John Elder

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Progress Report

# ELIMINATION OF STRATIFICATION AT LAKE CACHUMA, CALIFORNIA

By

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Prepared in cooperation with the
Santa Barbara County Water Agency

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Progress Report

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## ABSTRACT

A study was undertaken to determine the effects of air injection on Lake Cachuma, Santa Barbara County, Calif. Lake Cachuma has a capacity of 205,000 acre-feet.

A study of the elimination of stratification by air injection in other southern California reservoirs indicated that it is economically feasible to reduce undesirable tastes and odors, to increase dissolved oxygen in the hypolimnion, and to reduce the evaporation rate.

A correlation analysis indicated that a qualitative check can be made on certain phytoplankton populations by monitoring significant physical and chemical parameters.

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.

In the second test, a column of water was destratified by circulation with a centrifugal pump. Nitrate concentration and specific conductance were unaffected by the circulation. The temperature, dissolved oxygen, silica, orthophosphate, and pH were destratified. The concentration of silica and orthophosphate and the values of surface pH were lowered, but the overall dissolved-oxygen concentration was increased to 8 ppm (parts per million), enough to support fish. No significant blooms of phytoplankton occurred in the isolated column of water.

These results indicate that stratification of Lake Cachuma can probably be prevented. Water temperature and pH can both be lowered at the surface; therefore, the overall evaporation rate would be reduced and algae control would be more effective. Objectionable tastes and odors would be reduced as the undesirable dissolved gases are eliminated. Fish life should be enhanced as the dissolved-oxygen content of the lower levels of the lake is increased.

It seems the expected beneficial results of air injection outweigh the possibility of any nonbeneficial results. Two air compressors capable of discharging a total of 875 cfm (cubic feet per minute) should be in operation by March 1, 1967, to effect destratification.

## INTRODUCTION

This study of Lake Cachuma by the U.S. Geological Survey in cooperation with the Santa Barbara County Water Agency began in December 1965. There has been an annual history of water-quality deterioration due to thermal, chemical, and biological stratification during the summer months when disagreeable taste and odors develop and make the water less desirable for domestic use. It has been necessary to treat the reservoir with chemicals to control nuisance growth of phytoplankton; these treatments are costly and reportedly produce certain harmful effects related to fish life in the reservoir. The objective of the study has been to provide information needed to design an air-injection system to reduce the stratification and to determine the chemical and biological effects on the water, particularly with regard to the phytoplankton populations.

## DESCRIPTION OF LAKE CACHUMA

Lake Cachuma is 25.5 miles northwest of Santa Barbara in Santa Barbara County, Calif., lat 34°35' N. and long 119°59' W. (fig. 1). The lake was created by construction of Cachuma Dam across the valley of the Santa Ynez River. The Lake Cachuma reservoir has a capacity of 205,000 acre-feet with a corresponding area of 3,090 acres. During the test period of 1966, the contents of the reservoir averaged 178,000 acre-feet with a surface area of 2,800 acres.

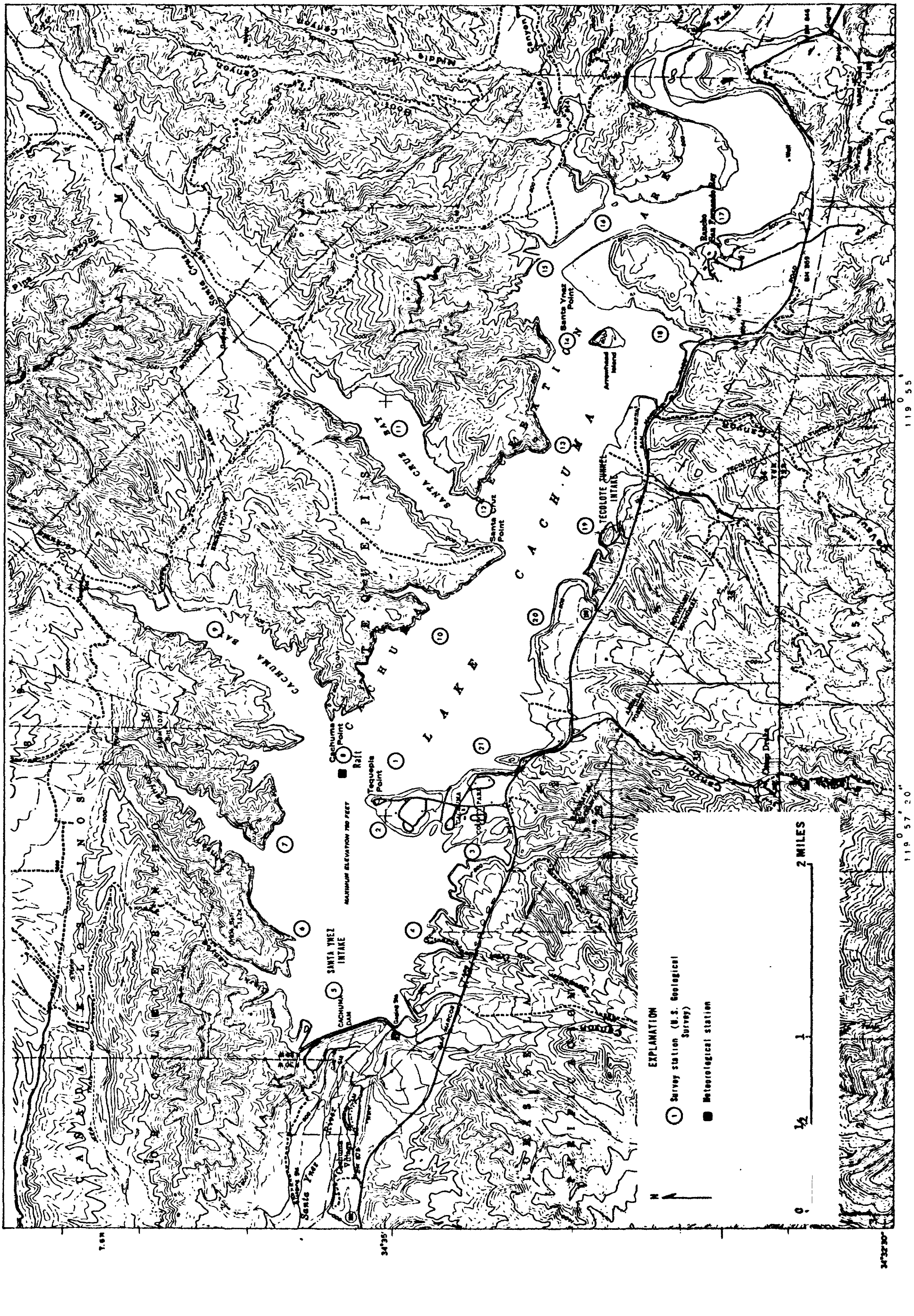


FIGURE 1.--Map of Lake Cachuma, Santa Barbara County, California.

The climate at Lake Cachuma is such that the temperature of the water always exceeds 4°C. Lakes and reservoirs with this characteristic are classified as tropical (Welch, 1952).

The city of Santa Barbara and the suburban and agriculture lands of the Goleta, Summerland, Montecito, and Carpinteria County Water Districts receive water from Lake Cachuma. The principal features of Lake Cachuma are Cachuma Dam, Tecolote Tunnel intake, which is used to regulate the flow of water from Lake Cachuma to the coastal area, and Santa Ynez intake, which is used to regulate the flow of water from Lake Cachuma to the lower Santa Ynez valley.

Lake Cachuma is approximately 6 miles long and 1½ miles wide. The long dimension of the lake lies approximately northwest to southeast. The lake narrows at Tequepis Point, 1½ miles upstream from the dam. The point extends from the south shore about two-thirds the width of the lake. Two prominent bays, Cachuma Bay and Santa Cruz Bay, and several smaller bays extend northeastward from the main body of the lake. The effect of these geographical features is important with respect to the location of an aeration system, as is discussed later in this report.

## Description of the Problem

A vertical temperature gradient is formed in Lake Cachuma in the spring and summer. During this period the surface-water temperatures rise much faster than the temperatures of the deeper water. A thermal stratification will then appear where the surface may be more than 10°C warmer than the deeper water. The degree of stratification is dependent on the time of year, the depth of the water, and the wind velocity. At Lake Cachuma the summer months have the greatest stratification, whereas the winter months have the least. Stratification is best defined by temperature distribution, as shown in figure 2. The epilimnion is the upper layer of water in which the temperature is nearly uniform; the thermocline is the middle layer exhibiting at least 1°C drop in temperature per meter of depth; the hypolimnion is the lowest layer in which the temperature is nearly uniform from its upper limit to the bottom of the lake (Welch, 1952).

Many interrelated problems exist in Lake Cachuma. The three problems that may be most affected by air injection are: The quality of the water for domestic use, fish reproduction and growth, and the reduction of the evaporation rate.

Induced circulation in a reservoir by air injection can be expected to reduce evaporation losses (Koberg and Ford, 1965), and, although the improvement in the recreational benefits is very difficult to evaluate economically, circulation would undoubtedly improve the environment for fish.

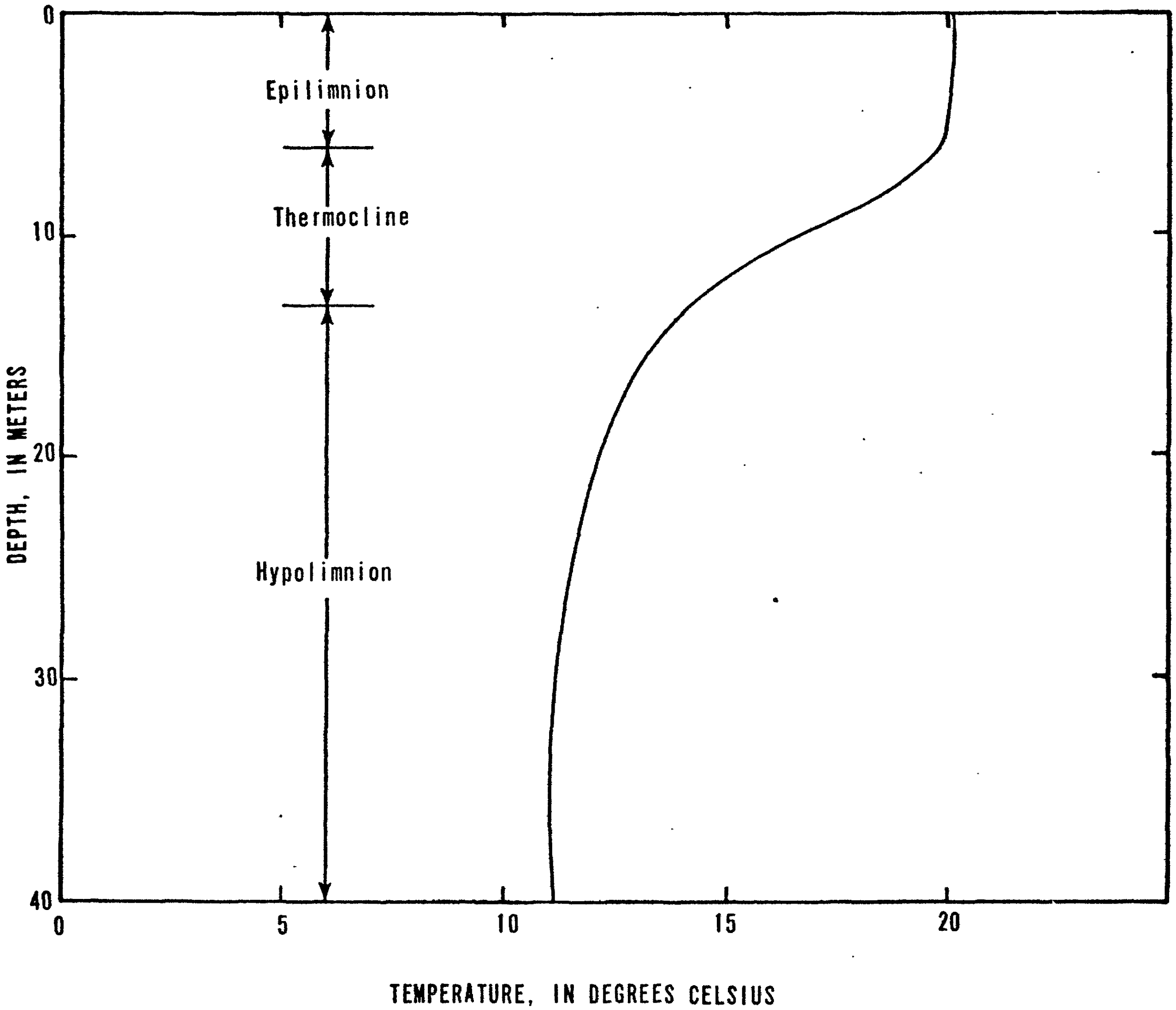


FIGURE 2.--Typical temperature profile with temperature zones indicated.

Induced circulation of water in stagnant lakes and reservoirs has been widely used for water-quality control (Reddick, 1957; Heath, 1961; Woods, 1961; Ford, 1963; and Koberg and Ford, 1965). Although the benefits of artificial circulation are sometimes very significant, the effect of destratification on algal growth in reservoirs is unknown. Artificial circulation of water in a reservoir changes the pattern of temperatures, solutes, and suspensoids (including plankton) within a very short time. Induced circulation could produce problems such as accelerated phytoplankton growth due to increased nutrients in the photosynthetic zone. This increase in nutrients could come from two sources. One source is the nutrients from the bottom of the lake being circulated into the photosynthetic zone. The other possible source is from warm inflow, either runoff or a release from an upstream reservoir. If this water is warmer than the destratified lake water, it would remain on or near the surface.

