Title
Fish Bulletin 141. Artificial Destratification of El Capitan Reservoir By Aeration. Part I: Effects on Chemical and Physical Parameters

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Publication Date
1968-04-01

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF FISH AND GAME
FISH BULLETIN 141
Artificial Destratification of El Capitan Reservoir By Aeration
Part I: Effects on Chemical and Physical Parameters

By

ARLO W. FAST

1968

ABSTRACT

Most lower elevation California lakes experience one yearly cycle of stratification. Thermal stratification generally starts about March and extends through November, greatly influencing chemical and biological stratification. The metalimnion and hypolimnion of eutrophic lakes often are devoid of oxygen. Concomitant with the oxygen deficit is the build-up of anaerobic decomposition products and the exclusion of biota from the oxygen deficient zones.

Artificial destratification by aeration reduces or eliminates thermal stratification. Oxygen is distributed to all depths and products of anaerobic decomposition are oxidized. Barriers to biotic distribution are minimal.

The diffuse aeration system is probably the most effective for destratifying large lakes. Other methods are discussed.

Artificial lake destratification increases the lakes's heat budget. The winter temperature regime is not affected by destratification. Summer surface temperatures during stratified and destratified periods are about equal. Bottom temperatures are greatly increased by destratification and may equal the surface temperatures. The coldest water temperature in a destratified lake may approach those found at the lake's surface during stratified periods. This increased heat content should benefit the fishery by increasing invertebrate forage production and decomposition of organic sediments. However, increased bottom temperatures may eliminate or preclude the establishment of a coldwater fishery.

Two hypolimnion aeration systems are discussed. These systems aerate the bottom waters without causing thermal destratification and enhance coldwater fisheries.

Lake aeration is economically feasible. Evaporation and chemical treatment savings alone may more than pay for the aeration system. Improved drinking water quality and fishery habitats results from aeration.

This report is the first of a series describing our El Capitan Reservoir destratification study. Subsequent reports will describe the effects of artificial destratification on the zoobenthos, phytoplankton and fishes.

TABLE OF CONTENTS

ACKNOWLEDGMENTS

I am greatly indebted to the City of San Diego's Utilities Department and Helix Irrigation District for their invaluable assistance. Costs of compressor installation, operation and maintenance were shared by these water managers. They also shared the expense of many chemical analyses made at my request and gave me free access to many of their records. City Chemists, Eugene I. Crossley, L. E. Tooks, Mary Middendorf and Jerard Sindelar, analysed most of our chemical samples and gave freely of their time and assistance.

I am especially thankful for the assistance of Edward G. Bauer, Richard P. Bacon and Kenneth G. Moye of the San Diego State College computer center. Their assistance and the use of the computer facilities, in conjunction with my graduate program, contributed immeasurably to the speedy analysis and conclusion of this project segment.

Gordon E. Koberg of the U.S. Geological Survey helped initiate our study and contributed substantially to its success. He designed and directed the installation of the air distribution system. He gave freely of his assistance and data.

The County of San Diego purchased the compressor with county fine monies. Without this assistance our program would have been set back a year or more.

Heinz Bernhardt and R. E. Speece permitted my use of their hypolimnion aerator illustrations.

James M. Symons, Robert W. Owen, Lee W. Miller, William M. Richardson, William E. Shafer and Alex Calhoun read my prepublication manuscripts of this bulletin and offered many useful suggestions. This bulletin is greatly improved by their much appreciated contributions.

Scott Soule, Alex Calhoun, Lee W. Miller, William M. Richardson, James Ryan, Leonard Fisk and Marvin J. Whalls, helped initiate and/or guide this study. They helped keep the investigations on the correct track and procure the funds necessary to complete our work.

Most of the figures in this report were constructed by Denny Yost, under my supervision. Kay T. O'Donnell typed, and retyped this report many times.

Many other individuals have contributed to this project. Without their assistance the work accomplished by this project would have been impossible.

ARLO W. FAST
April 1, 1968

INTRODUCTION[1]

The uneven distribution of heat within a lake often conflicts with man's use of the water. Thermal stratification within the lake can cause deteriorated drinking water quality, plankton blooms, fish kills, uneven distribution of ions, anaerobic and corrosive conditions, increased evaporation rates, and other undesirable properties.

In brief, reservoir stratification refers to the uneven vertical distribution of properties within the water column. These gradients are found in: (i) *Physical Properties* such as temperature, water density, and viscosity, (ii) *Chemical Properties* such as oxygen, and pH, and (iii) *Biological Properties* such as fish, plankton, and benthic plants and animals. Physical stratification is primarily related to thermal energy distribution as it affects water density. Chemical and biological stratification are greatly influenced by physical stratification.

