution of several species of zooplankton showed a tendency to be restricted to upper levels of the water stratum during the period when the reservoir was stratified; however, total numbers of zooplankton were significantly less during the summer stratification period. Peak abundance of zooplankton occurred just prior to the onset of stratification. Forced aeration had no apparent effect on the zooplankton community of the central pool of Eufaula Reservoir. As spatial changes in numbers of zooplankton from stations outside of influence by the aeration device were not different to those in the vicinity of the device —RS

APPLIED
reservoir
destratification
zooplankton
physical properties
chemical properties

Brezonik, P, Delfino, J, and Lee, G Fred, 1969
CHEMISTRY OF N AND Mn IN COX HOLLOW LAKE, WISCONSIN, FOLLOWING DESTRATIFICATION
J Sanit Eng Div, Am Soc Civ Engrs 95(SA5): 929-940

Concentrations and forms of nitrogen and manganese species were determined in Cox Hollow Lake, Wisconsin, after the lake was destratified by artificial aeration. Destratification of this impoundment was accomplished within 1 month of aeration, and dissolved oxygen appeared through the water column at the same time. Nitrogen (mainly Kjeldahl N) decreased in the lake during destratification, apparently as a result of sedimentation. Nitrate and nitrite appeared in the water column soon after the initial appearance of oxygen in the bottom water, but rates of nitrification were estimated to be low, 3 mg per 1-hour to 40 mg per 1-hour. Inorganic nitrogen remained low following destratification. Destratification was also effective in removing manganese from the hypolimnion; bottom concentrations decreased from about 2 mg Mn per 1 to about 0.3 mg Mn per 1 after 1 month of aeration. About 50 percent of the total Mn was particulate (as defined by a 0.45 μ filter). After reoxygenation some of the particulate Mn was found to be oxidized Mn, but most particulate Mn was Mn (II), presumably sorbed onto inorganic or organic particles —Authors

APPLIED
reservoir
destratification
physical properties
chemical properties
chemical reactions

Brinkhurst, R O, 1969
CHANGES IN THE BENTHOS OF LAKES ERIE AND ONTARIO
Bull of the Buffalo Soc of the Nat Sci 25: 45-71 (Not seen)

BASIC
lake
benthos

Bruijn, J and Tuinzaad, H, 1958
THE RELATIONSHIP BETWEEN DEPTH OF U-TUBES AND THE AERATION PROCESS
J Am Water Works Assoc 50(2): 879

Experiments were carried out on the use of an aeration tube —DWT

APPLIED
rivers
aeration
physical properties
chemical properties

Brundin, L, 1958
THE BOTTOM FAUNISTICAL LAKE TYPE SYSTEM AND ITS APPLICATION TO THE SOUTHERN HEMISPHERE
Moreover a theory in glacial erosion as a factor of productivity in lakes and oceans Vert Internat Ver Limnol 13: 288-297 (Not seen)

BASIC
lake
benthos

Brush, L M, McMichael, F C and Juo, C Y, 1969
ARTIFICIAL MIXING OF DENSITY-STRATIFIED FLUIDS: A LABORATORY INVESTIGATION
Publ Works, N Y 100(9): 172-176
The authors describe mixing artifically stratified water in the laboratory and circulation by (1) mechanical, (2) agitation using a propeller, (3) by pumping, and (4) by air jets —DWT

APPLIED
destratification
aeration
physical properties

Bryan, J G, 1964
PHYSICAL CONTROL OF WATER QUALITY
The British Waterworks Association Journal 46(383): 1-19
This paper describes aeration equipment, engineering considerations, and economic aspects of destratification. An example of the limnological effects of destratification is given for Blelham Tarn, Great Britain. This lake of 10.9 ha was destratified by an Aero-Hydraulics system during August, 1961. Thermal stratification was destroyed; 14 days after the outset of destratification the temperature distribution was isothermal. Bottom temperatures were 5° C higher than those at the outset, while surface temperatures were 1° C cooler. The clinograde distribution of O_2 was disrupted by destratification. Initially the O_2 was not detectable below 7.7 m. Two weeks later oxygen was present in the whole water column, 7.7 mg/l at the surface and 5.7 mg/l at the bottom (12.4 m). Ferrous iron was strongly stratified at the outset, but in 2 weeks it had become isochemical with respect to depth. The concentration of ferrous iron near the bottom decreased dramatically, e.g. at 12.4 m it decreased from about 4.00 mg/l to about 0.10 mg/l —DWT

APPLIED
lakes
destratification
physical properties
chemical properties

Bryan, J G, 1965
IMPROVEMENT IN THE QUALITY OF RESERVOIR DISCHARGES THROUGH RESERVOIR MIXING AND AERATION
In J F McLean (Chairman) Symposium on streamflow regulation for quality control U S Public Health Serv Publ No 999-WP-30 Cincinnati, Ohio pp 317-334
The economic feasibility of several designs of aerohydraulic reaeration systems to improve the quality of reservoir discharges was studied. Mathematical models describing the amount of aeration are given. Digital computer programs were used to determine optimum design and economy of reaeration systems. Practical application to several reservoirs is discussed —MM

REVIEWS
reservoir
destratification
aeration
reservoir releases

Bryan, Paul and Howell, H H, 1946
DEPTH DISTRIBUTION OF FISH IN LOWER WHEELER RESERVOIR, ALABAMA
Tenn Acad Sci 21(1): 4-9
One of several studies that establish depth preferences of fishes —JNJ

BASIC
reservoir
fish
physical properties

Burdick, M F, 1959
OPEN WATER IN WINTER
Wisconsin Conserv Bull 24(2): 21-23
Application of aeration for maintaining relatively small openings in ice covered water for ducks, fish salvage operations, and fish hatchery ponds is mentioned. Successful

REVIEW
pond
aeration
fish

application on a private lake for prevention of winterkill is briefly described. Cost for a hatchery pond was about S158 for maintaining an opening of 241 square meters for 45 days —RS

Burdick, G E, Lipscheutz, M, Dean, H F and Harris, E F, 1954
LETHAL OXYGEN CONCENTRATIONS FOR TROUT AND SMALLMOUTH BASS
J New York Fish and Game 1: 84-97

Curves for the mean oxygen concentrations lethal to fish over short exposure periods have been constructed for brook, brown, and rainbow trout and smallmouth bass. Lethal oxygen concentrations are determined at several temperatures by a procedure that involves the gradual reduction of oxygen by fish respiration in a sealed container to complete loss of equlibrium used as an end-point. The highest and lowest concentrations producing such an effect are noted for each temperature. It is not suggested the data obtained by this experimental procedure represent points above which fish can be maintained indefinitely, nor that slow and gradual acclimatization will not result in shifting the mean lethal level, but curves derived are believed to represent the lethal concentrations for certain hatchery trout and, reasonably well, fish under natural stream conditions. It is claimed the experimental procedure closely approximates the rapid decrease in oxygen in streams that is produced by intermittent discharges of organic wastes, and a comparison with conditions in one such polluted stream is made —Authors

BASIC
fish
physical properties
chemical properties

Busch, A W, 1970
BIOLOGICAL FACTORS IN AERATOR PERFORMANCE
Water Sewage Works 117: 384-388

Oxygen transfer in aeration systems can be conveniently and rapidly measured by measuring the change in total COD, but the BOD value is not suitable for this purpose —DWT

APPLIED
aeration
physical properties
chemical properties

Byrd, I B, 1952
DEPTH DISTRIBUTION OF THE BLUEGILL, *LEPOMIS MACROCHIRUS* RAF, IN FARM PONDS DURING SUMMER STRATIFICATION
Trans Am Fish Soc 81: 162-170

One of several studies relating depth distribution of fishes to environmental factors —JNJ

BASIC
pond
fish
physical properties
chemical properties

C

Cady, E R, 1945
FISH DISTRIBUTION, NORRIS RESERVOIR, TENN, 1943
I Depth distribution if fish in Norris Reservoir Rept Reelfoot Lake Biol Sta 9: 103-114
Reprinted in J Tenn Acad Sci 20(1): 103-114
One of several studies that establish depth preferences of fishes —JNJ

BASIC
reservoir
fish

Carufel, L H, 1962
WINTERKILL RESEARCH ON LAKE UPSILON, GORDON LAKE AND SCHOOL SECTION LAKE IN ROLETTE COUNTY
North Dakota Dingell-Johnson Proj F-2-R-8 Job No 6 6 p + 17 figures and 5 tables
The report describes the findings of the first year of a proposed 5-year study on the effects of a compressed air system on oxygen levels and fish survival in two winterkill lakes. The air-aqua system appeared to be successful in preventing winterkill at Lake Upsilon the first year. Oxygen readings dropped from 8.2 to 2.6 mg/l on the surface and 5.8 to 1.0 mg/l at the bottom near the pumps while the rest of the lake oxygen levels dropped from 11.8 to 4.1 mg/l at the surface and 7.7 to 0.0 mg/l at the bottom. Gordon Lake had a partial winterkill as oxygen levels dropped from 6.5 to 1.3 mg/l at the surface and 6.0 to 0.0 mg/l at the bottom. A complete kill of the trout population occurred. Oxygen levels at the bottom of School Section Lake, the control lake, dropped to 0.0 mg/l. Cost of operating the pumps for 27 weeks was $400.00 or $16.00 per 400 KWH —RS

APPLIED
lake
Aeration
fish
physical properties
chemical properties

Churchill, M A, 1965
CONTROL OF TEMPERATURE THROUGH STREAMFLOW REGULATION
In J F McLean (Chairman) Symposium on streamflow regulation for quality control Public Health Serv Publ No 999-WP-30 Cincinnati, Ohio pp 179-192
If water is released through low-level outlets in the dam, significant effects on downstream water temperature result during the warmer months. If water is released through high-level outlets, the reservoir may have little effect on water temperatures. This paper presents data observed in, and downstream from, certain impoundments operated by the Tennessee Valley Authority. The data have been collected over a period of approximately 26 years. The paper not only includes information to illustrate the magnitude of thermal effects produced, but also data designed to explain why and how these effects are produced —Author

APPLIED
reservoir
reservoir releases
physical properties
chemical properties

Clair, W F and Beck, J D, 1969
PITTSBURGH GIVES ITS WATER THE AIR
Water and Waste Eng June 1969
The authors describe an aeration system used to improve the quality of water in open storage reservoirs in the distribution system of Pittsburgh, Pennsylvania. Data provided indicate a slight decrease in pH and a decrease in turbidity. The authors report a decrease in taste and odor complaints and a decrease in concentration of *Fe and Mn* —DWT

APPLIED
reservoirs
aeration
chemical properties

Cleary, E J, 1966
THE REAERATION OF RIVERS
Industrial Water Eng *(June 1966): 16-21*
This paper describes aeration strategies, with particular emphasis on equipment —DWT

REVIEWS
river
aeration

Coke, M, 1968
DEPTH DISTRIBUTION OF FISH ON A BUS-CLEARED AREA OF LAKE KARIBA, CENTRAL AFRICA
Trans Am Fish Soc 97(4): 460-465
One of several studies that establish depth preference of fishes —DWT

BASIC
lake
fish

Colby, P J and Brooke, L T, 1969
CISCO (COREGONUS ARTEDII) MORTALITIES IN A SOUTHERN MICHIGAN LAKE, JULY 1968
Limnol Oceanogr 14: 958-960
Summer mortalies of the cisco (*Coregonus artedii*) in Halfmoon Lake, Mich., were studied in 1968. Oxygen and temperature conditions were compared to a nearby lake where no mortalities had been recorded. The DO in Halfmoon lake was found to be severely depleted in the hypolimnion and the thermocline which apparently forced fish into the epilimnion where they could not tolerate high temperatures —JNJ

BASIC
lake
fish
physical properties
chemical properties

Cooley, P and Harris S L, 1954
THE PREVENTION OF STRATIFICATION IN RESERVOIRS
J Inst Water Eng 8: 517-537
Experiments using models show how stratification could be prevented in reservoirs. The reliability of the models for predicting full-scale flow is discussed. Circulation could be effected by means of water jets issuing turbulently into the body of water. Results of tests performed on the model in Walton Reservoir and the application of results to other reservoirs are described —DWT

APPLIED
reservoir
destratification
physical properties

Cooley, P, Steel, A R and Ridley JE, 1967
discussion of "IMPOUNDMENT DESTRATIFICATION BY MECHANICAL PUMPING" by W H Irwin, J M Symons, and G C Robeck.
J Sanit Eng Div, Proc Am Soc Civ Eng 93(SA4): 139-141 Republished in 1969, pp 283-286 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio 161 p
The authors describe experiences on destratification efforts on water storage reservoirs in the United Kingdom —DWT

APPLIED
reservoirs
destratification
microorganisms
physical properties
chemical properties

Cooper, G P, and Washburn, G N, 1946
RELATION OF DISSOLVED OXYGEN TO WINTER MORTALITY OF FISH IN MICHIGAN LAKES
Trans Am Fish Soc 76: 23-33
Winterkill of fish in southern Michigan lakes during 1944-45 provided an opportunity to study the effect of different degrees of oxygen depletion on the extent of mortality and survival of several common species of fishes. Eleven lakes were investigated. Several inches of snow cover remained on the lakes from December 11 to February 15. This abnormal persistence of snow cover was accompanied by oxygen depletion in some of the lakes to midwinter lows occurring about February 14. Heavy winterkills occurred only in those lakes in which the dissolved oxygen was depleted to approximately 0.6 ppm or less. The mortality was greatest among bluegills and largemouth bass, apparently 100 percent in some lakes. Among the pumpkinseeds, mud pickerel, northern pike, chub suckers, bullheads, and golden shiners there was a large rate of survival even in lakes where the oxygen was reduced to 0.3 or 0.2 ppm. No complete kill of all fish in a lake was encountered —Authors

BASIC STUDY
lake
ponds
fish
chemical properties

Cowell, Bruce C, 1967
THE COPEPODA AND CLADOCERA OF A MISSOURI RIVER RESERVOIR: A COMPARISON OF SAMPLING IN THE RESERVOIR AND THE DISCHARGE
Limnol Oceanog, 12: 125-136
An automatic plankton sampler was installed in the powerhouse of Gavins Point Dam to monitor plankton in discharges from Lewis and Clark Lake. These data and samples from the reservoir taken with two nets indicated that the automatic sampler can be used exclusively to monitor changes in species compositions and densities of Copepoda

BASIC
reservoir
zooplankton
biological community

and Cladocera. The annual discharge of Copepoda and Cladocera from Lewis and Clark Lake was estimated to be 12,619 metric tons, wet weight. Discharges of zooplankton from Lake Francis Case (Ft. Randall Reservoir), 80 km upstream, appear to have considerably more influence upon standing crops in Lewis and Clark Lake than the water exchange rates or the inflow from tributary creeks —Author

Cremer, G A, and Duncan, A, 1969
A SEASONAL STUDY OF ZOOPLANKTON RESPIRATION UNDER FIELD CONDITIONS
Verh Int Verin Theor Angew Limnol 17: 181-190
The authors describe seasonal changes in numbers, biomass and respiratory rates of the standing crop of phytoplankton and zooplankton and physico-chemical characteristics of the water in three reservoirs of the London Metropolitan Water Board —DWT

BASIC
reservoir
zooplankton
microorganisms
physical properties
chemical properties
biological communities

D

Dausend, K, 1931
UBER DIE ATMUNG DER TUBIFIZIDEN
Zeitschr vergl Physiol 14: 557-608 (Not seen)

BASIC
benthos

Davis, C C, 1969
Seasonal distribution, constitution, and abundance of zooplankton in Lake Erie.
J Fish Res Bd Can 26: 2459-2476
The results of a survey of zooplankton in Lake Erie confirmed that there were distinct ecological differences between the western, central, and eastern basins. —DWT

BASIC
lake
zooplankton
biological
community

Davis, P and Ozburn, G W, 1969
THE pH TOLERANCE OF *DAPHNIA PULEX* (LEYDIG, EMEND, RICHARD)
Can J Zool 47: 1173-1175
The tolerance of *Daphnia pulex* was tested in regard to pH. Parthenogenesis was observed at pH values between 7.0 and 8.7 —DWT

BASIC
laboratory
zooplankton
chemical
property
secondary
productivity

DeMarco, J, Kubriel, J, Symons, J M, and Robeck, G G, 1967
INFLUENCE OF ENVIRONMENTAL FACTORS ON THE NITROGEN CYCLE IN WATER
J Am Water Works Assoc 59(5): 580-592 Republished in 1969, pp 207-227 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio 616 p
The authors describe laboratory experiments on the effect of various environmental factors on the nitrogen cycle in water —DWT

APPLIED
river
chemical
reactions

Dendy, J S, 1945
FISH DISTRIBUTION, NORRIS RESERVOIR, TENN, 1943
II Depth distribution of fish in relation to environmental factors, Norris Reservoir J Tenn Acad Sci 20(1): 114-135
This study was for the purpose of improving the harvest of fish in storage reservoirs by discovering means of predicting depth distribution of various species, especially in summer when fishing is comparatively poor. The relation of an O_2 poor density layer to the distribution of fish is shown by graphs for sauger *(Stizostedion canadense)*, walleye *(S. virtreum)*, spotted bass *(Micropterus punctatus)*, drum *(Aplodinotus grunniens)*, and shad *(Dorosoma cepedianum)*. For other species it is discussed. There is no evidence that fish distribution is influenced by the amount of DO where the concentration exceeds 3 mg/l. Some species seem to remain where O_2 content is only 1.6-3 mg/l. Determination of O_2 value in predicting distribution of fish except during occasional years when severe O_2 shortage exists at critical depths —Author

BASIC
reservoir
fish
physical
properties
chemical
properties

Dendy, Jack S, 1946
FURTHER STUDIES OF DEPTH DISTRIBUTION OF FISH, NORRIS RESERVOIR, TENNESSEE
Rept Reelfoot Lake Biol Sta, 10: 94-104 Reprinted in J Tenn Acad Sci, 21(1): 94-104
One of several studies relating depth distribution of fishes to environmental factors —JNJ

BASIC
reservoir
fish
physical
properties
chemical
properties

Dickman, M, 1969
SOME EFFECTS OF LAKE RENEWAL ON PHYTOPLANKTON PRODUCTIVITY AND SPECIES COMPOSITION
Limnol Oceanogr 14: 660-666

The author reports that primary production in Marion Lake, B. C., is inversely related to the rate at which water enters the lake. Increased flushing rates reduce the phytoplankton standing crop, thereby lowering the total primary productivity in the lake. Thus, inflow has a considerable influence on the annual productivity of the phytoplankton. The standing crop and primary productivity were higher in lake water artificially enclosed than in the lake. The ratio of standing crop to primary productivity can be used as an indication of the type of factor limiting phytoplankton production. Nannoplankton were the dominant plankters but larger species were found in the enclosures —DWT

BASIC
lake
microorganisms
primary productivity

Dryer, W R, 1966
BATHYMETRIC DISTRIBUTION OF FISH IN THE APOSTLE ISLANDS REGION, LAKE SUPERIOR
Trans Am Fish Soc 95(3): 248-259

One of several studies that establish depth preferences of fishes —JNJ

BASIC
lake
fish

Dryer, William, Erkkela, S F, and Tetzloff, C L, 1965
FOOD OF LAKE TROUT IN LAKE SUPERIOR
Trans Am Fish Soc 94: 169-176

One of several studies relating depth distribution of fishes to environmental factors —JNJ

BASIC
lake
fish

Dotson, P A, 1963
MIRROR LAKE AERATION STUDY
Alaska Dept of Fish and Game Dingell-Johnson Job Completion Report, Proj F-5-R-4, Job No 8-C-2 26 p

The aeration equipment was not utilized because dissolved oxygen concentrations remained above 5 mg/l. The highest concentrations of CO_2 encountered were 15 mg/l. Ice cover accumulated to a depth of 34 inches on March 28. The deepest snow depth recorded on Mirror Lake, for any one period, was 7 inches. The mean depth was 2.3 inches. Both the lake inlet and outlet remained free of ice throughout the winter. A few anglers fished up until midwinter taking a small number of 6- to 12-inch silver salmon; no rainbow trout were observed caught. Shortly after the ice had gone out, the shorelines were walked out to enumerate winterkill; only six dead fish were observed —Author

APPLIED
lake
aeration
fish
physical properties
chemical properties

Duodoroff, P and Shumway, D L, 1967
DISSOLVED-OXYGEN CRITERIA FOR THE PROTECTION OF FISH
In: Cooper, E L (ed) A symposium on water quality criteria to protect aquatic life Spec Publ No 4 Am Fish Soc Washington, D C pp 13-19

Oxygen concentrations well below 3 mg/liter can be tolerated for long periods by the fish and fish embryos. Fishery biologists should decline, therefore, to specify any particular dissolved oxygen level as a minimal requirement of any fish population or as a proper standard of water quality until the necessary guidelines or explicit definitions of terms are provided by pollution-control agencies desiring such simple criteria. No reduction of dissolved oxygen below natural levels probably is the only "standard" that would afford complete protection for fishery resources under all circumstances, but adoption of this standard for the regulation of waste disposal usually would be unrealistic and unnecessary. Any lower or less restrictive standards applicable over

REVIEW
fish
chemical properties

wide ranges of temperature probably should be expressed as oxygen concentrations (mg/liter) rather than as percentages of saturation. They should be designed to prevent, by limiting diurnal or other fluctuations of dissolved oxygen, frequent exposure of fish to nonlethal but very low dissolved oxygen levels even for periods of moderate duration —Authors

Dugdale, R C 1955
STUDIES IN THE ECOLOGY OF THE BENTHIC DIPTERA OF LAKE MENDOTA
PhD Thesis, Univ of Wisconsin, Madison

BASIC STUDIES
lake
benthos

Deals with several aspects of the ecology of the populations of those species of *Chironomus* (=*Tendipes:* Diptera, Chironomidae) inhabiting the profundal and sublittoral bottom of Lake Mendota, at Madison, Wisconsin. Quantitative studies were made using standard mudsampling techniques (Ekman dredge); certain new equipment, *viz.* an electrically driven ice-drill and an automatic recording balance used in obtaining and recording weights of larvae are described —JW

E

Eckenfelder, W W and Ford, D L, 1968
NEW CONCEPTS IN OXYGEN TRANSFER AND AERATION
Univ Tex Water Resour Symp No 1, pp 215-236
The authors review recent investigations and concepts of oxygen transfer mechanisms in an aerobic biological system. Methods for determining the performance of aeration equipment and data on the design of aeration equipment is given —DWT

APPLIED
aeration

Edwards, R W and Rolley, C J, 1965
OXYGEN CONSUMPTION OF RIVER MUDS
J Ecol, 53: 1-9
The effects of several chemical, physical, and biological parameters on the oxygen consumption of several river sediments were studied —MM

BASIC
rivers
benthos
microorganisms
physical properties
chemical reactions
biological communities

Eggleton, F E, 1931
A LIMNOLOGICAL STUDY OF THE PROFUNDAL BOTTOM FAUNA OF CERTAIN FRESH-WATER LAKES
Ecol Monogr 1: 231-331
A study of the benthic macroninverebrates in the profundal areas of two Michigan lakes. The principal emphasis was on ecological relations of the animals —JW

BASIC
lake
benthos

Elder, R A, Smith, M N and Wunderlich, W O, 1969
AERATION EFFICIENCY OF HOWELL-BUNGER VALVES
J Water Pollut Contr Fed 41: 629-639
The authors describe the effectiveness of the Howell-Bunger valve as a device for aerating discharges from reservoirs —DWT

APPLIED
reservoir
releases
physical properties
chemical properties

Eley, R L, Carter, N E, and Dorris, T C, 1967
PHYSICOCHEMICAL LIMNOLOGY AND RELATED FISH DISTRIBUTION OF KEYSTONE RESERVOIR
Reservoir Fishery Resources Symposium Reservoir Committee, Southern Div, Am Fish Soc, pp 333-357
One of several studies relating depth distribution of fishes to environmental factors —JNJ

BASIC
reservoir
fish
physical properties
chemical properties

Eller, J M and Gloyna, E F, 1969
OXYGEN PRODUCTION AND LOSS IN A MODEL RIVER
Univ Tex, Dept Civ Eng, Austin, CRWR-34 90 p
The authors describe studies carried out in a model river to evaluate the formation and escape of photosynthetically-produced gas bubbles —DWT

APPLIED
river
stream
aeration
chemical reactions

Eschmeyer, R W, 1950
FISH AND FISHING IN TVA IMPOUNDMENTS
Tenn Dept Conserv pp 1-28
Results of creel census on TVA reservoirs and a discussion of probable reasons for success is presented. Included is information of depth preference of several sport fishes —JNJ

REVIEW
reservoir
fish
physical properties

Eschmeyer, P H, and Bailey, R M, 1955
THE PYGMY WHITEFISH, *COREGONUS COULTERI*, IN LAKE SUPERIOR
Trans Am Fish Soc 84: 161-199
One of several studies that establish depth preferences of fishes —JNJ

BASIC
lake
fish

Eschmeyer, R W and Tarzwell, C M, 1941
AN ANALYSIS OF FISHING IN THE TVA IMPOUNDMENTS DURING 1939
J Wildlife Mgmt 5(1): 15-41
An inventory of fishing on Norris and Wheeler Reservoirs and the Wilson Dam tailwater is reported. Included in results of creel census is a discussion of the effects of chemical and thermal conditions on fishing. Smallmouth bass-largemouth bass ratio was affected by the occurence of oxygen depleted density currents —JNJ

BASIC
reservoir
river
fish
physical properties
chemical

Ewing, M S, 1971
BENTHIC MACROINVERTEBRATES OF EUFAULA RESERVOIR
In Influence of artificial destratification on distribution of fishes and fishfood organisms and primary productivity Dingell-Johnson Final Report, Oklahoma Proj F-24-R-2, Job No 4 10 p
Benthic marcoinvertebrates were collected from five stations within the central pool of Eufaula Reservoir, Oklahoma, in 1968 to ascertain abundance and species diversity in relationship to an artificial destratification project. No discernable effects were noted in the numbers or diversity index (d) of macrobenthos in relation to the aeration. However, the aerator was located too close to the power intakes to have an appreciable effect on the hypolimnion —RS

APPLIED
reservoir
destratification
benthos

F

Fast, A W, 1966

ARTIFICIAL DESTRATIFICATION OF LAKES AND ITS SIGNIFICANCE IN FISHERIES MANAGEMENT.

