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ITH SPECIAL EMPHASIS ON STUDY OF
AKE WOHLFORD, CALIFORNIA

ORDON E. KOBERG *and* MAURICE E. FORD, JR.

NTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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ELIMINATION OF THERMAL STRATIFICATION IN RESERVOIRS AND THE RESULTING BENEFITS, WITH SPECIAL EMPHASIS ON STUDY OF LAKE WOHLFORD, CALIFORNIA

By GORDON E. KOBERG [1] and MAURICE E. FORD, JR.[2]

ABSTRACT

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 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, Calif., 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.

INTRODUCTION

Stratification of the water occurs in many reservoirs and lakes because of the temperature distribution with depth. The degree of stratification will vary according to the season and the depth of water in the reservoir. The summer months generally have the greatest

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stratification whereas the winter months have the least. The stratification is best defined by the temperature distribution. Limnologists have divided the water by depth into three layers: (a) Epilimnion, the layer of isothermal water from the surface to the level where the temperature of the water begins to change rapidly with depth, (b) thermocline, the layer of water with rapidly changing temperature, and (c) hypolimnion, the layer of isothermal water between the thermocline and the bottom of the lake.

The quality of water stored in each of the three layers varies with the season of the year. McEwen (1941) stated that, in general, a gradient of the concentration of any dissolved substance gives rise to forces tending by diffusion to equalize the concentration. Likewise, a temperature gradient tends to be eliminated by the resulting conduction of heat. However, such processes tending to produce a uniform distribution of heat and dissolved substances in still water are very slow. Therefore, the quality of water stored in each layer depends on the natural mixing motion within the layer and how this mixing motion is transferred from one layer to another. This paper presents the results of a detailed study, made in collaboration with the Escondido Mutual Water Co. at Escondido, Calif., of mixing action induced into Lake Wohlford by an air-bubbling system.

In many reservoirs the water has seasonal changes of taste and odor because the mixing motions are limited to the epilimnion by the temperature distribution of the water, a condition which poses a problem if the reservoir is used for domestic water supply. To overcome this problem water is usually withdrawn from the epilimnion, which is generally of the best quality. The concentration of substances in the epilimnion are equalized by the wind and the process of photosynthesis. Some reservoirs are restricted to several levels at which water can be withdrawn, and consequently when large demands are placed on the stored water, some of the obnoxious water will be withdrawn. Furthermore, during periods when the water in the reservoir overturns, the water from the hypolimnion is distributed throughout the reservoir, and the quality of the water in the epilimnion is lowered.

Reservoir operators who cope with problems of taste and odor have experimented with various methods of changing the temperature distribution to induce mixing into the thermocline and hypolimnion. In most of these methods air is forced into the bottom of the reservoir and, as the air rises in the form of bubbles, a mixing action is induced into the water. This method of mixing has been the most successful, and various techniques of forcing air into the water are described in this paper.

The elimination of thermal stratification will change the seasonal rates of evaporation. Reservoirs with a large storage of water in the hypolimnion will have an appreciable reduction in evaporation during the late spring and summer months and a corresponding increase in evaporation during the fall and early winter months. However, the operation of a reservoir may be such that there is a net annual reduction in evaporation, as shown by measurements of evaporation at Lake Wohlford.

DISTRIBUTION OF TEMPERATURE WITH DEPTH

EFFECT OF SURFACE HEATING AND COOLING

The rate of heat exchange between the water in a reservoir and the atmosphere is dependent upon the temperature of the water at the surface and such external agencies as evaporation, conduction, and radiation. The rate of heat exchange between the surface and internal water is dependent upon the processes of conduction and diffusion and is controlled mainly by the temperature of the water at the surface.

The surface of the water is constantly undergoing changes in temperature because of the external agencies and the internal processes. These changes in temperature of the water surface are accompanied by corresponding changes in density. So long as the density of the water at the surface is less than that of the water below it, the water at the surface will remain in place. If the density becomes greater, however, particles of the water at the surface will descend until they reach a layer that is equal to their density.

The settling of particles of water due to an increase in density will cause a compensating upward displacement of warmer water. These particles of warmer water will move upward until they reach a layer of equal density. The vertical movement of particles of water that is caused by changes in density is considered to be a significant factor in the distribution of temperature with depth in a reservoir.

The diffusion process of warmer water rising to the surface will continue as long as the temperature of the water is above 4°C, the temperature at which the density of water is maximum. When the temperature of the water is below 4°C, the colder water will float on the surface, and the warmer water will sink toward the bottom.

The conduction of heat from the surface to the water below depends on the temperature gradient and the coefficient of thermal conductivity, which is approximately 0.0014 calorie per second per square centimeter times degrees Centigrade per centimeter for the normal range of water temperature. As the transfer of heat by conduction is a slow process in water, the effect of this process on the distribution of tem-

1949) illustrate this phenomenon best. Whenever water was released from the lower gate, approximately 200 to 300 feet below the surface, the temperature of the released water remained almost constant throughout the year, even though there was a 20°C range in temperature at the surface. If the release is great enough to change the storage in the reservoir appreciably, the distribution of temperature in the reservoir is changed for the layer at which water was taken from storage.

EFFECT OF WIND

The effect of wind in the distribution of temperature in the reservoir is considered an important factor in the diffusion process of vertical mixing. The frictional drag of winds upon the water surface results in a current directed with the winds. This upper layer in turn exerts a frictional drag upon the one underneath and so on to lower levels. Thus, particles of water are set in motion, and any tendency of the particles to move in the vertical directions is influenced by the different densities.

Horizontal currents, as induced by wind, cause the water to pile to the leeward side of the reservoir and to lower correspondingly at the

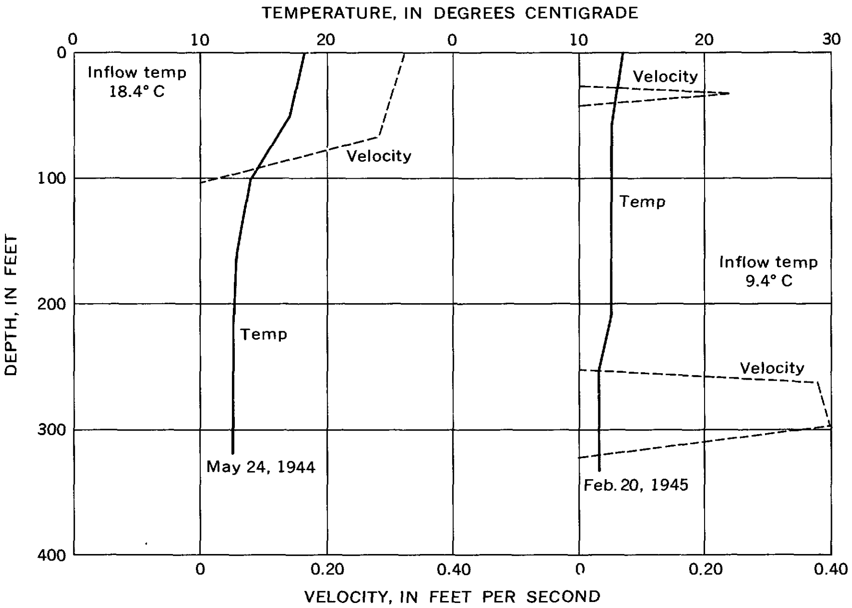

FIGURE 1.—Temperature and velocity profiles as measured at Iceberg Canyon, Lake Mead, Ariz., on indicated dates. Data from Lake Mead Density Currents Investigations (National Research Council, 1949).