## Approach to the Problem

The problem was approached in four ways. The first approach was to study the results of tests in other reservoirs that were being artificially destratified. The second approach was to analyze the data collected from preliminary surveys made at Lake Cachuma. The third approach was the examination of a simple correlation analysis for Lake Cachuma. The fourth approach was the study of columns of lake water which were isolated by polyethylene cylinders. The results of these four approaches were then combined to analyze the effects of air injection on Lake Cachuma and to provide information needed to assist in the design of an air-injection system.

# PREVIOUS STUDIES AND RESULTS IN OTHER LOCALITIES

Studies of the elimination of stratification have been made in several other southern California reservoirs. The results of these studies will help predict the effects of induced circulation in Lake Cachuma.

## Lake Wohlford

A study was made at Lake Wohlford, Calif. (Koberg and Ford, 1965). The lake is 7 miles northeast of Escondido, Calif., and has a capacity of 7,000 acre-feet 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 with a surface area of 130 acres. Koberg and Ford stated that the Lake Wohlford study indicated that an aeration system is economically feasible to remove undesirable taste and odors from water to be used for domestic purposes and to increase the dissolved-oxygen concentration in the hypolimnion of the lake. The concentration of hydrogen sulfide in the hypolimnion was reduced by the aeration system. The results also indicated that the elimination of thermal stratification in Lake Wohlford during May, June, and July, 1962, reduced the evaporation rate by 15 percent. However, the evaporation rate was increased 9 percent in September, October, and November; thus, the net reduction for the 6-month period was about 6 percent.

## El Capitan Reservoir

El Capitan Reservoir is formed by an earthfill dam on San Diego River, 7 miles east of Lakeside, Calif. The lake has a capacity of 112,810 acre-feet with a corresponding surface area of 1,560 acres. During the test period, July-October 1965 (written commun., G. E. Koberg, 1966) the contents of the reservoir averaged approximately 14,600 acre-feet with a surface area of 450 acres, and, during the 1966 water year, the average contents was approximately 18,800 acre-feet with a surface area of 530 acres. Figure 3 is a map of the reservoir showing the location of the thermal-survey stations, the meteorological station, the compressor and distribution system, and the outlet tower.

The induced-circulation equipment was put into operation in July 1965. This system consisted of a 210-cfm compressor powered by a 50-horsepower electric motor. Air was conducted from the compressor through a 2-inch galvanized pipe extending into the lake. Attached to the end of the pipe was a 1½-inch polyvinylchloride pipe that conducted the air to the point where it was released into the bottom water. At this point, 100 feet of the pipe was perforated with 90 holes, 9/64 inch in diameter, spirally located to equalize the thrust of the escaping air. The perforated pipe was suspended 5 feet above the bottom of the lake by a float-and-anchor system.

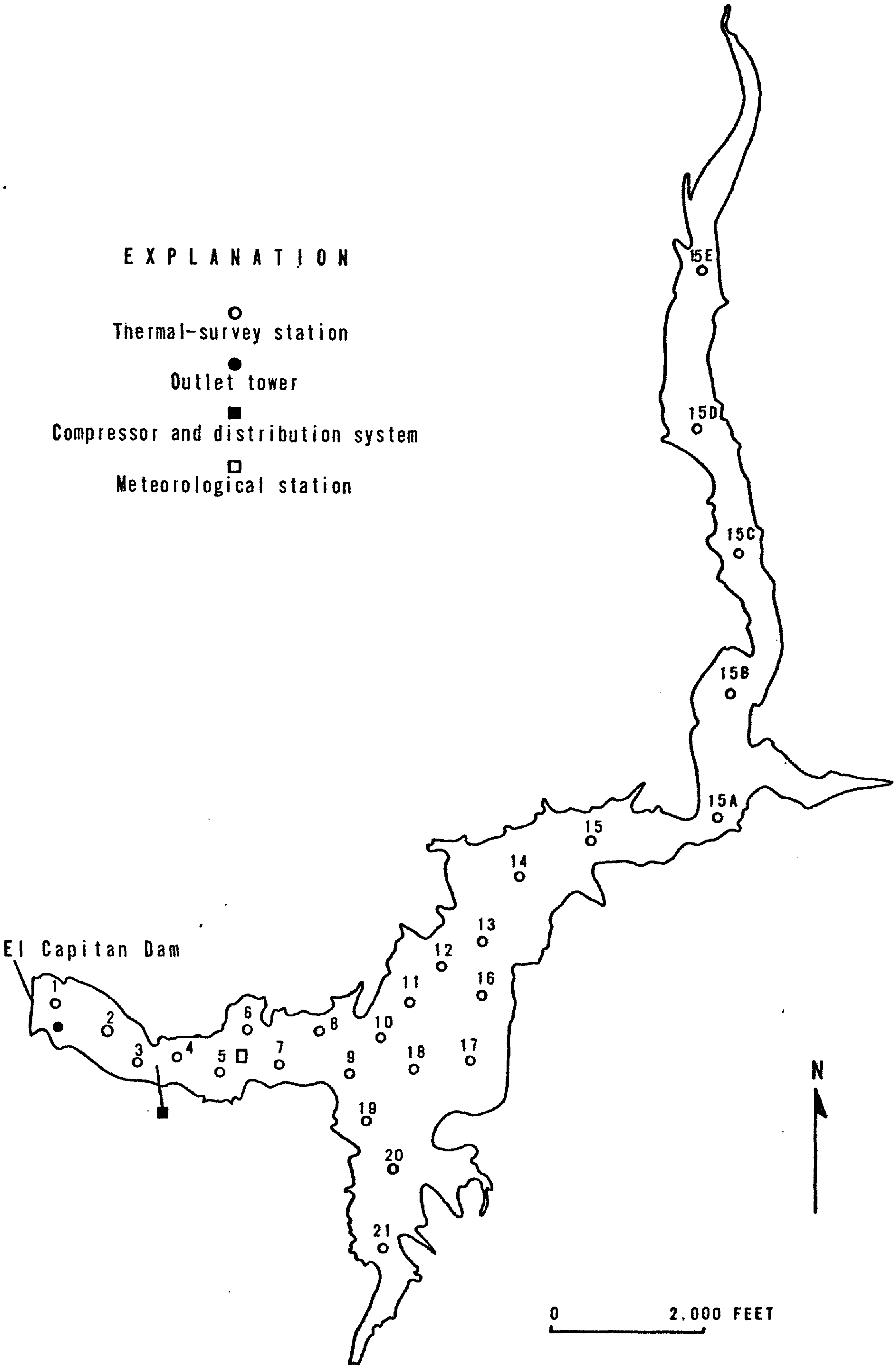


FIGURE 3.--Map of El Capitan Reservoir, San Diego County, California.

A complete thermal and dissolved-oxygen survey was made July 26, 1965, at the thermal stations shown in figure 3. In figure 4 the temperature data from this survey are compared with those from a survey made July 15, 1964; the 1965 temperatures at the surface and 3.8-meter depth are 2° to 3°C lower; the temperatures at the 6.9-meter depth are about the same; and the temperatures at the 13-meter depth are about 5°C higher. The temperature observations for the July 1965 survey show that the reservoir was destratified.

Figure 5 shows a comparison of observed dissolved oxygen, in percent saturation, for the surveys. After destratification the dissolved oxygen remained near 100-percent saturation at the 3.8-meter depth and showed an increase generally to above 70 percent at the 6.9- and 13-meter depths.

The operation of the aeration equipment was continued in 1966, and thermal and dissolved-oxygen surveys were made to observe the effect of the induced circulation. Figure 6 shows a comparison of temperature observations for the July 26, 1965, and May 25, 1966, surveys. The increased reservoir contents and the earlier seasonal date of the 1966 survey account for the lower isothermal temperatures. Figure 7 shows a comparison of dissolved oxygen, in percent saturation, at the thermal-survey stations for selected depths.

The dissolved-oxygen concentration was lower in the 1966 survey, but the induced circulation continued to cause an increase in the dissolved-oxygen concentration at the lower depths. The data from the two surveys cannot be compared directly because of the increased reservoir content and the earlier date of the 1966 survey.

## Lake Jennings

In 1966 induced-circulation techniques were also being used at Lake Jennings in San Diego County, Calif. (written commun., G. E. Koberg, 1966). Figure 9 illustrates the effect of aeration by showing temperature profiles of the induced destratification at Lake Jennings, Lake Wohlford, and El Capitan Reservoir, and a profile of the natural stratification at San Vicente Reservoir, San Diego County. Figure 10 shows a comparison of dissolved-oxygen profiles for the same four reservoirs. The dissolved-oxygen content was increased below the photosynthetic zone of the three aerated reservoirs.

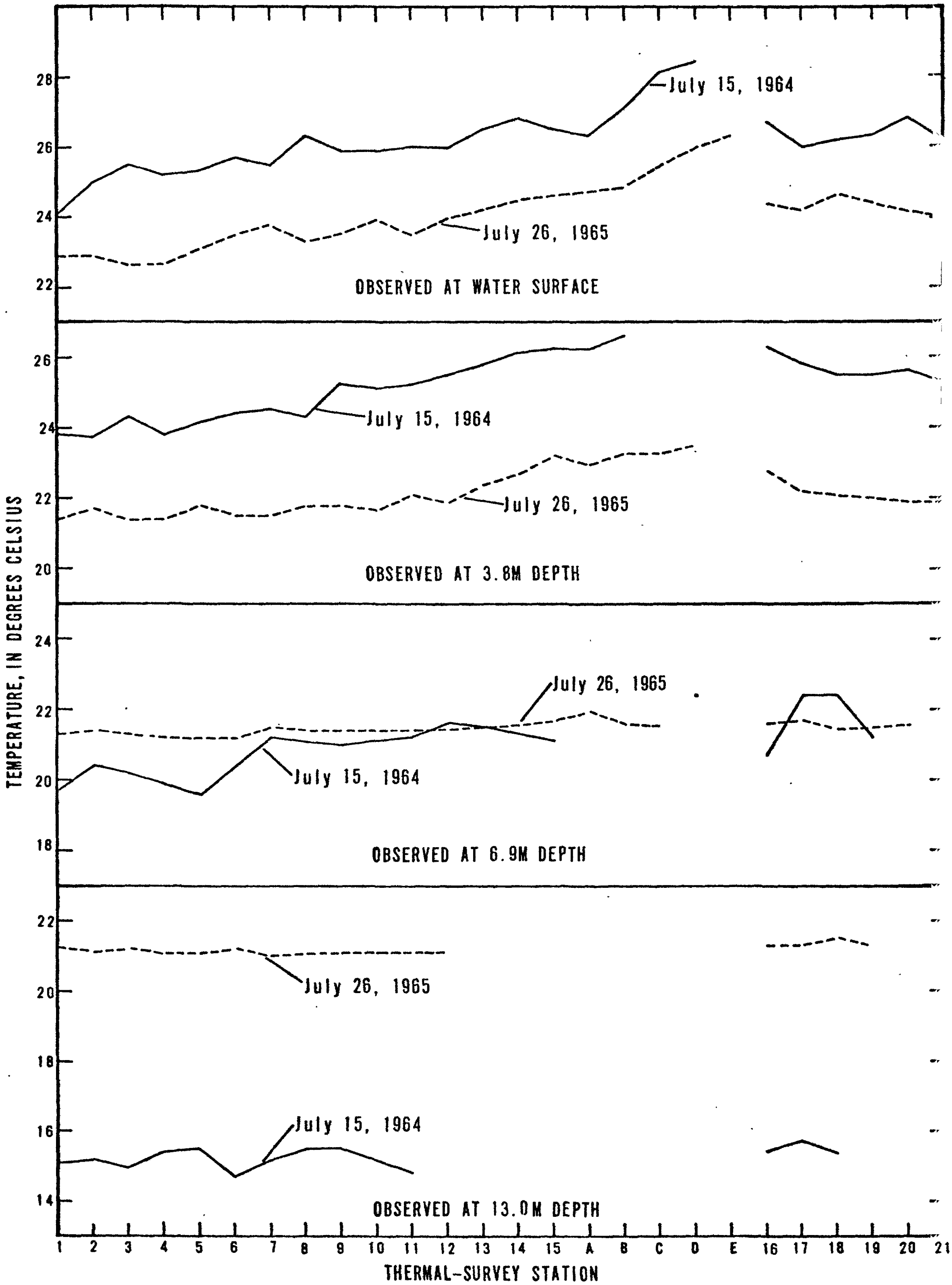


FIGURE 4.--Comparisons of observed water temperatures at El Capitan Reservoir thermal-survey stations.