Calif Dept Fish and Game Inland Fisheries Admin Report, No 66-16 16 p

This progress report describes initial results of the destratification effort on El Capitan Reservoir. Changes in water chemistry are described as well as changes in the phytoplankton and zoobenthos —DWT

APPLIED
reservoir
destratification
microorganisms
zooplankton
benthos
physical properties
chemical properties

Fast A W, 1968

ARTIFICIAL DESTRATIFICATION OF EL CAPITAN RESERVOIR BY AERATION

Part I: Effects on chemical and physical parameters, Calif Div Fish Game, Fish Bull No 141

Most lower elevation California lakes experience one yearly cycle of stratification. Thermal stratification generally starts about March and extends through November, greatly influencing chemical and biological stratification. The metalimnion and hypolimnion of eutrophic lakes often are devoid of oxygen. Concomitant with the oxygen deficit is the buildup of anaerobic decomposition products and the exclusion of biota from the oxygen deficient zones. Artificial destratification by aeration reduces or eliminates thermal stratification. Oxygen is distributed to all depths and products of anaerobic decomposition are oxidized. Barriers to biotic distribution are minimal. The diffuse aeration system is probably the most effective for destratifying large lakes. Other methods are discussed. Artificial lake destratification increases the lake's heat budget. The winter temperature regime is not affected by destratification. Summer surface temperatures during stratified and destratified periods are about equal. Bottom temperatures are greatly increased by destratification and may equal the surface temperatures. The coldest water temperature in a destratified lake may approach those found at the lake's surface during stratified periods. This increased heat content should benefit the fishery by increasing invertebrate forage production and decomposition of organic sediments. However, increased bottom temperatures may eliminate or preclude the establishment of a cold-water fishery. Two hypolimnion aeration systems are discussed. These systems aerate the bottom waters without causing thermal destratification and enhance coldwater fisheries. Lake aeration is economically feasible. Evaporation and chemical treatment savings alone may more than pay for the aeration system. Improved drinking water quality and fishery habitats result from aeration. This report is the first of a series describing our El Capitan Reservoir destratification study. Subsequent reports will describe the effects of artificial destratification on the zoobenthos, phytoplankton and fishes —Author

APPLIED
reservoir
destratification
microorganisms
physical properties
chemical properties

Fast, A W, 1971

THE EFFECTS OF ARTIFICIAL AERATION ON LAKE ECOLOGY

PhD Thesis Michigan State University, East Lansing 566 p

Two northern Michigan lakes were artificially aerated using compressed air. Hemlock Lake, a eutrophic lake, had only its hypolimnion aerated while thermal stratification was maintained. A special hypolimnion aeration device was used. Section Four, an oligotrophic lake, was completely destratified by releasing air from a perforated pipe at the deepest point in the lake. Both lakes were studied during 1969 under normal conditions, and during 1970 under test conditions. Artificial hypolimnion aeration of Hemlock Lake caused oxygen concentrations to increase from 0.0 mg/l to over 10.0 mg/l while thermal stratification was maintained. Zooplankton, zoobenthos and fish distributed throughout the lake after aeration, while limited to shallow depths before. Midges emerged from the deepest point following aeration. Aeration apparently reduced anaerobic nutrient regeneration, but increased nutrient regeneration through aerobic decomposition of the profundal sediments. These sediments were highly

APPLIED
lakes
destratification
hypolimnetic aeration
microorganisms
zooplankton
benthos
fish
physical properties
chemical reactions
primary productivity

organic and incompletely decomposed due to the previous anaerobic conditions. Artificial destratification of Section Four Lake greatly increased the minimum temperatures and heat budget. Although zoobenthos and surface phytoplankton standing crops were reduced, destratification had little apparent effect on the biota. Midges emerged from greater depths during aeration but depth distributions of most organisms, other than the crayfish, were not greatly altered. Crayfish distributed evenly throughout the lake during aeration. Changes in the behavior of the male are the most important factors determining their normal depth distributions —Author

Fast, A W and St Amant, J A, 1971
NIGHTTIME ARTIFICIAL AERATION OF PUDDINGSTONE RESERVOIR, LOS ANGELES COUNTY, CALIF
Calif Fish Game 57 (3): 213-216

Puddingstone Reservoir has a yearlong warm-water fishery, but a trout fishery only during the cooler months. The reservoir was artifically destratified during 1968 using a nighttime air injection schedule in an attempt to lower the water temperature and eliminate an oxygen deficit; thereby creating suitable summer trout habitat. Nighttime air injection maintained suitable oxygen levels, but increased minimum temperatures to intolerable levels. A system of hypolimnion aeration is recommended whereby both adequate oxygen and temperature for trout will be maintained for all times of the year —Authors

APPLIED
reservoir
destratification
fish
physical properties
chemical properties

Fast, A, Moss, B, and Wetzel, R G, 1972
EFFECTS OF ARTIFICIAL AERATION ON THE CHEMISTRY AND ALGAE OF TWO MICHIGAN LAKES
Depts Fisheries and Wildlife and Botany and Plant Pathology, Michigan State Univ, Hickory Corners Pre-publication

Two lakes were artificially aerated using compressed air. Section Four Lake, an unproductive lake, was completely mixed; while Hemlock Lake, a eutrophic lake had its hypolimnion aerated but thermal stratification maintained. Chemical and algal changes in Section Four Lake during destratification were not great. Although phytoplanktonic production potentials increased during mixing, phytoplankton standing crop appeared to decline slightly, possibly due to increased mixing depth and turbidity. Hemlock Lake hypolimnetic anoxia and conditions associated with it were eliminated during aeration. The lake gradually destratified during aeration due to leaks in the aeration tower. These leaks also released nutrient rich waters into the epilimnion which promoted algal growth —Authors

APPLIED
lake
destratification
hypolimnetic aeration
physical properties
chemical properties

Feng, Tsuan H, 1971
CONTROL OF BENTHIC DEPOSITS IN LAKES
Water Resour Res Center Univ Mass, Amherst, Mass Publ No 16 194 p

This final report comprises four parts: (1) Sediment-water interchange of plant nutrients in lakes. Mixing of the water at an energy level of 9.6×10^{-3} hp per million gallons of water greatly increased the dissolved oxygen concentration. While the mixing had no significant effects on nitrogen interchange, it suppressed phosphorus and iron in the overlying water. (2) Mathematical modeling of nutrient-transport. (3) A preliminary study on the utilization of laminar jet flows for removal of benthic deposit— laminar jet flows were developed in a laboratory flume, which scoured and transported sediments of specific gravity as high as 1.91 —Author

APPLIED
lake
reservoir
aeration
physical properties
chemical properties

Fitzgerald, G, 1970
AEROBIC LAKE MUDS FOR THE REMOVAL OF PHOSPHORUS FROM LAKE WATERS
Limnol Oceanog 15: 550-555

Phosphorus-limited *Selenastrum* and *Cladophora* sp. will grow or change in extractable PO_4-P in as little as 0.02 mg PO_4-P/l, but not when exposed for a period of 1 or 2 weeks to as much as 2 mg P/l as lake muds under aerobic conditions. As little as 0.4 g (dry wt) of mud could sorb about 0.05 mg PO_4-P in less than 30 minutes. The author suggests that lake muds under aerobic conditions can be used to remove P from lake water —DWT

BASIC
lake
reservoir
stream
river
chemical properties
chemical reactions

Fletcher, Douglas H, 1971
AERATION SAVES A LAKE
Parks and Recreation Nov 1971

This article describes the "benefits" of aeration of Lake Francis, Florida, particularly in respect to the sport fishery —DWT

APPLIED
lake
aeration
fish

Flick, W, 1968
DISPERSAL OF AERATED WATER AS RELATED TO PREVENTION OF WINTER KILL
Prog Fish Cult 30: 13-18

Aerated water was sprayed from an irrigation pipe into Bear pond in the northern Adirondack mountains, New York. When reentry of water occurred with a minimum of turbulence, there was little vertical mixing. The aerated water spread a considerable distance just below the ice, causing a rapid recovery of the level of oxygen —DWT

APPLIED
pond
aeration
fish
physical properties
chemical properties

Fogg, G E, 1966
ALGAL CULTURES AND PHYTOPLANKTON ECOLOGY
U Wisconsin Press, Madison, Wisconsin 126 p

REVIEWS
microorganisms
primary productivity

Fogg, C E, and Walsby, A E, 1971
BUOYANCY REGULATION AND THE GROWTH OF PLANKTONIC BLUE-GREEN ALGAE
Mitt Int Ver Theor Angew Limnol 19: 182-188

This paper describes a theory concerning the strategy blue-green algae use to adjust their position in a water column to take maximum advantage of nutrients and radiation —DWT

REVIEW
lakes
reservoirs
microorganisms
physical properties
chemical properties

Ford, M E, 1963
AIR INJECTION FOR CONTROL OF RESERVOIR LIMNOLOGY
J Am Water Works Assoc 55(3): 267-274

Forced circulation of the water by injection of compressed air was begun in the spring of 1962 in Lake Wohlford, California. Injection of air at a rate of about 210 ft^3 per min for 80 hours reduced the differential between the top and bottom temperatures. Mixing of the lake eliminated hydrogen sulphide and reduced the chlorine demand of the water —DWT

APPLIED
reservoirs
destratification
physical properties
chemical properties

Foye, R F, 1964
CHEMICAL RECLAMATION OF FORTY-EIGHT PONDS IN MAINE
Prog Fish Cult 26(4): 181-185

A study was conducted to evaluate the results of treatments of 48 ponds reclaimed in 1949-59. A discussion is included of the success of treatment by rotenone product and

APPLIED
ponds
fish
physical properties

concentration, effects of thermal stratification on effectiveness of toxicant distribution, and effects of alkalinity on toxicity —JNJ

chemical properties

Fraser, F J and Halsey, T G, 1969
THE APPLICATION OF AN AIRPERCOLATION SYSTEM FOR WATER TEMPERATURE REDUCTION IN ROBERTSON CREEK
Can Fish Cult No 40: 41-49

Compressed-air aeration systems are described which reduced high water temperature in a creek —DWT

APPLIED
stream
aeration
fish
physical properties

Fruh, E G and Clay, H M Jr, 1971
SELECTIVE WITHDRAWAL AS A WATER QUALITY MANAGEMENT TOOL FOR SOUTHWESTERN IMPOUNDMENTS
Environmental Health Engineering, Univ Texas, Austin 22 p

The objective of this study was the development of a preliminary simulation model of impoundment water quality that included an accurate description of stratified flow and selective withdrawal. Two stratified flow solutions were examined to test their applicability to describe reservoir withdrawal hydraulics under field condition. Although both appeared capable of accurate prediction of the outflow velocity profile, the Bohan-Grace solution, which required less input data, was selected allowing application to impoundments for which field data are minimum. The simulation model, including the Bohan-Grace solution for reservoir withdrawal hydraulics, was assessed for a 2-year period for which sufficient field data were available. The error in penstock temperature prediction ranged from 0 to 5° F —Authors

APPLIED
reservoirs
reservoir releases
physical properties

Funk, J L, 1970
WARM-WATER STREAMS
In N E Benson (ed) A century of fisheries in North America Spec Publ No 7, Amer Fish Soc, Washington, D C pp 141-152

A discussion of warm-water streams, their limnology and community structure is presented. Included are cursory comments on limiting factors affecting warm-water stream fishery —RS

REVIEW
stream
fish
physical properties
chemical properties

G

Galligan, J P, 1962
DEPTH DISTRIBUTION OF LAKE TROUT AND ASSOCIATED SPECIES IN CAYUGA LAKE, NEW YORK
New York Fish and Game 9(1): 44-68
One of several studies relating death distribution of fishes to environmental factors —JNJ

BASIC
lake
fish
physical properties

Gardner, W and Lee, G F, 1965
OXYGENATION OF LAKE SEDIMENTS
J Air & Water Poll, 9: 553-564
The kinetics of oxygenation of Lake Mendota sediments were studied using manometric techniques, and the rate of deoxygenation was found to be dependent on temperature and iron content of the sediment —Authors

BASIC
lake
chemical reactions
chemical properties

Goldman, C R, Gerletti, M, Jarvornicky, P, Santolini, U M and Amezaga, E D, 1968
PRIMARY PRODUCTIVITY, BACTERIA, PHYTO- AND ZOOPLANKTON IN LAKE MAGGIORE: CORRELATIONS AND RELATIONSHIPS WITH ECOLOGICAL FACTORS.
Memorie Ist Ital Idrobiol 23: 49-127
Data on transmitted and scattered light, conductivity, temperature, oxygen concentration and percentage saturation, pH value, alkalinity, inorganic carbon, silicates, protein, nitrates, primary productivity, extracellular products of photosynthesis, community diversity, and diversity per individual, obtained in studies on Lake Maggiore are described. The data were submitted to computer analysis to determine the correlation coefficients between the various parameters —DWT

BASIC
lake
physical properties
chemical properties
microorganisms
zooplankton
primary productivity
biological community
nutrient cycling

Golterman, H L, 1969
METHODS FOR CHEMICAL ANALYSIS OF FRESH WATERS
Int Biol Programme, IBP Handbook No 8, Blackwell Sci Publ Oxford and Edinburgh 187 p

REVIEWS
physical properties
chemical properties

Grace, J L, Jr, 1971
SELECTIVE WITHDRAWAL CHARACTERISTICS OF WEIRS
Technical Report H-71-4 U S Army Engineer Waterways Experiment Station, Vicksburg, Mississippi
During 1969, the Corps of Engineers initiated laboratory research at the US army Engineer Waterways Experiment Station to determine the characteristics of withdrawal zones resulting from release of flows from randomly stratified lakes over weirs for developing means of predicting and controlling the quality of water discharged through downstream, fixed-level regulating structures. Stratification was generated in experimental facilities by means of differentials in both temperature and dissolved salt concentration. Density distributions were determined from temperatures and salinities measured with thermistors and conductivity probes. Velocity distributions were obtained by dropping dye particles into the flow and photographing the resulting streaks with movie cameras. Generalized expressions describing the limits of the zone of withdrawal and distribution of velocities therein were developed from analyses of the velocity and density distribution data. Means for evaluating those conditions where the free surface and/or bottom boundary dictates the upper and/or lower limits of the withdrawal zones were also determined. With the capability of predicting the velocity distribution to be anticipated for any given density distribution upstream of a weir, the weighted average technique can be applied to predict the value of any water-quality parameter of the outflow for which a profile in the lake is known —Author

APPLIED
pond
destratification
micro-organisms
physical properties
chemical properties

Gravel, A, Fruh, E and Davis, E, 1969
LIMNOLOGICAL INVESTIGATIONS OF TEXAS IMPOUNDMENTS FOR WATER QUALITY MANAGEMENT PURPOSES—THE DISTRIBUTION OF COLIFORM BACTERIA IN STRATIFIED IMPOUNDMENTS
Technical Report No. 3 to the Office of Water Resources Research Department of the Interior The University of Texas at Austin, Department of Civil Engineering 91 p

The distribution of coliform bacteria in stratified impoundments was studied in an attempt to define the characteristics and causes for that distribution. A field sampling program was conducted to validate data in the literature which indicated that coliform densities were higher in hypolimnion than in epilimnion waters. The literature was reviewed and laboratory research conducted to evaluate the hypothesis that this coliform stratification was due to differences in death rates resulting from stratification of temperature, pH, and dissolved oxygen. Results showed this hypothesis to be a satisfactory explanation and indicated that differences in temperature and pH were most important —Authors

BASIC
reservoirs
microorganisms
physical properties
chemical properties

Greenbank, J, 1941
SELECTIVE POISONING OF FISH
Trans Amer Fish Soc 70: 80-86

When derris root was applied to the warmer surface waters of two small trout lakes, comparatively little seemed to penetrate to the colder, deeper water. Apparently the perch, rock bass, and largemouth black bass were destroyed, with very slight damage to the trout population. The study of the poisoned fish yielded information on fish populations and on habitat selection. The method of selective poisoning is suggested as a means of ridding certain trout waters of undesirable species of fish —Author

BASIC
lake
fish

Greenbank, J, 1945
LIMNOLOGICAL CONDITIONS IN ICE-COVERED LAKES, ESPECIALLY AS RELATED TO WINTER-KILL OF FISH
Ecol Monogr 15: 343-392

This paper describes the overriding influence of light penetration through ice and snow on oxygen production in winterkill lakes —DWT

APPLIED
lakes
biota
physical properties
chemical properties

Grim, J, 1952
EIN SEE WIRD UMGEKFLUGT
Allgemeine Fischerei-Zeitung 77 (14): 281-283.

This paper describes an effort to pump epilimnetic water into the hypolimnion with a mechanical pump in a Swiss lake. Bottom waters were warmed by pumping and thermal gradients between 6 m and the bottom were abolished. Thermal stratification was not destroyed. Chemical observations are reported —DWT

APPLIED
lake
destratification
physical properties
chemical properties

Grygierek, E, Ilkowska, A H and Spodniewska, I, 1966
THE EFFECT OF FISH ON PLANKTON COMMUNITY IN PONDS
Verh Int Verein Theor Angew Limnol 16: 1359-1366

Quantitative and qualitative changes in plankton of fishponds were followed by sampling every 3 days. The results show that the fish had a positive effect on the general abundance of plankton and affected the seasonal changes, species composition, and spatial distribution of the plankton communities —DWT

BASIC
pond
microorganisms
zooplankton
fish
biological community

H

Halsey, T G, 1968

AUTUMNAL AND OVER-WINTER LIMNOLOGY OF THREE SMALL EUTROPHIC LAKES WITH PARTICULAR REFERENCE TO EXPERIMENTAL CIRCULATION AND TROUT MORTALITY

J Fish Res Bd Canada 25(1): 81-99

The autumnal and over-winter limnological characteristics of two small eutrophic lakes differed considerably from those of third eutrophic lake. Thermal and chemical stratification was well defined in Marquette and Corbett Lakes; stratification in the more exposed Courtney Lake was ill defined. Complete natural autumnal oxygenation and circulation in Courtney Lake provided comparatively high concentrations of dissolved O_2 which permitted the over-winter survival of *Salmo gairdneri* and *Richardsonium balteatus.* Although Marquette and Corbett Lakes were isothermal in the late autumn, O_2 concentrations were well below saturation levels and circulation was probably incomplete. Consequently O_2 depletion during winter was severe and *S gairdneri* and *Salvelinus fontinalis* were subject to over-winter mortality. Experimental circulation of Corbett Lake, just prior to ice cover, confirmed the hypothesis that incomplete autumnal oxygenation is a cause of "winterkill" of fishes. Artificial autumnal circulation of the lake provided an O_2 concentration sufficient to prevent over-winter fish mortality. However, over-winter mortality of the entire fish population did occur in the control lake, Marquette (incomplete autumnal oxygenation) but not in Courtney Lake (complete autumnal oxygenation) —Author

APPLIED
lakes
aeration
fish
physical properties
chemical properties

Hamalainen, M, 1969

PREVENTING THE DEPLETION OF OXYGEN BY CHANGING THE HYPOLIMNION

Vestalous 10(3): 25-27 (Eng Summ)

Artificial lake Dammen, in Espoo, Finland, is subject to winterkill. The problem has been ameliorated by installing a siphon spillway composed of plastic pipes and extending into the hypolimnion so that a continuous circulation of water is maintained —DWT

APPLIED
lakes
chemical properties

Harnisch, O, 1938

STUDIEN ZUM ANAEROBEN- UND ERHOLUNGSSTOFFWECHSEL DER LARVE VON *CHIRONOMUS THUMMI*

I Wechsel im Glykogen-, Fett-, and N-Gehalt Z vergl Physiol 26: 200-229 Butyric and caproic acids were essential end products of anaerobic glycogen decomposition by *Chironomus* larvae. When anaerobic acid formation proceeded rapidly, it was less proportional over longer periods than over shorter periods and the acid deficit obtained over the longer period could not be explained through retardation of acid formation since there was continuous and even increased glycogen consumption; fat content increased —JW

BASIC STUDES
benthos
chemical reactions

Hasler, A D, 1947

EUTROPHICATION OF LAKES BY DOMESTIC DRAINAGE

Ecology 28: 383-395

This paper examines the consequences of inadvertent lake fertilization in an effort to forecast the outcome of deliberate fertilization projects. Case histories of lakes in Switzerland, England, Sweden, Finland and the United States are presented —JNJ

REVIEW
lake
microorganisms
fish
physical properties
chemical properties

Hasler, A D, and Einsele, W G, 1948
FERTILIZATION FOR INCREASING PRODUCTIVITY OF NATURAL INLAND WATERS
Trans N A Wildl Conf 13: 527-555

This paper describes theories on precipitation and solubilization of P in lakes —DWT

BASIC
lake
physical properties
chemical properties
chemical reactions

Hayes, F R and Livingstone, D A, 1955
THE TROUT POPULATION OF A NOVA SCOTIA LAKE AS AFFECTED BY HABITABLE WATER, POISONING OF THE SHALLOWS AND STOCKING OF THE SHALLOWS
J Fish Res Bd Can 12(4): 618-635

A stocking, partial-poisoning and creel census experiment was carried out on a stratified lake in an effort to increase the crop of speckled trout, *Salvelinus fontinalis*. Application annually for 5 years of about one-half ppm of derris dust to the 3-meter zone of the lake during summer stratification produced a heavy kill of coarse fish without harming the trout. Three independent estimates of the effect of the experiment upon the trout production of the lake are put forward —Authors