Lake stratification follows an annual cycle. Most lower elevation California lakes follow a similar cycle, designated "warm monomictic" by Hutchinson (1957), or "second order tropical" by Welch (1952). During the winter these lakes have more or less uniform temperature and chemical properties throughout (Figure 1) . The entire lake is circulated by the wind and oxygen is plentiful at all levels. Thermal and chemical barriers to biota distributions do not exist, or are minimal. As the seasons progress, the upper waters of the lake are heated faster than the lower. Consequently, the density and viscosity of the surface water decreases rapidly. These changes impede the continued mixing of all the water and a barrier to mixing is established. Concomitant with these developments is the formation of three zones: (i) *Epilimnion*. The warm water volume of the lake. It is circulated by the wind and oxygen concentrations are generally near saturation. Temperature and chemical properties are about homogeneous throughout. Most of the biota is restricted to this zone. (ii) *Metalimnion.* (also called the thermocline). A zone of rapid change in temperature, density, and chemical properties. Generally defined as a temperature change equal to, or greater than 1.0°C per 1.0 meter change in depth, and (iii) *Hypolimnion*. The cold water zone of the lake. This zone is completely sealed off from the surface. It characteristically stagnates by early summer in organically rich, eutrophic lakes. Stagnation results in an oxygen deficit, build-up of hydrogen sulfide, increased iron and manganese concentrations, anaerobic conditions, and overall deterioration of drinking water quality.

With the advent of cooler fall weather, surface waters are cooled and the epilimnion continues to erode the metalimnion and hypolimnion. The rate of erosion increases as the temperature of the epilimnion approaches that of the hypolimnion. Eventually, at the fall overturn, the entire lake is again circulated by the wind. Temperature and other

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[1] This work was performed as part of D-J Project California F-23-R, The Effects of Artificial Destratification on Lake Fisheries, supported by Federal Aid to Fish Restoration Funds.

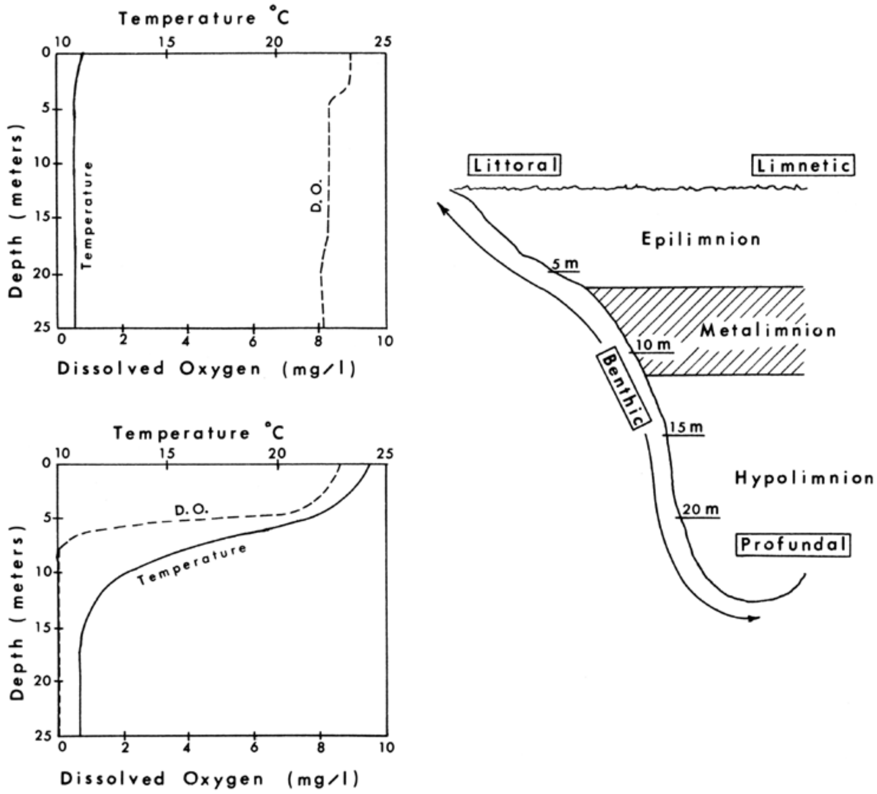

FIGURE 1. Hypothetical temperature-oxygen profiles during July and December, and lake zones during stratified periods.

FIGURE 1. Hypothetical temperature-oxygen profiles during July and December, and lake zones during stratified periods

properties are again homogeneous. Oxygen is plentiful at all levels and barriers to biotic distribution are minimal.

The purpose of artificial destratification is the reduction of the density barrier to complete circulation. After artificially induced circulation of a reservoir, the water temperature is about équal from top to bottom and many of the chemical properties are likewise homogeneous. The whole water mass and bottom area is theoretically habitable by the biota, which otherwise could only inhabit the epilimnion and metalimnion.