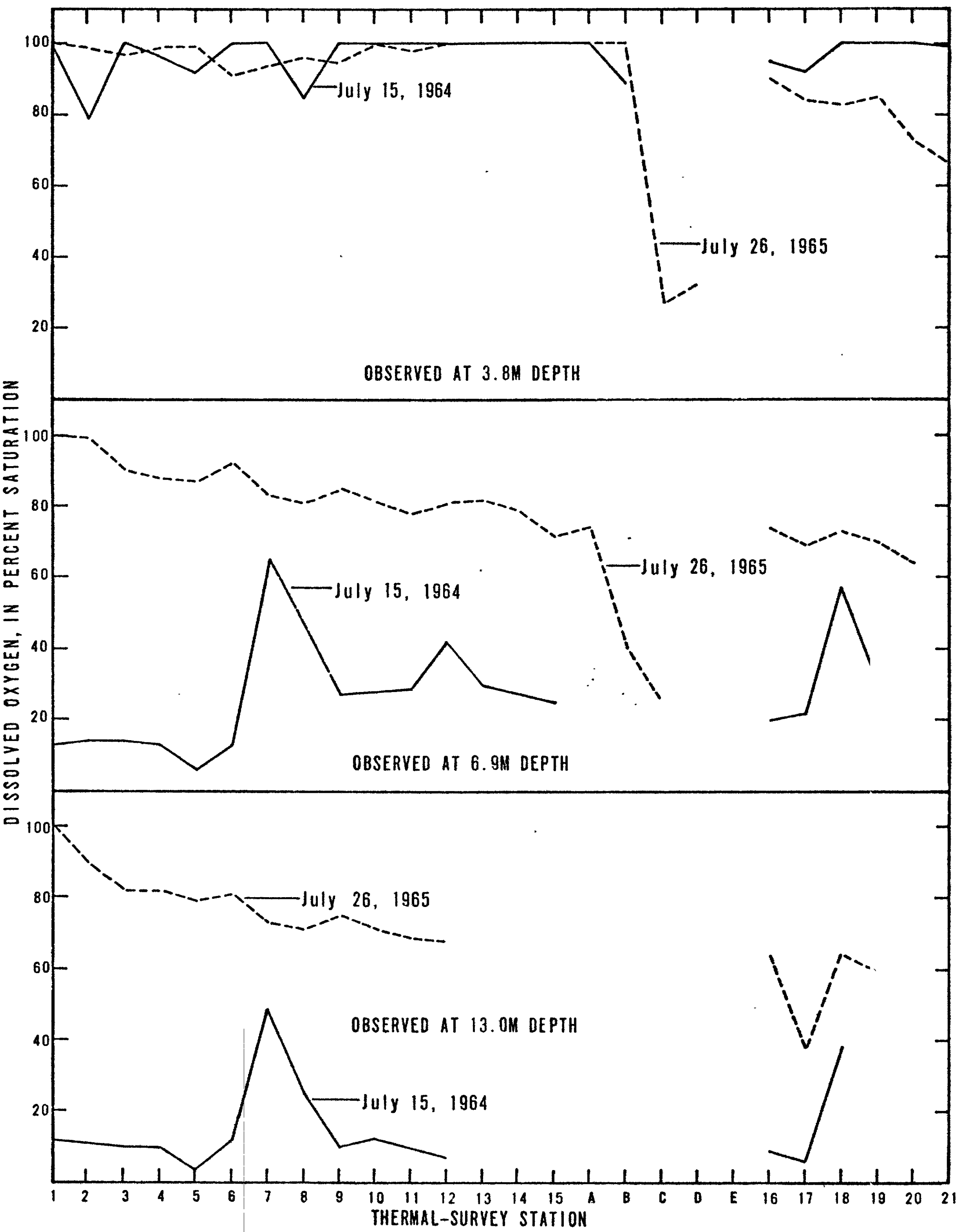


FIGURE 5.--Comparisons of observed dissolved-oxygen concentrations at El Capitan Reservoir thermal-survey stations.

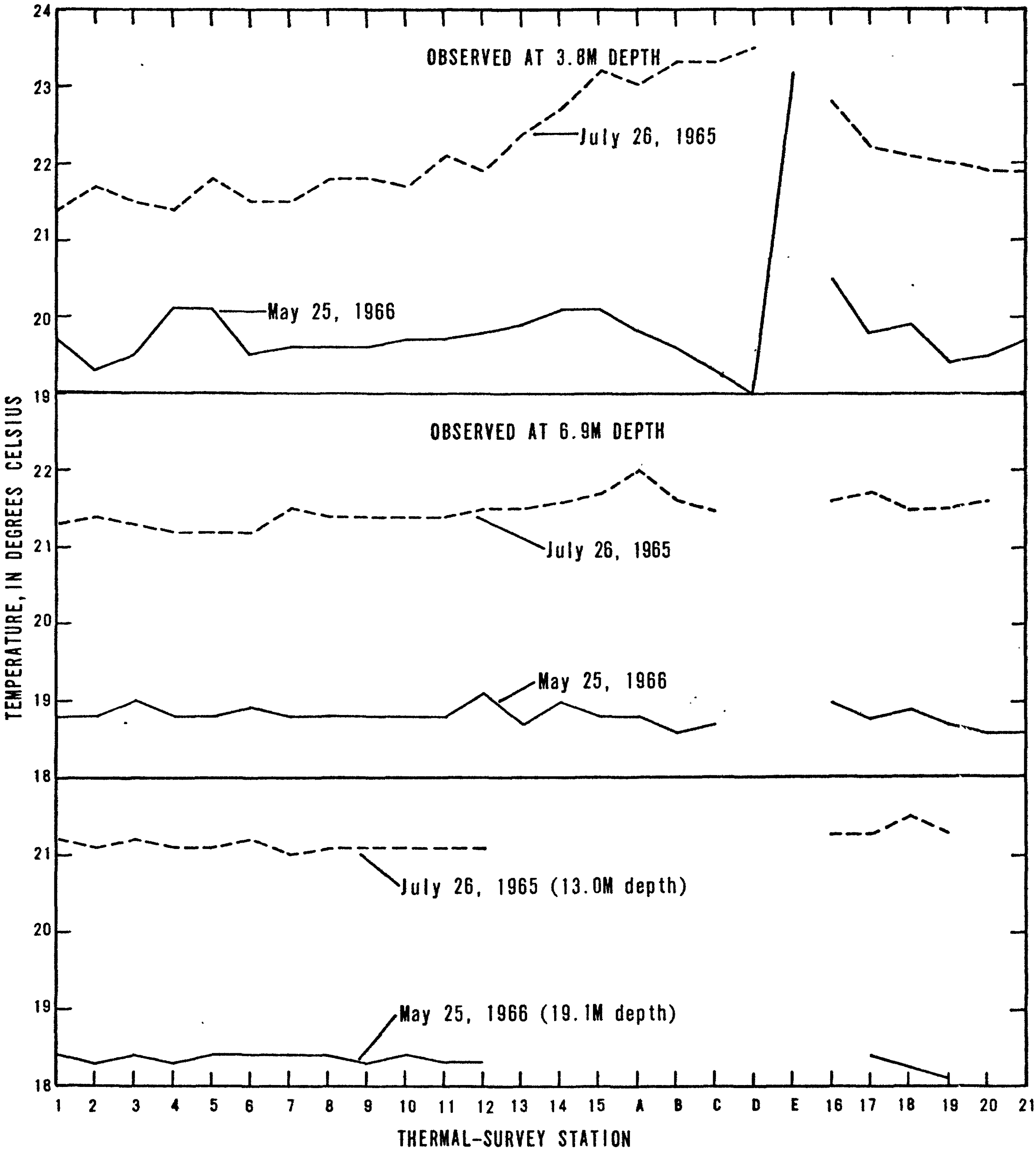


FIGURE 6.--Comparisons of observed water temperatures at El Capitan Reservoir thermal-survey stations.

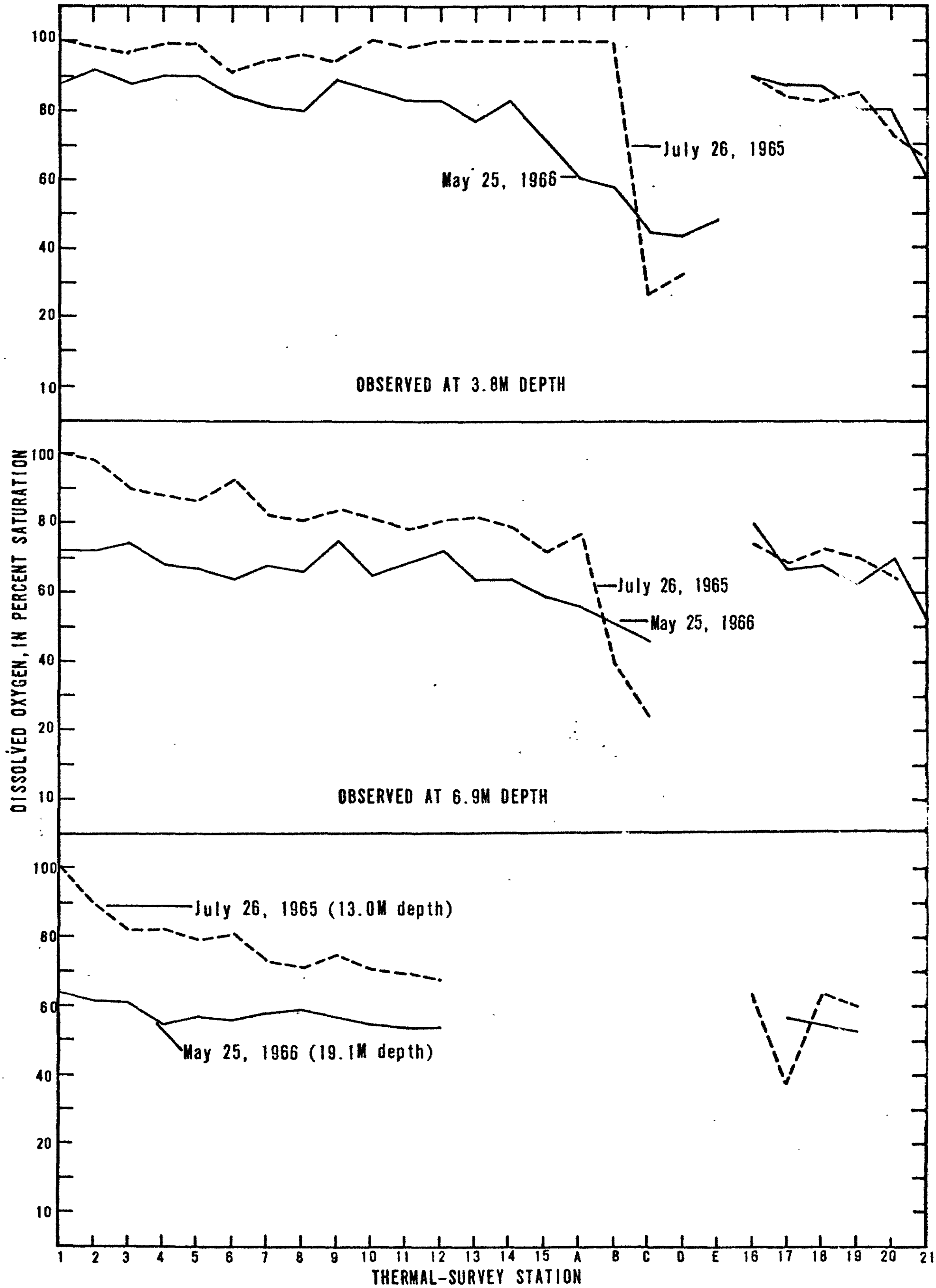


FIGURE 7.--Comparisons of observed dissolved-oxygen concentrations at El Capitan Reservoir thermal-survey stations.

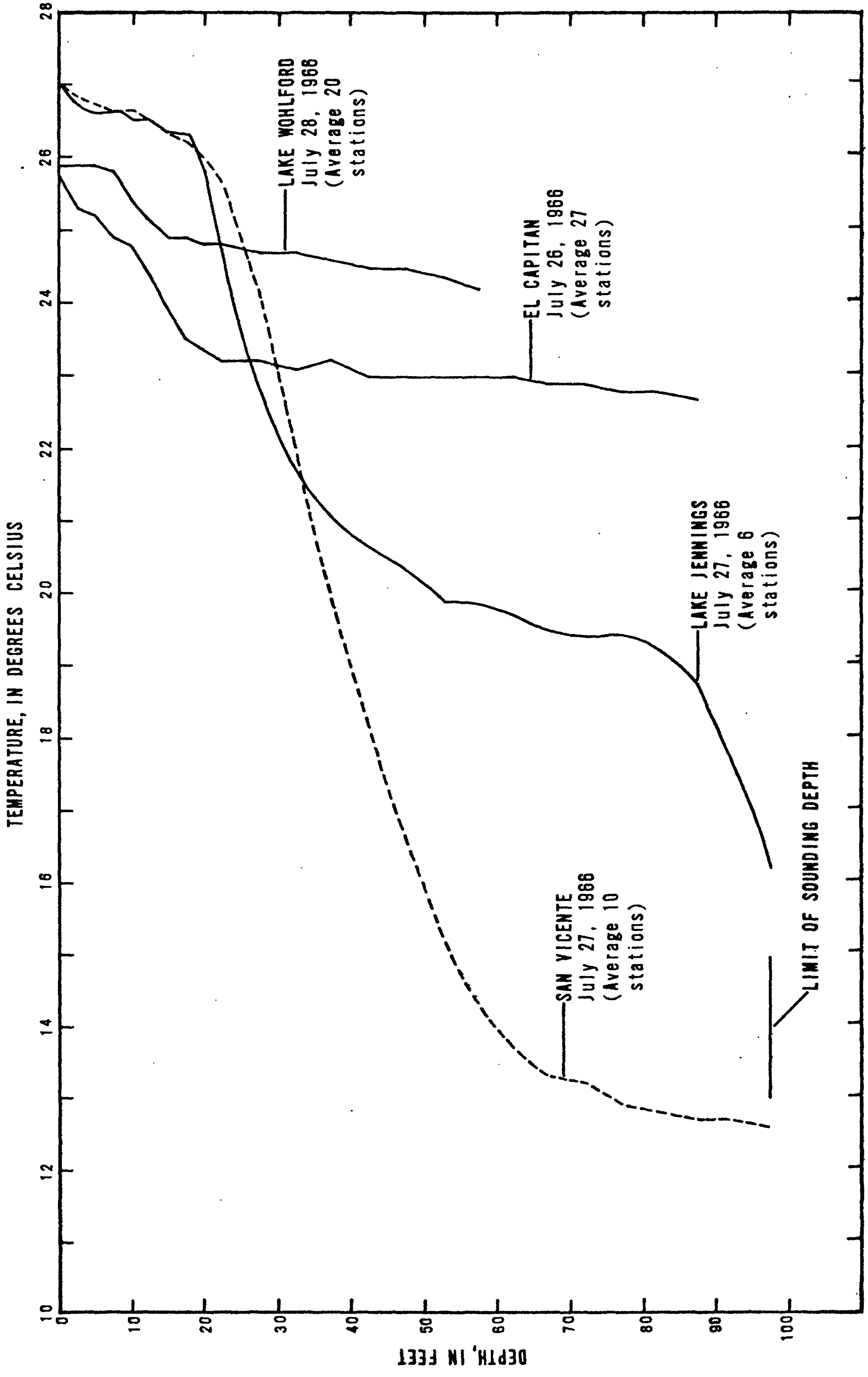


FIGURE 9.--Comparison of temperature profiles for Lake Jennings, Lake Wohlford, El Capitan Reservoir, and San Vicente Reservoir.