APPLIED
lake
fish
physical properties
chemical properties

Haynes, R, 1971
SOME ECOLOGICAL EFFECTS OF ARTIFICIAL CIRCULATION ON A SMALL EUTROPHIC NEW HAMPSHIRE LAKE
PhD Thesis Univ New Hampshire, Durham 165 p

Several years previous to the start of this investigation, Kezar Lake had developed annual noxious blue-green algal blooms. In an attempt to improve lake conditions, the New Hampshire Water Supply and Pollution Control Commission decided to try artificial circulation of Kezar Lake. The study reported here was made to help understand some of the ecological effect of mixing the lake. Samples were collected from meter intervals in the water column on at least a weekly basis during May through October for the years 1968 and 1969. Water chemistry was determined by standard methods. The distribution of Fe, Mn, Na, Ca, Mg, K, Zn, Cu, Cl, SiO_2 in the water column were measured before and after mixing. Nitrogen in the forms of NH_3-N, NO_2-N, NO_3-N and organic-N were studied. Ortho-P and total-P were determined. Chlorophyll-a was measured as an index of phytoplankton potential to assimilate carbon. Primary productivity studies were made to the level of 1 percent surface light. Phytoplankton were identified and counted from live and fixed material respectively under an inverted microscope. Physical measurements included temperature and transparency. Artificial circulation destratified Kezar Lake completely and isothermal conditions were maintained throughout the test periods. Mixing caused an increase in the heat budget of the lake, and the stability of stratification was reduced to zero when the lake became homothermous. Water transparency increased after remedial aeration in 1968 but decreased following mixing in 1969. Artificial circulation increased the oxygen content of bottom waters and concurrently removed large concentrations of carbon dioxide, which were lost to the atmosphere at the air-water interface. Most nutrients were distributed uniformly after the lake was mixed. The supply of nutrients before and after artifical circulation was sufficient to support phytoplankton populations. A uniform, vertical distribution of the bloom-forming algae *Aphanizomnenon flos-aquae* eventually declined, but following preventative aeration in 1969 *A flos-aquae* bloomed. After decline of the blooms of *A. flos-aquae* each year the phytoplankton became dominated by chlorophycean taxa. Levels of chlorophyll-a became uniformly dispersed in the water column after artificial circulation. Mean values for 1968 and 1969 were 0.14 and 0.20 g/m^2 respectively. Chlorophyll degradation to pheo-pigments appeared to be greater during a bloom of

APPLIED
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heterogeneous green algae than during the bloom of *A. flos-aquae*. The average rates of carbon fixation by phytoplankton during the two summers were 190 mg (particulate) C/m^2/hour in 1968 and 230 mg (total) C/m^2/hour in 1969. Extracellular release of organic carbon-14 increased with depth and accounted for 19.4 percent of the total carbon fixed in the euphotic zone for the summer of 1969. A discussion of the results included, and a comparison is made with the findings of other authors —Author

Heath, W, 1961
COMPRESSED AIR REVIVES POLLUTED SWEDISH LAKES
Wat Sew Works 108: 200

An 8-10 h.p. compressor, pumping air through a 500 m., perforated hose, was used to alleviate odor, low O_2, temperature stratification, and poor plant growth problems. Results and possible application are discussed —MM

APPLIED
lakes
destratification
physical properties
chemical properties

Hedman, E and Tyley, S, 1967
ELIMINATION OF STRATIFICATION AT LAKE CACHUMA, CALIFORNIA
United States Geol Surv, Water Resour Div, Menlo Park, Calif 40 p

A study was undertaken to determine the effects of air injection on Lake Cachuma, Santa Barbara County, California. Lake Cachuma has a capacity of 205,000 acre-feet. Two in-place tests were made in which columns of lake water, 1 square meter in cross section, were isolated with polyethylene cylinders. The columns of water were destratified, and the physical, chemical, and biological properties of the circulated water were compared with those of the stratified-reservoir water. The results from the first test indicated the water was destratified with respect to temperature and dissolved oxygen after a short period of air injection. Specific conductance, nitrate, orthophosphate, silica, bicarbonate, and free carbon dioxide were not appreciably affected. The changed environment in the circulated water was unfavorable to the existing phytoplankton populations, but the test did not continue long enough for a new group of organisms to appear —Authors

APPLIED
reservoir
destratification
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physical properties
chemical properties

Heimer, J F, 1968
EXPERIMENTAL CONTROL OF NONGAME FISH POPULATIONS IN ANDERSON RANCH RESERVOIR
Idaho Fish and Game Dept, Job Completion Report for Anderson Ranch Reservoir Studies Job No A1: 1-28

One of several studies relating depth distribution of fishes to environmental factors —JNJ

APPLIED
reservoir
fish
physical properties

Hemphill, J, 1954
A METHOD OF WINTERKILL PREVENTION
Ariz Game and Fish Dept Spec Rept 8p (multilith)

Aeration of a shallow (average depth 2.4 m) 232.3 hectare Arizona lake (2744 m m.s.l.) was accomplished using 223 m of perforated 3.75-cm pipe and a 210 cfm capacity air compressor. It was effective in opeining a channel 6 X 274 m in 72 hours and a 46 X 518 m channel in 11 days. It prevented a reoccurence of winterkill — RS

APPLIED
lake
aeration
fish

Hester, J M, 1965
DISCUSSION ON IMPROVEMENT OF THE QUALITY OF RESERVOIR DISCHARGES THROUGH CONTROL OF DISCHARGE ELEVATION
In J F McLean (chairman), Symposium on streamflow regulation for quality control U S Public Health Serv Publ No 999-WP-30, Cincinnati, Ohio

The author reviewed aspects of Knight's symposium report on a submerged weir for aerating water discharged from a thermally stratified reservoir with low-level outlets. Alternatively, multilevel openings were suggested for downstream fisheries management —RS

REVIEW
river
reservoir releases
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Hile, R, 1936
AGE AND GROWTH OF THE CISCO, *LEUCICHTYS ARTEDI* (LE SUEUR), IN THE LAKES OF THE NORTHEASTERN HIGHLANDS, WISCONSIN
Bull U S Bur Fish 48: 211-217
One of several studies relating depth distribution of fishes to environmental factors.

BASIC
lake
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Hilsenhoff, W L, 1966
THE BIOLOGY OF *CHIRONOMUS PLUMOSUS* (DIPTERA: CHIRONOMIDAE) IN LAKE WINNEBAGO, WISCONSIN
Annals of the Entomological Soc Am 59: 465:73
To develop possible methods for managing populations of *Chironomus plumosus*, the life cycle of the species was studied. Parameters studied included egg laying, egg development, larval stages, emergence, swarming and mating —JW

BASIC
lake
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Hilsenhoff, W L, 1967
ECOLOGY AND POPULATION DYNAMICS OF *CHIRONOMUS PLUMOSUS* (DIPTERA: CHIRONOMIDAE) IN LAKE WINNEBAGO, WISCONSIN
Annals of the Entomological Soc of Am 60(6): 1183-1194
To gain insight into the factors that cause fluctuations in populations of *Chironomus plumosus*, the ecology and dynamics of the population were studied. None of the measured physicochemical conditions in the water appear to affect *C. plumosus* populations, but several characteristics of the mud were related to these populations —JW

BASIC
lake
benthos
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physical properties

Hinde, J N, 1968
POLLUTION CONTROL THE NATURAL WAY
Water Pollution Control Fed Ann Conf 41: 1-12

REVIEW
aeration

Hinde, J N, 1969
REVITALIZING WATER THE NATURAL WAY
Hinde Engineering Co, Highland Park, Ill
This article describes the benefits of the Air-Aqua aeration system —DWT

REVIEWS
aeration

Hinde, J N, 1970
RESERVOIR MIXING AND AERATION SYSTEM
Water Wastes Eng 7(3): 50-53
A system for aerating and mixing impounded water is described —SWRA

REVIEWS
aeration

Hogan W T, Reed, F E and Starbird, A W, 1970
OPTIMUM MECHANICAL AERATION SYSTEMS FOR RIVERS AND PONDS
Water Pollut Contr Res Series 16080 DOO 07/70 EPA/WQO 135 p
The total annual cost of providing supplemental aeration of streams and lakes by tested and untested aeration equipment was estimated —Authors

APPLIED
river
stream
aeration
chemical properties

Hooper, Frank F, Ball, Robert C and Tanner, Howard A, 1953
AN EXPERIMENT IN THE ARTIFICIAL CIRCULATION OF A SMALL MICHIGAN LAKE
Trans Am Fish Soc 82: 222-241
The authors found that the pumping of the waters of a lake induced an overturning like that of the fall circulation. A centrifugal pump was used to bring waters from the hypolimnion to the epilimnion in a small trout lake in Michigan. 20.7 percent of the volume of water in the lake was displaced during the test period, as the result of which, the volume of the epilimnion was increased by 49.9 percent, the hypolimnion was decreased in volume accordingly, and the thermocline was lowered steadily. No

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significant change in water temperature was observed during, nor in the period immediately following, the pumping. Conductivity and alkalinity increased in both zones during the pumping period, and dissolved oxygen increased rapidly in the bottom water. The total phosphorus in the epilimnion increased during the first 48 hours of pumping but decreased thereafter to the prepumping level; the ultimate addition was only a small one. The volume of phytoplankton in the epilimnion increased by 8-10 times during the period of pumping; it remained high for the 3 weeks following conclusion of the experiment. The growth of periphyton also increased during the pumping period —SWRA

Horak, D L and Tanner, H A, 1964
THE USE OF VERTICAL GILL NETS IN STUDYING FISH DEPTH DISTRIBUTION, HORSETOOTH RESERVOIR, COLORADO
Trans Am Fish Soc 93(2): 137-145
One of several studies relating depth distribution of fishes to environmental factors —JNJ

BASIC
reservoir
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chemical properties

Hrbacek, J, 1969
RELATION OF PRODUCTIVITY PHENOMENA TO WATER QUALITY CRITERIA IN PONDS AND RESERVOIRS
In Proc 4th Int Conf Water Pollut Res, Prague pp 717-727
The effect of fish on zooplankton can be used to learn their effects on the turnover rate for the whole plankton community. Using the concentration of nutrients and the composition of the zooplankton, it is possible to estimate the respiration of the whole community and thus predict the effect of the size of a fish stock on the concentration and distribution of oxygen —DWT

BASIC
reservoir
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Hull, C H, 1958
DISCUSSION ON EFFECTS OF IMPOUNDMENTS ON OXYGEN RESOURCES
In Oxygen relationships in streams Proc Seminar, Cincinnati, Ohio Oct 30 – Nov 1, 1957 U S Public Health Serv, Tech Rept W58-2, Cincinnati, Ohio pp 124-129
Reviewed engineering modifications used to enhance quality of reservoir discharges —RS

REVIEW
reservoir
reservoir releases
chemical properties

Hunter, J V and Whipple, W Jr, 1970
EVALUATING INSTREAM AERATION OF POLLUTED RIVERS
J Water Pollut Control Fed 42(8): R249-R262.
This paper reviews general topics in the aeration of polluted rivers. Subjects described are aerator characteristics and costs, oxygen transfer rate, instream aerator in a water quality control system. Systems analysis, BOD mass-balance analysis, comparison of alternatives and other theoretical considerations —DWT

APPLIED
river
stream
aeration
chemical properties

Hutchinson, G E, 1957
A TREATISE ON LIMNOLOGY
Vol 1 Geography, physics, and chemistry John Wiley and Sons, Inc New York 1015 p

REVIEW
biota
physical properties
chemical properties
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ecosystem functions

Hutchinson, G E, 1967
A TREATISE ON LIMNOLOGY
Vol 2 Introduction to lake biology and the limnoplankton John Wiley and Sons, Inc New York 1115 p

REVIEW
biota
ecosystem
functions

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Imberger, J and Fischer, HB, 1970
SELECTIVE WITHDRAWAL FROM A STRATIFIED RESERVOIR
Water Pollut Contr Res Series 15040EJZ 12/70 EPA/WQO U S Govt Printing Off, Washington, D C 116 p

A detailed mathematical and experimental study was carried out to predict the thickness of the withdrawal layer for managing the quality of outflows from stratified reservoirs —DWT

APPLIED
reservoirs
reservoir releases

Imhoff, K R, 1969
OXYGEN BALANCE AND ARTIFICIAL REAERATION OF LAKE BALDENEY AND THE LOWER RUHR,
In Proc 4th Int Conf Water Pollut Res, Prague pp 761-781

The author describes the system of impoundments which supplement the system of sewage-treatment plants in the Ruhr Valley and the aeration devices installed in one of these lakes, Lake Baldeney. In discussion, L. Fiala and H. Bernhardt report studies comparing various methods for the aeration of deep reservoirs, including a compressed-air bubbling device near the bottom of the reservoir, an aeration device with a cylindrical extension which transports the oxygenated water from the lower to the upper parts of the hypolimnion, and a new aeration device first tested in the Wahnbach Reservoir, Germany, which permits the mixing and aeration of water in only a part of the hypolimnion —DWT

REVIEWS
destratification
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Inland Fisheries Branch, 1970
EFFECTS OF ARTIFICIAL DESTRATIFICATION ON DISTRIBUTION OF BOTTOM ORGANISMS IN EL CAPITAN RESERVOIR
Calif Dept Fish Game Fish Bull 148 30 p Report written by Alex Calhoun and Paul Hubbell

The bottom fauna of El Capitan Reservoir, San Diego County, California, was sampled during 1964, under normal conditions, which included prolonged stratification. The lake was then destratified artificially for 2 years. The benthic organisms, including midge larvae and pupae, oligochaete worms, nematode worms, and fresh-water clams, rapidly invaded the profundal zone. They had previously been absent there in summer. Their total numbers in the lake increased dramatically. A combination of anoxia and toxic conditions in the hypolimnion had presumably excluded them from the deeper parts of the lake when it was stratified. In 1967 thc lake was permitted to stratify again. By August the normal summer distributional pattern of bottom organisms was beginning to reappear. Extending the distribution of midges throughout the lake by artificial destratification should increase the amount of food available to game fish. This is not so with oligochaetes, clams, and nematodes, which do not usually enter the food chains culminating in game fish. The long-term implications of artificial destratification for reservoir fishery management are discussed —Author

APPLIED
reservoir
destratification
benthos

Irwin, W H, Symons, J M and Robeck, G G, 1966
IMPOUNDMENT DESTRATIFICATION BY MECHANICAL PUMPING
J Sanit Eng Div, Proc Am Soc Civ Eng 92(SA6): 21-40 Republished in 1969, pp 251-274 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers, Public Health Serv Publ No 1930 Cincinnati, Ohio 616 p

This paper describes studies carried out on four impoundments to determine the efficiency of mechanical pumping for destroying thermal stratification. An axial-flow pump was used to draw cold water from the bottom layers and discharge it at the surface; this was effective in modifying the density profile and resulted in an improvement in the quality of the entire water mass. The usual autumn bloom of Cyanophceae did not occur in any of the reservoirs —DWT

APPLIED
reservoir
destratification
physical properties
chemical properties

Irwin, W H, Symons, J M and Robeck, G G, 1967
WATER QUALITY IN IMPOUNDMENTS AND MODIFICATIONS FROM DESTRATIFICATION
In C E Layne, Jr (ed) Reservoir fishery resources symposium. So Div Am Fish Soc, Athens, GA 558 p Republished in 1969, pp 363-388 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio, 130-152

The success of projects that propose to regulate streamflow for improving water quality depends on a source of good quality impounded water that can be used for downstream flow control. Research was initiated to develop engineering methods that would overcome or prevent water quality deterioration that occurs during storage. This paper describes some of the reactions that take place in reservoirs and lakes and it also presents data to demonstrate the effectiveness of artificial destratification as a means of maintaining good quality water. Impounded water can become thermally stratified. If this occurs, the lower waters in the impoundment are effectively sealed from the atmosphere by the light-warm water floating on the surface. Because atmospheric reaeration is prevented, the naturally occurring oxygen-demanding reactions reduce the dissolved oxygen (DO) concentration to zero. Under anaerobic conditions, the occurrence of reducing reactions such as sulfide production and iron and manganese dissolution, can bring about water quality degradation. Because very little energy is required per unit volume to lift the cooler water to the surface of a stratified impoundment, an attempt was made to artificially destratify two small lakes in northern Kentucky, one 2,900 ac-ft and the other 4,600 ac-ft. In 1965 a raft-mounted pump was used, while in 1966 a diffused air system was used. The data show that considerable improvement in water quality resulted from the mixing. Nearly uniform water temperatures, better vertical distribution of the DO, decreases in the concentration of reduced materials and prevention of reduction reactions from continuing all resulted from the destratification operation. These improvements in the quality of this water made it a better source for streamflow regulation and improved its recreational potential —Authors

APPLIED
reservoirs
destratification
physical properties
chemical properties

Isom, B G, 1971
EFFECTS OF STORAGE AND MAINSTREAM RESERVOIRS ON BENTHIC MACROINVERTEBRATES IN THE TENNESSEE VALLEY
In: Hall, G E (ed) Reservoir fisheries and limnology Am Fish Soc Spec Publ No 8 Am Fish Soc, Wash, DC, pp 179-191

Studies involving benthic macroinvertebrates in the Tennessee Valley region have generally shown that benthic fauna may be limited by siltation, rheotactile deprivation, water level fluctuation, increased hydrostatic pressure, light, and most pertinently by hypolimnetic oxygen deficiency in the storage impoundments —Author

REVIEW
reservoirs
rivers
reservoir releases
benthos
fish
physical properties
chemical properties

J

JBF Scientific Corporation, 1971
ENGINEERING METHODOLOGY FOR RIVER AND STREAM REAERATION
Water Pollut. Contr. Res Series 16080 FSN 10/71 EPA/WQO 119 p

Results of recent activities in river and stream aeration by artificial techniques are reviewed, and a rational engineering methodology is developed for future river and stream aeration projects —Authors

APPLIED
river
stream
aeration
chemical properties

Johnson, R C, 1966
THE EFFECT OF ARTIFICIAL CIRCULATION ON PRODUCTION OF A THERMALLY STRATIFIED LAKE
Fish Res Papers Washington Dept Fisheries 2(4): 5-15

Compressed air used to mix the waters of Lake Erdman in the summers of 1961-1963. This increased the numbers of salmon produced and their survival rate, but the average length of smolts was slightly less —DWT

APPLIED
lake
destratification
physical properties
fish
chemical properties

K

Keeney, D, 1972
THE FATE OF NITROGEN IN AQUATIC ECOSYSTEMS
Eutrophication Information Program, Univ Wisconsin, Madison, Literature Review 3

This paper is a literature review of the nitrogen cycle in lakes with primary emphasis on chemistry and microbiotic fluxes. The presentation on transformations in sediments is recent and most useful —DWT

REVIEWS
lake
reservoir
microorganisms
physical properties
chemical properties
chemical reactions

Kemmerer, A J, 1970
REBUTTAL TO J VERDUIN'S CRITIQUE OF RESEARCH METHODS INVOLVING PLASTIC BAGS IN AQUATIC ENVIRONMENTS
Trans Am Fish Soc 99(3): 612-613

This paper defends the use of polyethylene cylinders in productivity studies —DWT

BASIC
lakes
reservoirs
physical properties
chemical properties
primary production

King, D L, 1970
REAERATION OF STREAMS AND RESERVOIRS – ANALYSIS AND BIBLIOGRAPHY
U S Dept Inter Bureau of Reclamation REC-OCE-70-55 131 p

REVIEWS
aeration

King, W and E C Kinney, 1965
COOPERATION IN THE SOLUTION OF WATER QUALITY PROBLEMS ASSOCIATED WITH FLOW REGULATION
In J E McLean (chairman) Symposium on streamflow regulation for quality control HEW Publ Health Serv Publ no 99-WP-30 pp 373-401

Legal basis for federal-state cooperation in water resource planning and flow regulation was reviewed and examples given for the Roanoke, Arkansas-White, and the Potomac Rivers. The impact of low temperature discharges from stratified reservoirs was briefly reviewed —RS

REVIEW
river
reservoir
release
physical properties

Kirkland, L and Bowling, M, 1966
PRELIMINARY OBSERVATIONS ON THE ESTABLISHMENT OF A RESERVOIR TROUT FISHERY
Proc S E Assoc Game Fish Comm 20: 364-374

A sport fishery for rainbow trout *(Salmo gairdneri)* and brown trout *(Salmo trutta)* was created in the lower one-third of a 38,000-acre oligotrophic reservoir. Maximum temperatures of 70° F. and a minimum of 3 ppm oxygen were evaluated as criteria for establishing this "two-story" fishery. Stockings of 8- to 10-inch trout were made in the winter months and weight gains were up to threefold in a 6-month period. Food utilized by the trout was primarily the threadfin shad *(Dorosoma petenense)*. Movement of trout did not exceed 10 miles from the stocking locations, and a majority was caught within 5 miles —Authors

BASIC STUDY
reservoir
fish
physical properties
chemical properties

Kittrell, F W 1965
THERMAL STRATIFICATION IN RESERVOIRS
In J E McLean (Chairman) Symposium on streamflow regulation for quality control Public Health Ser Publ 999-WP-30 Cincinnati, Ohio, pp 57-66

REVIEWS
reservoirs
physical properties

Factors involved in thermal stratification of lakes are reviewed. Density changes of water with changes in temperature exhibit two characteristics: (1) the minimum effect of temperature changes on density occurs at 4° C and increases on either side of this value; (2) the same degree of temperature change produces larger density differences at high temperatures than at low temperatures. Thermal stratification may assume many patterns, dependent on geographical location, climatological conditions, depth, surface area, and other physical configurations of the lake. Thermal stratification in reservoirs may have different, more drastic effects on downstream areas than do natural lakes because of the facilities for control of discharge and depth at which that discharge comes from –MM

Klaassen, H E and Marzolf, G R, 1971
RELATIONSHIPS BETWEEN DISTRIBUTIONS OF BENTHIC INSECTS AND BOTTOM-FEEDING FISHES IN TUTTLE CREEK RESERVOIR
In Reservoir Fisheries and Limnolgy, Amer Fish Soc Special Publ 8: 385-395
Explored the contention that aquatic insect distribution can be related to the distribution of bottom-feeding fishes. The analysis deals primarily with the catch and stomach content data from river carpsucker, channel catfish, and fresh-water drum. The results suggest relationships between dominant benthic organisms and some size classes of the fishes studied –JW

BASIC
reservoir
fish
benthos

Knight, W E 1965
IMPROVEMENT OF THE QUALITY OF RESERVOIR DISCHARGES THROUGH CONTROL OF DISCHARGE ELEVATION
In J F McLean (Chairman) Symposium on streamflow regulation for quality control Public Health Serv Publ 999-WP-30 Cincinnati, Ohio, pp 279-289
This paper describes tactics to improve the quality of water releases through variation in discharge regulation –DWT

APPLIED
reservoir
reservoir releases
physical properties
chemical properties

Knoppert, P L, Rook J J, Hofker, T, and Oskam, G, 1970
DESTRATIFICATION EXPERIMENTS AT ROTTERDAM
J Am Water Works Assoc 62: 448-454
The experiments of Lake Maarsseveen showed that using compressed air as a method of artificial destratification permits the maintenance of a sharp thermocline at a chosen level. Also, these experiments showed that during artificial destratification, the thermocline sank to the same level over the entire lake, at any given time. Comparison of two techniques, for injecting air, an air bubble screen across the lake, and a single diffusor at one point, showed that the air bubble screen gave better results. From the Zeeuws-Vlaanderen experiment the tentative conclusion may be drawn that the depth of the lake in relation to optical characteristics of the water is an important parameter for the algal behavior of an impoundment, if the thermal conditions are modified artifically –SWRA

APPLIED
reservoirs
destratification
microorganisms
physical properties
chemical properties