Until recently, little was done to reduce stratification economically. Destratification was tried with mechanical water pumps; however, this method is generally inefficient, slow, and costly. Several successful artificial destratification techniques using compressed air were recently developed. These techniques are generally efficient, rapid, and relatively inexpensive. often the cost of installing and operating aeration equipment is more than met by savings derived from the use of aerated water.

This report is the first in a series dealing with our investigations of artificial destratification. It serves as a general introduction to the topic of lake aeration and presents some of the results of our El

Capitan Reservoir study. I present the effects of destratification on certain chemical-physical properties of El Capitan Reservoir and attempt to relate some observed chemical-physical changes to fisheries management practices. Some changes are seen to affect directly the fishery, while the consequences of other effects can only be inferred. Subsequent reports will present analyses of the effects of aeration on the zoobenthos, phytoplankton population dynamics, fish distribution and growth, and other aspects of the study.

1. PRINCIPLES AND TECHNIQUES OF ARTIFICIAL DESTRATIFICATION AND AERATION

1.1. Principles of Destratification By Air Injection

Although air injection may be used to aerate isothermal water, it is generally used to aerate stratified water. Indeed, its consequences are most dramatic to the entire lake regime when it is applied under these conditions. Its economic feasibility is usually determined by the degree and nature of the stratification.

In theory, destratification by diffuse air injection is accomplished as shown in Figure 2. Figure 2-A illustrates a thermally stratified lake before air injection. It is characterized by horizontal, iso-density strata. These strata are thickest in the epilimnion and hypolimnion since these zones are almost uniform in temperature. The metalimnion is the zone of rapid change in density and is characterized by narrow iso-density strata.

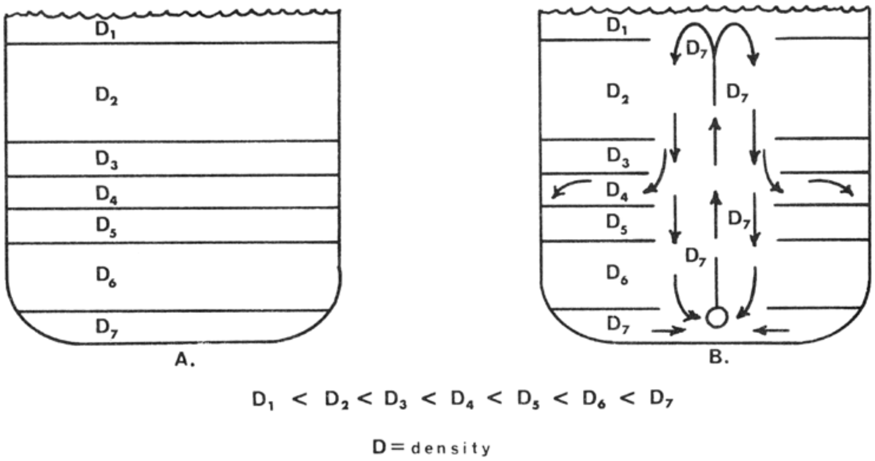

FIGURE 2. Hypothetical destratification patterns caused by a diffused aeration system. Figure A illustrates a stratified lake, and Figure B a lake being destratified.

FIGURE 2. Hypothetical destratification patterns caused by a diffused aeration system. Figure A illustrates a stratified lake, and Figure B a lake being destratified

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

Upon reaching the surface, the upwelled water diverges radially. The now horizontally flowing cold bottom water converges and sinks below the warm, surface water. The vertical flow downward is perpetuated by density differences. Upon converging with the warm surface water and sinking, the cold water mixes with the epilimnion and metalimnion water along its periphery to form water of intermediate temperature and density. This mixed water now spreads out horizontally at levels of equal density. The depth of outflow depends on the degree of mixing and initially may be confined mostly to the metalimnion. As the mixing process progresses, the shape and number of the iso-density strata change. Concomitant with this change is a change in the rate of mixing. The rate of destratification is greatest when injection begins and approaches zero apparently as an exponential function as the lake approaches isothermy (Koberg and Ford, 1965). The lake will approach either an isothermal or a steady-state condition as the mixing continues. The time it takes to reach this condition depends on the time of year, size of lake, and method of injection. The best method of injection and equipment specifications for a given lake situation are not well defined.

Artificial destratification of a lake by compressed air is commonly called "lake aeration". The reasons for this are two-fold: (i) Eutrophic lakes experience an oxygen deficit below the metalimnion during the summer. By artificially circulating the lake, the oxygen deficit is reduced or eliminated, and (ii) compressed air is used to circulate the water. While the compressed air adds oxygen directly to the upwelled water, oxygen is also gained from contact of the water with the atmosphere and by photosynthesis of aquatic plants.