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windward side. When the density is equal throughout, a return gradient current due to this difference in pressure is generated in the deep strata, extending to a shearing zone near middepth which divides the water mass into two currents flowing in opposite directions. The horizontal currents are connected by one directed downward at the leeward side and upward at the windward side; thus a complete circuit is formed, and eventually the whole mass is thoroughly mixed.

The complete circulation of water in a reservoir as induced by the wind occurs only during the winter months or whenever the reservoir has an equal density throughout. For these periods of equal density, the lake water is overturned by the wind, and as the hypolimnion water is brought to the surface, a change in quality is easily detected. The complete overturn is usually noted in early and late winter for northern lakes. For southern lakes, one overturn can be detected in the late fall, and then the lake usually remains isothermal until the warming cycle is again resumed in the spring. During the other seasons, a circulation of this type is resisted by the different densities of water which restrict the circulation to the epilimnion and leave the thermocline and hypolimnion in a condition approaching stagnation. Also, the differences in viscosities corresponding to the water temperature contribute to the resistance to mixing.

PREDICTING THE DISTRIBUTION OF TEMPERATURE IN A RESERVOIR

A mathematical expression was formulated by McEwen (1929) to predict the distribution of temperature with depths as a result of external agencies and internal processes. The expression is very complex and is based on many assumptions. McEwen (1929) also considered the chemical properties of the water so that the expression may be applied to the oceans.

As most lakes and reservoirs in a particular geographical area follow the same seasonal pattern of temperature distribution, engineers can predict with confidence the temperature distribution for a proposed reservoir from temperature observations of nearby reservoirs and lakes that have sufficient depth. Therefore, the use of such an expression as formulated by McEwen (1929) had very little practical use.

THE STABILITY OF THERMALLY STRATIFIED WATER

Water in a reservoir, which is thermally stratified and resists mixing and thereby causes the concentration of undesirable substances, justifies the formulation of a precise definition and a method of calculating this definition. Schmidt (1915) used the amount of work that must be expended to change the initial stratification into a stratification of equal density throughout; this energy, which he called the stability, is the work required to raise the whole mass of water through a distance equal to the difference in height of the centers of gravity in the two conditions. The calculation of this energy requires observation of the temperature distribution from the surface to the bottom and of the relation of the horizontal sectional area of the reservoir with respect to depth.

To compute stability as defined by Schmidt, the reservoir is divided into layers of 1 to several meters thick, from the surface to the bottom with a known respective volume of water. The summation of each volume times its distance from the surface to its center of gravity which is divided by the total volume determines the center of gravity in reference to the surface. After the center of gravity is determined, the algebraic sum (plus above the center of gravity and minus below) of each volume times its distance from the center of gravity times its density determines the work required to raise the water for the two conditions. McEwen (1941) developed a tabular method for determining the stability which he described in detail.

The seasonal changes in the computed stability are illustrated in figure 2 for four lakes of different sizes. For these lakes, stability, or the work required to create isothermal conditions, is divided by the surface area for comparative purposes and is expressed as kilogram-meter per square meter.

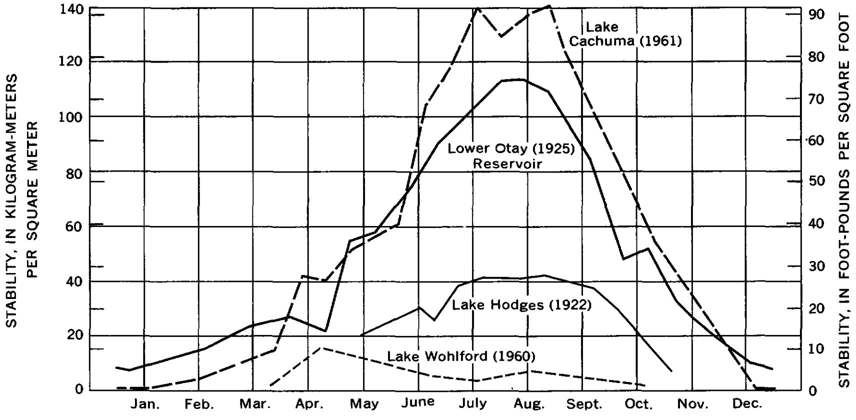

FIGURE 2.—A comparison of seasonal changes in stability expressed in terms of energy per unit area of surface for Lake Cachuma (200,000 acre-ft), Lower Otay Reservoir (57,000 acre-ft,) Lake Hodges (38,000 acre-ft), and Lake Wohlford (2,500 acre-ft) in California. Data for Lower Otay Reservoir and Lake Hodges (McEwen, 1941, fig. 5).

TECHNIQUES TO ELIMINATE THERMAL STRATIFICATION

Three of the techniques that have been described in the literature use air bubbling as the means of inducing a mixing motion in the thermocline and hypolimnion. Each of these techniques uses a different approach to force air into the water.

FLOATING AERATOR

Reddick (1957) described a floating aerator which he designed for use on Indian Brook Reservoir at Ossining, N.Y. This reservoir has a maximum depth of 28 feet and a capacity of 316 acre-feet. The aerator, which is 40 feet long, floats on the surface at the deepest part of the lake. By use of a 3-inch steel pipe, which is submerged 7½ feet below the surface, 160 cubic feet per minute (cfm) of free air is forced through nozzles on 1-foot centers. The bubble size, as visually evaluated, ranged from ½- to 8-inch diameters.

After the aerator was installed, Reddick (1957) reported that the temperature of the water at the start of continuous operation ranged from 14° to 24°C and the dissolved oxygen ranged from less than 1 part per million (ppm) to 8 ppm. After a week of operation the dissolved oxygen was constant with depth at approximately 6.5 ppm, or approximately 75 percent saturation. After 1 month of operation the dissolved oxygen was still constant with depth and had increased to 90 percent saturation.

The floating aerator, as designed by Reddick, required that the air compressor be located on the shore and that air be conveyed to the aerator by two 2-inch plastic hose lines, 400 feet in length. These lines floated on the surface and could present a problem of maintenance. The floating aerator could be adapted to larger and deeper reservoirs, but maintenance problems may be such that a submerged aerator is preferable.

AEROHYDRAULIC TECHNIQUE

The aerohydraulic technique utilizes a device manufactured by Aero-Hydraulics Corp. of Montreal, Canada, that is patented and commercially available. This device, called an Aero-Hydraulic Gun, consists of a polyethylene stack pipe of various lengths in diameters of either 12 or 18 inches. The design of an air distributor at the bottom end permits the formation of a large bubble which acts as a piston in its movement up through the pipe. The manufacturer claims that an 18-inch pipe with a vertical length of 25 feet will move water at the rate of 12 acre-feet per day with a power input of less than 1 horsepower.

The manufacturer has reported, in a pamphlet, the results of two field tests of the Aero-Hydraulic Gun. The first field test was made at Belham Tam Lake, Westmorland, England. This lake has a capacity of approximately 300 acre-feet and a maximum depth of 44 feet. Five 12-inch guns 17 feet long were installed in the deepest part of the lake. The combined output of the guns was restricted to 11 acre-feet per day.

At the start of the test, the temperature of the water ranged from 9° to 15°C, and the dissolved oxygen ranged from less than 1 to 9 ppm. After 2 weeks of operations, the temperature of the water ranged from 12° to 14°C, and dissolved oxygen ranged from 6 to 8 ppm.