Koberg, G E and Ford, M E, 1965
ELIMINATION OF THERMAL STRATIFICATION IN RESERVOIRS AND THE RESULTING BENEFITS
Geol Surv Water-Supply Paper 1809-M
Thermal stratification in lakes and reservoirs increases the concentration of certain undesirable substances in the hypolimnion with an accompanying decrease in the dissolved-oxygen concentration. Thermal stratification considered in this report is due to temperature variation with depth which controls the respective density of the water. The temperature distribution within a lake is a function of diffusion and

APPLIED
reservoir
destratification
physical properties
chemical properties

conduction, and such external agencies as solar radiation, wind, inflow, and outflow. The use of air bubbling to artificially induce mixing in a lake has been successful in several investigations reported in the literature. A detailed study of this technique in Lake Wohlford in collaboration with the Escondido Mutual Water Co. of Escondido, California, is presented. The results of the Lake Wohlford study indicate that the air-bubbling system is economically feasible to remove undesirable taste and odors from the water used for domestic purposes and to increase the dissolved-oxygen concentration in the hypolimnion of the lake. The results also indicate that the elimination of thermal stratification can reduce evaporation. The elimination of thermal stratification in Lake Wohlford during May, June, and July reduced the evaporation 15 percent. Although the evaporation was increased 9 percent in September, October, and November, the net reduction for the 6 months was about 6 percent. The Lake Wohlford study and other tests cited have not presented enough data to define criteria for design of an air-bubbling system for a thermally stratified reservoir of a given capacity. Further studies are needed on larger reservoirs before design criteria can be established —Authors

Kolbe, F F, 1964
ARTIFICIAL OXYGEN REGENERATION AT GOREANGAB DAM
Civ Eng S Africa 6(1): 5-8

The author describes the use of a modified air-lift pump for aerating Goreangab Dam, the larger of two reservoirs supplying water to Windhoek, S W Africa —DWT

APPLIED
reservoir
destratification
physical
properties
chemical
properties

Kryutchkova, N M, 1968
THE ROLE OF ZOOPLANKTON ON THE SELF-PURIFICATION IN WATER BODIES
Hydrobiologia 31: 585-596

The role of zooplankton in the production and utilization of organic matter in polluted water is described from observations made on sewage lagoons and polluted reservoirs in Czechoslovakia —DWT

BASIC
reservoirs
microorganisms
zooplankton
chemical
processes
nutrient
cycling

L

Lackey, R T, 1970
EFFECTS OF ARTIFICIAL DESTRATIFICATION ON PARVIN LAKE, COLORADO
Colorado Div Game, Fish and Parks Dingell-Johnson Progress Report, Colorado Proj F-46-R-1, Job No 2 71 p

This progress report describes the first results of lake aeration of Parvin Lake, Colorado —DWT

APPLIED
lake
destratification
physical properties
chemical properties

Lackey, R T, 1971
EFFECTS OF ARTIFICIAL DESTRATIFICATION OF A LAKE ECOSYSTEM
Colorado Div Game, Fish and Parks, Dingell-Johnson Job Completion Report, Colorado Proj F-46-R, Job No 2 71 p

Effects of maintaining a 19 ha Colorado montane lake in a thermally destratified condition year around were evaluated. Water temperatures were kept vertically and horizontally isothermal throughout the year. Water temperatures for the entire lake were 1°-2° C colder than normal in winter and 1°-2° C warmer in summer. Deep water in summer was 5°-6° warmer than normal hypolimnion temperatures. No reduction in summer surface temperature was observed. Dissolved oxygen depletion normally develops in summer and winter, but oxygen was kept at near saturation throughout the year. Hydrogen ion concentration, alkalinity, conductivity, and total residue were not significantly affected. Seston decreased and this was probably mainly due to declines in planktonic diatom populations. Deep water increases in iron and manganese did not develop during destratification. Calcium increased slightly. Magnesium and most anions (chloride, nitrate-N, and silica) were not greatly altered, but sulfate was reduced in concentration. Total phytoplankton numbers for the year were reduced, but phyla varied in their responses. Green phytoplanktonic algae decreased in abundance during treatment. Diatoms were nearly eliminated by destratification. Blue-green algae, however, increased in abundance. Vertical distribution of phytoplankton was not affected. The zooplankton community was generally reduced. Cladocerans, copepods, and rotifers generally exhibited slight declines. Vertical distribution was not pronounced in the zooplankton and this did not change with destratification. Benthic populations remained at about the same level or increased slightly. The amphipod *(Hyalella)* and chironomids were the most affected. Summer depth distribution of rainbow trout was unaffected by destratification —Author

APPLIED
lake
destratification
microorganisms
zooplankton
benthos
fish
physical properties
chemical properties

Langford, R R, 1938
DIURNAL AND SEASONAL CHANGES IN THE DISTRIBUTION OF LIMNETIC CRUSTACEA OF LAKE NIPISSING, ONTARIO
Univ Stud Biol, Ser No 45 (Publ Ontario Fish Lab 56), 1-42

This paper describes diurnal and seasonal changes in zooplankton density —DWT

BASIC
lake
zooplankton
biological community

Lathbury, A, Bryson, R A, and Lettau, B, 1960
SOME OBSERVATIONS OF CURRENTS IN THE HYPOLIMNION OF LAKE MENDOTA
Limnol and Oceanogr 5: 409-413

The authors describe observations of currents in the hypolimnion in Lake Mendota, Wisconsin. Seiche currents and turbulence were found to be of insufficient magnitude to explain the observed currents —DWT

BASIC
lake
physical properties

Laurie, A H, 1961
THE APPLICATION OF THE "BUBBLE-GUN" LOW LIFT PUMP, A REMEDY FOR STRATIFICATION PROBLEMS
Water and Waste Treatment 8 (Not seen)

APPLIED
destratification

Laverty, G L and Nielsen, H L, 1970
QUALITY IMPROVEMENTS BY RESERVOIR AERATION
J Am Water Works Assoc 62(2): 711-714

This paper describes preliminary results of aeration of Lafayette Reservoir, California. It reports a reduction in the temperature of the surface layers of water, and an increase in dissolved oxygen in the hypolimnion —DWT

APPLIED
reservoir
destratification
chemical properties

Leach, L E, 1968
EUFAULA RESERVOIR AERATION RESEARCH – 1968
Okla Acad Sci 49: 174-181

Artificial destratification of a 4372 ha pool of a 41,498 ha Oklahoma reservoir was attempted using compressed air distributed through microporous diffusers. The initial objective was not accomplished because proximity of the diffusers to the power penstocks caused aerated water to be pulled through the dam as fast as aeration was occurring. Physiochemical changes within the reservoir were restricted mainly to the stations closest to the diffusers. A comprehensive study of the biological impacts of the planned artificial destratification by Bowles (1972), Ewing (1972), Summerfelt and Hover (1972), and Toetz (1972) was greatly hampered by the limited within reservoir effects. The aeration did increase the DO of the discharge below the dam from 4.0 to 5.5 mg/l —RS

APPLIED
reservoir
destratification
physical
properties
chemical
properties

Leach, L E, Harlin C C, Jr, 1970
INDUCED AERATION OF SMALL MOUNTAIN LAKES
Nat Water Quality Control Res Program, Region VI, Ada Environmental Protection Agency, Water Quality Office Program #16080 63 p

Summer stratification in small mountain trout-fishery lakes restrict trout habitat to the thin layer of surface waters. As atmospheric temperatures increase during later summer months, the epilimnion waters reach temperatures intolerable for trout. A technique of managing trout-fishery lakes, through introduction of compressed air, was studied at Lake Roberts in southern New Mexico during the summer of 1969. Research findings and further research required for optimum development of induced aeration systems as management tools for trout-fishery lakes are discussed —Authors

APPLIED
reservoir
destratification
fish
physical
properties
chemical
properties

Leach, L E, Duffer, W R and Harlin, C C, Jr, 1968
PILOT STUDY OF DYNAMICS OF RESERVOIR DESTRATIFICATION
Water Quality Control Research Program, Robert S Kerr Water Research Center, Ada, Oklahoma 22 p

The pilot study of dynamics of reservoir destratification has advanced development and design of a system to destratify large reservoirs. Rate of change of the volume of water affected and the magnitude of aeration were determined in the central pool of Eufaula Reservoir. The pilot system was undersized for circulating the entire volume of the central pool, yet 65,000 acre-feet of water below a depth of 22 feet was aerated by the 25th day of operation. Aeration effects extended as far as 2.5 miles from the point where the system was installed covering an area of approximately 3,000 acres at a depth of 22 feet. Rate of change of hydrodynamic aeration trajectories and thermal effect versus mechanical energy input are discussed. Pilot system design and operational limitations served as a guide for design of a more effective system for continued research and development of destratification of large reservoirs. Interesting changes in vertical distribution and concentrations of fish have prompted proposals from other agencies to conduct parallel research on effects of destratification on fish populations and other biological parameters —Authors

APPLIED
reservoir
destratification
physical
properties

Leach, L E, Duffer, W R and Harlin, C C, Jr, 1969
PILOT STUDY OF DYNAMICS OF RESERVOIR DESTRATIFICATION
Public Works 100(3): 138-142

This paper describes pilot studies on destratification of Lake Eufaula, Oklahoma. Air was piped to a cross-shaped diffuser system near the bottom. The effects of aeration were noticed by the second day of operation, when the depth at which oxygen was 4 mg/l was lowered from 8 to 10 m. Thermal restratification was rapid after aeration ceased, but the dissolved oxygen did not restratify as fast. During aeration, fish were observed at much greater depths than previously —DWT

APPLIED
reservoir
destratification
physical
properties
chemical
properties

Leach, L E, Duffer, W R and Harlin, C C, Jr, 1970
INDUCED HYPOLIMNION AERATION FOR WATER QUALITY IMPROVEMENT OF POWER RELEASES
Water Pollut Contr Res Series 16080 10/70 EPA/WQO 32 p

Induced aeration of the hypolimnion was tested in Eufaula Reservoir during the summer of 1968. Dissolved oxygen transfer efficiency of the aeration system ranged from 1.8 to 3.0 pounds of dissolved oxygen per horsepower-hour of expended energy resulting in an operating cost of 4.10 to 6.25 dollars per thousand pounds of oxygen incorporated in the power releases. Research needs for development of the induced aeration system are discussed —Authors

APPLIED
reservoir
destratification
reservoir
releases
physical
properties
chemical
properties

Lee, G F, 1970
FACTORS AFFECTING THE TRANSFER OF MATERIAL BETWEEN WATER AND SEDIMENTS
Eutrophication Information Program, University of Wisconsin, Madison. Occasional papers 50 p

This paper describes factors affecting the exchange between the sediment and the open water —DWT

REVIEWS
lakes
ponds
reservoirs
rivers
streams
microorganisms
physical
properties
chemical
properties
chemical
reactions

Lee, G F, 1970a
ROLE OF PHOSPHORUS IN EUTROPHICATION
Presented at Symposium of Am Chem Soc, Div Water, Air, and Waste Chemistry Los Angeles, Calif

Significance of phosphorus as the key element in excessive fertilization of natural waters is presented and its role on plant growth in lakes. Tools to assess phosphorus and other elements fertilizing natural waters are mathematical models, enzymatic and tissue assay procedure —SWRA

REVIEW
microorganisms
aquatic
plants
chemical
properties
chemical
reactions
cycling
nutrients

Lind, O T, 1971
THE ORGANIC MATTER BUDGET OF A CENTRAL TEXAS RESERVOIR
In: Hall, G E (ed) Reservoir fisheries and limnology Spec Publ No 8 Am Fish Soc Washington, D C pp 193-202

The allochthonous and autochthonous organic matter budget of Lake Waco, Texas was determined. The total quantity of organic matter discharged from the reservoir was not appreciably different from that received by inflow. Seasonal fluctuations in

BASIC STUDY
reservoir
chemical
properties
primary
productivity

downstream organic flow was much less than fluctuations in input. The major source of organic matter as a basic food source in the reservoir was said to come from autochthonous primary production –RS

Linder, C H and Mercier, P, 1954
ETUDE COMPARATIVE DE LA REPARTITION DU ZOOPLANKTON AU LAC DE BRET AVANT ET APRES RAERATION
Schweiz Zeitschr Hydrol 16(2): 309-317

The authors report the results of zooplankton analyses of samples obtained during 1943 and 1951, respectively, four years before and 5 years after aeration of the hypolimnion of Lac de Bret began. The average number of planktonic copepoda and cladocera decreased by about 2070 in 1951 compared to 1943. But, copepods increased and cladocerans decreased. When the lake was oligotrophic, the copepods also were of greater importance. The authors believe the present results are a reflection of the return towards oligotrophy. The changes in abundance of *Corethra plumicornis, Diaphanosoma brachyurus, Synchaeta pectinata* and *Notholca longispina* are thought to be associated with the changing conditions since aeration –DWT

APPLIED
lake
destratification
zooplankton
physical properties
chemical properties

Lund, J W G, 1950
STUDIES ON *ASTERIONELLA FORMOSA* Hass II. NUTRIENT DEPLETION AND THE SPRING MAXIMUM
J Ecol 38(1): 15-35

Excerpts and analyses have been made on populations of *Asterionella* and the results therefrom considered in relation to observations on natural populations in lakes, in the English Lake District and elsewhere. It is held that the close of the spring period of increase is not directly due to light or temperature nor is it due to grazing, lack of P, N, C or Ca. It is often due to lack of silica. Occasionally it is due to competition with other diatoms which become dominant when the number of *Asterionella* are depressed by fungal parasitism. Large growths of diatoms do not occur at silica concentrations of less than approximately 0.5 mg. SiO_2 per l. P and CA can be stored in the cells in excess of immediate requirements. Phosphate P can be utilized when its concentration in the water is 1 γ per l. or less. The amount of silica per unit area of cell is constant. Limitation of growth due to lack of silica differs from that due to lack of light. The supply of available silica does not provide an explanation of all fluctuations in numbers in the lakes considered; in some lakes it is never utilized to any appreciable extent. What other substances are lacking is unknown –Author

BASIC
lake
microorganisms
chemical properties
primary production

Lund, J W G, 1971
AN ARTIFICIAL ALTERATION OF THE SEASONAL CYCLE OF DIATOM *MELOSIRA ITALICA* SUBSP *SUBARCTICA* IN AN ENGLISH LAKE
J Ecol 59: 521-533

The seasonal cycle periodicity in density of *M. italica* ssp. *subarctica* was studied in a small lake for over two decades. The effect of a previous artificial destratification in 1961 on both species was small. Lund suggests that the normal, seasonal alternation of periods of stratified and unstratified water are of biological advantage to *Melosira* –DWT

APPLIED
lake
destratification
microorganisms
chemical properties
physical properties

Lund, J W G, 1971a
THE SEASONAL PERIODICITY OF THREE PLANKTONIC DESMIDS IN WINDERMERE
Mitt Int Ver Theor Angew Limnol 19: 3-25

Observations have been made on the annual periodicity of three desmids for 25 years in an English lake. One desmid, *Cosmarium contractum,* reached its annual maximum

BASIC
lake
microorganisms
biological communities

in September or October, the other two, *C. abbreviatium* and *Staurastrum lunatum* usually were most numerous in July or August, after which the populations declined. Estimations were made of the growth of the desmids in cultures suspended in the lake. *C. contractum* grew more slowly than the other two species at all times and depths. It is suggested that this relatively slow potential rate of growth is one reason why *C. contractum* has its maximum later than the other two species. Despite its relatively slow growth rate, *C. Contractum* is a major desmid species in the lake. Its late maximum ensures relatively large numbers in winter. One reason for the greater fluctuations in the numbers of *C. abbreviatum* and *S. lunatum* during summer is severe fungal parasitism. The very regular rise and fall of the population of *C. contractum* each year is, in part at least, a reflection of the lesser frequency of severe parasitism —Author

M

MacCallum, W R and Regier, H A, 1970
DISTRIBUTION OF SMELT, *OSMERUS MORDAX,* AND THE SMELT FISHERY IN LAKE ERIE IN THE EARLY 1960's
J Fish Res Bd Canada 27: 1823-1846
One of several studies that establish depth preferences of fishes —JNJ

BASIC
lake
fish
physical properties
chemical properties

Mackenthun, K M, and Herman, E F, 1948
A HEAVY MORTALITY OF FISHES RESULTING FROM THE DECOMPOSITION OF ALGAE IN THE YAHARA RIVER, WISCONSIN
Trans Amer Fish Soc 75: 175-80
A heavy loss of fish occurred in the Yahara River below Lake Kegonsa, Wisconsin, during the latter part of September and the early part of October, 1946. All species of fish in the river were affected in the mortality. Chemical analyses of the water were made in successive periods, and experiments were performed to determine the toxicity of the river water to experimental fish. Death was attributed primarily to the depletion of the oxygen supply by the decomposing algal mass consisting of almost a pure culture of *Aphanizomenon flos aquae.* Secondarily, toxic substances liberated into the water by the decomposing algae probably contributed to the death of the fish —Author

BASIC
river
microorganisms
fish
physical properties
chemical properties

Malueg, K, Tilstra, J, Schults, D and Powers, C F, 1971
THE EFFECT OF INDUCED AERATION UPON STRATIFICATION AND EUTROPHICATION PROCESSES IN AN OREGON FARM POND
International Symposium on Man-Made Lakes, Knoxville, Tennessee, May, 1971
A pond, 0.4 hectare, was divided into three sections by watertight barriers of polyethylene sheeting, extending from surface to bottom, along two transects. Sections A and 8, north and middle respectively were of equal area and similar bathymetry, with maximum depths of 4.9 meters. Induced aeration produced currents of sufficient magnitude to disrupt chemical and thermal stratification and supplied air directly to the pond water. Section B was not manipulated and served as a control. A bloom of the blue-green algae, *Anabaena,* developed in the control in August and September, whereas only trace numbers were found in the aerated sections. The algal bloom in the control was accompanied by a pH of 9, a dissolved oxygen concentration of 15 mg/l and a chlorophyll *a* concentration of 110 mg/m^3 in surface waters. The total phytoplankton concentration was reduced sharply in the aerated section following initiation of pumping. Later, a green flagellate, *Trachelomonas,* developed in cell numbers exceeding the total phytoplankton in the control section. Transparency, as measured by underwater photometer and Secchi disc, was greater in the aerated section. Other chemical and physical measurements are reported together with algal identifications —Authors.

APPLIED
pond
destratification
aeration
microorganisms
physical properties
chemical properties

Malz, F and Bortlisz, J, 1968
VERGLEICHENDE BETRACHTUNGEN DER SAUERSTOFF GEHALTE IN GESTAUTEN UND UNGESTAUTEN FLUSS
Die Wasserwirtschaft, Stuttg 58: 6-9
The authors discuss the biological, chemical and physical changes caused by dam construction in free-flowing waters. Special consideration is given to the use of three different aeration systems for increasing dissolved oxygen —DWT

APPLIED
reservoir
river
stream
aeration
physical properties
chemical properties

Markofsky, Mark and Harleman, Donald R F, 1971
A PREDICTIVE MODEL FOR THERMAL STRATIFICATION AND WATER QUALITY IN RESERVOIRS
Ralph M Parsons Laboratory for Water Resour and Hydrodynamics Dept Civil Eng, Mass Inst Tech, Cambridge 283 p

Previous research on thermal stratification in reservoirs has provided analytical methods for predicting the thermal structure and internal flow field of a reservoir characterized by horizontal isotherms. A one-dimensional analytical thermal stratification prediction method developed by Huber and Harleman is reviewed and modified to include the time required for the inflowing water to reach the dam face —Authors

APPLIED
reservoir
physical properties
chemical properties

Mathis, B J, and Cummings, T F, 1971
DISTRIBUTION OF SELECTED METALS IN BOTTOM SEDIMENTS, WATER, CLAMS, TUBIFICID ANNELIDS, AND FISHES OF THE MIDDLE ILLINOIS RIVER
Water Resour Center Report 41, Water Resour Center, Ill Univ, Urbana 44 p

This study was designed to assess the potential application for further research of metal contamination in a large midwestern river that is utilized by industries and certain cities as a source of potable water as well as for sewage disposal. Analyses were made for 13 metals in bottom sediments, 12 in water, and 10 in tubificid worms, clams, and fishes. The study revealed that the 10 metals, for which analyses were made in biota, do not concentrate along successive tropic levels as is the case with pesticides. Organisms such as clams and worms that inhabit the mud or mud-water interface where metal concentrations were observed to be the highest, exhibited the highest metal concentrations. At higher trophic levels, however, concentrations were lower, with fishes that are primarily carnivorous in nature exhibiting the lowest concentrations —Authors

APPLIED
river
fish
benthos
chemical properties

Mayhew, J, 1963
THERMAL STRATIFICATION AND ITS EFFECTS ON FISH AND FISHING IN RED HAW LAKE, IOWA
Biology Section Report, Iowa Cons Comm 24 p

One of several studies relating depth distribution of fishes to environmental factors —JNJ

BASIC
reservoir
fish
chemical properties

McConnell, W J, 1968
LIMNOLOGICAL EFFECTS OF ORGANIC EXTRACTS OF LITTER IN A SOUTHWESTERN IMPOUNDMENT
Limnol Oceanogr 13: 343-349

Watershed litter in semiarid southeastern Arizona is relatively unleached, and the accumulation of a year or more is occasionally delivered to lakes within the first few days of the summer rainy season. Pena Blanca Lake received at least 750 g/m^2 of oak litter during the summer of 1959. About 329 kg cal/m^2 were delivered to the lake in oak litter extracts of which 26 percent were probably from carbohydrates, 54 percent from phenolic compounds, and 20 percent from unidentified compounds. Oak leaf extracts were experimentally effective as an energy source for microorganisms used as food by filter-feeding organisms *(Xenopus laevis)* and snails. Efficiency of the extract-microorganisms–*Xenopus* and snail food chain was 3.28 percent. Based on an estimated ecological efficiency of 0.56 percent for the food chain: litter extract-microorganisms-zooplankton-young *Micropterus* salmoides, *Micropterus* biomass production may have been increased 0.4 g/m^2 by organic components in oak litter extracts contributed to Pena Blanca Lake in 1959. This increase represents 16.7 percent of the average annual fish harvest for 1959, 1960, and 1961 —Author

BASIC
reservoir
microorganisms
benthos
fish
physical properties
chemical properties

McKeown, J J, 1968
STUDIES ON INSTREAM AERATION
In 23rd Industrial Waste Conf, Purdue Univ, Lafayette, Ind, pp 1134-1146
The author summarizes studies on aeration of streams and ponds by weirs and surface aerators –DWT

APPLIED
rivers
streams
aeration
physical properties
chemical properties

McLachan and McLachan, 1971
BENTHIC FAUNA AND SEDIMENT IN THE NEW LAKE KARIBA (CENTRAL AFRICA)
Ecology 52:800-809

APPLIED
lake
benthos

McNall, W J, 1971
DESTRATIFICATION OF LAKES
Job Progress Report Job C-8, Statewide Fisheries Investigations New Mexico Federal Aid Proj No F-22-R-11 31 p
Lake Roberts, a 70 surface acre high use trout lake located in the Gila National Forest, was destratified. After 144 hours of aeration, dissolved oxygen measured over 6 ppm from the surface down to the bottom, 30 feet, all the hydrogen sulfide disappeared, trout were found living in 30 feet of water and zooplankton was greatly increased in all portions of the impounded water. The lake was allowed to restratify from June 22 until July 9. The lake immediately showed signs of thermal and chemical restratification after aeration was terminated. A second aeration period was initiated at 6:30 p.m. on July 9. Dense algae blooms were present in the epilimnion where aeration began. July 10 found cloudy sky conditions and concern was mentioned about the possibility of a mass die-off of algae thus causing a great strain on the already limited dissolved oxygen concentration. A very hard rain pelted the lake's surface at 3:00 a.m., July 11, and by 6:00 a.m. the trout were in stress. By 8:00 a.m. the lake was nearly anaerobic from top to bottom and a fish kill had occurred. Aeration continued until August 26 and the lake remained nearly anaerobic –Author