1.2. Air Injection Techniques

Several successful techniques are available for artificially destratifying lakes. Many of these techniques differ in their approach to the problem. Although few comparative studies are reported, the most appropriate method of aerating depends ultimately on the specific limnology of the lake under consideration.

1.2.1. Diffuse Air Injection

This system is now operational at El Capitan Reservoir, Lake Wohlford (Koberg and Ford, 1965) and many other reservoirs. I believe this technique is the most efficient method of destratifying large reservoirs. Bernhardt (1967) indicates an average efficiency value of about 0.42% for diffuse aeration, as opposed to 0.14% for mechanical pumping. Symons and Robeck (1966) present a method of calculating the efficiency based on stability and power input.

The El Capitan and Lake Wohlford systems are essentially identical. A detailed description of the El Capitan system is presented in the Compressor Installation and Operation section of this report. Koberg and Ford (1965) describe the Lake Wohlford system. In brief, the El Capitan system consists of a large compressor situated on the shore (Figure 3) .

Air is pumped from the compressor via a single iron pipe. The terminal 31 meters of plastic pipe are suspended from the bottom by a float and anchor system and are perforated for air release.

The Lake Wohlford system eliminated stratification in 24 hours with 4.44 X 10^6 cubic meters volume. However, about one week of continuous pumping with this system during June of 1965 reduced, but did not eliminate stratification, at El Capitan. The volume of El Capitan was about 18 X 10^6 cubic meters. A further discussion of El Capitan appears later.

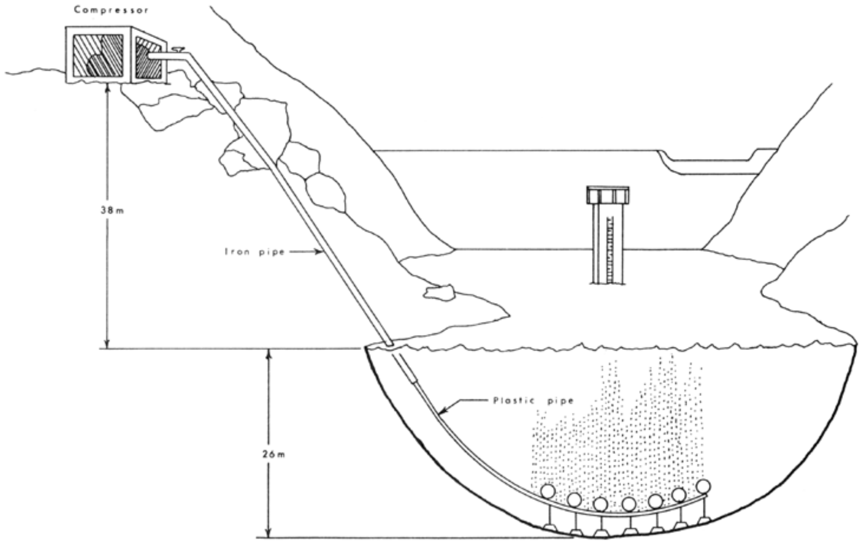

FIGURE 3. The diffuse air injection system at El Capitan Reservoir. El Capitan dam and control tower are in background.

FIGURE 3. The diffuse air injection system at El Capitan Reservoir. El Capitan dam and control tower are in background

Figure 3 of Bernhardt (1967) indicates he obtained similar results with his diffuse aeration system. He used two compressors, an 11.0 kw compressor and a 36.5 kw compressor in Wahnbach Reservoir with about 37 X 10^6 cubic meters volume.

1.2.2. Aero-Hydraulic Cannons

This technique is patented and commercially available from the Aero-Hydraulic Corp., Montreal, Canada. The guns consist of polyethylene tubes, 30.5 cm or 45.7 cm in diameter and various lengths. Figure 4 illustrates a single cannon. Generally, five or more cannons are situated in a lake and fed by a single small compressor.

Air enters a chamber at the bottom of the tube. When the chamber is full of air, the air breaks a seal and is released as a single bubble by reverse siphon action. The single, large bubble rises in the tube like a bullet, or piston, pushing water ahead of it and drawing water up behind it. At least one bubble should be in the tube at all times for maximum efficiency. Under this condition, water is in constant motion in the tube. The tubes generally are situated at the deepest point in the lake and extend to near the surface. A peripheral flow is also set up along side the tube by the effluent water. This system has the advantage of requiring a small compressor. A 5-hp compressor is adequate