The second test was made at Inniscarra Reservoir, County Cork, Ireland. The capacity of this reservoir is 38,400 acre-feet with a maximum depth of 103 feet. Six 12-inch guns, 44 feet long, were installed so that the bottoms of the guns were 86 feet below the surface. The combined output of the guns was 61 acre-feet per day.

The purpose of the test at Inniscarra Reservoir was not to eliminate thermal stratification completely but only to eliminate it sufficiently to raise the dissolved-oxygen content to more than the minimum safe limit of 5 ppm for fish in the hypolimnion. However, this test was not completely successful as the dissolved oxygen was less than the safe limit for depths greater than 75 feet during the summer months.

The aerohydraulic technique may be more efficient than other methods in moving water from the hypolimnion to the epilimnion; however, if the density of the water does not change appreciably, the water will immediately sink back to the hypolimnion. For this reason it is difficult to determine whether the aerohydraulic technique is more efficient than other methods in mixing water.

PLASTIC HOSE AIR-DISTRIBUTION SYSTEM

The plastic industry has formulated a special plastic tubing with a lead keel encapsulated to the bottom of the tubing. Fabricated into the ⅝-inch tubing are tiny, barely visible check valves spaced 1½ inches apart.

Meyer (1962) described the installation of the special fabricated tubing for a 2.8-acre oxidation lagoon in an unincorporated area of DuPage County, Ill. In this installation 7,500 feet of the tubing was laid on the bottom of the lagoon, 4.5 feet below the surface. The amount of free air delivered to the distribution system was 150 cfm. The cost of the system amounted to approximately $6,500.

The purpose of the system as reported by Meyer (1962) was to increase the biological load capacity of the lagoon by a factor of four. It is not known at this time if the system has increased the load factor by 4, but the results have been encouraging. The dissolved-oxygen content of the lagoon averaged 10 ppm for the winter of 1962. During this period subzero weather was prevalent, and 10 percent of the lagoon was kept ice free by the air-bubbling system.

Another field test (Heath, 1961) using the perforated plastic tubing was made at a small idyllic lake called Langsjon in Sweden. This lake was completely devoid of dissolved oxygen and incapable of supporting plant or fish life. In this field test 1,640 feet of perforated plastic was weighted at intervals and laid on the bottom of the lake. A 10-horsepower compressor was used to supply air to the distribution system. After the system had been in operation 3 weeks, the dissolved oxygen had risen to 57 percent of saturation, and a growth of new plant life was well established. At the time the system was placed in operation, a temperature difference of 12°C existed between the surface and the bottom of the lake; and after 3 weeks of operation, the lake was completely isothermal.

In the field tests of the perforated plastic tubing, an elaborate distribution system has been used. In the field test at Lake Wohlford the system for distributing the air in the lake was only 60 feet long. Although, except for Inniscarra Reservoir, Lake Wohlford is much larger than any of the lakes used for previous field tests, the system was very successful in eliminating thermal stratification, and for this reason more detailed information is presented.

TEST OF AIR-BUBBLING SYSTEM AT LAKE WOHLFORD

DESCRIPTION OF LAKE WOHLFORD

Lake Wohlford is a canyon-type reservoir formed by an earthfill dam on Escondido Creek 7 miles northeast of Escondido, Calif. The lake has a capacity of 7,000 acre-feet at full pool with a corresponding surface area of 222 acres. During the test period of 1962, the contents of the reservoir averaged approximately 2,500 acre-feet wth a surface area of 130 acres. Figure 3 shows a map of the lake during the test period.

The climate at Lake Wohlford is such that the temperature of the water always exceeds 4°C. According to Welch (1952), lakes and reservoirs with this characteristic are classified as tropical. The annual temperature cycle is illustrated in figure 4, which shows temperature profiles for various seasons of the year.

Natural inflow into Lake Wohlford is contributed by Escondido Creek; however, as there is very little flow in the creek, the main source of supply is a diversion from San Luis Rey River by a canal with a maximum capacity of 70 cubic feet per second (cfs). The outlet for releasing water from the lake consists of a concrete tower with three gates for releasing water into the 48-inch pipe. The outlet gates are 25 feet apart, the bottom gate being at the lowest level of the lake.

QUALITY-OF-WATER PROBLEMS

Water that is released from Lake Wohlford is used primarily for irrigation, about 20 percent being used for domestic purposes. The

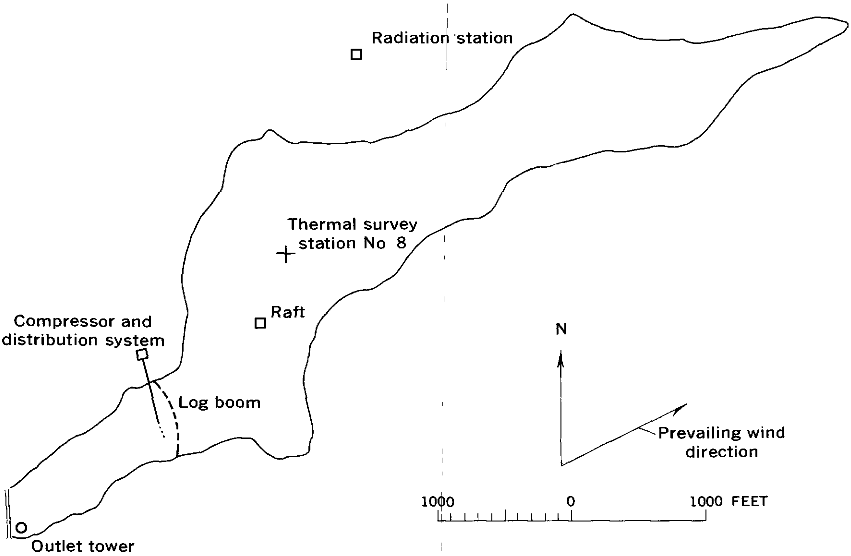

FIGURE 3.—Lake Wohlford, Calif., showing location of instrumentation and air-bubbling system.

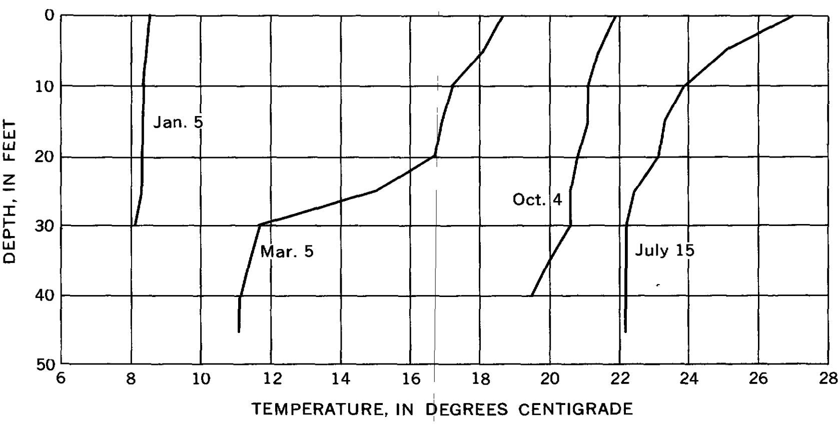

FIGURE 4.—Temperature profiles of Lake Wohlford, Calif., for the various seasons in 1960.

treatment of the water consists of a disinfection by chlorine when the water is released and occasional application of copper sulfate to the water in the lake.