APPLIED
lake
destratification
fish
physical properties
chemical properties

Mercier, P, 1948
AERATION PARTIELLE SOUS-LACUSTRE D'UN LAC EUTROPE
Verh Int Ver Limnol 10: 294-297
This paper describes the aeration strategy used to aerate the waters of Lake Bret and early results –DWT

APPLIED
lakes
aeration

Mercier, P, 1955
EVOLUTION D'UN LAC EUTROPHE SOUMIS A L'AERATION ARTIFICIELLE SOUS-LACUSTRE
Verh Inter Ver Limnol 12: 679-686
This paper describes the mechanical aeration of Lake Bret. Water was pumped from 13.5 m to a station on shore, aerated by spraying and returned to the 13.5 m level about 178 m from the intake between May 15 and the end of September. The author reports that the water was not warmed. Input of supplemental oxygen had resulted in an amelioration of problems involving iron in water distribution systems and an accelerated rate of oxidation of the sediments –DWT

APPLIED
lake
hypolimnetic aeration
physical properties
chemical properties

Mercier, P, and Gay, S, 1949
STATION D'AERATION AU LAC DE BRET, RESULTATS OBTENUS EN 1947 et 1948

APPLIED
lake
aeration

Rev Suisse Hydrol 11: 423-429

The small lake called "Lac de Bret" is situated near Lausanne (Switzerland) at a height of 676 m (length 1.5 km, width about 400 m, maximum depth 20 m; capacity 5 millions cubic metres). Systematic researches, covering the years 1939-43, indicated that the lake has to be classified among the "eutrophic" lakes. During the summer stagnation the dissolved oxygen disappears rapidly in the depth and the free CO_2 increases. At the end of this summer period the presence of Fe could be shown in appreciable quantity in the water flowing through the filtration plant. This iron was not checked in the filters and made a deposit in form of ferric hydroxide in the pipelines. To avoid this trouble the Company of the Lausanne-Ouchy Railway and Bret Waters erected, in the year 1947, on the lake shore an aeration plant, based on the principle that has been described by Dr. P. Mercier in his report at the 10th International Congress of Limnology. A water pump located at the point P, with an outflow over 120 l/s, draws the raw water 13.5 m below the surface at a point N. This water is pulverised in the aeration chamber. Saturated with oxygen, it falls in a decantation basin and, per gravity, flows back to the lake to a point S which is at 177 m downstream. More than 10,000 m^3 per 24 hours of aerated water spread out in form of an horizontal layer and takes the place which corresponds to its density in the thermic stratification. The starting point A of the water flowing to the filter station is at the same level as the points N and S and, therefore, in the aerated zone —Authors

physical properties
chemical properties

Mercier, P, and Gay, S, 1954
EFFETS DE L'AERATION ARTIFICIELLE SOUSLACUSTRE AU LAC DE BRET
Schweizer Z f hydrol 16: 248-308

The aeration station of the Lac de Bret started operating in 1947 is described in the *Bulletin de la Societe suisse de l'Industrie du Gaz et des Eaux,* No. 2, 1949. It functions every year during 4-1/2 months, from May 15 to the end of September. 10,000 m^3 of water are being aerated in 24 hours. The aeration system adopted provokes no disturbances in the thermal stratification of the lake. The aeration station produced an essential amelioration as far as the utilization of the lake water is concerned. Before, during the summer, important quantities of iron passed through the filters as soluble bicarbonates and were then deposited as iron hydroxide in the distribution system. The additional amounts of oxygen in the hypolimnion facilitate the mineralisation of organic matter as well as the process of self purification of the water. This action is confirmed by the appearance of the sediments whose colour has become lighter. Analyses do not anymore reveal the presence of hydrogen sulfide in the sludge. The elimination of CO_2 produces a raise of the pH value and changes the reaction of the milieu diminishing its reduction capacity in the depths —Authors

APPLIED
lakes
aeration
physical properties
chemical properties

Mercier, P and Perret, J, 1949
AERATION STATION OF LAKE BRET
Monatsbull Schweiz Ver Gas-u Wasserfachm 29: 25

An aeration plant was constructed at the southern end of the Lake Bret and water was withdrawn from a depth of 13.5 m, aerated, and returned to the lake at the same level. The aeration plan is described and the amount of oxygen absorbed during aeration is given —DWT

APPLIED
lakes
aeration
chemical properties

Meyer, O L, 1962
AERATION SYSTEM INCREASES LAGOON CAPACITY— ADDS OPERATING FLEXIBILITY
Public Works 93(8): 79-80

Installing a $6,500 Air-Aqua aeration system to an oxidation pond in DuPage County, Illinois, has avoided the necessity of adding a second pond originally planned to meet the needs of that area. Differences between influent and effluent are: BOD, 120 to

APPLIED
pond
aeration
chemical properties

12.3; total SS, 182 to 41; volatile SS, 62 to 18; organic N., 9 to 14; NH_3-N, 5 to 13. Operating results have been consistently satisfactory. Aquatic life seems to do well in the pond —Author

Miller, G W and Rabe, F W, 1969
A LIMNOLOGICAL COMPARISON OF TWO SMALL IDAHO RESERVOIRS
Hydrobiologia 33: 523-546
Physical and chemical parameters and zooplankton populations in two adjacent reservoirs with differing features situated near Malad, Idaho, were compared and the productivity of nannoplankton during the summer was measured —DWT

BASIC
reservoir
zooplankton
microorganisms
chemical properties
physical properties
biological communities

Morris, J E and Stumm, W, 1967
REDOX EQUILIBRIA AND MEASUREMENTS OF POTENTIALS IN THE AQUATIC ENVIRONMENT.
In: Gould, R F (Ed) *Equilibrium Concepts in Natural Water Systems,* pp 270-285 Amer Chem Soc, Washington, D C 344 p
This paper discusses the use of equilibrium models and electrochemical measurements of potential in describing redox equilibria of natural water systems —MM

REVIEW
chemical reactions

Mortimer, C H, 1941-42
THE EXCHANGE OF DISSOLVED SUBSTANCES BETWEEN MUD AND WATER IN LAKES
Ecology 29: 280-329
The classical papers describing the exchange of chemical substances between water and lake sediments —DWT

BASIC
lake
physical properties
chemical properties
chemical reactions

Mortimer, C H, 1942
THE EXCHANGE OF DISSOLVED SUBSTANCES BETWEEN MUD AND WATER IN LAKES
J Ecol 29: 280-329, 1941; & 30 (1): 147-201
The author reports results of a study of the physical-chemical changes taking place at the mud-water interface in the hypolimnion of lakes and the resulting exchange reactions between the water and the sediments —DWT

BASIC
lakes
microorganisms
chemical reactions

Moser, B B, 1968
FOOD HABITS OF THE WHITE BASS IN LAKE TEXOMA WITH SPECIAL REFERENCE TO THE THREADFIN SHAD
M S thesis Univ of Oklahoma Norman, Oklahoma 319p
A study was made of the food habits of the white bass of Lake Texoma between February, 1963 and December, 1964. White bass were found to prey mainly on fish during most months of the year. Shad were the principal food fish of Lake Texoma white bass, threadin shad being taken more often than gizzard shad during all seasons except winter. Mississippi silversides were the next most important fish after shad. Aquatic insects became a very important part of the white bass diet during spring months. The diet of the white bass was found to depend to a large extent on what acceptable food organisms were most abundant and available at the time —JNJ

BASIC
reservoir
microorganisms
fish

Munk, W H and Riley, G A, 1952
ABSORPTION OF NUTRIENTS BY AQUATIC PLANTS
J Marine Research 11:215-240
Describes factors affecting nutrient assimilation by algae —DWT

BASIC
lake
reservoir
microorganisms
physical factors
chemical factors

Murphy, G I 1962
EFFECT OF MIXING DEPTH AND TURBIDITY ON THE PRODUCTIVITY OF FRESH-WATER IMPOUNDMENTS
Trans Am Fish Soc 91(1): 69-76
Mixing depth and turbidity negatively affect the productivity of an aquatic environment through the control they exert on the effective energy available for photosynthesis. A feedback equation is developed that defines the interaction of these two quantities with the production by phytoplankton. The equation permits calculation of the relative productivity of any body of water provided nutrients are assumed adequate, and provided depth of mixing and turbidity are known. Calculated relative production corresponded very well with observed production for a series of 33 small shallow ponds. The possibility is advanced that the same principles apply to reservoirs when thermocline depth can be regarded as mixing depth, and further, it is suggested that the productivity of reservoirs might be increased by reducing the depth of the mixed layer by withdrawing from the surface. In addition, this practice might further enhance production by mixing deeper water, richer in nutrients, into the euphotic zone during the productive season —Author

BASIC
reservoirs
physical properties
chemical properties
primary production

Murro, R and Yeaple, D, 1971
ENGINEERING METHODOLOGY FOR RIVER AND STREAM REAERATION
Environmental Protection Agency. Water Pollut Control Res Series 16080 FSN10/71 119 p
Results of recent activities in river and stream aeration by artificial techniques are reviewed, and a rational engineering methodology is developed for future river and stream aeration projects. The development of the methodology follows from a thorough review of the oxygen dynamics in rivers and streams and the capabilities of aeration systems within the present state of the art. The report shows how the theoretical work can be simplified considerably and applied to the solution of river and stream water quality problems. It is assumed that aeration would only be used as a "polishing" action after all identifiable waste sources have received at least secondary treatment. The results indicate that, with careful consideration of site factors, artificial aeration can be applied successfully to raise dissolved oxygen to 5 ppm, using mechanical surface aerators, diffusers, downflow contactors, and sidestream mixing. However, since the transfer of oxygen from air into water is relatively inefficient above 5 ppm DO, the introduction of molecular oxygen through sidestream mixing, U-tubes, and possibly diffusers should be considered, depending on the volume of water to be aerated. In cases where DO may be maintained at levels lower than 5 ppm, systems using air are competitive with molecular oxygen, depending on site conditions —Authors

APPLIED
rivers
streams
aeration
chemical properties

Muttkowski, R A, 1918
THE FAUNA OF LAKE MENDOTA: A QUALITATIVE AND QUANTITATIVE SURVEY WITH SPECIAL REFERENCE TO THE INSECTS
Trans Wis Acad Sci, Arts, Let, 19: 374-482 (Not seen)

BASIC
lake
benthos

N

Nickerson, H D, 1961
GLOUCESTER– FORCED CIRCULATION OF BABSON RESERVOIR
Sanitalk Massachusetts Dept Public Health, Div Sanit Eng 9(3): 1-10 27 p

A study program was undertaken during 1960 to study the effects of forced circulation by aeration of Babson Reservoir, Gloucester, Massachusetts. Actual aeration was started on September 2, 1960, and except for brief breakdowns has been continued. Studies of temperature, dissolved oxygen, and dye dispersion have indicated definite circulation such that there is no stratification, and no turnovers have been observed. Aerobic bottom conditions and increased biological life have been noticed, due primarily to the forced circulation. Further studies are being undertaken to study the effectiveness of color reduction. There has been no addition of chemical for control during this phase of the study, nor is any intended at this time —Author

APPLIED
reservoir
destratification
physical
properties
chemical
properties

Norton, J, 1968
THE DISTRIBUTION, CHARACTER AND ABUNDANCE OF SEDIMENTS IN A 3000-ACRE IMPOUNDMENT IN PAYNE COUNTY, OKLAHOMA
M S Thesis, Oklahoma State University, 76 p

The author describes factors affecting turbidity in an impoundment —DWT

BASIC
reservoir
physical
properties
chemical
properties

O

O'Connell, R L and Thomas, N A, 1965
EFFECT OF BENTHIC ALGAE ON STREAM DISSOLVED OXYGEN
J Sanit Eng Div, Am Soc Civil Engrs 91(SA3): 1-16

The authors show that benthic algae and other attached plants having respiratory activity at night, can cause very low concentrations of oxygen during the day. —DWT

BASIC
streams
reservoirs
microorganisms
chemical reactions

Ogborn, C M, 1966
AERATION SYSTEM KEEPS WATER TASTING FRESH
Public Works, Apr 1966

This paper describes the results of using compressed air to aerate Laurel Run and Millcreek Reservoirs in Pennsylvania. The author reports that after adding alum (9 mg/1) and aeration, turbidity decreased to almost zero in Laurel Run Reservoir. In Millcreek Reservoir the distribution system for compressed air was installed on contours about 2 meters above the hypolimnion to avoid mixing all the septic water. This strategy was apparently unsuccessful —DWT

APPLIED
reservoir
destratification
physical properties
chemical properties

Olinger, L W, 1968
THE EFFECT OF INDUCED TURBULENCE ON THE GROWTH OF ALGAE
Water Resour Center, Georgia Inst Tech, Atlanta 81 p

A laboratory study was made of the relationship between turbulence and utilization of incident light by algal cultures. It was found that the maximum growth rate constant of the Monod growth equation increased with increasing turbulence and that the rate at which constant growth occurred was a function of turbulence. With constant illumination of 600 ft - candles and variable turbulence, the growth rate constant varied from 1.65 to 8.5 —SWRA

BASIC
microorganisms
physical properties
primary productivity

Olsen, T A and Rueger, M E, 1968
RELATIONSHIP OF OXYGEN REQUIREMENTS TO INDEX-ORGANISM CLASSIFICATION OF IMMATURE AQUATIC INSECTS
J Wat. Pollut Contr Fed 40: R188-R202

The rates of oxygen consumption of some common benthic insects from rapidly flowing streams in Minnesota were determined —DWT

BASIC
river
benthos

Olszewski, P, 1961
VERSUCH EINER ABLEITUNG DES HYPOLIMNISCHEN WASSERS AUS EINEM SEE
Verh Int Verein Theor Angew Limnol 14(2): 855-861

Describes effort to improve hypolimnetic water quality by selective withdrawal of lower strata in a natural lake —DWT

APPLIED
lake
hypolimnetic aeration

Oskam, Gijsbert, 1971
A KINETIC MODEL OF PHYTOPLANKTON GROWTH, AND ITS USE IN ALGAL CONTROL BY RESERVOIR MIXING
Internation Symposium on Man-Made Lakes, Their Problems and Environmental Effects, Knoxville, Tennessee, May 3-7, 1971

A reliable in-reservoir method of algal control is of primary importance, as many of these reservoirs will draw upon nutrient-rich river water. It is thought that under certain circumstances turbulent mixing in a layer of sufficient depth might provide such a method of control. Although not very prominent in limnological studies, the relationship between (natural) turbulent mixing and algal growth is long since known in oceanography with quantitative formulation in Sverdrup's "critical depth" theory. The effect of mixing on phytoplankton populations was confirmed in many destratification experiments of fresh-water impoundments, mostly resulting in a decrease of the standing crop. It is the object of this paper to explain this effect by relating the algal growth rate to the depth of mixing and the optical characteristics of the water —Author

REVIEWS
lake
reservoir
destratification
aeration
physical properties
chemical reactions
primary productivity

P

Pacha, R E and Ordal, E J, 1970
MYXOBACTERIAL DISEASES OF SALMONIDS
In S F Snieszko (ed), A symposium on diseases of fishes and shellfishes Spec Publ No 5, Amer Fish Soc, Washington, D C, pp 243-257

Population congestion of migrating salmonids around dams and water temperature alterations in the Columbia River basin as a result of impoundments has increased the incidence of columnaris disease in salmonids. Some observations of the impact of columnaris disease on declining runs of Columbia River sockeye salmon are given. Virulent strains are favored by warming of the water —RS

BASIC
reservoir
river
physical properties

Parsons, J W, 1957
THE TROUT FISHERY OF THE TAILWATER BELOW DALE HOLLOW RESERVOIR
Trans Amer Fish Soc 85: 75-92

Cold tailwater discharge (7.8 - 13.4 C) below Dale Hollow Dam, Tennessee, was developed as a trout fishery in 1950. Observations on the history of the trout fishery are reported. Growth and survival of fingerling and catchable rainbow trout was good and the stocked fish provided over 700 trout-fishing hours annually at a low cost —RS

BASIC
river
reservoir
release
fish
physical properties

Patalas, K, 1963
SEASONAL CHANGES IN PELAGIC CRUSTACEAN PLANKTON IN SIX LAKES OF WEGOZEWA DISTRICT
Rocs Nauk Rolniczych Ser B Zootechiczna (Aool) 82(2): 209-234 (Russian and Eng Summ)

Samples were collected from the following limnological types (after Stangenberg): (1) Swiecajty and Goldopiwo, b-mesotrophic; (2) Krzywa Kuta, Zabinki, Bimbinek, eutrophic; (3) Biala Kuta, pond-like. The lakes in the first group were subject to intensive mixing of water in the summer period; they were marked by a deep epilimnion (9-10 m) and a warm hypolimnion (11°-13° C); full autumnal circulation occurred as early as the end of September. The lakes in the second group exhibited a high stability (shallow epilimnion 3-5 m, cold hypolimnion, 5°-6° C). Full circulation first took place in November. Biala Kuta Lake did not exhibit a stable thermal stratification in summer. The changes in abundance of the different species throughout the year were analyzed. Particular attention was paid to the difference in development cycles which were related to environmental conditions. Although no consistent succession of phyto- and zooplankton cycles was established, a greater variation in crustacean abundance was displayed by the lakes in which the variation in phytoplankton abundance (measured as Secchi disc transparency) was greater. This can be regarded as an indirect proof of the existence of a dependence between phyto- and zooplankton abundance. Epilimnion temperature did not seem to be a factor in the diversity of the two types of dynamics since differences amounted to not more than 0.5° C in the two groups of lakes. More essential might be the difference in the intensity of mixing of water although it would be difficult at present to explain the mechanism of this agent in its action upon plankton development. Another feature of strongly mixed lakes, as distinguished from stable lakes, was the low proportion of Cladocera in the plankton, as well as the generally small number of dominant species in summer. In analyzing the causes of the sudden decline in Crustacea abundance, especially *Daphnia* sp., it was assumed that one of the essential agents could be predation by fishes. On the basis of the difference in availability of the different Crustacea species established in the research on fish food, the possibility was accepted of the following interpretation of plankton relations in August: a high share of easy catchable forms (*Daphnia* sp., *Bosmina* sp.) in the plankton may be an index of poor plankton utilization by fishes and vice versa —Author

BASIC
lake
zooplankton
biological communities
physical parameters
chemical parameters

Patrick, R, Crum, B and Coles, J, 1969
TEMPERATURE AND MANGANESE AS DETERMINING FACTORS IN THE PRESENCE OF DIATOM OR BLUE-GREEN ALGAL FLORAS IN STREAMS
Proc Nat Acad Sci, U S A 64: 472-478

BASIC
microorganisms
chemical properties

When the temperature increased to 34°-38° C the dominant component of the algal flora of stream waters changed from the usual diatoms to blue-green algae. Blue-green and green algae of species typically found in organically polluted water were favored by very low concentrations of manganese, but diatoms remained dominant when the concentration of manganese averaged 0.02 to 0.043 mg/l in the natural stream water and 0.04 to 0.28 mg/l in recycled water —DWT

Pearse, A S and Achtenberg, H, 1920
HABITS OF YELLOW PERCH IN WISCONSIN LAKES
Bull U S Bur Fish, 36: 293-366

BASIC
lake
microorganisms
benthos
fish

The habits of perch in a small, shallow, and muddy lake were compared with those of perch in a neighboring large, deep, and clean lake. The perch is a versitile feeder but usually gets its food on or near the bottom. Percentage by volume of foods eaten are discussed. Perch do not take any abundant food but select certain things. Perch contain food which is available at depths where they are caught, which indicates that extensive vertical migrations are infrequent. Though perch are able to recognize the proportions of oxygen and carbon-dioxide in water, they enter regions where conditions are unfavorable for respiration and may remain in oxygen-free water for as much as 2 hours without dying. When in water without oxygen perch use part of the oxygen in the swim bladder —JNJ

Pearson, W D, Kramer, R H and Franklin, D R, 1968
MACROINVERTEBRATES IN THE GREEN RIVER BELOW FLAMING GORGE DAM, 1964-65 and 1967
Proc Utah Acad Sci, Arts and Letters 45 (part 1): 148-167

BASIC
river
reservoir releases
benthos
physical properties
chemical properties

Low summer temperatures and large daily fluctuations of discharges of Flaming Gorge Dam affected the taxonomic diversity and density of macroinvertebrates downstream in the first 20 km below the dam —RS

Pechlaner, R, 1971
FACTORS THAT CONTROL THE PRODUCTION RATE AND BIOMASS OF PHYTOPLANKTON IN HIGH-MOUNTAIN LAKES
Mitt Int Ver Theor Angew Limnol 19: 125-145

BASIC
microorganisms
physical properties
chemical properties
primary production

Clear lakes above the timber line are inhabited throughout the year by a considerable diversity of nannoplanktic algae. Only a few species are of quantitative importance, but these show a biomass (maximum in the ice-free period) greater than that of the phytoplankton of many lowland lakes. The production rate of alpine phytoplankton is low, limited by nutrients in summer and autumn, and by light in winter and spring. Throughout the winter and spring autotrophic rather than heterotrophic production dominates, the algae being adapted to those low intensities of radiant energy that enters the lake in spite of ice and snow cover. The vertical distribution of phytoplankton is characterized by a concentration of algae in the surface layers in winter, and in deep water during summer stagnation. Light limitation and physical properties of the water cause the surface maximum in winter, whereas in the open season a better balance between availability of nutrients and energy income explains the fact that the peak of phytoplankton biomass and production rate is in the meta- and hypolimnion. Only the downward migration of Peridineae immediately before ice break is directly caused by excessive light. Ultraviolet radiation adds to the incoming energy; a specific determental effect of it is unlikely —Author

P — Continued

Pennak, Robert W, 1946
THE DYNAMICS OF FRESH-WATER PLANKTON POPULATIONS
Ecol Monogr 16: 339-355

The general composition and nutritional interrelationships of the fresh-water plankton ecosystem are discussed, with emphasis on the role of bacteria —Author

BASIC
lake
zooplankton
biological community
chemical properties

Pennak, R W, 1953
FRESH-WATER INVERTEBRATES IN THE UNITED STATES
The Ronald Press Co, New York, N Y 769 p

Peterka, John J, 1970
PRODUCTIVITY OF PHYTOPLANKTON AND QUANTITIES OF ZOOPLANKTON AND BOTTOM FAUNA IN RELATION TO WATER QUALITY OF LAKE ASHTABULA RESERVOIR, NORTH DAKOTA
OWRR Proj No A-011-NDAK North Dakota Water Resour Res Inst North Dakota State Univ Fargo; Univ North Dakota, Grand Fords 79 p

Lake Ashtabula, a 5,430-acre reservoir in southeastern North Dakota, was found to be a highly productive impoundment. Chemical, physical, and plankton samples were taken in 1967-68; benthic invertebrates in 1967 —SWRA

BASIC STUDIES
reservoir
microorganisms
zooplankton
benthos
chemical properties
primary productivity
secondary productivity

Pneumatic Breakwaters, Ltd (London), 1961
BUBBLE GUN FOR DESTRATIFICATION
Water Eng 65: 780 70

APPLIED
destratification
aeration

Poon, C P C and Lee, F M, 1969
SURFACE AERATION BY MECHANICAL AGITATION
Water Sewage Works 116: 262-266

Various factors affecting the oxygen absorption coefficient were studied in experiments with mechanical aeration in laboratory-scale circular tanks —DWT

APPLIED
aeration

Powers, E B and Clark, R T, 1943
FURTHER EVIDENCE OF CHEMICAL FACTORS AFFECTING THE MIGRATORY MOVEMENTS OF FISHES, ESPECIALLY THE SALMON
Ecology 24(1): 109-113

Results of an experiment designed to show that migratory salmonids respond to slight gradients in CO_2 tension are presented. The two species of fishes tested responded to very slight gradients. It was suggested that a response to a CO_2 tension gradient is a dominant factor in the spawning migratory movements of fishes, especially the salmon —JNJ