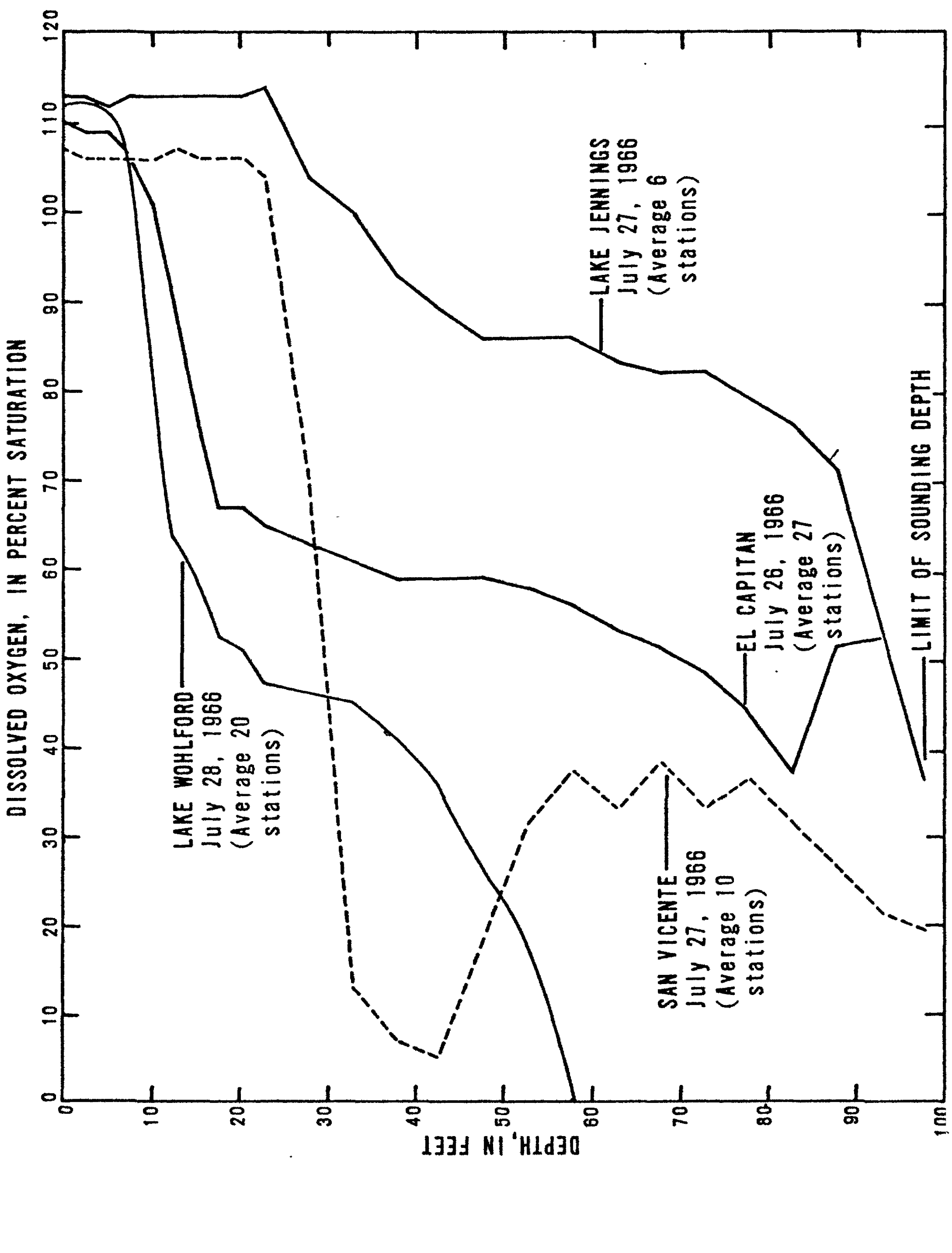


FIGURE 10.--Comparison of dissolved-oxygen profiles for Lake Jennings, Lake Wohlford, El Capitan Reservoir, and San Vicente Reservoir.

## PRELIMINARY SURVEYS

One of the objectives of the Lake Cachuma study is to provide information needed to design an air-injection system for use in the reservoir. Therefore, various surveys are being made and recorders are being operated to determine which parameters may affect or be affected by air injection. These parameters can then be monitored after the air-injection system has been operating, and the actual effectiveness of the air-injection equipment can be determined.

Equipment for continual recording of wet-bulb temperature, surface-water temperature, air temperature, and windspeed has been installed on a raft 0.4 mile northeast of Tequepis Point. These four parameters are used in computing evaporation rate by the mass-transfer method. This evaporation rate can then be compared to the evaporation rate for the lake during air injection, and the resulting reduction in the evaporation rate can be determined. A comparison also can be made between the water and air temperatures before and during air injection.

Temperature profiles have been taken at 21 stations (fig. 1) since March 1966. The profiles for March 8, 1966 (fig. 11), show that at that time little stratification was present. However, 2 weeks later on March 24, 1966 (fig. 12), stratification had developed at a number of stations to the point where a 4°C difference existed between the surface and the bottom temperatures. These two groups of profiles point out the need for beginning air injection in early March before the lake stratifies. The profiles for August 29-30, 1966 (fig. 13), show the degree to which stratification developed at Lake Cachuma. These profiles also show that the dissolved oxygen stratifies in the same manner as temperature, except the difference between maximum and minimum values is greater. Below the 10-meter level the dissolved-oxygen concentration was near 0 ppm. This low dissolved-oxygen concentration was due to biological degradation in the thermocline. However, stations 4 through 8, showing an increased dissolved-oxygen content below the thermocline, indicated the dead phytoplankton were not falling into the hypolimnion because of the increased density of the cooler hypolimnetic water.

Specific-conductance measurements were made periodically, but were found to undergo little change with time. Visibility-index figures determined by the standard Secchi-disk method ranged from 1.8 meters in April to 1.2 meters in August 1966. The higher the figure, the clearer the water.

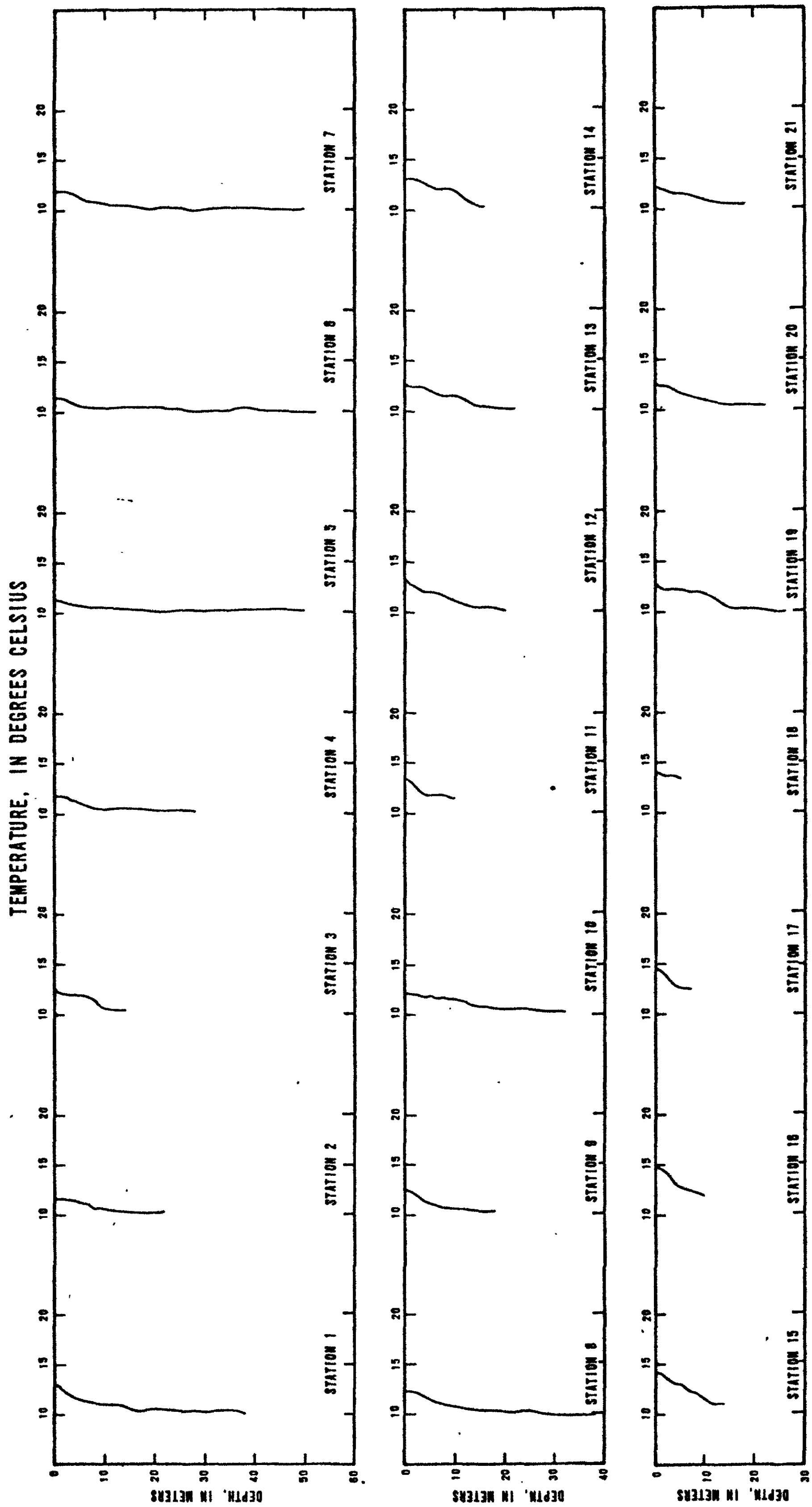


FIGURE 11.--Temperature profiles, showing destratified conditions in Lake Cachuma, March 8, 1966.

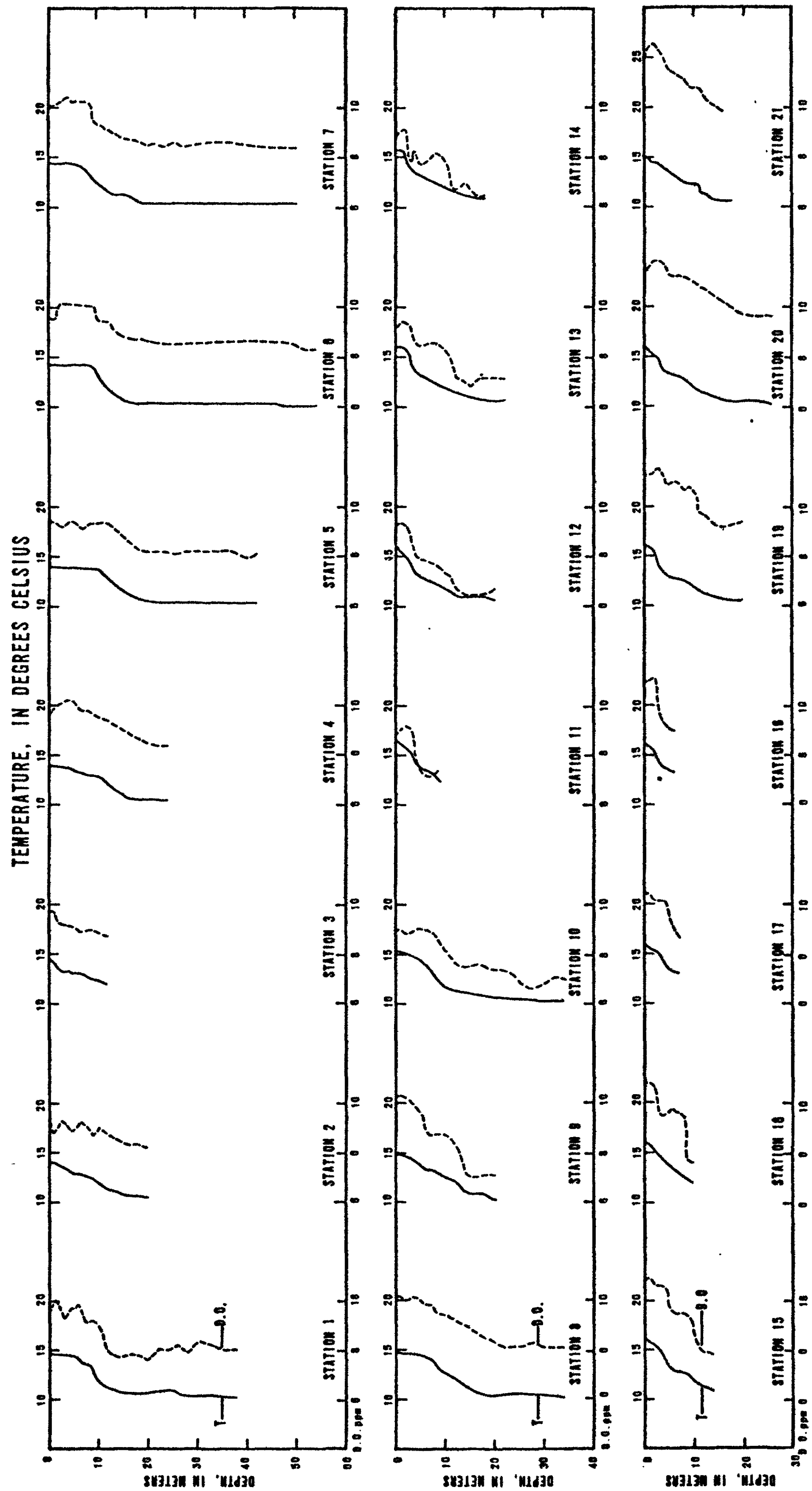


FIGURE 12.--Temperature (T) and dissolved-oxygen (D.O.) profiles, showing incipient thermal and chemical stratification in Lake Cachuma, March 24, 1966.