The seasonal changes in climate at Lake Wohlford are accompanied by changes in the quality of the water. These changes are attributed to the life cycle of the various organisms, such as plankton and algae, which tend to proliferate at temperature levels peculiar to each genus and then to die and sink to the bottom of the lake when the life cycle is completed. The accumulation of organic matter on the lake bottom has increased the demand for oxygen in the decaying process; consequently, by 1959 the oxygen had been depleted from Lake Wohlford to the extent that most varieties of fish died.

In 1960, samples of water at the surface and near the bottom were taken near the dam at intervals of approximately a month. The samples were analyzed by the Escondido Mutual Water Co. for dissolved-oxygen concentration and pH. Table 1 shows the results of the samples on indicated dates and how the dissolved-oxygen concentration at the bottom decreased from 10 ppm in January to 1 ppm in August. The decrease of dissolved oxygen at the surface was not as great as the bottom, but may have been approaching the safe limit for fish production.

TABLE 1.—*Dissolved-oxygen and* pH *analyses of water taken from Lake Wohlford in 1960 on indicated dates*

Date	pH		Dissolved oxygen (ppm)	
	Surface	Bottom	Surface	Bottom
Jan. 5	8.4	8.4	10	10
Feb. 1	8.4	8.2	10	7
Apr. 1	8.3	7.4	9	4
May 31	8.6	7.5	7	4
Aug. 2	9.0	7.6	6	1

Table 1 shows that pH increased in the surface water from January to August and decreased in the bottom water. These seasonal changes in pH as exhibited by Lake Wohlford appear to be normal, as observations made in other lakes show this same characteristic. Weiss and Oglesby (1962) observed this same phenomenon in the University Lake near Chapel Hill, N.C. They attributed the changes in pH at the surface to the photosynthetic activity of chlorophyll-bearing micro-organisms that use carbon dioxide, and the decrease in pH at the bottom as the result of an accumulation of carbon dioxide from respiratory activity.

Samples of water collected at the bottom of Lake Wohlford in the middle of April 1960 indicated the presence of hydrogen sulfide. The presence of hydrogen sulfide indicates a depletion of oxygen and a corresponding increase in the anaerobic organisms which can survive in the absence of oxygen. The concentration of hydrogen sulfide in the hypolimnion caused a very disagreeable taste and odor in the water whenever it was released through the lowest gate. The reason for releasing water through the lowest gate during the summer months was to gradually reduce the water stored in the hypolimnion to a minimum so that when the reservoir water overturned in late fall, the taste and odor problems would be minimized. This type of reasoning may be questionable, as some people would prefer to obtain the best quality of water as long as possible and then endure the disagreeable taste and odor when they occur.

DESCRIPTION OF AIR-BUBBLING SYSTEM

In April 1961 experiments were undertaken to determine the feasibility of using air to induce mixing from the epilimnion to the hypolimnion by bubbling air from the bottom of Lake Wohlford. A temporary line was lowered into the lake through which compressed air was forced by a portable compressor. In this experiment, thermal stratification was eliminated throughout the lake, which, in turn, improved the quality of the water.

As a result of the April experiment, a permanent air-bubbling system was installed. This system consisted of a 210-cfm (free-air) compressor powered by a 50-horsepower electric motor. Air is conducted from the compressor through a 2-inch galvanized pipe extending into the lake a sufficient distance to cool the air. Attached to the end of the pipe is a 1½-inch polyvinylchloride plastic pipe that conducts the air to the point where it is forced into the bottom water. At this point, 60 feet of the plastic pipe is perforated with 90 holes, 9/64 inch in diameter, and spirally located to equalize the thrust of the escaping air. The plastic pipe is suspended 5 feet above the bottom of the lake by an anchor as shown in figure 5. The location of the air-bubbling system in relation to Lake Wohlford is shown in figure 3.

The general plan of operation for the air-bubbling system was to start the compressor in the morning and let it remain in operation for approximately 9 hours each day. Of course, changes were made in the plan to meet the requirements of the special lake studies. The general plan was based on the hypothesis that, the bottom water, as it was brought to the surface, would be heated by solar energy and then would remain at the surface.

MIXING OF STRATIFIED WATER

The operation of the air-bubbling system in 1962 was delayed until April 18, when the lake exhibited a definite thermal stratification.

At that time, the storage in the lake was 2,500 acre-feet, and the maximum depth was 50 feet. On the 17th of April, 17 profiles of temperature were taken at stations representing equal surface areas. The measurements of temperature were made with a standard resistance thermometer. These profiles were taken approximately daily thereafter to show the progress of the air-bubbling system in mixing the lake water. The 17 profiles were averaged for each day and are shown in figure 6. The temperature profile on April 25 indicates that the lake was nearly isothermal. For the period April 18–25, the compressor was operated 9 hours each day until April 24, when the compressor was left in operation for 24 hours.

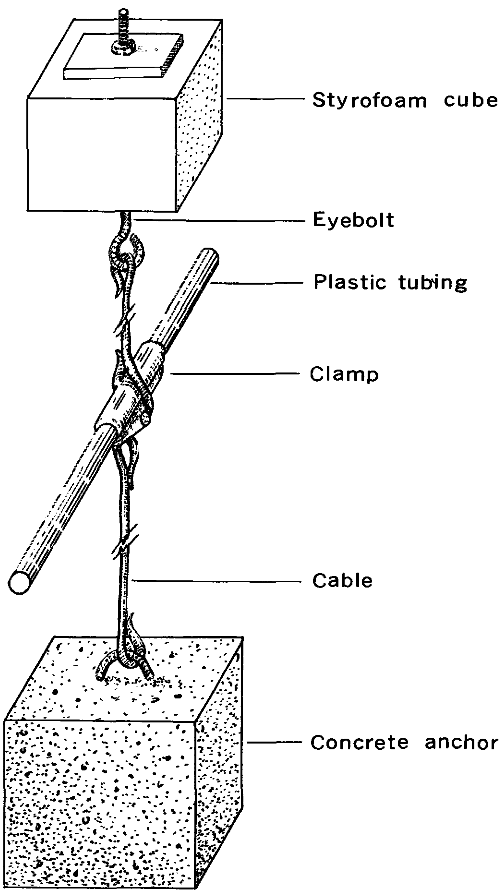

FIGURE 5.—Anchor system to support plastic pipe 5 feet above bottom of lake.