BASIC
fish
physical properties
chemical properties

Prins, R and Davis, J, 1966
THE FATE OF PLANKTONIC ROTIFERS IN A POLLUTED STREAM
Occ Pap C C Adams Cent Ecol Stud No 15 14 p

Results are given of studies on planktonic rotifers at four stations in the Kalamazoo River, Michigan —DWT

BASIC
river
zooplankton
chemical properties
biological communities

Rael, Chester D, 1966
THE DISTRIBUTION OF FISHES IN RELATION TO WATER QUALITY, FONTANA RESERVOIR
North Carolina Wildlife Resourc Commission, Fish-Management Research Work Plan III Power Reservoir Investigations, Job III-D
C.ie of several studies relating depth distribution of fishes to environmental factors —JNJ

BASIC
reservoir
fish
physical properties
chemical properties

Rapoza, Donald, 1971
RESERVOIR AERATION IMPROVES WATER QUALITY
Public Works 102(5): 86-87
The author presents data in this paper to show an increase in the quality of water from Greenv'lle Reservoir, New Hampshire, after aeration. The lake was aerated at maximu n depth with compressed air. Limited data show oxygen depletion near the bottom before aeration, but high concentrations afterward. Color, Fe and Mn were reduced by a factor of 10 after aeration. The pH increased by one unit and turbidity dropped to zero. The last five parameters apparently refer to concentrations or conditions in surface waters —DWT

APPLIED
reservoir
destratification
physical properties
chemical properties

Rassmussen, D H, 1960
PREVENTING WINTERKILL BY USE OF COMPRESSED AIR SYSTEM
Prog Fish Cult 22(4): 185-187
A compressed-air system used to remove part of the ice cover on a small high mountain cutthroat brood-stock lake is described. Air is circulated from a 75-cfm compressor through two 1,100-foot sections of plastic pipe. Pumping operations starting in November lasted 162 stays at a cost of $950, exclusive of the operator's wages. Physical and chemical features of the lake during this period are described. The operation was successfully terminated in April —Author

APPLIED
lake
aeration
fish
physical properties
chemical properties

Reid, G K, 1961
ECOLOGY OF INLAND WATERS AND ESTUARIES
Reinhold Publishing Corp., New York, N Y 375p

Reynolds, J Z, 1966
SOME WATER QUALITY CONSIDERATIONS OF PUMPED STORAGE RESERVOIRS
Ph D Thesis Univ Mich, Ann Arbor 184 p
This thesis describes water-quality characteristics (principally temperature and dissolved oxygen) of large pumped-storage reservoirs. The design of such reservoirs is discussed. . he author shows how they may improve water quality through mixing, and presents criteria for estimating mixing effects. Such reservoirs have the mixing potential to eliminate thermal stratification and its effects —DWT

APPLIED
reservoirs
aeration
physical properties
chemical properties

Richerson, P, Armstrong, R and Goldman, C, 1970
CONTEMPORANEOUS DISEQUILIBRIUM, A NEW HYPOTHESIS TO EXPLAIN THE "PARADOX OF THE PLANKTON"
Proc Nat Acad Sci, U S A 67(4): 1710-1714
The diversity of lake phytoplankton is unexpectedly high, since the epilimnion of a lake is continuously mixing and might be expected to have only one or at most a few niches for primary producers. However, a carefully replicated series of samples from Castle Lake, California, showed a high degree of patchiness for many phytoplankton species, indicating that the rate of mixing is slow enough relative to the reproductive rate of the algae for many different niches to exist simultaneously. Productivity per unit biomass ratios, measured at Lake Tahoe, California-Nevada, shows that the turnover times for C in even this ultraoligotrophic lake are often less than 1 day. High diver-

REVIEW
lake
microorganisms
primary productivity
biological communities

sity is associated with high productivity per unit biomass and high zooplankton populations in this lake. A contemporaneous disequilibrium model to explain the diversity of the lake phytoplankton is therefore highly plausible. At any one time, many patches of water exist in which 1 sp. is at a competitive advantage relative to the others. These water masses are stable enough to permit a considerable degree of patchiness to occur in phytoplankton, but are obliterated frequently enough to prevent the exclusive occupation of each niche by a single species —Authors

Riddick, T M, 1957
FORCED CIRCULATION OF RESERVOIR WATERS YIELDS MULTIPLE BENEFITS AT OSSINING, NEW YORK
Water and Sewage Works 104(6): 231-237

Indian Brook Reservoir was thrown into continuous circulation by employment of floating aerator. Mixing effects and physical and chemical changes are described —DWT

APPLIED
reservoir
aeration
physical properties
chemical properties

Ridley, J, 1964
THERMAL STRATIFICATION AND THERMOCLINE CONTROL IN STORAGE RESERVOIRS
Proc Soc Water Treatment Exam 13: 275-279

This paper describes methods of destratification and mixing employed in water storage reservoirs in the United Kingdom —DWT

APPLIED
reservoirs
destratification
physical properties
chemical properties

Ridley, J, 1971
WATER SUPPLY LAKES AND RAW WATER STORAGE RESERVOIRS
Report on the influence of artificial mixing on the phytoplankton of selected lakes and storage reservoirs in the U S A Water Quality Office, Environment Protection Agency 34 p

This report is the result of a trip Dr. Ridley made during the autumn of 1971 as a consultant to the Water Supply Programs Division of the Environmental Protection Agency. In this report he describes the general problem of water quality in impoundments, the effect of mixing on the growth of algal populations in reservoirs and the results of mixing on water quality at selected impoundments in the United States that he visited. He stresses the timing and the intensity of the mixing process as being of great importance in the control of algae. Specific recommendations include the need for an international data bank and retrieval system for research on the effects of artificial mixing, standardization of techniques and adoption of the determination of chlorophyll *a* as a measure of algal biomass —DWT

REVIEWS
reservoir
lake
destratification
aeration
microorganisms
physical properties
chemical properties

Ridley, J E, Cooley, P and Steel, J A P, 1966
CONTROL OF THERMAL STRATIFICATION IN THAMES VALLEY RESERVOIRS
Proc Soc Water Treatment Exam 15: 225-244

The authors report on the control of thermal stratification in two types of reservoirs in the Thames Valley and some effects on water quality. In Queen Elizabeth II Reservoir, destratification is achieved by introducing the incoming water through jets on the reservoir floor. In King George VI Reservoir, floating pumps are used to lower the thermocline and reduce its thickness —DWT

APPLIED
reservoir
destratification
microorganisms
physical properties
chemical properties

Robinson, E L, Irwin, W H, and Symons, J M, 1969
INFLUENCE OF ARTIFICIAL DESTRATIFICATION ON PLANKTON POPULATIONS IN IMPOUNDMENTS

APPLIED
reservoir
microorganisms

Trans Ky Acad Sci 30(1&2): 1-18 Republished in 1969, pp 429-448 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio 616 p

The total plankton numbers declined during most mixings. Except for a somewhat higher surface density in test lake 2, Falmouth Lake, the plankton densities were similar at all depths in all study lakes. During most mixings the blue-green algal populations declined more than the green algal populations. During artificial destratification the number of algal species was about the same as in a test lake where no mixing occurred —DWT

physical properties
chemical properties

Rock, L F and Nelson, H M, 1965
CHANNEL CATFISH AND GIZZARD SHAD MORTALITY CAUSED BY *AEROMONAS LIQUEFACIENS*
Prog Fish Cult 27(3):138-141

An epizootic of *Zeromonas liquefaciens* in a 30-mile section of Rock River, Illinois, in 1961 is discussed. Symptoms of the infection, identification of the cultures and a discussion of the history of the disease is included —JNJ

BASIC
river
microorganisms
fish
physical properties
chemical properties

Rogers, H H, Raynes, J J, Posey, F H, Jr and Ruland, Willis E, 1971
LAKE DESTRATIFICATION BY UNDERWATER AIR DIFFUSION
Presented at the International Symposium on Man-Made Lakes in Knoxville, Tenn, May 7, 1971 South Atlantic Division, Corps of Engineers

The operation of a diffused-air system for the stratification periods of 1968-69 in Lake Allatoona in Georgia has provided useful information re-operations and improvement of water quality: 1. The system is sized sufficiently to maintain the lake in an adequately destratified condition if started when stratification begins and if operated continuously during the stratification season. 2. Water quality within 2½-3 miles upstream of the dam and in 2-3 miles downstream was improved when operating at about 80 percent capacity and starting 2 months after stratification began. When starting with stratification and operating the system at full capacity dissolved oxygen levels in both low and high discharges were maintained at 4.0 mg/liter and better except for a few days in early August. 3. Temperatures of the discharged waters were elevated 6°-8° C maximum above those discharges from a stratified lake at the same season —Authors

APPLIED
reservoir destratification
reservoir releases
physical properties
chemical properties

Round, F E, 1971
THE GROWTH AND SUCCESSION OF ALGAL POPULATIONS IN FRESHWATERS
Mitt Int Ver Theor Angew Limol 19: 79-99

This paper discusses the seasonal wax and wane of algal populations in fresh waters —DWT

BASIC
lake
reservoir
microorganisms

Ruttner, F, 1963
FUNDAMENTALS OF LIMNOLOGY
Trans from German by D G Frey & F E J Fry Univ Toronto Press, Toronto 295 p

S

Saether, O A, 1970
A SURVEY OF THE BOTTOM FAUNA OF THE OKANAGAN VALLEY, BRITISH COLUMBIA
Fish Res Board Canada Tech Rept 196
An attempt was made to determine pollution effects in three lakes from a study of the bottom fauna. General characteristics of the lakes are summarized together with information on volumes of sewage currently discharged —JW

BASIC
lake
benthos
physical properties
chemical properties

Scheithauer, E, and Bick, H, 1964
ECOLOGICAL INVESTIGATIONS ON *DAPHNIA MAGNA* AND *DAPHNIA PULEX* IN THE FIELD AND IN THE LABORATORY
Sb vys Sk Chem-technol Phrase, Technol Vod 8(1): 439-481
This paper describes observations on the impact of two species of *Daphnia* on algae and physical-chemical conditions of the water —DWT

BASIC
laboratory
zooplankton
biological community

Schmitz, W R, 1959
RESEARCH ON WINTERKILL OF FISH
Wis Conserv Bull 24 (2): 19-21
A generalized review of methods to prevent winterkill is given. Physical and biological considerations are discussed —MM

REVIEW
lakes
destratification
aeration
fish
physical properties

Schmitz, William R and Hasler, A D, 1958
ARTIFICIALLY INDUCED CIRCULATION OF LAKES BY MEANS OF COMPRESSED AIR
Science 128(3331): 1088-1089
Turbulence induced by air bubbles causes circulation in small thermally stratified lakes. Tests were made under summer and winter (ice-cover) conditions. Homoiothermal conditions, isometric concentrations of phosphorus, and increases of dissolved oxygen were achieved, at various rates of treatment. The application of the technique for lake management and in studies of lake dynamics is suggested —Authors

APPLIED
lake
destratification
physical properties
chemical properties

Schuurman, J F M, 1932
A SEASONAL STUDY OF THE MICROFLORA AND MICROFAUNA OF FLORIDA LAKE, JOHANNESBURG, TRANSVAAL
Transvaal Trans Roy Soc South Africa 20: 333-386
Seasonal changes in the tow-net plankton of this shallow artificial lake are described —DWT

BASIC
lake
zooplankton
biological communities

Scott, R H and Wisnieswski, T F, 1960
HYDRO-TURBINE AERATION OF RIVERS WITH SUPPLEMENTAL DATA ON CASCADES AERATION
Pulp Paper Mag Can 61: T45
This paper describes advantages of aeration and the use of hydroturbines in improving the oxygen balance in polluted streams. Results obtained on various rivers in Wisconsin using either the Francis turbine or the propeller-type turbine are described —DWT

APPLIED
stream
river
aeration
chemical properties

Scott, R H, Wisniewski, T F, Lueck, B F, and Wiley, A J, 1958
AERATION OF STREAM FLOW AT POWER TURBINES
J Water Pollut Contr Fed 30: 1496
Studies have been carried out on the use of power turbines for aeration of the Flambeau River, Wisconsin, at Pixley Dam. Operating procedure is described, and the results are given —DWT

APPLIED
stream
river
aeration
chemical properties

Seaburg, K G, 1966
AERATOR EVALUATION
Montana Fisheries Div, Dingell-Johnson Report F-12-R-11, Job III 12 p

Brown and Georgetown Lakes were aerated in the winter by use of air compressors to evaluate the effects of water temperatures and DO. Effects of aerators were very limited, mainly not detectable beyond 7.6 m from the air line. It appears that the apparatus was inadequate for the job —RS

APPLIED
lake
aeration
physical properties
chemical properties

Seattle University, 1970
THE OXYGEN UPTAKE DEMAND OF RESUSPENDED BOTTOM SEDIMENTS
Water Pollut Contr Res Series 16070 DCD09/70 E P A/W Q O 37 p

This paper describes laboratory experiments designed to learn the oxygen uptake demand of resuspended bottom sediments. The principal conclusions were as follows —DWT "(1) The oxygen demand of resuspended bottom sediments can be determined by using the Warburg respirometer, especially useful for determining oxygen uptake rates. (2) The magnitude of the maximum oxygen uptake rate is sensitive to the elapsed storage time of the samples. Storage at 4 degrees C does not eliminate this problem. (3) The bottom sediments tested in this study did not require external seeding to initiate the biochemical reaction. No lag phases were encountered in any of the experiments. (4) Distilled water was used as the suspending medium in this study. Maximum oxygen uptake rates were not changed when the suspending medium was modified by introducing NaCl (concentrations up to 30,000 mg/l) or B.O.D. dilution salts. (5) Maximum oxygen uptake rates of bottom sediments do not appear to be light sensitive. (6) The magnitude of the initial oxygen uptake rate is sensitive to temperature and degree of agitation. (7) Suspension can increase the quiescent, maximum oxygen uptake rate by more than a multiple of ten" —Author

BASIC
microorganisms
chemical reactions

Seattle University, 1970
THE OXYGEN UPTAKE DEMAND OF RESUSPENDED BOTTOM SEDIMENTS
Water Pollut Contr Res Series 16070 DCD 09-70 EPA/WQO 37 p

This paper describes the effect of resuspending bottom sediments on oxygen demand —DWT

BASIC
lake
reservoir
pond
river
stream
physical properties
chemical properties
chemical reactions

Silvey, J K G, and Roach, A W, 1964
STUDIES ON MICROBIOTIC CYCLES IN SURFACE WATERS
J Am Water Works Assoc (January 1964): 60-72

Describes seasonal cycles of microflora in southwestern United States reservoirs —DWT

BASIC
reservoir
microorganisms
physical properties
chemical properties

Simmons, G M, Jr and Neff, S E, 1969
THE EFFECT OF PUMPED-STORAGE RESERVOIR OPERATION ON BIOLOGICAL PRODUCTIVITY AND WATER QUALITY
Va Water Resour Res Center, Bull 21, VPI, Blacksburg, VA

Smith Mountain Lake, Virginia, is a pump-storage impoundment in which quantities of water are recycled on a daily and weekly basis. The reservoir behaves as a warm

APPLIED
reservoir
destratification
microorganisms
abiotic environment

monomictic lake. Recycling affects the stratification of the reservoir in summer and causes mixing of water in the vicinity of the dam. Effects of mixing can be observed up to 6.5 miles from the dam —SWRA

primary productivity

Slack, K and Ehrlich, G, 1967
WATER-QUALITY CHANGES IN A DESTRATIFIED WATER COLUMN ENCLOSED BY A POLYETHYLENE SHEET
U S Geol Survey Prof Paper 575B, B235-B239

A 21-meter vertical column of water in a reservoir, enclosed in a polyethylene cylinder 1 square meter in cross section, was destratified with compressed air. Nearly complete thermal and chemical destratification rapidly followed air injection. Thermal stratification rapidly reformed when airflow ceased, but nearly complete chemical homogeneity persisted. Dissolved-oxygen concentration increased during 4 days of intermittent air injection. Phytoplankton concentrations and photosynthesis decreased inside the cylinder relative to the outside water. Apparently the environment following air injection was unfavorable for existing phytoplankton species —Authors

APPLIED
reservoir destratification
microorganisms
physical properties
chemical properties

Speece, R E, 1969
U-TUBE STREAM REAERATION
Public Works Mag 100: 111-113

This paper describes the general strategy of stream reaeration using a U-Tube, the use of pure oxygen in U-Tube aeration, and the problem of dissolved nitrogen supersaturation associated with U-Tube operation —DWT

APPLIED
reservoir
stream
river
chemical properties

Speece, R E, 1969a
U-TUBE OXYGENATION FOR ECONOMICAL SATURATION OF FISH HATCHERY WATER
Trans Am Fish Soc 98(4): 789-795

The U-Tube oxygenation process is described with particular application made to saturation of fish hatchery waters. In U-Tube oxygenation, the water is under a baffle and then rises back to the surface. Air bubbles are injected just beneath the surface as the water starts downward. The downward velocity of the water is designed to be from 3 to 10 feet per second. This is sufficient to drag the air bubbles along with the water down underneath the baffle. The hydrostatic head pressurizes the bubbles making it possible to saturate or supersaturate water in one pass through the U-Tube. A U-Tube installation has been operating continuously for over a year at a Federal fish hatchery. It utilizes a free fall of 3 feet to entrain sufficient air bubbles to 100 percent saturate a flow of 300 gallons per minute with no external power requirements —Author

APPLIED
pond
aeration
chemical properties

Speece, R E, 1969b
THE USE OF PURE OXYGEN IN RIVER AND IMPOUNDMENT AERATION
Presented at the 24th Purdue Industrial Waste Conf, May 8, 1969 22 p

The application of a generalized finite-element method to the static and dynamic analysis of plate and shell structures is presented. The displacement formulation of the finite-element method is used. A particular form of generalized variational principle is used, admitting completely arbitrary displacement functions for an element. The form of the matrix equations is presented and the method of solution and the problem of dependent algebraic equations are discussed. Numerical results for a variety of polynomial displacement forms and continuity requirements are discussed. Limitations of the method are pointed out —Author

APPLIED
reservoir
stream
river
aeration
chemical properties

Speece, R, 1970
AERATION OF OXYGEN - DEFICIENT IMPOUNDMENT RELEASES
Paper presented at Fifth International Conference on Water Pollution Research, San Francisco, California
This paper describes strategies of aeration of reservoir releases —DWT

APPLIED
reservoir aeration
reservoir releases
physical properties
chemical properties

Speece, R E and Adams, J L, 1967
U-TUBE AERATION
Tech Rept 38 Water Resour Res Inst 77 p
This paper describes engineering aspects of U-Tube aeration —DWT

REVIEWS
aeration
chemical properties

Speece, R E and Orosco, Rudolph, 1970
DESIGN OF U-TUBE AERATION SYSTEMS
J Sanit Eng Div, Proc Am Soc Civil Engrs 96(SA3): 715-725
Four independent parameters were studied in the design of U-Tube aeration systems: (1) Air-water ratio; (2) inlet dissolved oxygen concentration; (3) depth; and (4) water velocity. Each different combination of parameters will result in different capital and operating costs. Outlet dissolved oxygen concentration is reported in this study for the following range of independent parameters: (1) Air-water ratio = 5 to 25 percent; (2) inlet dissolved oxygen = 0 to 100 percent saturation; (3) depth = 20 to 40 ft; and (4) water velocity — 3.6 to 9.2 ft per sec. A computer model of the gas transfer equation, adapted to the U-Tube aerator was used to evaluate the reaeration coefficient, K_2. Transfer of gases other than oxygen is analyzed —Authors

BASIC
aeration
physical properties

Speece, R E, Madrid, M and Needham, K, 1970
DOWNFLOW BUBBLE CONTACT AERATION
Presented at 25th Purdue Industrial Waste Conf, May 1970 20 p
A simple system has been developed to efficiently absorb commercial oxygen and air into water. It consists of passing water down through a submerged cone-shaped hood. Oxygen or air is injected into the hood. The water velocity entering the smaller, top end of the hood is greater than the buoyant velocity of the bubbles. The water velocity leaving the larger, open bottom is less than the buoyant velocity of the bubbles. Thus, the bubbles are "trapped" inside the hood for efficient absorption. Oxygen absorption in excess of 90 percent was achieved with very low power input. The system has potential application in activated sludge, river reaeration, fish hatcheries, yeast production and hypolimnion aeration —Authors

REVIEWS
aeration
physical properties
chemical properties

Sport Fishing Institute, 1971
COLUMBIA RIVER FISH BENDS
Sport Fishing Inst Bull 229: 5-6 Washington, D C
A review was given of the problem of nitrogen supersaturation in reports by Beiningen and Ebel (1970) and the National Marine Fisheries Services. Entrainment of atmospheric nitrogen as surface waters of Columbia and Snake Rivers cascade into deep stilling basins has caused significant mortalities of migrating adult and juvenile salmon —RS

REVIEW
rivers
fish
physical properties

Spurgel, G M, 1951
AN EXTREME CASE OF THERMAL STRATIFICATION AND ITS EFFECT ON FISH DISTRIBUTION

BASIC
pond
fish

Iowa Acad Sci 58: 563-566
One of several studies relating depth distribution of fishes to environmental factors —JNJ

physical properties
chemical properties

Streiff, A, 1955
COMPRESSED AIR VERSUS DROUGHT
Compressed Air Mag 60(8): 232-235

APPLIED
aeration

Strickland, J D H, and Parsons, T R, 1968
A PRACTICAL HANDBOOK OF SEAWATER ANALYSIS
Bulletin 167 Fisheries Research Board Canada, Ottawa 311 p

REVIEWS
physical properties
chemical properties

Stroud, R H, 1970
POWER DEVELOPMENT AND AQUATIC ECOLOGY
Sport Fish Inst Bull 218: 5-6 Washington, D C
Hydroelectric dams constitute a hazard to anadromous fishes, and there is a significant increase in average river water temperature (Columbia River) which can alter susceptibility to certain bacterial diseases. A study by the Sport Fishing Institute under contract from the Corps of Engineers is designed to evaluate the influence of penstock depth on aquatic life within multipurpose reservoirs. Low penstock discharges increased average DO concentrations within the reservoir —RS

REVIEW
reservoir
river
reservoir releases
physical properties

Stumm, W, and Morgan, J J, 1970
AQUATIC CHEMISTRY
Wiley-Interscience, New York, N Y 583 p

REVIEWS
chemical reactions

Sublette, J E, 1957
THE ECOLOGY OF THE MACROSCOPIC BOTTOM FAUNA IN LAKE TEXOMA (DENSION RESERVOIR), OKLAHOMA AND TEXAS
Amer Midl Natur 57: 371-402
The results of a 15 month's study of the ecology of benthic macroinvertebrates in a reservoir are presented. Emphasis was placed on the horizontal distribution and seasonal changes —JW

BASIC
lake
benthos

Summerfelt, R C, 1971
FACTORS INFLUENCING THE HORIZONTAL DISTRIBUTION OF SEVERAL FISHES IN AN OKLAHOMA RESERVOIR
In Gordon E Hall (ed) Reservoir Fisheries and Limnology Special publication number 8 Amer Fish Soc, Washington, DC, pp 425-435
Organic content, hydrogen-ion concentration, median particle diameter, depth, and density of sediment, water depth, total biomass of benthos, biomass of Chironomidae, Tubificidae, Culicidae, and Ephemeridae were used as independent variables in the analysis of the horizontal distribution of carp, carpsucker, channel catfish, flathead catfish, white crappie, white bass, gizzard shad, and freshwater drum in Lake Carl Blackwell, Oklahoma. Catch of fish (kg/net day) by use of 45.7 m, 2.5 cm, 5.0 cm, and 7.5 cm mesh experimental gill nets was used as the dependent variable. Independent variables were used in arithmetic and logarithmic form in a linear regression. Variables with statistically significant linear regression coefficients were used as independent variables in multiple regression analyses —Author