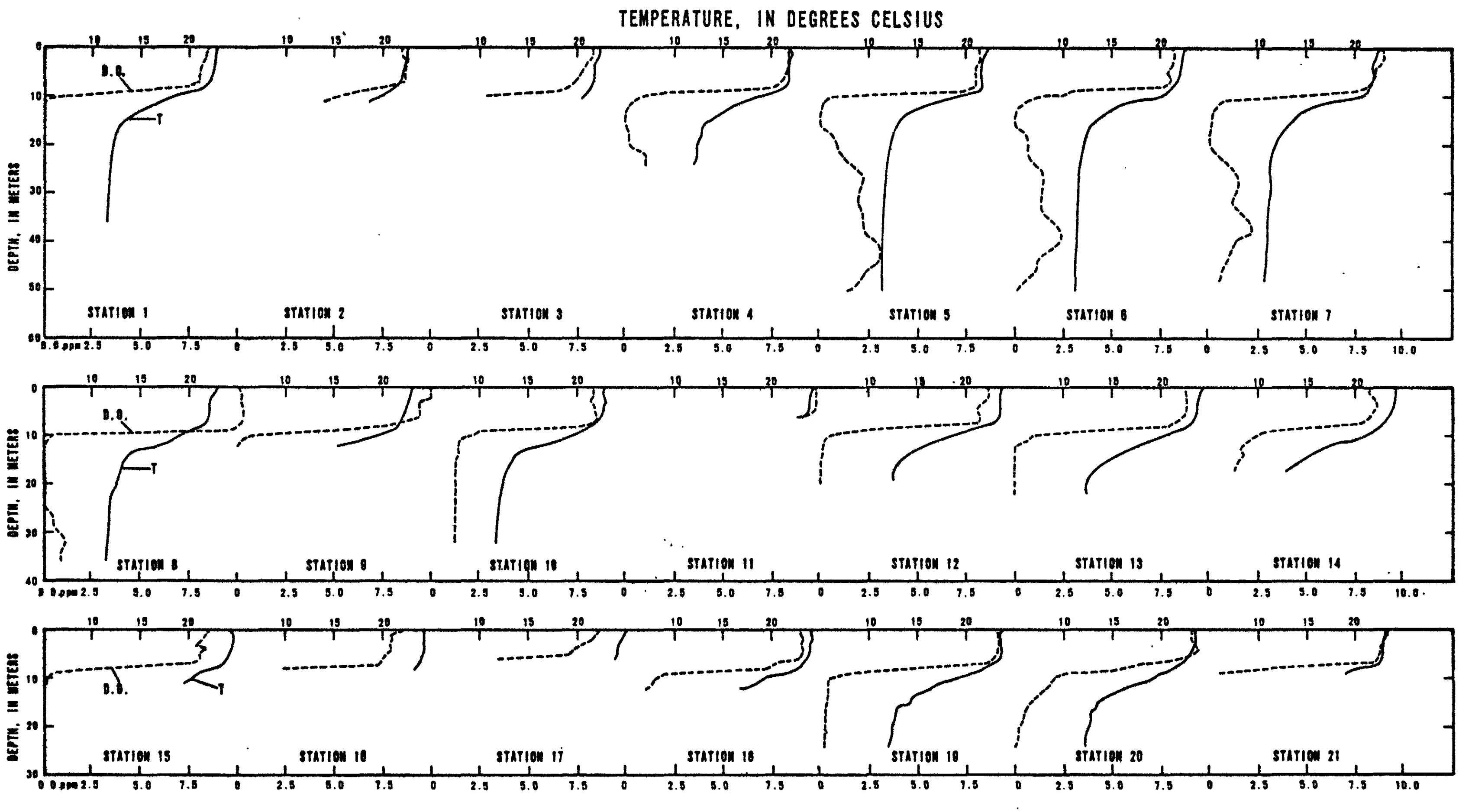


FIGURE 13.--Temperature (T) and dissolved-oxygen (D.O.) profiles, showing advanced stage of thermal and chemical stratification in Lake Cachuma, August 29-30, 1966.

## SPECIFIC STUDIES

### Correlation Analysis

A correlation analysis was used to evaluate the change in the phytoplankton populations in Lake Cachuma when various chemical and physical parameters changed.

The lake was divided (fig. 14) into 5 segments to relate the phytoplankton count to the chemical data. These segments of the lake were each represented by 1 of the 5 water-quality stations: A, B, C, D, and SYI. The phytoplankton data for each of these stations are from the phytoplankton-count stations in the corresponding segment of the lake. The data for the correlation analysis cover the period January-August 1966.

Seventeen variables were used in the analysis: Dissolved oxygen, pH, nitrate, ammonia nitrogen, orthophosphate, temperature, turbidity, and solar radiation; *Scenedesmus, Anabaena, Ankistrodesmus, Chlorella, Dinobryon, Monas, Oscillatoria, Peridinium,* and total phytoplankton count.

Correlation coefficients were determined for the correlation of any one variable on any other variable. If a correlation coefficient has an absolute value greater than 0.5, there is better than a 95-percent chance that the two variables have some correlation. If the correlation was greater than +0.5, a direct correlation was presumed to exist. If the correlation was less than -0.5, an inverse correlation was presumed to exist; that is, as the dependent variable becomes larger, the independent variable becomes smaller. Of the 136 correlation coefficients, 20 had an absolute value greater than 0.5 (table 1). These correlation coefficients apply only to Lake Cachuma during the analysis period.

Some of these results will be discussed in connection with the results of the polyethylene cylinder experiments.

The correlation coefficients relating *Ankistrodesmus* and *Chlorella* to total phylankton count have the greatest absolute value. This indicates that *Ankistrodesmus* and *Chlorella* were the dominant forms of phytoplankton in Lake Cachuma and, therefore, affected the total phytoplankton count the most. Another significant result is the increase in *Chlorella* population with temperature. This is corroborated by the phytoplankton-count data taken by the Lake Cachuma Operation and Maintenance Board. The direct correlation of temperature and solar radiation is self-explanatory. The increase in *Oscillatoria* as solar radiation decreases is borne out by the fact that the *Oscillatoria* population decreases in the summer.

The results of the correlation analysis are reliable enough to be used in a general way. These results could be used to set up a monitoring program whereby a close watch on a few physical and chemical parameters would indicate changes in phytoplankton populations.

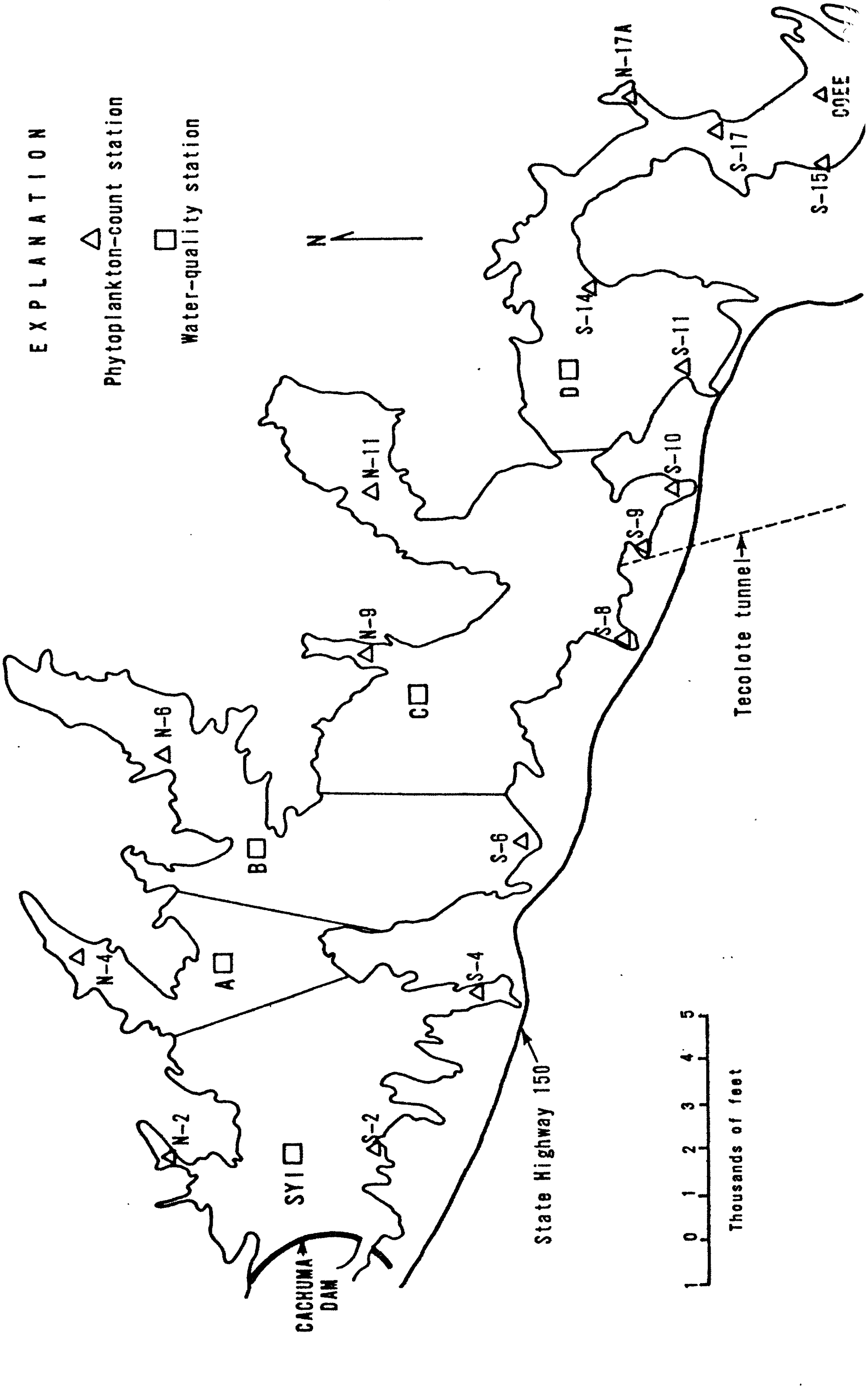


FIGURE 14.--Lake Cachuma water-quality and phytoplankton-count stations.

TABLE 1.--*Correlation coefficients for Lake Cachuma*

(January to August 1966)

| | | | |
|---|---|---|---|
| pH v. nitrate------------------- | -0.52 | Nitrate v. water temperature---- | -0.53 |
| pH v. orthophosphate------------ | -.58 | Nitrate v. *Peridinium*----------- | +.54 |
| pH v. water temperature--------- | +.69 | Orthophosphate v. water temperature------------------ | -.66 |
| pH v. *Chlorella*----------------- | +.60 | Orthophosphate v. solar radiation--------------- | -.71 |
| pH v. total phytoplankton count- | +.58 | Orthophosphate v. *Chlorella*----- | -.50 |
| Water temperature v. solar radiation--------------- | +.67 | Solar radiation v. *Oscillatoria*- | -.53 |
| Water temperature v. *Chlorella*-- | +.76 | *Anabaena* v. *Chlorella*----------- | +.50 |
| Water temperature v. total phytoplankton count----------- | +.60 | *Ankistrodesmus* v. total phytoplankton count----------- | +.77 |
| *Scenedesmus* v. *Ankistrodesmus*--- | +.66 | *Chlorella* v. total phytoplankton count----------- | +.72 |
| *Scenedesmus* v. *Dinobryon*-------- | +.58 | | |
| *Scenedesmus* v. total phytolpankton count----------- | +.52 | | |

## Polyethylene Cylinders

The effects of destratification by induced circulation were unknown; therefore, empirical approaches had to be taken to predict what would happen. The first step used at Lake Cachuma was the previously mentioned correlation analysis. This was used to determine the correlation of environmental changes with phytoplankton-population changes. This program augmented the results determined from the second step--enclosing columns of lake water in polyethylene cylinders for in-place examination.