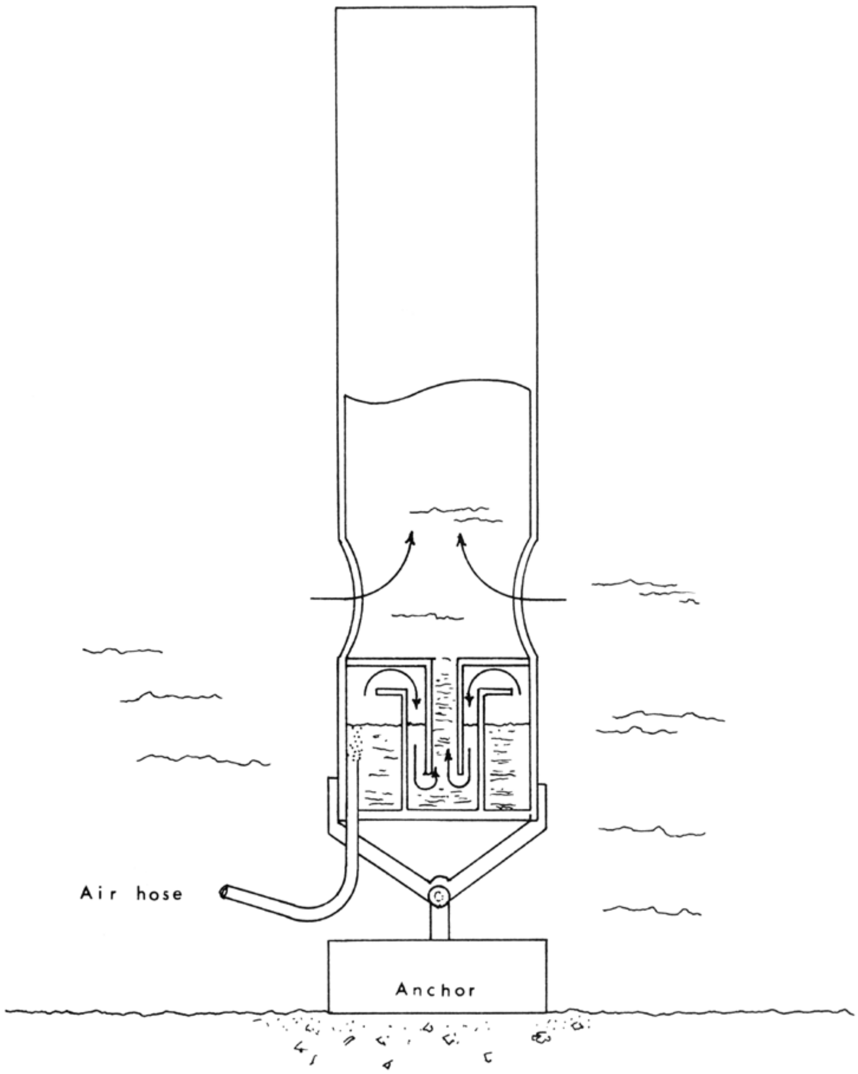

FIGURE 4. An aerohydraulic cannon. The air chamber at the bottom of the barrel is being filled with air from a shore compressor.

FIGURE 4. An aerohydraulic cannon. The air chamber at the bottom of the barrel is being filled with air from a shore compressor

to destratify 1.48 X 10^6 cubic meters, Cox Hollow Lake (Wirth and Dunse, 1966). The maximum depth is about 8.9 meters.

Bryan (1964) describes this device and presents results for several small lakes. To date, they have only been used in relatively small lakes, but may be applicable to large lakes as well. They also have general use in sewage oxidation ponds.

1.2.3. Floating Aerator

This system consists of a perforated iron pipe suspended from a float. Riddick (1957) used a 7.6 cm I.D. pipe, 12.3 meters long, suspended horizontally at 2.4 meters from the surface. His point of air release is over the deepest point in the lake. He eliminated stratification in 6 days of pumping at Indian Brook Reservoir. He released about 160 cfm in this 0.37 X 10^6 cubic meters reservoir. The reservoir has a maximum depth of 8.6 meters. Apparently the aerator caused an upwelling of deep water over the point of air release. The circulation pattern is probably similar to that described for diffuse air injection. However, in large reservoirs, the depth of air release must be increased to accomplish complete mixing.

This system has the advantage of mobility and easy accessibility. Riddick used it to disperse lime. A chemical dispersion system can be installed on the float. Rotenone, copper sulfate, alum and other chemicals could also be dispersed by this technique.

Mobility of the system is desirable from the standpoints of: maintenance, selection of mixing depth, and use in more than one lake. It is possible to mix a lake only partially by proper selection of air release depth and location. By positioning the float at locations of less than maximum depth, or by using a relatively shallow release depth, partial destratification is possible. This situation may be desirable under certain conditions.

1.2.4. Blower-Type

Nickerson (1961) uses this technique at Babson Reservoir, Mass., to eliminate stratification. Air from a Roots-Connerville blower is released from the 2.5 meter depth. About 470 cfm of air at 7 p.s.i. is delivered. This system is sufficient to destratify this 0.87 X 10^6 cubic meters reservoir in a few days. Maximum depth of the reservoir is about 12.3 meters.