BASIC
reservoir
benthos
fish
physical properties
chemical properties

Summerfelt, R, and Hover, R, 1972
VERTICAL DISTRIBUTION OF FISHES
In R C Summerfelt (Principal Investigator), Influence of artificial destratification on distribution of fishes and fish food organisms and primary productivity Oklahoma State University, Stillwater Dingell-Johnson Final Report, Oklahoma Proj F-24-R-2, Job No 1 53p

Vertical distribution of fishes was studied at sites in the central pool area of Eufaula Reservoir within and outside areas affected by an attempted reservoir destratification project. The objective was to determine whether fish distribution in the area affected by the aeration was different from that elsewhere in the central pool which was not affected by the aeration. Five netting stations were used, ranging from 0.5 to 10.0 km from the dam where the aeration apparatus was installed. Of the 8 species for which depth distribution was critically examined, carp consistently maintained the greatest mean depth of capture. Weekly mean depth of capture of carp was 10 m the first week of June, 18 m the last week of June, and about 15 m July through September —RS

APPLIED
reservoir
destratification
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physical
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Summerfelt, R C, and Lewis, W M, 1967
REPULSION OF GREEN SUNFISH BY CERTAIN CHEMICALS
J Water Pollut Contr Fed 39(12): 2030-2038

Behavioral response of green sunfish to low DO, CO_2, NH_4, and 36 other compounds was tested in a special trough. Fish were not repelled by low DO or CO_2 alone, but anoxia and high CO_2 did produce some repelling action. Toxic concentrations of ammonia greater than 8.5 mg/l were repelling —RS

BASIC
fish
chemical
properties

Summerfelt, R C, Mauck, P E, and Mensinger, G, 1972
FOOD HABITS OF RIVER CARPSUCKER AND FRESHWATER DRUM IN FOUR OKLAHOMA RESERVOIRS
Proc Okla Acad Sci 52: In Press

One of several studies which shows that organic detritus, presumably derived by feeding on the reconsolidated mud-water interface, comprises the major volumetric component in the alimentary tracts of the river carpsucker from large impoundments. The study reinforces the view that organic detritus is an important organic imput to reservoir fish production —RS

BASIC
reservoir
microorganisms
benthos
fish

Summers, Phillip B, 1961
OBSERVATIONS ON THE LIMNOLOGICAL DYNAMICS OF TENKILLER FERRY RESERVOIR
Okla Dept Wildl Conservation, Fed Aid Div Job Completion Report, Project F-7-R-1 52 p

Limnological determinations were conducted on Tenkiller Ferry Reservoir for a period of 8 months. The data were collected for indications to the success of walleye stocking proposed for the spring of 1961. The limnological investigations did not indicate any chemical or physical limitations that would be undesirable to the introduction of walleye in 1961 —AUTHOR

BASIC
reservoir
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properties
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communities

Susag, R H, Robins, M L, and Schroepfer, G J, 1967
IMPROVING RIVER AERATION AT AN UNDERFLOW DAM
J Sanit Eng Div, Proc Am Soc Civ Engrs 93(SA6): 133-144

This paper describes rearation of river water at a low water dam on the Mississippi River near Hastings, Minnesota —DWT

APPLIED
river
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chemical
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Swedberg, D V and Walburg, C H, 1970
SPAWNING AND EARLY LIFE HISTORY OF FRESHWATER DRUM IN LEWIS AND CLARK LAKE, MISSOURI RIVER

BASIC
reservoir
fish

Trans Amer Fish Soc 99: 560-570
The early life history of the fresh-water drum, *Aplodinotus grunniens,* was studied to determine factors influencing first-year class strength —DWT

Swingle, H S, 1966
FISH KILLS CAUSED BY PHYTOPLANKTON BLOOMS AND THEIR PREVENTION
In 1966 FAO World Symp on Warmwater Pond Fish Cult, FAO Fish Rept 5(44): 407-411
Growths of species of *Microcystis, Anabaena,* and occasionally *Trachelomonas* and *Gymnodinium* that form dense concentrations or scum in surface waters have been a primary cause of fish kills in ponds. Dense concentrations of these algae absorbed heat from sunlight, causing a sharp rise in temperature on surface waters. This in turn caused shallow stratification and light winds stirred only the top waters. The heavy concentrations of algae absorbed and reflected sunlight and consequently insufficient light for photosynthesis penetrated to depths below 1 m. Continuation of these conditions for approximately 1 week had the result that insufficient dissolved oxygen was present in waters below 1 m to support fish life. Subsequent upwelling of deeper oxygen-deficient waters caused distress or death of fish from lack of oxygen. Upwellings were caused by cold air masses, heavy winds or cold rains —Author

BASIC
pond
microorganisms
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Symons, J M, 1969
WATER QUALITY BEHAVIOR IN RESERVOIRS— A COMPILATION OF PUBLISHED RESEARCH PAPERS
Public Health Service Publication No 1930 Cincinnati, Ohio, 616 p

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chemical properties
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Symons, J M and Robeck, G G, 1966
IMPOUNDMENT RESEARCH: KEY TO STREAMFLOW REGULATION PROBLEMS
Water Wastes Eng Part I, 3(1): 42-44; Part II, 3(2): 66-68 Republished in 1969, pp 509-527 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio 616 p
Investigations of the behavior and quality of water in impoundments are described. Observations are described on destratification of a large lake by pumping, and laboratory studies on the course of nitrogen transformation in completely aerobic water —DWT

REVIEW
reservoirs
destratification
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physical properties
chemical properties
chemical reactions

Symons, J M, Carswell, J K and Robeck, G G, 1970
MIXING OF WATER SUPPLY RESERVOIRS FOR QUALITY CONTROL
J Am Water Works Assoc 62(9): 322-334

APPLIED
reservoir
destratification

This paper summarizes several years of research on artificial destratification as a method of reservoir water quality control and describes the results achieved when the method was used at several municipal water supply lakes —DWT

physical properties
chemical properties
chemical reactions

Symons, J J, Irwin, W H and Robeck, G G, 1967
IMPOUNDMENT WATER QUALITY CHANGES CAUSED BY MIXING
J Sanit Eng Div, Proc Am Soc Civ Eng 93 (SA 2): 1-20 Republished in 1969, pp 299-326 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio 616 p

Mechanical pumping was used to artificially destratify a 2,380-acre-foot lake (Boltz Lake) in northern Kentucky. Analysis of samples taken weekly, from May to October 1965, throughout the depth of the lake, showed the influence of mixing on water quality. A nearby lake of nearly equal volume (Bullock Pen Lake), sampled similiarly, was used as a control. Results showed a warming and oxygenating of the lower layers of the test lake that resulted in the precipitation of manganese and the oxidation of sulfide. Mixing neither increased the concentration of any nitrogen form, or the total hydrolyzable phosphorus, nor decreased the clarity in the surface. There was no increase in algal densities. Data on work requirements and efficiencies are also given. (Auen-Wisconsin) —SWRA

APPLIED
reservoir destratification
physical properties
chemical properties

Symons, J M, Irwin, W H, and Robeck, G G, 1968
CONTROL OF RESERVOIR WATER QUALITY BY ENGINEERING METHODS
In R A Elder, R A Krenkel, and E L Thackston (ed) Proceedings of the Specialty Conf on Current Research into the Effects of Reservoirs on Water Quality Tech Rep No 17 Dept Environ and Water Resourc Eng Vanderbilt Univ, Nashville, Tenn Republished in 1969, pp 449-480 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio, pp 335-390

This paper presents major conclusions relating to the limnological effects of artificial destratification efforts on Kentucky reservoirs. Artificial destratification will affect only those water quality parameters that: (a) initially show a concentration gradient with depth, or (b) are influenced by the vertical transport of some other water quality constituent. Artificial destratification affected the vertical distribution of the following parameters, as contrasted with their distribution in a nearby unmixed lake: temperature, concentrations of DO, sulfides, manganese, ammonia nitrogen, nitrate nitrogen, organic nitrogen, plankton (temporarily lowered), hydrogen ions (pH), carbon dioxide, and calcium. Artificial destratification did not substantially influence the vertical distribution of the following water quality parameters, as compared with their vertical distribution in a nearby unmixed lake: conductivity and concentrations of iron, COD, dissolved acid, hydrolyzable phosphorus, alkalinity, magnesium, and sulfates —Authors

APPLIED
reservoir destratification
physical properties
chemical properties

Symons, J M, Weibel, S R, and Robeck, G G, 1965
IMPOUNDMENT INFLUENCES ON WATER QUALITY
J Am Water Works Assoc 57(1): 51-75 Republished in 1969, pp 103-143 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio 616 p

This paper is concerned with inadequately studied problem of the quality of impounded water and the practicability of release for stream regulation. Success of this method will require additional research in the systems analysis field, behavior of iron, manganese, nitrogen, phosphorus, and oxygen in impounded environments,

APPLIED
destratification
microorganisms
physical properties
chemical properties
chemical reactions

influence of physical factors and fertilization, and the effect of impoundment release on the quality of downstream water. Research now in progress is concerned with small-scale simulation of stratified impoundments and nitrogen transformations —SWRA

Symons, J M, Weibel, S R, and Robeck, G G, 1966
INFLUENCE OF IMPOUNDMENTS ON WATER QUALITY: A REVIEW OF LITERATURE AND STATEMENT OF RESEARCH NEEDS
Public Health Serv Publ No 999-WP-18 78 p Republished in 1969, pp 3-102 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio 616 p

Since streamflow regulation is currently being considered as a method of water quality control and impoundments will be the source of water for regulated streamflow, the changes in water quality that occur during storage in a given environment must be understood and predictable. Much has been written in the sanitary engineering and limnology literature that bears on the broad problem of determining the influence of impoundments on water quality. This report is a review of that literature. It is impossible to report on all of the literature, but sufficient selected references are reviewed to accomplish three purposes: (1) to indicate to readers who are new to the field of impoundment behavior the enormous breadth of the field, (2) to discuss each topic in sufficient detail to give the reader insight into the current understanding of that topic, and (3) to indicate the major research needs in each area and to suggest possible fruitful avenues of study to satisfy these needs. In addition to the major section on impoundment behavior, this report contains sections on the influence of impoundment releases on downstream water quality and operations research for water quality management —Authors

REVIEWS
reservoirs
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rivers
chemical properties
chemical reactions
physical properties

Symons, J M, DeMarco, J, Irwin, W H, and Robeck, G G, 1966
ENHANCING BIODEGRADATION OF SYNTHETIC ORGANICS IN STRATIFIED IMPOUNDMENTS BY ARTIFICIAL MODIFICATION OF THE THERMAL PROFILE
Symposium of Garda - hydrology of lakes and reservoirs Publ No 70 of De L'Assn Int D'Hydrol Sci Gentbrugge, Belgium Republished in 1969, pp 520-544 *In J M Symons* (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio, pp 383-391

The authors describe laboratory studies on the effects of thermal stratification on the degradation of organic substances, LAS and 2,4-D in lakes and reservoirs and the results of artificially modifying the thermal profile of two stratified reservoirs by pumping —DWT

APPLIED
reservoir destratification
physical properties
chemical properties
chemical reactions

Symons, J M, Irwin, W H, Clark, R M, and Robeck, G G, 1967
MANAGEMENT AND MEASUREMENT OF DO IN IMPOUNDMENTS (ENGINEERING PORTION)
J Sanit Eng Div, Proc Am Soc Civ Eng 93(SA 6): 181-209 Republished in 1969, pp *327-234 In* J M *Symons* (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio 616 p

A basis for the comparison of various mechanical devices used for artificially destratifying impoundments by calculating their hydraulic performance based on impoundments stability is given. Three problems are discussed for clarification: influence of size and geometry on stability, natural changes in stability with time, and the basic hydraulic inefficiency of spring mixing if cold water is raised. A mathematical model is developed for studying the dissolved oxygen budget in impoundments with a solution presented, using specially designed dissolved oxygen determination equipment. Finally, data are presented on the destratification of a 2,930-acre-foot impoundment in northern Kentucky by pumping. The hydraulic

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chemical properties

performance of the pump is calculated and the influence of mixing on the reduced substances and dissolved oxygen resources in the impoundment shown. The most favorable period for destratification is discussed. (Auen-Wisconsin) –SWRA

Symons, J M, Irwin, W H, DeMarco, J, and Robeck, G G, 1967
EFFECTS OF IMPOUNDMENTS ON WATER QUALITY: A RESEARCH SUMMARY
Trans 17th Annu Sanit Eng Conf Bull Eng and Architecture No 57 Univ Kansas, Lawrence Republished as: Symons, J M 1969 The project report, pp 545-586 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio, pp 28-36

This paper presents the summary of work by Symons, Irwin, DeMarco and Robeck on artificial destratification of lakes during the 1960's by mechanical pumping and lake aeration –DWT

APPLIED
reservoirs
destratification
microorganisms
physical
properties
chemical
properties
chemical
reactions

Symons, J M, Irwin, W H, Robinson, E L, and Robeck, G G, 1967
IMPOUNDMENT DESTRATIFICATION FOR RAW WATER QUALITY CONTROL USING EITHER MECHANICAL OR DIFFUSED-AIR PUMPING
J Am Water Works Assoc 59(10): 1268-1291 Republished in 1969, pp 389-427 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio 616 p

The purpose of this paper was twofold; one, to compare two methods for artificially destratifying impoundments, mechanical and diffused-air pumping and, two, to determine whether one mixing in the late summer or a series of mixings periodically throughout the season was a better method for maintenance of good quality water –Authors

APPLIED
reservoir
destratification
microorganisms
physical
properties
chemical
properties

T

Tafanelli, R, Mauck, P E, and Mensinger, G, 1971
FOOD HABITS OF BIGMOUTH AND SMALLMOUTH BUFFALO FROM FOUR OKLAHOMA RESERVOIRS
Proc SE Assoc Game and Fish Comm 24(1970): 649-658
This paper discusses the seasonal and interspecific food habits of the bigmouth and smallmouth buffalo from four Oklahoma reservoirs —MM

BASIC STUDY
reservoirs
fish

Talling, J F, 1971
THE UNDERWATER LIGHT CLIMATE AS A CONTROLLING FACTOR IN THE PRODUCTION ECOLOGY OF FRESHWATER ALGAE
Mitt Int Ver Theor Angew Limnol 19: 214-243
The underwater light climate for phytoplankton is discussed in terms of three groups of factors— surface solar radiation input, vertical attenuation, and depth of mixing— and their varying combinations. Their quantitative assessment is considered from the standpoint of current mathematical models of light factors in photosynthetic productivity, and illustrated by situations drawn particularly from the English lakes. These include the range in optical diversity of English lake waters, the spring phytoplankton increase associated with rising radiation input, and the autumn-winter decline associated with a declining input and increased vertical mixing. A dimensionless parameter (q) is proposed which expresses, for vertically homogeneous populations, the combined action of the three factor-groups in the light climate. It is also used to restate conditions for the "critical depth" situation. Self-regulation of the effective light climate is discussed with reference to the self-shading behaviour and active vertical migrations of some dense populations of the dinoflagellate *Ceratium hirundinella* —Author

BASIC
lakes
physical properties
chemical properties
primary productivity

Tanner, H A, 1960
SOME CONSEQUENCES OF ADDING FERTILIZER TO FIVE MICHIGAN TROUT LAKES
Trans Amer Fish Soc 89: 198-205
Inorganic fertilizer was applied to four of a group of six Michigan trout lakes. The thermocline in the three lakes receiving the most fertilizer shifed to a more shallow position. Three of the fertilized lakes decreased in total alkalinity at a greater rate than did the two lakes not fertilized. Fertilization resulted in the oxygen being depleted from the hypolimnion and some oxygen reduction occurred in the thermocline. The volume of oxygenated water remaining under the ice during the critical period of late winter was reduced in the fertilized lakes, and lakes fertilized at the highest rate very nearly approached winterkill conditions. The reduction of oxygen both in summer stagnation periods and in late winter was more severe after the second season of fertilization —Authors

APPLIED
lake
physical properties
chemical properties

Tarzwell, C M, 1938
CHANGING THE CLINCH RIVER INTO A TROUT STREAM
Trans Amer Fish Soc 68: 228-233
The construction and operation of Norris Dam has changed about 20 miles of the Clinch River from a warm-water to a cold-water stream as the water which is released from the base of the dam usually has a temperature below 50° F. Many of the warm-water fishes were killed by this change. It is hoped this portion of the Clinch River will develop into a trout stream. Quantitative studies of the bottom organisms were made at four localities in this section of the river to discover changes in the warm-water fauna and to determine whether or not a cold-water fauna suitable as a food supply for trout was developing. These studies demonstrated that some of the warm-water forms had disappeared so that only a small residual population was present and that the bottom fauna was not as yet typical of a trout stream —Author

BASIC
reservoir
reservoir releases
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fish

Teerink, J R, and Martin, C V, 1969
ARTIFICIAL DESTRATIFICATION IN RESERVOIRS OF THE CALIFORNIA STATE WATER PROJECT
J Am Water Works Assoc 62(9): 436-440 Also presented at annual conf Calif Dept Water Resources, Sacramento, Calif May 20, 1969

Destratification and aeration in California reservoirs are accomplished by air injection and multiple-level outlet structures. Mixing returns nutrients to the photosynthetic zone for use by organisms, and oxidizes iron and manganese. The effects may be beneficial or detrimental to intended water uses. Evaporation is usually reduced because surface water temperatures are lowered. Dissolved oxygen is increased. Because artificial destratification can produce both benefits and detriments, a study should be made of priority of uses and the effects of mixing, and cost-benefit analyses should be made, placing a value on the various quality changes related to mixing –SWRA

REVIEWS
reservoir
destratification
physical properties
chemical properties

Thackston, E L, and Speece, R E, 1966
REVIEW OF SUPPLEMENTAL REAERATION OF FLOWING STREAMS
J Water Pollut Control Fed 38(10): 1614-1622

The authors review some basic considerations affecting supplemental stream aeration, and factors influencing the choice of aeration site. They outline some actual examples of supplementary aeration reported in the literature by diffused air, turbines, weirs, surface aerators, pressure injection and U-Tubes –DWT

REVIEWS
stream
river
aeration
physical properties
chemical properties

Thackston, E L, and Speece, R E, 1966a
SUPPLEMENTAL REAERATION OF LAKES AND RESERVOIRS
J Am Water Works Assoc 58(10): 1317-1324

Stratification has several disadvantages; among them are the depletion of dissolved oxygen, the solution of iron and manganese, and the accumulation of CO_2. Methods of mixing the water column may help alleviate stratification, but some means of reaeration to increase the concentration of dissolved oxygen is also needed. The authors discuss various methods to reaerate bodies of water by the use of compressed air, the aerohydraulic gun, direct aeration, submerged weirs, selective withdrawal of water, multilevel intake towers, and Howell-Bunger valves –MM

REVIEWS
reservoir
stream
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aeration
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chemical properties

Thienemann, A, 1928
DIE BEIDEN CHIRONOMUS ARTEN DER TIEFENFAUNA DER NORDDEUTSCHEN SEEN
Verh int Ver Limnol Kiel Stuttgart I, 108

BASIC STUDIES
benthos

Thienemann, A, 1954
CHIRONOMUS, LEBEN, VERBREITUNG UND WIRTSCHAFTLICHTEN BEDEUTUNG DER CHIRONOMIDEN-LARVEN. DIE BINNENGEWASSER
Vol 20 E Schweitzerbartsche Verlagsbuchhandlung, Stuttgart

This reference gives a comprehensive limnological study of the dipterous families Chironomidae (Tendipedidae) and Ceratopogonidae (Heleidae) –DWT

BASIC
benthos

Thomas, E A, 1966
DER PFAFFIKERSEE VOR, WAHREND UND NACH KUNSTLICHER DURCHMISCHUNG
Verh Int Verein Limnol 16: 144-152

This paper describes physical and chemical conditions in Pfaffikersee before, during, and after lake mixing –DWT

APPLIED
lake
destratification
physical properties
chemical properties

Thomas, H A, 1958
MIXING AND DIFFUSION OF WASTES IN STREAMS
In: Oxygen relationships in streams Robt A Taft Sanit Eng Center Tech Rep W58-2 US Public Health Serv Cincinnati, Ohio 206 p

This paper describes factors causing longitudinal mixing of waste waters that have been discharged to streams, the effects of such mixing, and methods of determining and expressing the results of similar studies —DWT

APPLIED
river
stream
aeration
physical properties
chemical properties

Tibbles, J J G, 1956
A STUDY OF THE MOVEMENTS AND DEPTH DISTRIBUTION OF THE PELAGIC FISHES OF LAKE MENDOTA

One of several studies that establish the depth preference of fishes —JNJ

BASIC
lake
fish
physical properties

Toetz, D, 1972
VERTICAL DISTRIBUTION OF PLANT NUTRIENTS
In R C Summerfelt (Principal Investigator) Influence of artificial destratification on distribution of fishes and food organisms and primary productivity. Oklahoma State University, Stillwater Dingell-Johnson Final Report, Oklahoma Proj F-24-R-2, Job No 2 10 p

It was hypothesized that destratification would produce homothermy and an orthograde distribution of nutrients. Two sampling sites, each having two substations, were established; one site was located within 1.6 km from the aerator, while the other was 8.0 km from aerator. Water samples were collected at 1 m, 5 m, and just above the bottom. During most of the study, nitrate was found near the bottom in water containing less than 0.2 mg/l DO. Denitrification was probably not occurring. Oxygen at 0.2 mg/l might have been sufficient to inhibit denitrification. Prior to destratification, near bottom concentrations of total phosphorus were very large (269-474 mg/m^3) but near orthograde. Total phosphorus concentrations occurring after aeration could not be associated with aeration as similar changes occurred outside of the zone of influence of the aerator. Concentation of chlorophyll *a* ($\mu g/l$) in surface water areas was used as a measure of the biomass of primary producers. Concentration of chlorophyll *a* declined in the vicinity of the aerator after commencing aeration which may have resulted from the turbulence. However, 19 days after aeration started, concentration of chlorophyll *a* was about the same in the vicinity of the aerator as at the other site. Because of the relatively high flow of aerated water through the dam, no clear conclusions can be drawn except that the hypolimnetic water of the entire basin of the central pool may have been more turbulent than the oxygen profiles suggested —DWT

APPLIED
reservoir
destratification
physical properties
chemical properties

Tressler, W L and Domogalla, B P, 1931
LIMNOLOGICAL STUDIES OF LAKE WINGRA
Wisconsin Acad Sci, Trans 26: 331-352

Lake Wingra, Wisconsin, shows very little stratification, temperature difference between surface and bottom being less than 5° C —DWT

BASIC
lake
microorganisms
zooplankton
chemical properties
physical properties

Tubb, R, 1966
LIMNOLOGICAL CONDITIONS IN AERATED LAKES OF THE TURTLE MOUNTAINS, N DAKOTA

APPLIED
lake
destratification

Dingell-Johnson Preliminary Report, N Dakota Proj F-2-R-13, Job No 19 19 p
Limnological data were obtained to assess the effect of aeration of winterkill lakes in North Dakota. Aeration prevented thermal stratification and brought aoout orthograde distribution of oxygen. The problem of ammonia-oxygen relationships is discussed –DWT

aeration
fish
physical properties
chemical properties

Turner, W R, 1959
EFFECTIVENESS OF VARIOUS ROTENONE-CONTAINING PREPARATIONS IN ERADICATING FARM POND FISH POPULATIONS
Ky Dept Fish and Wildlife Resources Fish Bull 25: 1-22
A comparison of four different rotenone-containing products based on their effectiveness in eradicating fish populations was made in 56 Kentucky farm ponds representative of various seasonal conditions. The studies revealed that complete fish population eradication was most successful during the summer period of June through mid-September. Rotenone penetration was investigated in 38 of the 56 ponds and was found to be essentially the same in ponds treated during the fall overturn period, October and November, as it was in ponds that were thermally stratified. The maximum depth to which rotenone penetrated in amounts lethal to fish was 8 feet, regardless of the prevailing water conditions –Author