Briefly, columns of the lake water were enclosed by polyethylene cylinders 1 square meter in cross-sectional area. The cylinders were sealed from the surrounding water at the bottom by heavy iron anchor rings embedded in the mud. The tops of the cylinders were held above the water surface by wooden frames supported by four styrofoam floats. The cylinders which were 21 meters in length were positioned nearly vertically in the water. The first test was made in June 1966 and the second in August 1966.

### June 1966 Test

The site of the first polyethylene cylinder experiment was at the mouth of Santa Cruz Bay about 0.7 mile north of the Tecolote Tunnel intake tower. This site was selected because the water was deep enough to include a part of the hypolimnion, the surface was largely protected from wind, and it was in the shallow upper part of the lake where many nuisance algal growths first appear.

The cylinder was lowered into the water June 6, 1966, and allowed to equilibrate for 24 hours. The column of water in the cylinder was destratified by induced circulation with compressed air. The air was discharged into the water column through a riser pipe located about 1 meter above the bottom of the lake.

Depth profiles of temperature, dissolved oxygen, and specific conductance were made. Temperatures at 4 fixed depths inside the cylinder and 2 fixed depths outside the cylinder were recorded sequentially. Water samples for chemical and phytoplankton analyses were collected from various depths. Chemical determinations were made at the site and later in the laboratory. The samples which were to be analyzed in the laboratory were treated with preservatives. The phytoplankton samples were preserved before filtering through 0.45-micron filters.

Initially the water was stratified in the lake and in the cylinder. However, with the onset of air injection, the water temperature at depths of 1 and 9 meters inside the cylinder dropped rapidly. Only a slight temperature gradient existed above the riser pipe during the test period. The water temperature below the riser pipe was unaffected.

The dissolved-oxygen content of the cylinder water above the riser pipe steadily increased to supersaturation; the water below the pipe was unaffected. Some of the results of the test may have been affected by the oxygen supersaturation. Supersaturation probably will not occur if air injection is installed at Lake Cachuma, because the lake is large enough to absorb the oxygen that will be needed to induce circulation.

No change in specific conductance resulted from destratification. Nitrate, phosphate, and silica values were nearly the same at depths of 5 and 15 meters. This suggests that chemical homogeneity was maintained after destratification. Nitrate and phosphate concentrations were significantly higher at the 5-meter depth inside the cylinder than at the 5-meter depth outside the cylinder. At a depth of 15 meters nitrate and phosphate concentrations were about the same inside and outside the cylinder. Silica concentration was uniform with depth, both inside and outside the cylinder. Slack and Ehrlich (written commun.) stated that their analyses indicated pH, bicarbonate, and free carbon dioxide were not appreciably affected by air injection.

Destratification changed some of the physical and chemical properties of the water. Apparently the changed environment was unfavorable for the existing phytoplankton species which began to die off. The population decline was indicated in the series of phytoplankton samples and possibly in differences in nutrient concentrations inside and outside the cylinder. The test did not continue long enough for a new group of organisms, adapted to the changed conditions, to appear.

## August 1966 Test

On August 24, 1966, two identical polyethylene cylinders were lowered into the water. The location of this test was the same as the June test to permit a comparison of results. One cylinder, called the experimental cylinder, was destratified by circulating water at 20 gpm (gallons per minute) with a centrifugal pump through a 2-inch hose from the surface of the isolated column to the bottom. The other cylinder, called the control cylinder, was located 20 feet east of the experimental cylinder. The column of water in the control cylinder was left undisturbed and remained stratified.

A small laboratory was set up on a raft anchored close to the two cylinders. Temperatures at 5 fixed depths inside the cylinder and 1 outside were recorded sequentially on a recording milliammeter using thermistors and a 6-channel automatic sequencer. The profiles of temperature and dissolved-oxygen content were made by lowering sensing elements into the column. Water samples for chemical and phytoplankton analyses were collected from both cylinders and the lake, and suitable preservatives were added to the samples which were analyzed later.

A major change from the June test was the destratification of the water in the cylinder by use of a centrifugal pump. This change removed the problem of supersaturating the column of water with dissolved oxygen. Destratification by water circulation probably has the same chemical and biological effects as destratification by air injection, except that it does not supersaturate the water with dissolved oxygen.

Ninety-one water samples were taken before, during, and after pumping from depths of 1, 5, 9, 13, and 17 meters. These samples were analyzed at the U.S. Geological Survey laboratory in Sacramento. Complete chemical analyses were made on nine samples. Three of these samples were collected August 24 from depths of 1, 9, and 17 meters in the experimental cylinder soon after it was lowered into the water. These samples were representative of both of the cylinders and of the lake before water pumping began. Six samples were taken September 2 during pumping; three from the experimental cylinder and three from the lake. Partial analyses for silica, nitrate, and orthophosphate were made on nine samples from the three environments collected each day from August 25 to September 1.

The same number of samples were collected for phytoplankton analysis. The phytoplankton samples were analyzed by the Lake Cachuma Operation and Maintenance Board Laboratory.

*Nitrate.*--Nitrate concentrations in the water from the lake, the control cylinder, and the experimental cylinder, as shown by figure 15, followed the same trend. All three had an average value of about 1.0 ppm with no stratification. Therefore, neither the isolation of the column of water by the polyethylene cylinder nor the circulation by pumping had any effect on nitrate concentration.

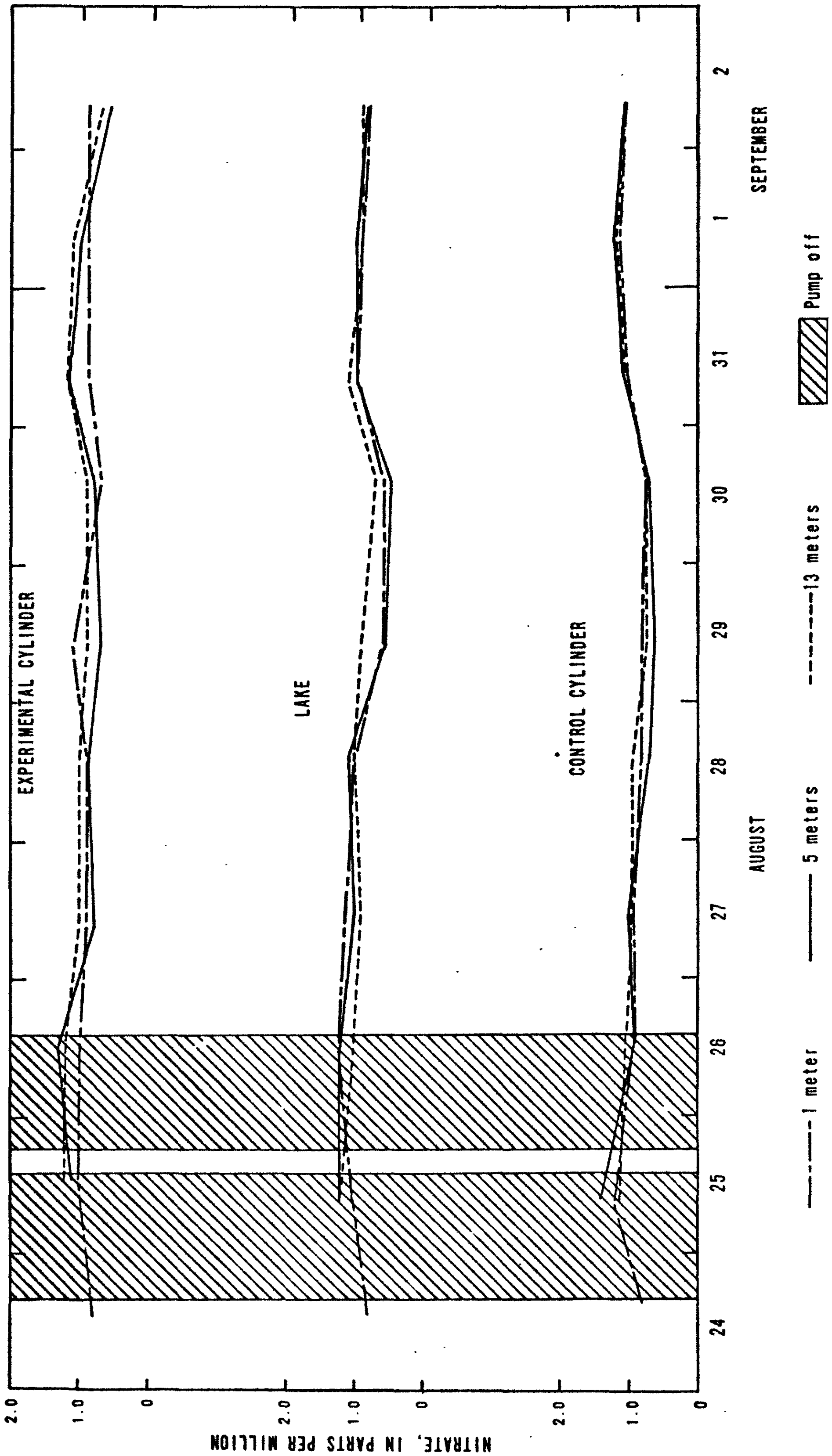


FIGURE 15.--Comparison of nitrate values for 1-, 5-, and 13-meter depths in the experimental cylinder, the lake, and the control cylinder.

*Silica.*--Figure 16 shows that stratified conditions existed in the lake and in the control cylinder. In the experimental cylinder the silica was destratified and its overall average was lowered approximately 0.5 ppm. This was due mainly to the lowering by 2 ppm of its concentration at a depth of 13 meters.

*Orthophosphate.*--Significant stratification existed in the lake and in the control cylinder, as shown in figure 17. The undisturbed layers at 13 meters in the lake and in the control cylinders were 0.3 to 0.5 ppm higher in concentration than the upper layers. This indicated less photosynthetic activity in the 13-meter layers. This was to be expected because solar radiation does not penetrate to that depth. Also, the correlation analysis indicated a definite inverse correlation between orthophosphate and *Chlorella*. In the experimental cylinder the overall average orthophosphate concentration was lowered significantly, especially in the 13-meter layer.

*pH analyses.*--Figure 18 shows that a definite stratification of pH existed in the control cylinder and in the lake. The higher pH at the 1- and 5-meter levels was an indication of greater photosynthetic activity. This was also proven by the positive correlation between pH and total phytoplankton count of the correlation analysis. In the experimental cylinder the water was destratified with respect to pH. The overall trend was an increasing pH with the average about 0.2 higher; however, the surface pH values were lowered about 0.2. Algae control by copper sulfate would be more effective with the lower pH values at the surface. Concentrations of iron and manganese would decrease in the deeper water because of a higher pH (Hutchinson, 1957, p. 802).

*Other chemical properties.*--A comparison of the September 2 chemical data in table 2 shows little significant difference between the lake and the experimental cylinder, except for alkalinity, fluoride, nitrate, hardness, and orthophosphate, all at the 13-meter level. Nitrate and orthophosphate have been discussed. The decrease in alkalinity and hardness can be explained by the fact that an increase in photosynthesis results in a decrease in bicarbonate concentration (Hutchinson, 1957). Little is known about the relation of fluoride and photosynthetic activity; therefore, no conclusions can be drawn at this time. The specific conductance was unaffected by the water circulation.

*Temperature.*--Figure 19 shows the polyethylene cylinder did not affect the water temperature because the profiles of the water in the lake and in the control cylinder are very similar. The water in the experimental cylinder tended to destratify to an average temperature equal to the median temperature of the thermocline of the lake profile. The warmer water was pumped from the surface down to the hose outlet at 18 meters; this had a definite warming effect on the water in the cylinder at the depth of the outlet. This warming effect dissipated above about 16 meters. The upper 3 meters in the column did not destratify completely. The increase in the surface-water temperature of the column August 30 resulted from warm lake water entering through a small hole in the top of the cylinder. The temperatures separated again after the hole was repaired.