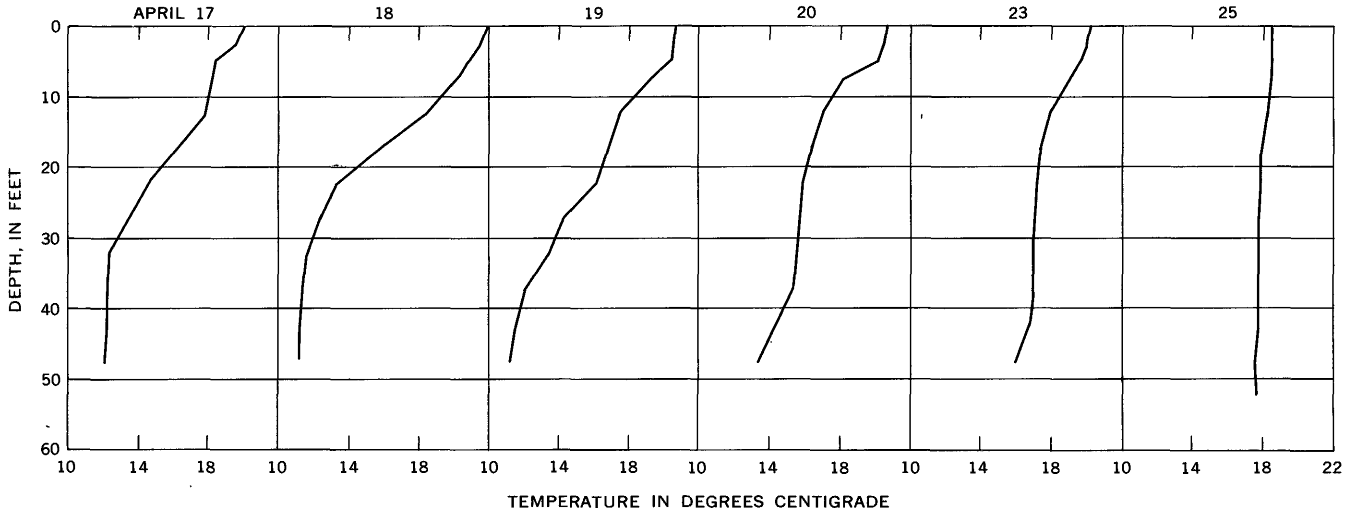

Figure 6.—Average of 17 temperature profiles for Lake Wohlford, Calif., which show the changes in the thermocline during the initial operation in 1962 of the air-bubbling system.

The air-bubbling system was stopped from July 15 to July 24 in order that a thermocline could re-form in the lake. When the compressor was started again, detailed studies were made of the temperature of the boil which was formed by the air rising to the surface, the velocity profiles of the water in the lake, and the temperature profiles at the location of the velocity measurements.

The temperature studies of the boil formed by the air-bubbling system showed that the temperature of the water in the boil was constant throughout the upward movement of the boil. The surface area of the boil could be easily detected by the sharp contrast in the temperature between the outer edge of the boil and the unmixed lake water. During the period July 24–26, when the air-bubbling system was continuously operated, the surface area of the boil was approximately determined at daily intervals from the temperature contrasts at the edge of the boil. The changes in the surface area of the boil in relation to the number of hours of operation of the compressor are shown in figure 7. The rate of free-air injection was 210 cfm. Figure 7 shows that the boil does not reach its maximum size until the compressor is operated for approximately 30 hours.

The velocity measurements were made with an aluminum vane which was designed by Shulman and Bryson (1961). This vane was supported at a particular depth by a string and a small polyethylene bottle which floated at the surface. The design of the vane was such that the area of vane was 20 times the area of the supporting bottle to minimize the surface velocities and wind effect. The movement of the bottle was followed by a transit on shore and a stadia in a boat. Whenever the boat was at the same location as the bottle, stadia distance and time readings were taken. These readings were plotted on a map of the surface area of the lake, and the velocities were determined from these plots. The velocity profiles are shown in figure 8 as observed for the raft and in figure 9 for the thermal survey station No. 8 during the period July 24–26. The temperature profiles at these stations and the temperature of the boil are also shown.

During the velocity studies it was difficult to separate the effect of the boil from that of the wind. Also, most of the velocity profiles indicate that all the water is going in one direction, which, of course, is impossible; but attempts to determine the location of the return flow were unsuccessful. The return flow probably occurs along the shores and shallow water, and the system of vanes and bottles was probably not satisfactory in the attempt to locate these flows. The velocity profiles as shown in figures 8 and 9 were influenced by the wind, but the changes in velocity distribution are considered to be caused by the temperature of the boil, as the wind was nearly constant during the study period.

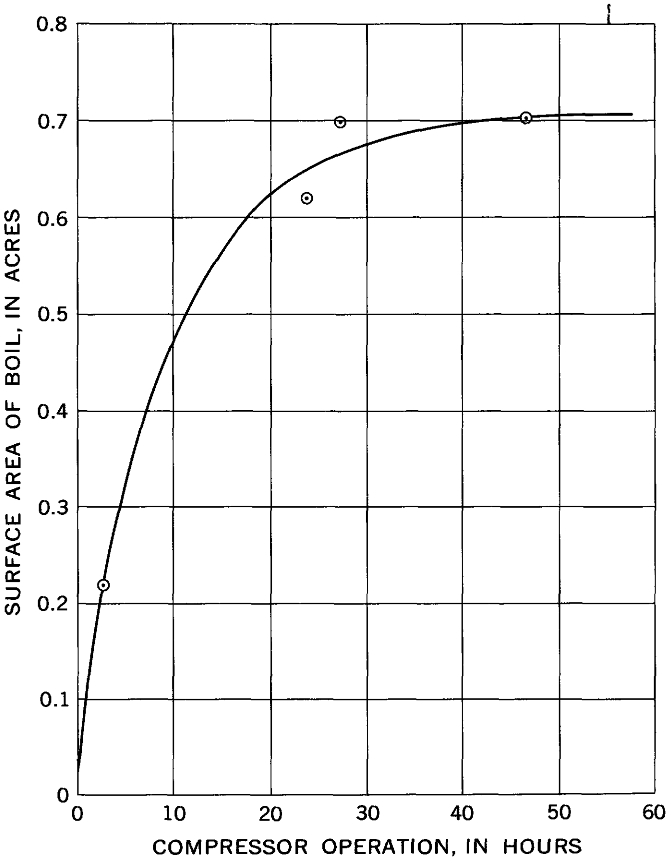

Figure 7.—Relationship between the surface area of the boil formed by the air-bubbling system and the number of hours of compressor operation for Lake Wohlford, Calif.

Figures 8 and 9 indicate that the velocities were influenced by the temperature of the boil in relation to the temperature profile. As the boil begins to form, its temperature is near that of the hypolimnion. At the same time, the velocity profiles indicate an increase in the velocity in this layer away from the boil area. As the mixing continues, the temperature of the boil increases, and the water becomes isothermal toward the surface. Also, as the water becomes isothermal, the velocities increase toward the surface with a corresponding decrease in the velocity of the water in the hypolimnion. This process will continue until the lake is isothermal.

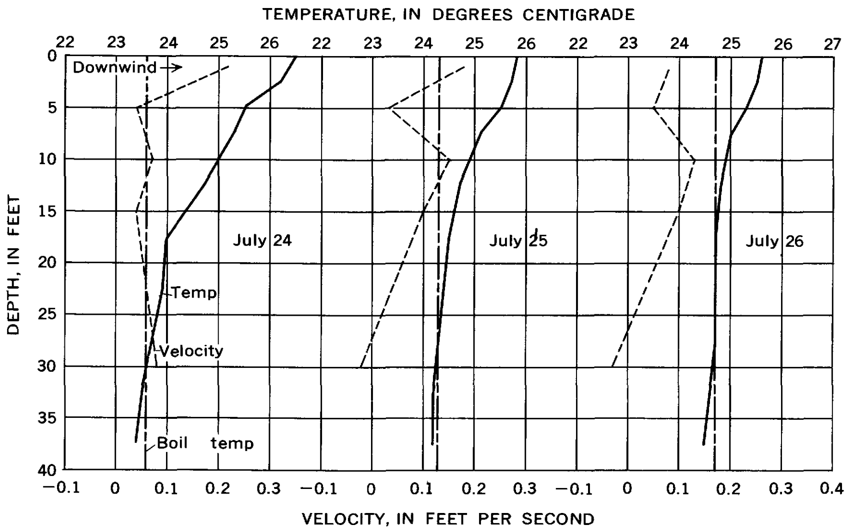

FIGURE 8.—Velocity and temperature profiles as observed at the raft station in 1962 for Lake Wohlford, Calif.