Although this technique may be applicable to some small reservoirs, it does not appear to be as efficient as other methods of aeration.

1.2.5. Plastic Hose Air Distribution System

This system is commercially available from the Hinde Engineering Corp. It consists of a grid-work of weighted air hoses on the bottom of the lake or pond, Meyer (1962). The hoses have numerous small perforations. Compressed air from a small shore compressor is distributed by the hoses and released from the perforations.

This system apparently has never been used in a large stratified lake, although the manufacturer claims it can be used successfully. The system is specifically designed to increase the biological load capacity of sewage oxidation ponds. It supposedly increases the capacity of these ponds by a factor of four.

1.2.6. Diffuse Air Tubes

This system consists of a vertical tube extending from near the bottom of the lake to near the surface. The tube may be suspended from a float on which an air compressor is also situated. The diameter of the tube may vary as a function of air volume. Müller (1963) uses a 2-meter diameter tube with 117 cfm of air, whereas Johnson (1966) uses a 0.46 meter diameter tube with 5 cfm air.

Air is released near the bottom of the tube. Air and water rise in the tube. Hypolimnion water is drawn in from the bottom of the tube and discharged into the epilimnion at the top. This system may be more efficient than a diffuse aerator if small volumes of air are injected.

Johnson (1967) initially used this system to mix a small Washington lake, but later switched to a diffuse aeration system. This was done in conjunction with a program to develop lowland lakes as natural rearing impoundments for coho salmon, Oncorhynchus kisutch. After removing the existing fish population, young salmon are introduced and grow to smolt size. The smolts migrate through the natural outlets to the sea. Hypolimnion oxygen deficits, either through natural causes or artificial fertilization, limits the production of smolts. Prior to aeration, only about 15% of the lake was suitable for salmon due to high epilimnion temperatures and low hypolimnion oxygen concentrations. Johnson indicates a very substantial increase in smolt survival, but a slightly decreased growth rate associated with destratification.

1.3. Mechanical Pumping Techniques of Destratification

Two methods of mechanical destratification are used. The more common technique employs a water pump located on a float, or on shore. A pipe extends into the hypolimnion. Water is drawn from the hypolimnion, passes through the pump and is discharged into the epilimnion where it mixes. Hooper et al. (1953) used this technique to partially mix a small Michigan lake. They displaced about 21% of the lake volume during ten days of pumping. This increased the volume of the epilimnion by about 50%. They observed an 8 to 10-fold increase in the phytoplankton and they considered this equivalent to adding about 43 pounds of fertilizer. Hypolimnion dissolved oxygen increased rapidly with pumping.

Schmitz (1958) induced artificial circulation by mechanical pumping in two small lakes during the summers of 1952 and 1954. He also circulated the water of one small ice covered lake, using a water pump. He compared the efficiency of mechanical pumping with air injection and concluded the latter is considerably more efficient.

Symons et al. (1967) describes another type of mechanical water pump. This device consists of a motor located on a moveable float. A 30.5 cm tube extends from the float into the hypolimnion. A propeller and shaft extend into the tube. The propeller draws water into the bottom of the tube where it is forced to the surface and discharged. He compared the efficiency of this system with air injection and found the latter more efficient.

1.4. Hypolimnion Aerator—Aeration Without Destratification

This new and revolutionary technique for aerating the hypolimnion without affecting stratification holds much promise for fisheries management. It appears to possess most of the beneficial qualities of destratification systems without some of the more deleterious. It has just recently been developed and used successfully (Bernhardt 1967). It is especially beneficial for potential coldwater fishery lakes. These lakes have suitable hypolimnion water temperatures, but lack adequate oxygen concentrations. Although destratification may increase oxygen concentrations to adequate levels, the lake may absorb enough additional thermal energy to raise the coldest water temperature above that tolerated by coldwater fish. Hence a year-round coldwater fishery cannot be established. However, using a hypolimnion aerator, the hypolimnion oxygen concentrations may be increased to accommodate coldwater fishes without increasing hypolimnion temperatures. Thus, a strictly warmwater lake may be transformed into a two-story lake that will sustain both warmwater and coldwater fisheries year-round.