APPLIED
pond
fish
physical properties
chemical properties

Turner, PR and Summerfelt, R C, 1970
FOOD HABITS OF ADULT FLATHEAD CATFISH, *PYLODICTUS OLIVARIS* (Rafinesque), IN OKLAHOMA RESERVOIRS
Proc S E Assoc Game and Fish Comm 24: 387-401
Food habits of flathead catfish from six Oklahoma reservoirs were determined from specimens taken by gill and trammel nets. Fish comprised more than 95 percent of total food volume and total number of food items in all six reservoirs. Gizzard shad contributed from 49.5 to 91.7 percent of total stomach volumes. Fresh-water drum were second in importance as forage. Gizzard shad decreased in importance as forage during spring and summer months in most reservoirs. Flathead catfish predation in reservoirs is probably determined by the availability of suitable-sized forage species near the reservoir bottom in water depths inhabited by flathead catfish –JNJ

BASIC
reservoir
fish

U

Uhlmann, D, 1971
INFLUENCE OF DILUTION, SINKING AND GRAZING RATE ON PHYTOPLANKTON POPULATIONS OF HYPERFERTILIZED PONDS AND MICRO-ECOSYSTEMS
Mitt Int Ver Theor Angew Limnol 19: 100-124

An overall-rate-of-change equation Turner, P R and Summerfelt, R C, 1970 represented by importation and growth, losses by dilution, grazing sedimentation. All rate-constants are assumed to be proportional to biomass concentration of phytoplankton. This is evident for dilution from theoretical considerations and for sedimentation from experimental results. It reveals only a rough approximation in the case of grazing —Author

BASIC
lake
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physical properties
chemical properties
primary production

Uttormark, P, 1968
DISCUSSION BY SYMONS, J M, IRWIN, W H, AND ROBECK, G G, 1968 CONTROL OF RESERVOIR WATER QUALITY BY ENGINEERING METHODS."
In: Proceedings of the Specialty Conference on Current Research Into the Effects of Reservoirs on Water Quality. R A Elder, P A Krenkel, and E L Thackston, Eds Tech Rep No 17 Dept Environmental and Water Resources Engineering, Vanderbilt Univ, Nashville, Tenn 1968 pp 335-90 Republished in 1969, pp 449-497 *In* J M Symons (ed) Water quality behavior in reservoirs: a compilation of published research papers Public Health Serv Publ No 1930 Cincinnati, Ohio 616 p

Paul Uttormark describes a mixing cell at Cox Hollow Lake induced by Aero-Hydraulic "guns" —DWT

APPLIED
reservoir
destratification
physical properties

Vanicek, C D, and Kramer, R D, 1969
LIFE HISTORY OF THE COLORADO SQUAWFISH, *PTYCHOCHEILUS LUCIUS,* AND THE COLORADO CHUB, *GILA ROBUSTA,* IN THE GREEN RIVER IN DINOSAUR NATIONAL MONUMENT, 1964-1966
Trans Amer Fish Soc 98(2):193-208

Investigations of the ecology and life history of the Colorado squawfish, *Ptychocheilus lucius,* and the Colorado chub, *Gila robusta,* in the Green River in Dinosaur National Monument, Colorado-Utah, were conducted from May 1964 to October 1966. The operation of Flaming Gorge Reservoir (74.0 km above the Monument) has reduced the range of these two species in this area. Age and growth determinations were made from scales from 182 squawfish and 333 chubs. Both species grew slower in years after reservoir operation began (1963-1965) than before (1958-1962); this reduction in growth rate was related to the alteration of seasonal stream-temperature pattern caused by these operations —Authors

BASIC
river
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Vanicek, C D, Kramer R H, and Franklin, D R, 1970
DISTRIBUTION OF GREEN RIVER FISHES IN UTAH AND COLORADO FOLLOWING CLOSURE OF FLAMING GORGE DAM
S W Nat 14(3): 297-315

Closure of Flaming Gorge Dam on the Green River in 1962 caused reduction in downstream water temperatures for 104.6 km to the confluence of the Green and Yampa Rivers. Native fish populations, particularly in the first 41.8 km below the dam were largely replaced by introduced rainbow trout *(Salmo gairdneri)* in 1964 and 1966 when summer discharge was high, no reproduction of native fishes occurred in the Green River above the mouth of the Yampa River —RS

BASIC
river
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properties

Van Ray, L C, 1967
EVALUTATION OF ARTIFICIAL AERATION IN STOCKADE LAKE, SOUTH DAKOTA
South Dakota Dept of Game, Fish and Parks Dingell-Johnson Project Rept No F-15-R-2, Job No 1 13 p

An unsuccessful attempt to modify environmental conditions of an eutrophic lake by aeration was made with the use of three small air compressors and plastic air-lines. The aeration system operating during the project did not produce any noticeable modifications in the lake environment which were beneficial to management of the lake as a trout fishery. Nutrients in the effluent from a sewage treatment plant were the major cause of accelerated eutrophication in the study lake —JNJ

APPLIED
lake
aeration
fish
physical
conditions
chemical
conditions

Varley, J D, Regenthal, A F, and Wiley, R W, 1971
GROWTH OF RAINBOW TROUT IN FLAMING GORGE RESERVOIR DURING THE FIRST SIX YEARS OF IMPOUNDMENT
In: Hall, G E (ed) Reservoir fisheries and limnology Am Fish Soc Spec Publ No 8 Am Fish Soc, Wash, DC, pp 121-136

Rainbow trout age, growth, and condition data were collected on Flaming Gorge Reservoir for the first 6 years of impoundment. At least 10 statistically different trout populations (distinguished by heterogeneity in growth) existed during this period. These populations were related to characters of area, time, and growth. Relative condition factors increased with increased distance from the dam —Authors

BASIC STUDY
reservoir
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Verduin, J, 1969
CRITIQUE OF RESEARCH METHODS INVOLVING PLASTIC BAGS IN AQUATIC ENVIRONMENTS
Trans Amer Fish Soc 98: 335-336

This paper criticizes the use of polyethylene cylinders in productivity studies —DWT

BASIC
lakes
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W

Wagner, H, 1967
ARTIFICIAL AERATION OF LAKES
Fod Eur Gewasserschutz, Inf Bull No 14: 82-84

This paper reviews Bernhardt's *artificial* aeration efforts *in* Wahnbach *reservoir,* Germany —DWT

REVIEWS
reservoirs
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chemical properties

Walshe, B M, 1947
ON THE FUNCTION OF HAEMOGLOBIN IN CHIRONOMUS AFTER OXYGEN LACK
J Exp Biol 24: 329

When *Chironomus plumosus* larvae receive aerated water after a period of anaerbosis their oxygen consumption increases immediately to a value above normal. The increased oxygen consumption is due to increased activity and represents repayment of an oxygen debt. The haemoglobin of the larvae does not function during the repayment in fully aerated water of the small oxygen debt —JW

BASIC
lake
benthos

Walshe, B M, 1953
LE METABOLISME DE *CHIRONOMUS PLUMOSUS* DAN DES CONDITIONS NATURELLES
Physiol Comp Oecol 3(2): 135-154

Oxygen consumption on the final instar larvae of *C. p. plumosus* L. at 17° C was measured under a variety of experimental conditions —DWT

BASIC
benthos
chemical reactions

Watanabe, T, Kusama, M, Kubota, S, Yahagi, H and Tsuda, M, 1966
EFFECT OF FERTILIZING WITH HEN EXCREMENT AND AERATION *IN* POND ORGANISMS
Jap J Ecology 16: 119-123 Not seen

APPLIED
pond
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benthos
biological community

Water Quality Criteria, 1968
REPORT OF THE NATIONAL TECHNICAL ADVISORY COMMITTEE ON WATER QUALITY CRITERIA
Fed Water Poll Contr Admin, Washington, D C 234 p

Water quality criteria are recommended as guidelines for assisting State and Federal agencies in setting and evaluating standards for five major categories of water uses: (1) recreation and aesthetics; (2) public water supplies; (3) fish and other aquatic life, and wildlife; (4) agricultural uses; (5) industry. Quality criteria are characteristerics of a physical, chemical, or biological nature demanded by aquatic life, industrial process, or other use. The Committee report summarized several pertinent references on environmental requirements essential for growth, reproduction and well-being of aquatic life —RS

REVIEW
microorganisms
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Wedemeyer, G, 1970
THE ROLE OF STRESS IN THE DISEASE RESISTANCE OF FISHES
In: S F Snieszko (ed) A Symposium on Diseases of Fishes and Shellfishes Amer Fish Soc, Washington, DC, pp 30-35

The literature dealing with stress and fish diseases is reviewed. The generalized decrease in disease resistance which follows nonspecific stress is discussed in terms of the probable physiological and biochemical mechanisms involved. These include steroid hormone metabolism, the inflammatory response, and interferon and antibody production —Author

REVIEW
microorganisms
fish

Welch, P S, 1952
LIMNOLOGY, 2nd ED
McGraw-Hill Book Co, New York 538 p

Wells, L, 1966
SEASONAL AND DEPTH DISTRIBUTION OF LARVAL BLOATERS *(COREGONUS HOYI)* IN SOUTHEASTERN LAKE MICHIGAN
Trans Am Fish Soc 95(4): 338-396
One of several studies that establish depth preferences of fishes --JNJ

BASIC
lake
fish
physical
properties

Wells, L, 1968
SEASONAL DEPTH DISTRIBUTION OF FISH IN SOUTHEASTERN LAKE MICHIGAN
U S Fish and Wildlife Service, Fish Bull 67(1): 1-15
One of several studies relating depth distribution of fishes to environmental factors –JNJ

BASIC
lake
fish
physical
properties

Wetzel, R, 1965
NUTRITIONAL ASPECTS OF ALGAL PRODUCTIVITY IN MARL LAKES WITH PARTICULAR REFERENCE TO ENRICHMENT BIOASSAYS AND THEIR INTERPRETATION
In C R Goldman (ed) Primary productivity in aquatic environments Mem Ist Ital Idrobiol, 18 Suppl, Univ of Calif Press, Berkeley
This paper describes the role of the monovalent: divalent cation in primary production –DWT

BASIC
lake
microorganisms
chemical
properties

Whipple, W, Coughlan, E P and Yu, S L, 1970
INSTREAM AERATORS FOR POLLUTED RIVERS
J Sanit Eng Div Am Soc Div Eng 96(SA5): 1153-1165
Field tests and performance analysis of instream aeration equipment on the Passaic River showed mechanical aerators were more efficient than diffusers. Transfer rates varied markedly with oxygen deficit, temperature, and velocity of flow. Unexpectedly, the rate of deoxygenation increased greatly downstream of the aerators. Cost estimates indicate that nine 75-hp mechanical aerators with a total rated capacity of 675 hp would have total annual costs of $102,000 or $151 per annual hp of rated capacity. Electric-drive diffuser aerators rated at 80 hp each would have total annual costs of $141,400 or S147 per annual hp of rated capacity. No injured fish were observed in two seasons of operation. A systems analysis, based upon the principle of BOD mass balance analysis, showed that aerators would achieve a given dissolved oxygen level at about one-fourth the cost of advanced waste treatment. Application should be considered for those streams where secondary waste treatment is not sufficient to achieve dissolved oxygen levels desired. (Upadhyaya-Vanderbilt) –SWRA

APPLIED
river
stream
aeration
physical
properties
chemical
properties

Whipple, W, Jr, Hunter, J V, Dittman, F W, Yu, S L, Davidson, B and Mattingly, G, 1971
OXYGEN REGENERATION OF POLLUTED RIVERS: THE PASSAIC RIVER
Water Pollut Contr Res Series 16080 FYA 03-71 EPA/WQO 56 p
Field tests were made of a mechanical surface aerator and of pure oxygen diffusers in a small polluted river, the upper Passaic. Results generally corroborated results of previous tests, as to performance of surface aerators on such rivers, in excavated pools. A somewhat higher oxygen transfer rate was obtained with a flow concentration device, which, in a permanent installation, would take the form of low rock spur dikes, one extending from each bank, or flow concentration groins. Tests in shallower water, about 7 feet deep, were inconclusive. Tests of oxygen diffusers were fragmentary, due to mechanical difficulties with the equipment; but it was largely absorbed in the water.

APPLIED
river
stream
aeration
physical
properties
chemical
properties

A dye dispersion test gave a very high longitudinal dispersion coefficient downstream of the aerator. Mathematical modelling indicated that during the test period, parameters of biochemical deoxygenation were not changed by the artificial aeration process —Authors

Whipple, William, Jr, and Yu, S L, 1971
AERATION SYSTEMS FOR LARGE NAVIGABLE RIVERS
J Sanit Eng Div, Proc Am Soc Civ Engrs 97(SA6): 883-902
River aeration systems using only slight modifications of commercially available components, appear to offer a very economical means of achieving dissolved oxygen standards on major rivers. Whether surface aerators or bottom air diffusers are applicable to a given site depends primarily upon requirements of navigation. Spacing of aerator sites would require an analysis of dispersion characteristics and bio-chemical-oxygen-demand regimen. On critical areas of the Delaware estuary costs of obtaining the last milligram per liter of dissolved oxygen by river aeration are estimated to be less than one third of the cost of obtaining the same objective through waste treatment only. There is a possibility that even lesser costs could be realized through use of pure oxygen dispersers, but these possibilities do not appear to have been fully explored —Authors

APPLIED
river
stream
aeration
physical properties
chemical properties

Whitmore, C M, Warren, C E, and Douderoff, P, 1960
AVOIDANCE REACTIONS OF SALMONID AND CENTRARCHID FISHES TO LOW OXYGEN CONCENTRATIONS
Trans Amer Fish Soc 89(1): 17-26
Results of experiments to determine degree of avoidance of four selective concentrations of DO by juvenile chinook salmon, coho salmon, largemouth bass and bluegill sunfish in a channeled avoidance tank are reported. All four species avoided DO concentrations of 1.5 mg/l —RS

BASIC
fish
physical properties
chemical properties

Wiebe, A H, 1938
LIMNOLOGICAL OBSERVATIONS ON NORRIS RESERVOIR WITH SPECIAL REFERENCE TO DISSOLVED OXYGEN AND TEMPERATURES
North Am Wildl Conf 3: 440-457
This paper describes the distribution of temperature, dissolved oxygen, free CO_2, pH, and total alkalinity in Norris Reservoir during the summer and fall of 1937. Distributions are related to stratification and reservoir operation —MM

BASIC
reservoir
physical properties
chemical properties

Wiebe, A H, 1940
THE EFFECT OF DENSITY CURRENTS UPON THE VERTICAL DISTRIBUTION OF TEMPERATURE AND DISSOLVED OXYGEN IN NORRIS RESERVOIR
J Tenn Acad Sci 15: 301-308
During the summer most of the inflow into Norris Reservoir flows through the reservoir at some distance below the surface as a density current. The inflow in 1938 was much larger than in 1937. Since the inflow is warmer than the lower strata of the reservoir and because of the high O_2 demand of the inflow, the warming up of the reservoir and the depletion of O_2 in 1938 were accelerated as compared with 1937 —Author

Wiley, A J, Lueck, B F, Scott, R H, and Wisniewski, T F, 1962
COMMERCIAL-SCALE STREAM REAERATION
J Water Pollut Contr Fed 34(4): 401
Describes present status of commercial-scale stream aeration as means for accelerating recovery of oxygen depleted waters —DWT

REVIEWS
river
aeration
chemical properties

Wilkins, P, Kirkland, L, and Hulsey, A, 1967
THE MANAGEMENT OF TROUT FISHERIES IN RESERVOIRS HAVING A SELF-SUSTAINING WARM WATER FISHERY
In Reservoir Fishery Resources Symposium, Amer Fish Soc, Washington, DC pp 444-452

REVIEWS
reservoir
fish
physical properties
chemical properties

A national survey indicated that management of trout in reservoirs with self-sustaining warm-water fish populations for production of trout is an important segment of the fisheries program in 31 of 47 responding states. Most of these trout fisheries originated and are maintained from stocked fish. Previously established criteria of 70° F maximum temperature and 3 ppm minimum dissolved oxygen for determining suitability of reservoirs for rainbow and brown trout were verified. Two basic situations that produce water of this quality are discussed. A recovery rate of 50 percent by weight is suggested by the authors to justify stocking. The consensus of the survey was that costs of maintaining these fisheries were justified —Authors

Wirth, T L, 1970
MIXING AND AERATION SYSTEMS IN WISCONSIN LAKES
In E Schneberger (ed) Symposium on the management of midwestern winterkill lakes, Dec 1970 Winnipeg, Manitoba, Canada North Central Div, Am Fish Soc Spec Publ, pp 31-45

APPLIED
lake
aeration
fish
physical properties
chemical properties

Equipment designed for waste water treatment in lagoons is well fitted to add oxygen to lakes subject to winterkill of fish. Besides providing artificial aeration, these systems are capable of utilizing in-lake heat to maintain sizeable ice-free areas to enhance photosynthetic oxygen production. The systems were shown to induce considerable horizontal mixing under the cover of ice. Winter operation is described for two lakes 96 and 2,625 acres in size and a system designed for a 6,600-acre lake is described

Wirth, T L, and Dunst, R C, 1967
LIMNOLOGICAL CHANGES RESULTING FROM ARTIFICIAL DESTRATIFICATION AND AERATION OF AN IMPOUNDMENT
Wisconsin Conservation Department Res Rep No 22 (Fisheries) 15 p

APPLIED
reservoir
destratification
physical properties
fish
chemical properties

This paper describes the limnological effects of destratification of Cox Hollow Lake in southwestern Wisconsin during 1966. Data on water chemistry were collected before and after aeration by an Aero-Hydraulics system capable of moving 1/7 of the lake volume per day. Before aeration began, temperature, O_2, Fe, Mn, NH_3 and PO_4-P (dissolved and total) showed clinograde distributions. Aeration brought about isothermal conditions, reduced the concentration of O_2. All forms were more or less isochemical in distribution, except for NH_3, which remained clinograde for a period after aeration began. The NH_3 then decreased to undetectable concentrations and increased toward the end of the period of observation. The pH of hypolimnetic water in 1966 was 0.9 to 1.4 units lower than epilimnetic water the year before aeration, while the pH of water from the surface and the bottom was the same during aeration (8.3). The transparency of the water was reported to have been greater during the year of aeration, compared to the previous year. The authors attributed this to a diminution of the regular bloom of algae in late summer. The algae bloom which developed was reported not to be offensive —DWT

Wirth, T L, Dunst, R C, Uttormark, P D and Hilsenoff, W, 1970
MANIPULATION OF RESERVOIR WATER FOR IMPROVED QUALITY AND FISH POPULATION RESPONSE
State of Wis Nat Resour Dept, Conserv Div, Bureau Res & Planning, Research Report 62 23 p

APPLIED
reservoir
reservoir releases
microorganisms
physical properties

This paper describes the downstream effects of hypolimnetic releases of water from Twin Valley Lake, a highly eutrophic impoundment in southwestern Wisconsin. A theoretical discussion of thermal effects of such discharges is given. Hypolimnetic releases decreased stream temperatures below the impoundment during the summer. Nutrients were high in water released, e. g. dissolved phosphorus was 0.8 mg/l. A massive bloom of *Sphaerotilus* occurred during May and June for the first 155 m below the dam. During the summer the population waned and the species was restricted to the outlet pipe —DWT

chemical
properties

Wisniewski, T F, 1965
IMPROVEMENT OF THE QUALITY OF RESERVOIR DISCHARGES THROUGH TURBINE OR TAILRACE AERATION
In J F McLean (Chairman) Symposium on streamflow regulation for quality control U S Public Health Serv Publ No 999-WP-30 Cincinnati, Ohio, pp 299-316
This paper describes the strategies of turbine aeration and tailrace aeration used on Wisconsin rivers —DWT

APPLIED
river
stream
aeration
chemical
properties

Woods, D E, 1961
THE EFFECTS OF COMPRESSED AIR ON WINTER OXYGEN LEVELS IN A FERTILE SOUTHERN MINNESOTA LAKE
Minn Dept Conservation, Minn Fish & Game Invest, Fish Ser No 3, pp 51-62
The removal of a portion of the ice cover with compressed air proved to be an unsuccessful means of maintaining adequate winter dissolved oxygen levels in a small fertile southern Minnesota lake. Turbulence set up by the rising air bubbles circulated the water under the open areas, mixing and diluting it with surrounding water. This condition prevented the buildup of dissolved oxygen. Penetration of 2.6 percent of the light available at the surface was required for photosynthetic replacement of oxygen taken up by decomposition. At anything more than 3 inches of loose snow light penetration fell below this level of compensation intensity. The depth of ice regardless of its structure had little effect on light penetration compared to the depth of snow cover. Recovery of dissolved oxygen commenced after the first thaw in the water surrounding weed beds, suggesting the possibility of winterkill prevention by plowing snow over submerged vegetation —Author

APPLIED
lake
aeration
fish
aquatic
plants
physical
properties
chemical
properties

Z

Zebe, E C, McShan, W H, 1957
LACTIC AND A-GLYCERO-PHOSPHATE DEHYDROGENASE IN INSECTS
J Gen Physiol 40: 779-790

Tissues from insects belonging to various taxonomic groups were extracted and assayed for their lactic dehydrogenase (LDH) and a glycerophosphate dehydrogenase (GDH I) activities from the comparative point of view —DWT

BASIC
benthos

Zieminski, S A, and Whittemore, R C, 1970
INDUCED AIR MIXING OF LARGE BODIES OF POLLUTED WATER
Water Pollut Contr Res Series 16080 DWP 11/70 EPA/WQO, 46 p

The work discussed in this report constitutes the Phase I of the investigation of induced air mixing of large bodies of water. The objective of this work was to conduct a pilot scale study to estimate the effects of variables such as the airflow rate, geometry of the body of water, energy input, size of air bubbles, and the pumping capacity of the air plume on the time of mixing. The latter was defined as the time required to reach 90 percent of the equilibrium concentration of the KC1 tracer. The study emphasis was put on the direction and relative magnitudes of the variables in order to obtain guidelines for large-scale investigation —Authors

APPLIED
lake
reservoir
destratification
aeration
physical properties

Zweiacker, P L, 1970
POPULATION DYNAMICS OF LARGEMOUTH BASS IN AN 808-HECTARE OKLAHOMA RESERVOIR
Ph D thesis, Okla State Univ, Stillwater, Oklahoma 126p

Largemouth bass were collected from Lake Carl Blackwell, an 808-ha reservoir by electrofishing. Electrofishing was found to be effective for collecting sufficient numbers of bass for making estimates of several population parameters. Population dynamics studied include food habits, population estimates, age and growth, coefficient of condition, total mortality rates, fishing mortality rates, standing crop, production and yield —JNJ

BASIC
reservoir
benthos
fish
physical properties

7-1750 (3-71)
Bureau of Reclamation

CONVERSION FACTORS–BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

*U. S. Government Printing Office: 1972-782-497/83 Region 8

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.7299	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	*0.965873×10^{-6}	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	*0.3048	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	*4.4482×10^5	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor) transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

ABSTRACT

The state of the art of research concerning the biological effects of reaeration and destratification is described, with emphasis on lakes and reservoirs. Research needs are discussed, based on this review. Useful descriptions of methods and devices for reaeration and destratification and a comprehensive annotated bibliography of 337 references are included.

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REC-ERC-72-33
Toetz, D; Summerfelt, R; Wilhm, J
BIOLOGICAL EFFECTS OF ARTIFICIAL DESTRATIFICATION AND AERATION IN LAKES AND RESERVOIRS—ANALYSIS AND BIBLIOGRAPHY
Bur Reclam Rep REC-ERC-72-33, Div Gen Res, Oct 1972. Bureau of Reclamation, Denver, 117 p, 19 fig, 337 ref

DESCRIPTORS—/ *water quality/ chemical properties/ *reaeration/ water quality control/ aeration/ aquatic environment/ *reservoirs/ *lakes/ mixing/ biological properties/ *reviews/ *bibliographies/ *environmental effects
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