TABLE 2.--*Chemical analyses of water, Lake Cachuma, Calif., 1966*

| | August 24 experimental cylinder | | | September 2 lake | | | September 2 experimental cylinder | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1m | 9m | 17m | 1m | 5m | 13m | 1m | 5m | 13m |
| Silica | 9.1 | 9.3 | 11.0 | 8.7 | 8.9 | 11.0 | 8.7 | 8.5 | 9.0 |
| Iron | .03 | .03 | .04 | .03 | .03 | .04 | .04 | .04 | .04 |
| Calcium | 67 | 74 | 79 | 68 | 66 | 76 | 67 | 68 | 68 |
| Magnesium | 42 | 40 | 39 | 43 | 44 | 43 | 44 | 43 | 43 |
| Sodium | 44 | 43 | 40 | 44 | 44 | 39 | 44 | 44 | 44 |
| Potassium | 3.8 | 3.5 | 3.5 | 3.7 | 3.7 | 3.6 | 3.7 | 3.7 | 3.7 |
| Alkalinity as $HCO_3$ | 195 | 214 | 234 | 200 | 200 | 237 | 200 | 200 | 200 |
| Alkalinity as $CaCO_3$ | 160 | 175 | 192 | 164 | 164 | 194 | 164 | 164 | 164 |
| Sulfate | 242 | 233 | 217 | 241 | 245 | 220 | 240 | 242 | 247 |
| Chloride | 16 | 16 | 15 | 16 | 16 | 15 | 17 | 16 | 17 |
| Fluoride | .5 | .5 | .5 | .5 | .5 | .5 | .5 | .5 | .3 |
| Nitrate | .8 | 1.0 | .9 | .8 | .8 | .9 | .9 | .6 | .7 |
| Boron | .4 | .4 | .4 | .5 | .5 | .4 | .4 | .4 | .4 |
| Total hardness | 341 | 350 | 357 | 346 | 346 | 367 | 348 | 345 | 345 |
| Orthophosphate | .11 | .17 | .64 | .02 | .02 | .49 | .03 | .03 | .02 |

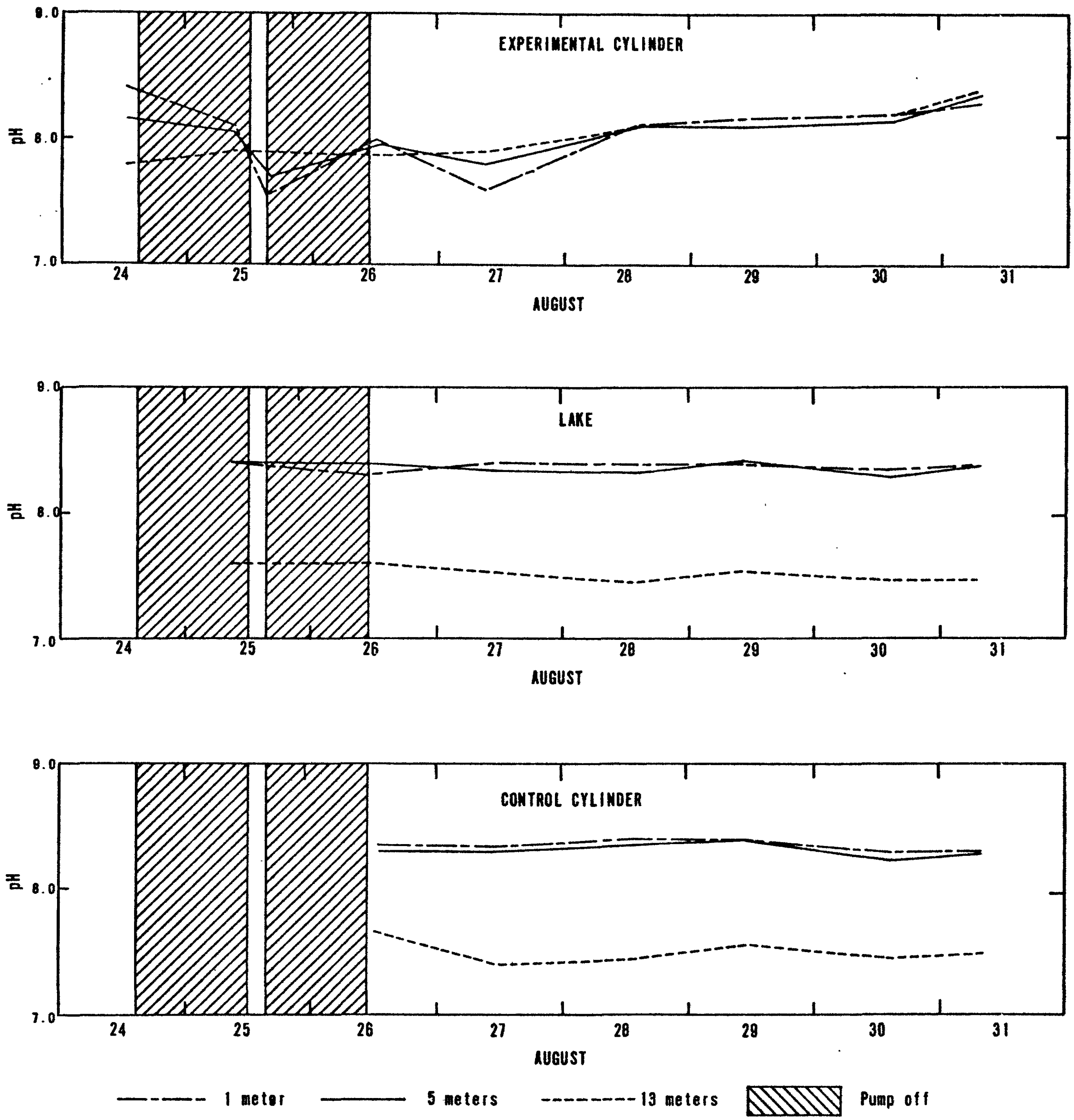


FIGURE 18.--Comparison of pH values for 1-, 5-, and 13-meter depths in the experimental cylinder, the lake, and the control cylinder.

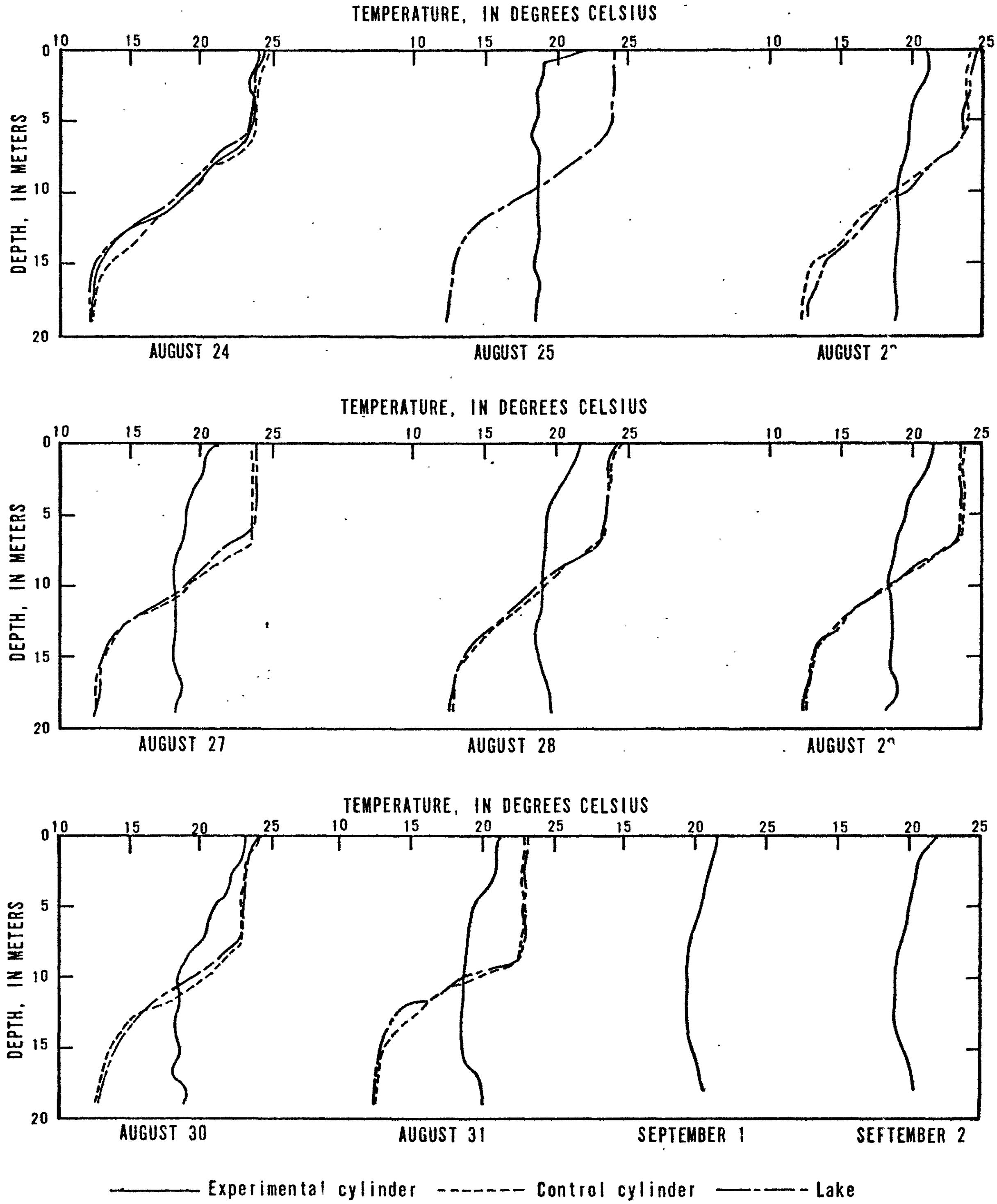


FIGURE 19.--Temperature profiles of the experimental cylinder, the lake, and the control cylinder during August and September 1966.

*Dissolved oxygen.*--The water in the lake and in the control cylinder had similar dissolved-oxygen profiles, as shown in figure 20, indicating the polyethylene cylinder did not affect the dissolved oxygen. The first dissolved-oxygen profiles were taken August 24 before the pumping was started. The pump was then run about 3 hours. The next profiles were taken in the lake and the experimental cylinders immediately before pumping was resumed August 25. Another profile in the experimental cylinder only was taken an hour and a half later. The effect of the intermittent pumping can be noted in the profiles of August 25. The data for August 26 show that the water in the experimental cylinder became destratified during the first full day of pumping. Initially the column of water had a homogeneous value of about 5 ppm dissolved oxygen. This concentration slowly increased to about 8 ppm throughout the entire column before monitoring was ceased. This concentration is enough to support cold- or warm-water fish (Welch, 1952). The stagnant hypolimnetic water was most affected as its dissolved-oxygen concentration was raised from 0 to 8 ppm. The increased dissolved-oxygen concentration in the experimental cylinder resulted from increased photosynthesis and from absorption of atmospheric oxygen by the constantly renewed layer of water at the surface.

*Phytoplankton analysis.*--No nuisance blooms were observed in the circulated water of the experimental cylinder. Figure 21 shows that a large increase in phytoplankton occurred in the experimental cylinder August 29. However, this sudden increase was followed by a decrease of similar magnitude to a level nearly the same as that in the lake and in the control cylinder. Table 3 shows that the daily average phytoplankton population was less for the 1- and 5-meter depths in the experimental cylinder than it was in the lake and in the control-cylinder water. This fact points out that within the accuracy of the phytoplankton count there was no nuisance blooms in the experimental cylinder. The dominant species in the water of both cylinders and in the lake was *Chlorella* which comprised nearly 90 percent of the total phytoplankton count. The remaining 10 percent were, in order of concentration, *Ankistrodesmus*, *Scenedesmus*, and a few *Navicula*.

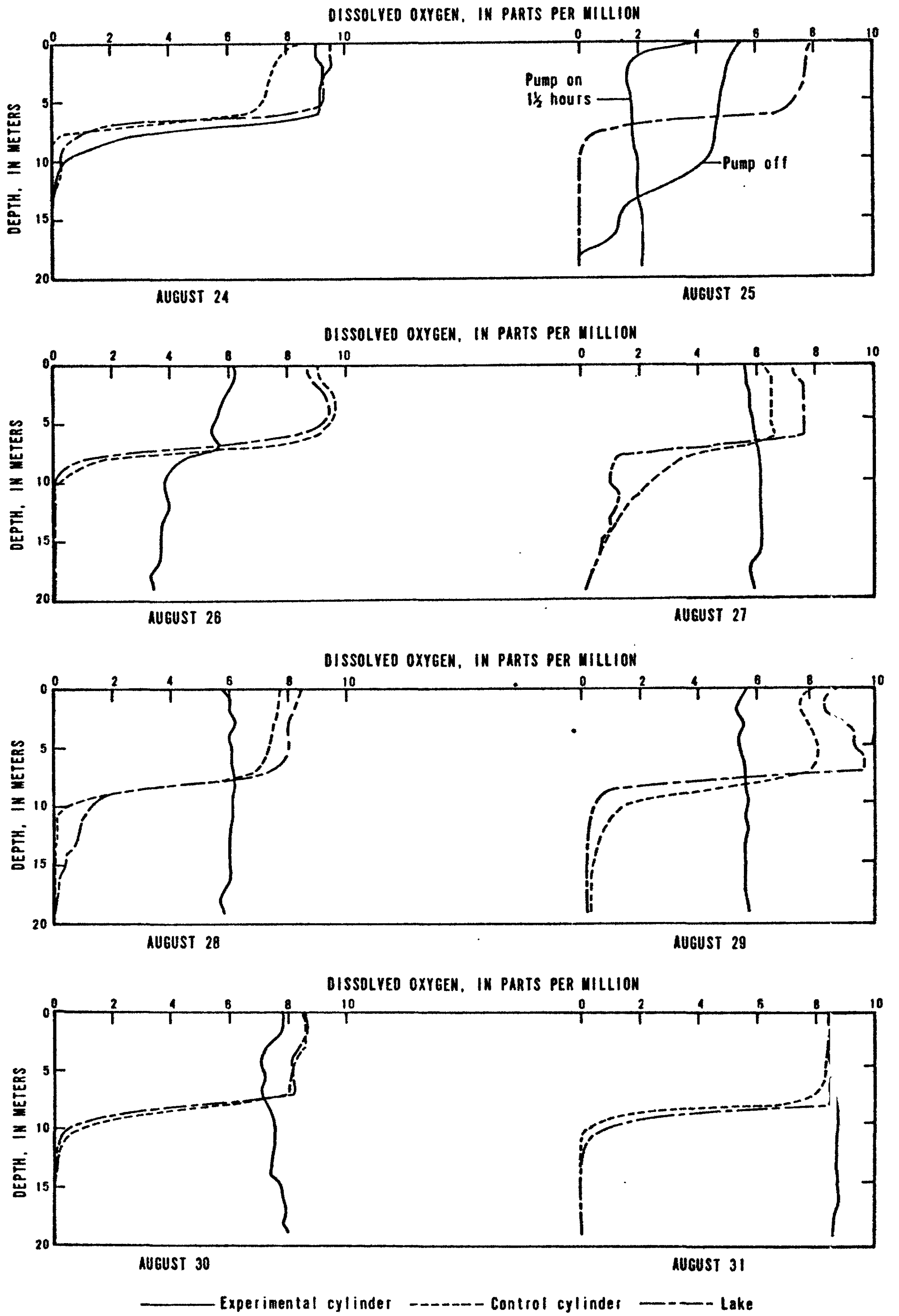


FIGURE 20.--Dissolved-oxygen profiles of the experimental cylinder, the lake, and the control cylinder during August 1966.