1.4.1. Bernhardt Hypolimnion Aerator

This aerator consists of a large diameter pipe extending from the lake bottom to above the lake surface (Figure 5) . Inlet ports are located near the bottom of the pipe and outlet ports are located below the metalimnion. The top of the pipe is open to the atmosphere. Air is

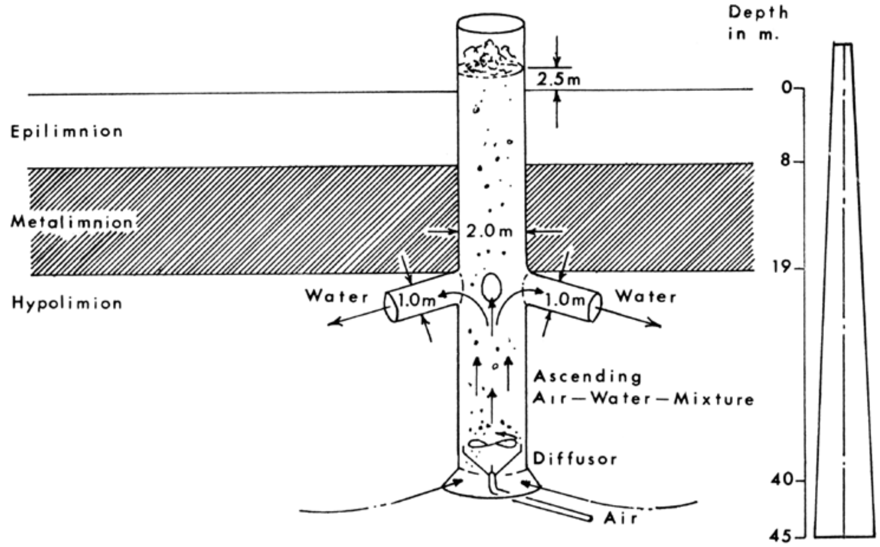

FIGURE 5. Hypolimnion aerator of Bernhardt, (1967). This illustration is reconstructed with his permission.

FIGURE 5. Hypolimnion aerator of Bernhardt, (1967). This illustration is reconstructed with his permission

released and passes through a diffusor near the bottom of the pipe. As air rises in the pipe, water is drawn in through the bottom ports and rises. Oxygen diffuses into the water as it rises. Water and air are carried to the top of the pipe where the air escapes to the atmosphere. The water, however, cannot escape at the surface and sinks to the outlet port level where it flows back into the hypolimnion. Once a hydraulic head is established in the pipe, water may flow directly from the inlet to outlet ports without rising to the top of the pipe. Consequently, hypolimnion water is aerated, but not significantly heated or mixed with epilimnion or metalimnion water. Thermal stratification is not affected by this technique if the outlets are below the metalimnion.

Bernhardt (1967) uses the hypolimnion aerator in Wahnbach reservoir near Siegburg, Federal Republic of Germany. This domestic water supply reservoir is about 37 X 10^6 cubic meters volume with 43.4

meters maximum depth. His main objective is to supply cold, well oxygenated water for domestic and industrial uses. Previously, he used a diffuse air injection system to aerate the water, but this technique increased the water temperatures to undesirable levels.

Bernhardt estimates .167 X 10^6 cubic meters per day are aerated by the hypolimnion aerator using about 117 cfm of compressed air. Contact time within the aerator is about 54 seconds and increases the oxygen concentrations from about 5 mg/l to about 10–11 mg/l.

Oxygen transfer occurs primarily within the bottom 7.5 to 20.0 meters of pipe and decreases rapidly thereafter. This is primarily a function of: hydrostatic pressure, lower oxygen saturation of the water, greater oxygen content of the air bubbles, and bubble size. As water and air rise higher in the pipe, conditions for oxygen transfer become progressively less favorable.

It may be possible to increase the oxygen concentration of the hypolimnion to greater levels than found in the epilimnion or metalimnion. This is possible because of the greater hydrostatic pressures and lower temperatures of the hypolimnion water.

1.4.2. Speece Hypolimnion Aerator

R. E. Speece, presently of New Mexico State University, is developing a different hypolimnion aerator (personal communications). His aerator consists of two vertical pipes that extend from the surface to below the metalimnion (Figure 6) . Water is drawn from the hypolimnion through the pipe on the left. A water pump draws the water up the left pipe and forces it down the right pipe. As water passes through the descending pipe, low pressure air is injected near the surface. The force from the water pump is greater than the positive buoyancy caused by air injection and the air-water mixture descends. As the mixture descends, oxygen diffuses into the water. The descending pipe is bent horizontally after penetrating the metalimnion and extends under the ascending pipe. A slot is cut along the top of the horizontal section and a funnel shaped, bubble collector is situated above the slot. As the air-water mixture passes through the horizontal pipe, the air will rise vertically in the pipe, pass through the slot and be collected in the bubble collector. The aerated water will flow out the end of the pipe and into the hypolimnion. Air in the bubble collector will escape through an opening at its top and pass into the ascending pipe. Thus, the rising air will help aerate and draw hypolimnion water up the ascending pipe. After reaching the top of the ascending pipe, the air escapes to the atmosphere and the water is forced down the descending pipe and injected with air.

Although an outboard motor may be used as the water pump, other water pumps are more efficient.

The principal advantage of Speece's system is his method of air injection. A low pressure compressor, or blower, can be used. This is more economical to operate than a high pressure compressor. In addition, air is re-used. Injected air aerates the descending water as well as the ascending. It also helps lift the ascending water.