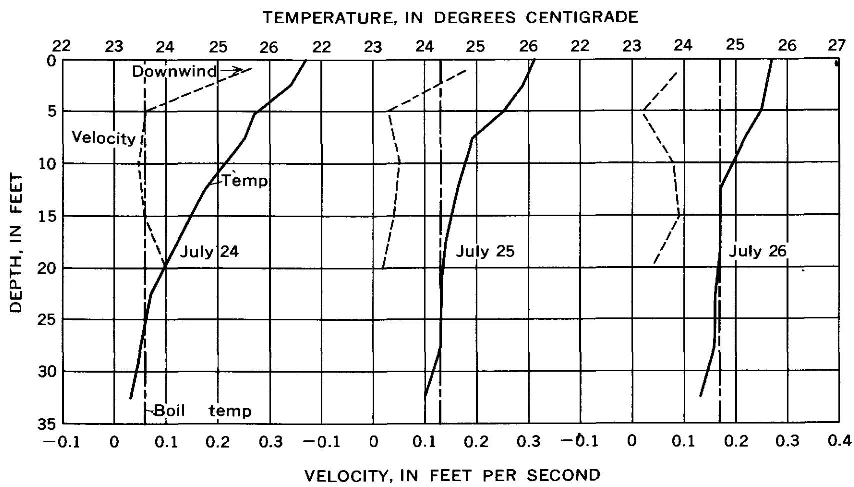

FIGURE 9.—Velocity and temperature profiles as observed at thermal survey station No. 8 in 1962 for Lake Wohlford, Calif.

The changes in the velocity distribution are considered to be caused by an excess of water around the perimeter of the boil, and this water has a temperature almost equal to that in the boil. The circulation in the boil cannot support this water, and consequently this water will descend in the lake until it reaches a layer of equal density. An accumulation of this water near the boil area will cause the water to move away in a horizontal direction and increase the velocity of the water at this depth. Therefore, this phenomenon would indicate that the rate of mixing in the lake is dependent on the size of the boil area. The rate of mixing, in turn, affects the ratio of the accumulated volume of excess water near the boil area to the volume of water in the lake of the same density. As this ratio decreases, the rate of mixing decreases.

The stability of the water in the lake has been computed daily for the period April 18–25 and July 24–26. Figure 10 shows the decrease in stability as the hours of operation of the compressor accumulate. The curve in figure 10 indicates that stability decreases much more

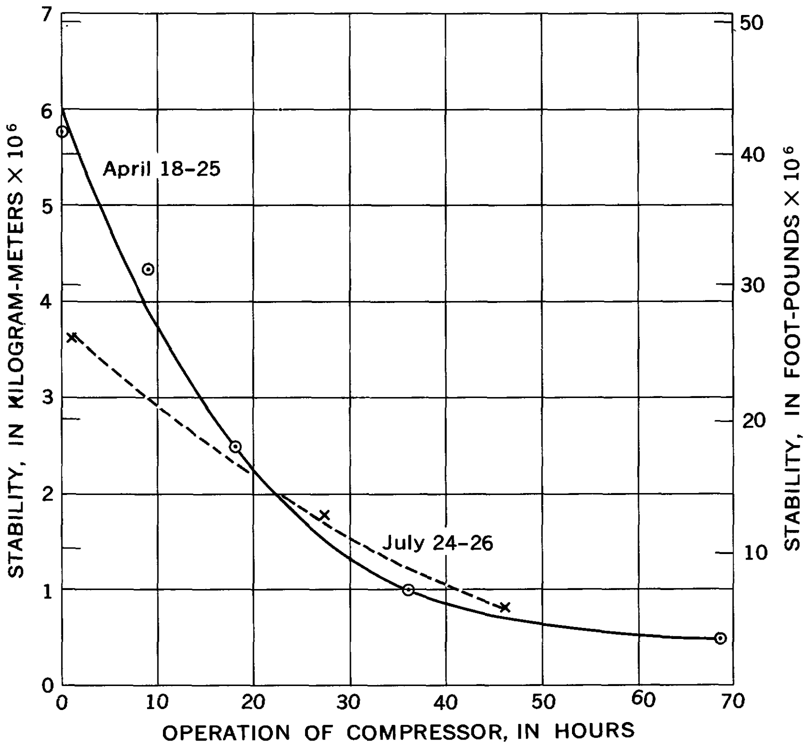

Figure 10.—The decrease in stability in relation to the number of hours of compressor operation on indicated dates in 1962 for Lake Wohlford, Calif.

rapidly when the lake is thermally stratified than when it is nearly isothermal. This curve confirms the previous reasoning that if the ratio of the volume of excess water to the volume of lake water of the same density decreases, the rate of mixing decreases.

WATER QUALITY RESULTS

During 1962, the Escondido Mutual Water Co. obtained weekly samples of water near the dam. These weekly samples were collected near the bottom and surface of the lake and were analyzed in the laboratory for dissolved-oxygen concentration and pH by the Hellige color comparator and applicable reagents. The results of these samples are shown in figure 11.

Figure 11, showing the seasonal variations in the concentration of dissolved oxygen near the surface and bottom of Lake Wohlford, indicates that the air-bubbling system maintained the dissolved-oxygen concentration in the hypolimnion above 5 ppm from April 18 to September 5 except for one period in August. During the rest of the year, the natural mixing motion of the wind maintained the concentration above 5 ppm. The concentration at the surface indicates that the water is occasionally supersaturated during the summer months. As this concentration seems to be extremely high, analyses of the water samples may be questionable, and a better method of determining the concentration of dissolved oxygen may be needed.

The pH determination shown in figure 11 indicates that the surface remained fairly constant during the year but that the bottom exhibited the same seasonal variation as in table 1. From this comparison, the air-bubbling system does not seem to affect the pH of the water in the lake.

During 1960, the standards of the U.S. Public Health Service for drinking water required a maximum dosage rate of chlorine of 12 ppm. In 1962, the maximum dosage rate was reduced to 7 ppm. The decrease in the required dosage rate is attributed to the air-bubbling system. Laubush (1958) stated that theoretically one part of H_2S will oxidize with 8½ parts of Cl_2. The high dosage rate of 1960 was then required because the large concentration of H_2S in the hypolimnion oxidized approximately half the chlorine before free available residual chlorine was obtained. In 1962, the concentration of H_2S in the hypolimnion was reduced by the air-bubbling system, and the reduction in concentration of H_2S in turn reduced the required chlorine dosage rate.