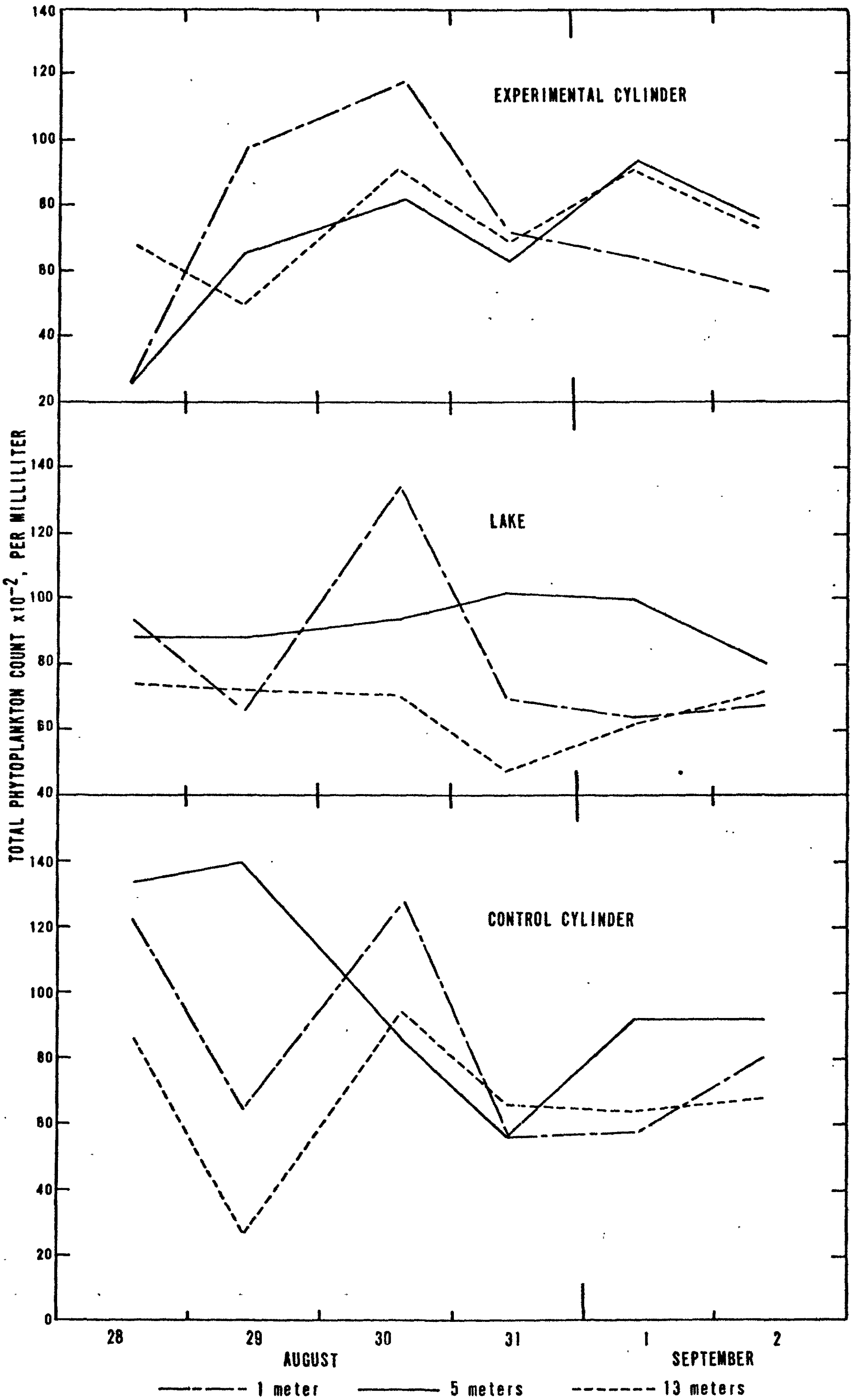


FIGURE 21.--Comparison of total phytoplankton count in the experimental cylinder, the lake, and the control cylinder.

TABLE 3.--*Phytoplankton count* x$10^{-2}$, *per milliliter, in the experimental cylinder, the lake, and the control cylinder, August 28-September 2, 1966*

| | | 1-m depth | | | 5-m depth | | | 13-m depth | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Experimental cylinder | Lake | Control cylinder | Experimental cylinder | Lake | Control cylinder | Experimental cylinder | Lake | Control cylinder |
| August | 28 | 26 | 94 | 122 | 26 | 88 | 134 | 68 | 74 | 86 |
| | 29 | 98 | 64 | 64 | 66 | 94 | 140 | 50 | 72 | 26 |
| | 30 | 118 | 134 | 128 | 82 | 88 | 86 | 92 | 70 | 94 |
| | 31 | 70 | 70 | 56 | 70 | 102 | 56 | 72 | 48 | 66 |
| September | 1 | 64 | 64 | 58 | 94 | 100 | 92 | 92 | 62 | 64 |
| | 2 | 74 | 68 | 80 | 76 | 80 | 92 | 50 | 72 | 68 |
| Average | | 75 | 82 | 85 | 69 | 92 | 100 | 71 | 66 | 67 |

## CONTINUING STUDIES AND SURVEYS

Continuing surveys and studies are planned if an air-injection system is installed at Lake Cachuma. Beginning with actual air injection, the frequency of data-collecting surveys will be increased, as necessary. These surveys will be continued throughout the 1967 summer and autumn seasons. Water, air, and wet-bulb temperatures; windspeed and direction; and solar radiation will continue to be recorded. Surface and underwater-current studies will be undertaken to determine the magnitude, direction, and depth of the currents. A close watch will be kept on any other possible avenue of approach to be sure the destratification process is well monitored. Water samples for complete chemical analysis will be collected at one or more of the Lake Cachuma Operation and Maintenance Board phytoplankton-count stations. This will provide data for the correlation analysis discussed earlier in this report. A final report will be prepared summarizing the data and the effects of air injection.

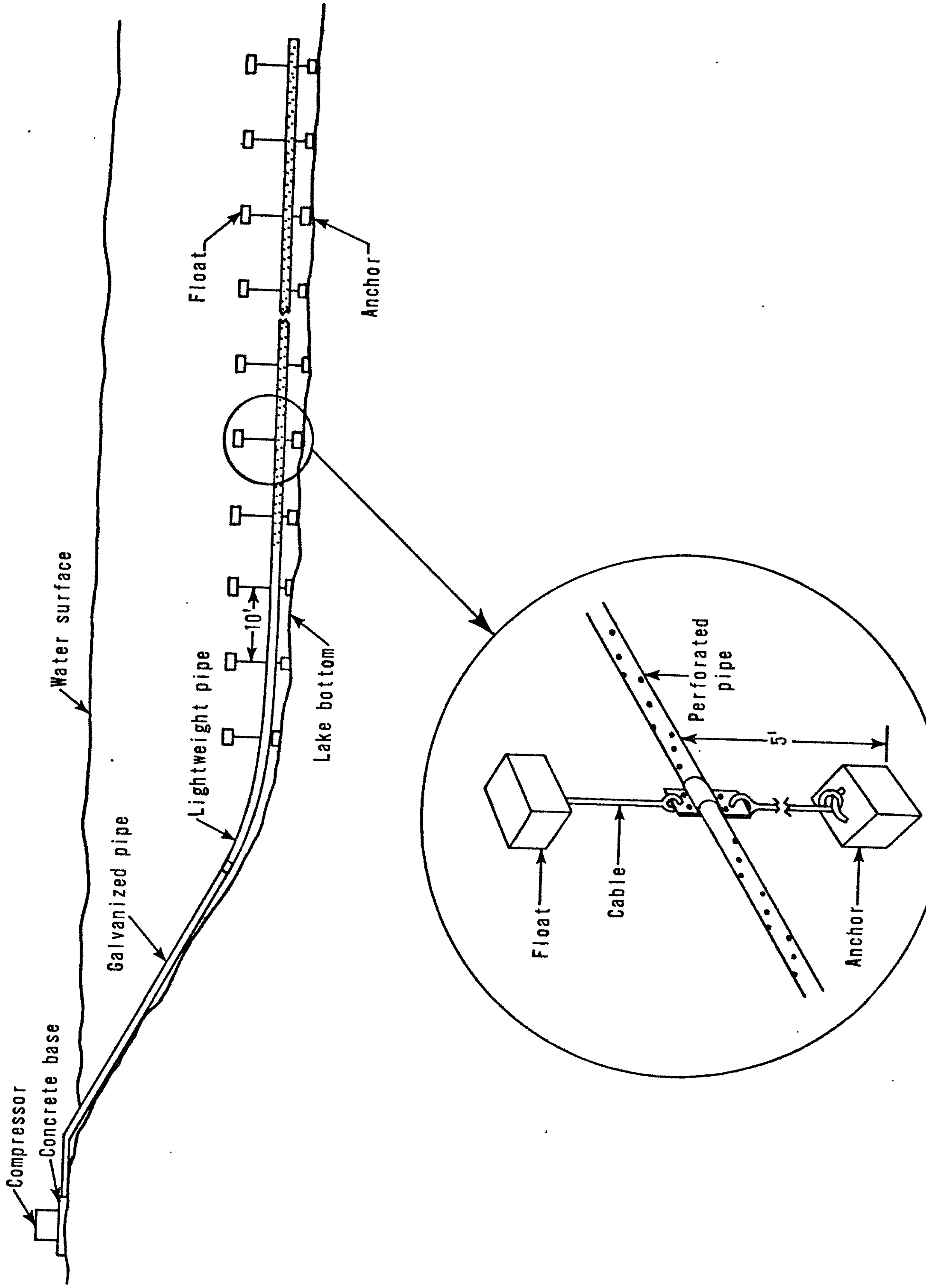


FIGURE 23.--A proposed air-injection system for Lake Cachuma.

## SUMMARY AND CONCLUSIONS

This study was undertaken to determine the effects air injection would have on Lake Cachuma. Four approaches were made to answer this question.

Results from previous studies on other artificially aerated reservoirs have in general been favorable. The aeration system at Lake Wohlford was found to be economically feasible to remove undesirable taste and odors from the lake water. The dissolved-oxygen concentration was increased in the hypolimnion, and overall evaporation was reduced about 6 percent. Results at El Capitan Reservoir showed that a 210-cfm compressor was more than sufficient to destratify 14,600 acre-feet of water with a corresponding surface area of 450 acres.

Preliminary surveys at Lake Cachuma indicate temperature and dissolved-oxygen stratification began in early March. The surveys also indicated that in late summer anaerobic conditions prevailed at depths below 10 meters.

The correlation analysis indicated that a monitoring program might be developed; that is, by monitoring physical and chemical parameters, such as temperature, solar radiation, nitrate, orthophosphate, and pH, a qualitative prediction might be made of phytoplankton populations (*Chlorella*, *Peridinium*, and *Oscillatoria*).

An in-place examination of the problem involved isolating a column of lake water with a polyethylene cylinder. Two tests of this type were made. The results from the first test (June 1966) 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 by air injection. The changed environment was unfavorable to existing phytoplankton populations, but the test was not of sufficient duration to determine whether or not cool-water algae species would develop over a sustained period of injection. The test indicated that destratification did not stimulate growth of the algae species dominant at the time.

In the second test (August 1966) the water in the experimental cylinder was destratified by circulating water with a centrifugal pump. The control-cylinder water was left undisturbed, and the results showed that thermal and chemical stratification remained. Nitrate concentration and specific conductance were unaffected by water circulation. However, silica, orthophosphate, and surface pH were destratified, and their overall values were lowered. The water temperature destratified to a value equal to the median temperature of the thermocline. The dissolved-oxygen concentration became destratified and the overall average rose to 8 ppm throughout the entire column; the concentration would be enough to support cold- and warm-water fish. *Chlorella* composed about 90 percent of the phytoplankton population in both cylinders and in the lake. No significant blooms of phytoplankton occurred in the experimental cylinder.

In view of these results, stratification of Lake Cachuma can be prevented. Water temperature and pH values can be reduced at the surface; therefore, the overall evaporation rate would be reduced and algae control would be more effective. Objectionable tastes and odors will be eliminated as the undesirable dissolved gases are eliminated. Fish life will be enhanced as the dissolved-oxygen content of the lower levels of the lake is increased.

The expected beneficial results of air injection outweigh the possibility of any nonbeneficial results. The aeration equipment should be ready to operate by March 1, 1967. A 125-hp unit should be installed at the north end of Tequepis Point and a 50-hp unit at the Tecolote Tunnel intake.

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