The difference in the taste and odor of the water delivered to the city of Escondido in 1960 and 1962 is difficult to analyze quantitatively. However, the citizens of Escondido must have noted a definite change

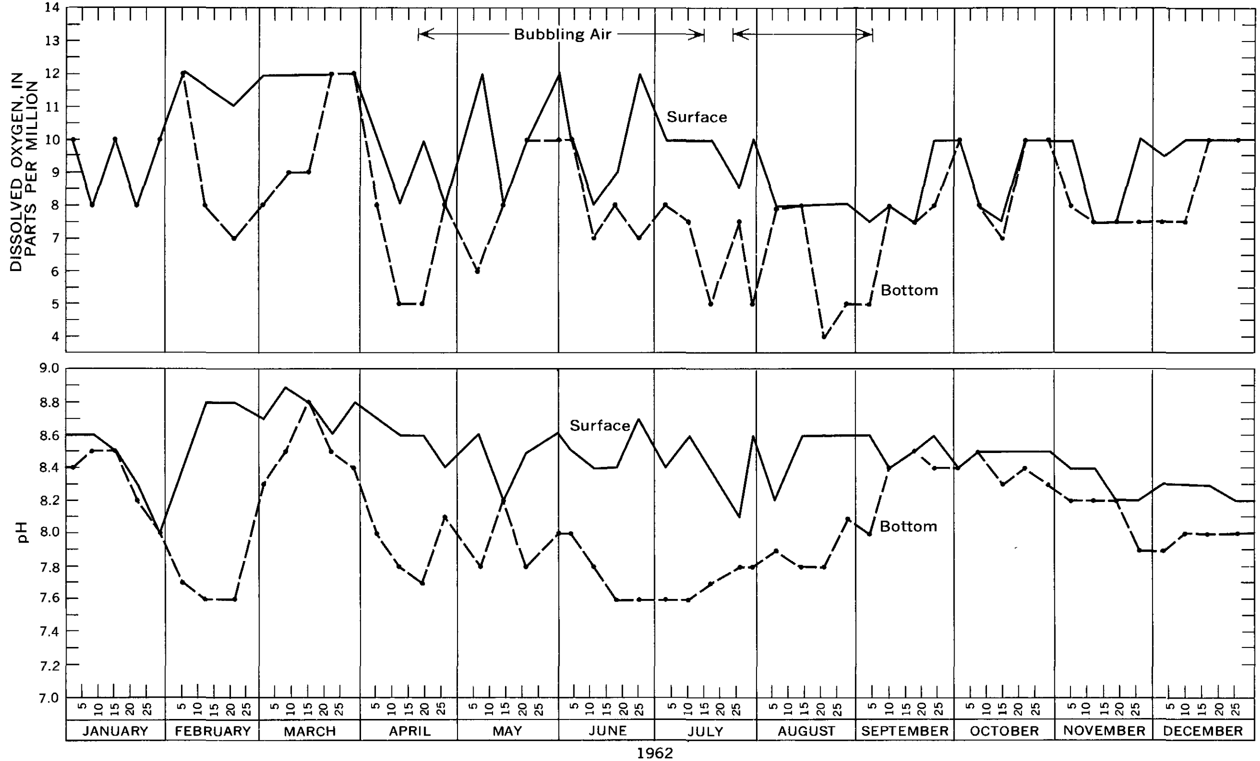

Figure 11.—Seasonal variation in the concentration of dissolved oxygen and pH as determined from water samples collected near the bottom and surface of Lake Wohlford, Calif.

in the taste and odor of the water because complaints were received by the water company in 1963 when thermal stratification began to form in the lake and the dissolved-oxygen concentration in the hypolimnion was reduced.

EVAPORATION RESULTS

The measurement of evaporation from Lake Wohlford in 1962 was made by both the energy-budget and mass-transfer methods. The use of the energy-budget method in this study was mainly to determine the coefficient for the mass-transfer method which is utilized in the computations to evaluate the changes in evaporation rates. For a complete description of the two methods and necessary instrumentation, the reader is referred to the paper by Harbeck and others (1958).

The mass transfer equation is expressed as

$$E=N\,u\,(e_o-e_a),$$

in which

E=evaporation in inches per day,
N=coefficient as determined by the energy-budget method,
u=wind speed in knots,
e_o=saturation vapor pressure corresponding to the temperature of the water surface in millibars, and
e_a=vapor pressure of the air in millibars.

The measurements of wind speed (anemometer) and temperature of the water surface (thermograph) were made at the raft station and the measurement of vapor pressure (thermocouple psychrometer) at the radiation station (figure 5). The instruments were installed in November 1961. Previous to this time, the only measurement that could be used in the analysis to determine the changes in evaporation rates were observations of temperature of the water surface taken by the Escondido Mutual Water Co. at approximately 4-day intervals.

In order to determine the changes in the temperature of the water surface because of the air-bubbling system, the temperature observations of water surface were averaged to obtain monthly means for the period 1959–61. The mean temperatures were then compared with the 1962 average monthly temperatures as determined by the thermograph at the raft. Figure 12 shows the comparison of temperatures between the period 1959–61 and the year 1962.

Figure 12 indicates that the air-bubbling system in 1962 reduced the surface temperature of Lake Wohlford in May, June, and July and increased it in October, November, and December. This type of deviation in temperature was expected. During the period May–July, the air-bubbling system was mixing the cold water normally found in the hypolimnion with the warm water in the epilimnion. The mixing action decreased the temperature of the water surface during this period with an accompanying decrease in the evaporation rate. Because of the decrease in the evaporation rate and the gain in energy from incoming radiation and conduction, more energy was stored in the lake until the surface reached its normal temperature in August. The mean surface temperature for September 1959–61 indicated that the lake had started its cooling cycle; but the drop in surface temperature for September 1962 was less than that of 1959–61. The temperatures of the surface during the cooling cycle of 1962 remained higher in order to dissipate the additional energy.

Changes in the temperature of the water surface attributable to the air-bubbling system were accompanied by changes in the evaporation rates. To estimate the rate changes based on the sparse data available prior to 1962, the humidity and wind data observed in 1962 were assumed to be the mean for the period 1959–61. Using

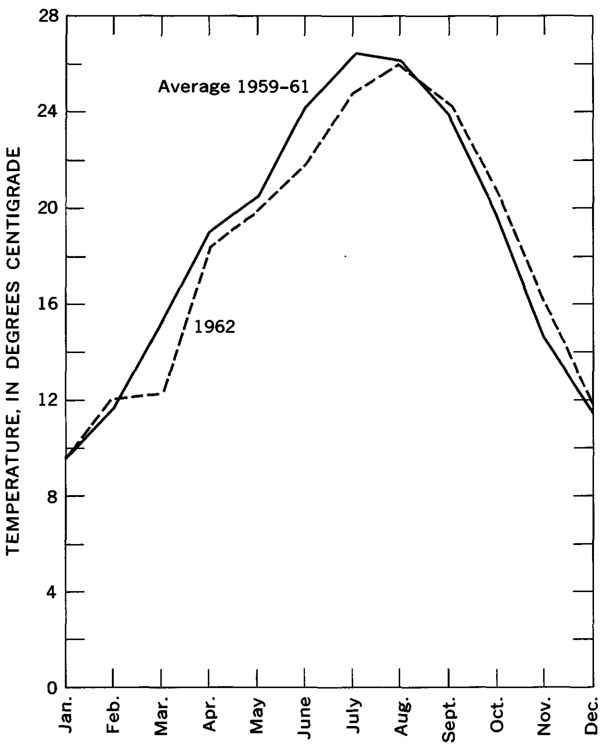

FIGURE 12.—A comparison of the monthly mean temperature of the water surface for the period 1959–61 with the 1962 monthly average for Lake Wohlford, Calif.

these data, monthly evaporation rates have been computed by the mass-transfer method for 1962 and an estimated monthly mean evaporation rate for the period 1959–61. The results of these computations are shown in figure 13.

Figure 13 indicates that evaporation was appreciably reduced in June and July of 1962 with a corresponding increase in October and November. The decrease in evaporation for the 2 summer months

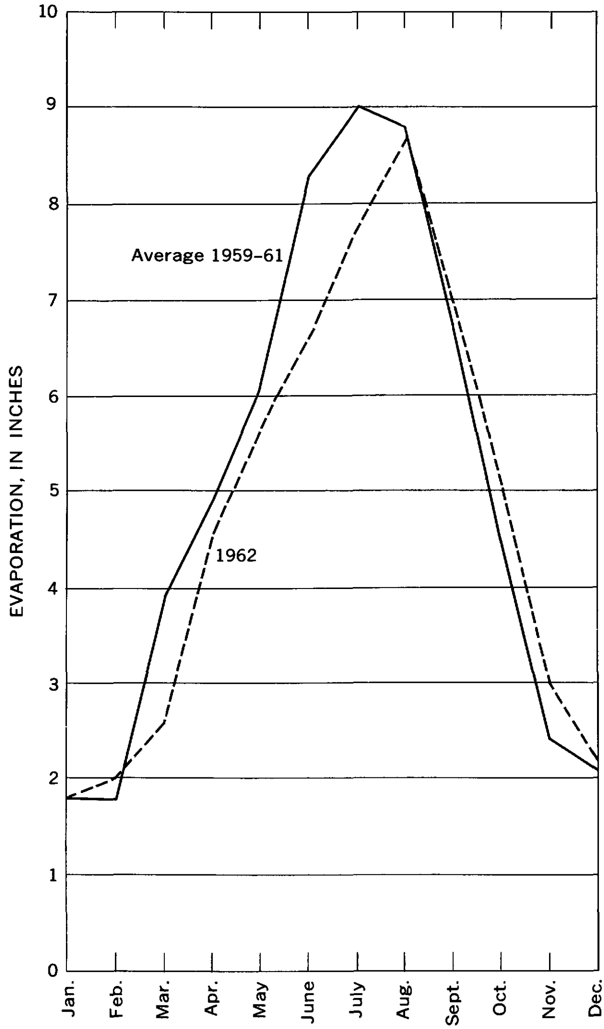

FIGURE 13.—A comparison of the 1962 monthly evaporation rates as determined by the mass-transfer method with monthly mean evaporation rates for the period 1959–61 for Lake Wohlford, Calif.

was 2.9 inches, whereas the increase was only 1.3 inches for the two fall months. Because of the sparse data available prior to 1962, it is difficult to explain why the increase in evaporation during the fall months did not equal the decrease in the summer months.

The operation of Lake Wohlford is such that change in evaporation rates results in a greater saving in volume of water than if the surface area of the lake had remained constant through the year. During the winter and spring months water is stored in the lake, and the stage at the end of the storage period is maintained at this level through the summer months for recreational purposes. In the fall months, the stage of the lake is reduced in anticipation of winter and spring runoff. With this type of operation, the volume of evaporation saved by the air-bubbling system, may be determined.

To determine the net saving in volume of water for the 1962 year, the average area of the water surface for each month of this year was considered to be the same as the monthly mean surface area for the period 1959–61. Using the evaporation rates as determined previously and the respective areas, the volume of evaporation was computed for each month of 1962 and the monthly means for the period 1959–61. The accumulated evaporation by months for the year 1962 and the period 1959–61 are shown in figure 14.

Figure 14 shows that the divergence between the two curves is greater during the summer months than during the fall months; during the September–November period they are almost parallel, a fact indicating that the evaporation for this period in 1962 is almost the same as the period 1959–61. The total divergence between the two curves at the end of December indicates the net reduction in evaporation to be 35 acre-feet, and this reduction is attributed to the operation of the air-bubbling system.

CONCLUSIONS

Thermal stratification in lakes and reservoirs retards the natural-mixing motions between the hypolimnion and the surface until the concentration of certain substances in the hypolimnion becomes undesirable. To overcome this problem, a few investigators tried bubbling air from the bottom of the reservoir to artificially mix the water and break up the stratification. In the investigations cited, the investigators were pleased with the results obtained. However, none of these investigators presented enough data to define certain criteria needed for the design of such a system for other lakes and reservoirs. The Lake Wohlford study has presented considerably more detail; but, because of the rapid-mixing motions, there are still not enough data to define an air-bubbling system for a thermally stratified reservoir of a given capacity. During 1963, additional data were obtained at Lake Wohlford; however, as the operator must serve the users, it was difficult to let the reservoir stratify to a condition desirable for further study. Additional studies of this type should be undertaken on larger reservoirs, for it is very difficult to extrapolate data from a reservoir whose capacity is 2,500 acre-feet to a reservoir 100 or 1,000 times as large.

The Lake Wohlford study has shown the importance of the wind in mixing the water in the lake if no thermal stratification is present. The only need of the air-bubbling system at Lake Wohlford is when the lake begins to store energy in the spring and summer.

The mixing motions as induced into the hypolimnion and epilimnion by the air-bubbling system are still not thoroughly understood. One conclusion that the operator made in 1962 was that the compressor should be operated for periods longer than 9 hours as first planned. The reasoning for this conclusion was the time needed to

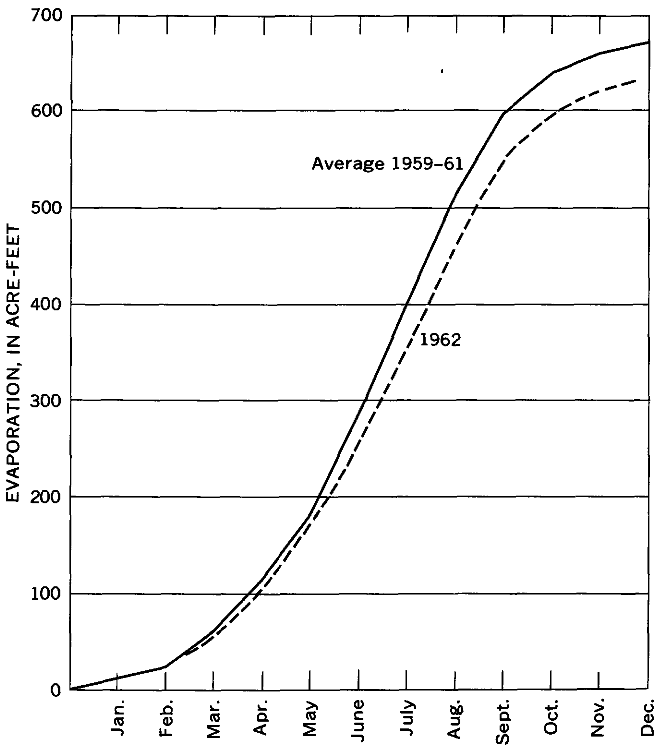

Figure 14.—A comparison of the accumulated evaporation in acre-feet by months for 1962 with the monthly mean evaporation for the period 1959–61 for Lake Wohlford, Calif.

build up the boil and horizontal circulation to patterns in the lake. The operating procedure now is to operate the air-bubbling system until thermal stratification is eliminated. The compressor is then stopped until thermal stratification begins to form and dissolved oxygen in the hypolimnion approaches the safe limit for fish.

The economics of operating the air-bubbling system are difficult to evaluate. The operator stated that the reduction in chlorine needed to meet health standards compensated for the cost of operating the compressor. The removal of tastes and odors from the water supply could have been accomplished by a water treatment plant, but the difference between the cost of a compressor and a water treatment plant is considerable. Also, the difference in maintenance cost between a compressor and a water treatment plant is substantial. The improvement in the recreational benefits is very difficult to evaluate economically. For example, an air-bubbling system might forestall a fish kill such as occurred in 1959; if the game fish in the lake die, the lake is completely lost as a recreational facility for the remainder of the season. The savings in evaporation may not be considered significant when compared to the improvement in taste and odor and recreational facilities; but, because the problem of water shortage is increasing, an air-bubbling system may become economically feasible to reduce evaporation for some of the larger reservoirs.

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