Speece's aerator is mounted on floats and can be moved about the lake to insure adequate contact with hypolimnion waters.

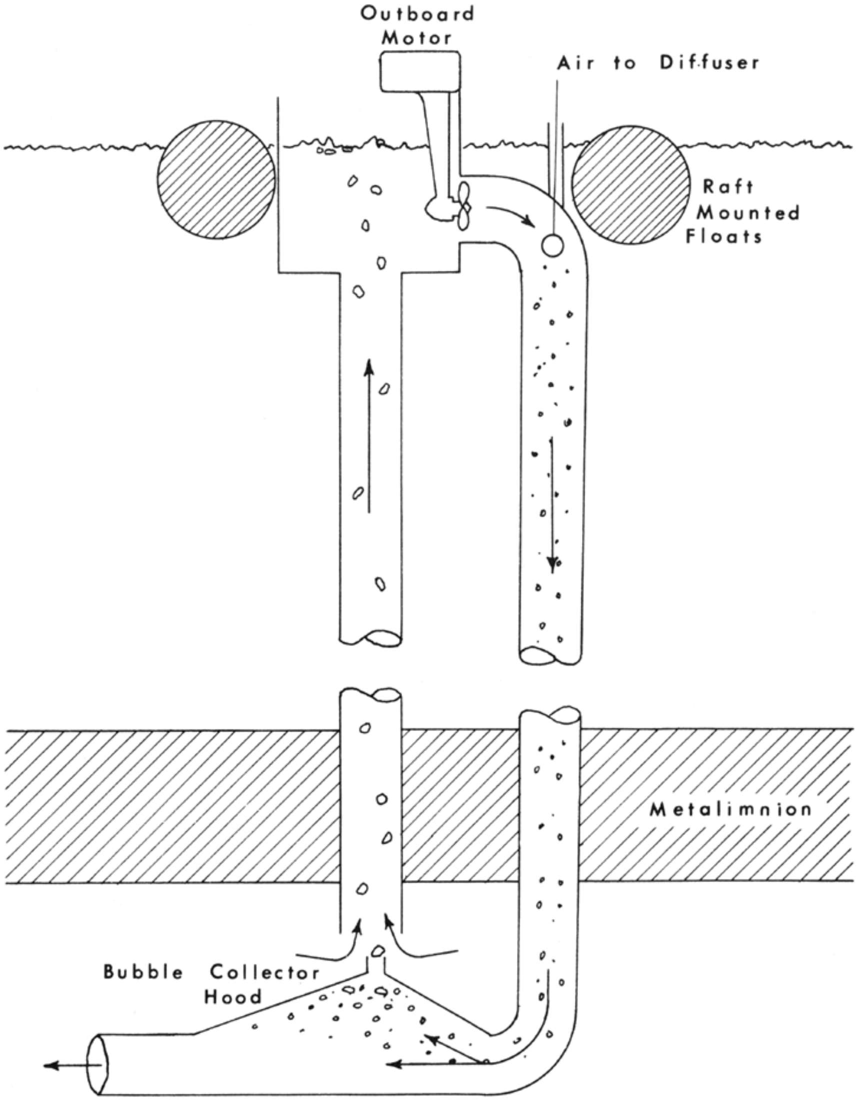

FIGURE 6. A hypolimnion aerator designed by R. E. Speece. This illustration is reconstructed from a sketch provided by R. E. Speece and presented here with his permission.

FIGURE 6. A hypolimnion aerator designed by R. E. Speece. This illustration is reconstructed from a sketch provided by R. E. Speece and presented here with his permission

Although Speece's aerator has not yet been tested, it appears technically sound and may be more efficient and economical than Bernhardt's aerator.

2. COMPRESSOR INSTALLATION AND OPERATION

The diffuse aeration system at El Capitan Reservoir uses a LeRoi 50-S-2 air compressor. A 50-hp, 3-phase, 480-volt electric motor drives the compressor and uses about 31.7 kilowatt-hours per hour at 85% capacity.

Varying amounts of free air are delivered to the lake. The volume released is primarily a function of hydrostatic pressure at the release depth, air friction in the distribution system, compressor speed, and temperature. The compressor is rated at 215 c.f.m. with 125 p.s.i. However, I never observed a release pressure of 125 p.s.i. With about 20 meters of water over the release point, the pressure in the system, as measured at the compressor, is about 50 p.s.i. of this, hydrostatic pressure alone accounts for about 30 p.s.i.

The compressor is located on a permanent concrete slab at about 6 meters elevation above the spillway. Figure 10 illustrates the relative locations of the compressor and sampling stations. A heavy steel mesh cage protects the compressor. The cage isolates the compressor from visitors but does not reduce exposure to the weather. Figures 7 and 8 show the compressor with and without its protective cage.

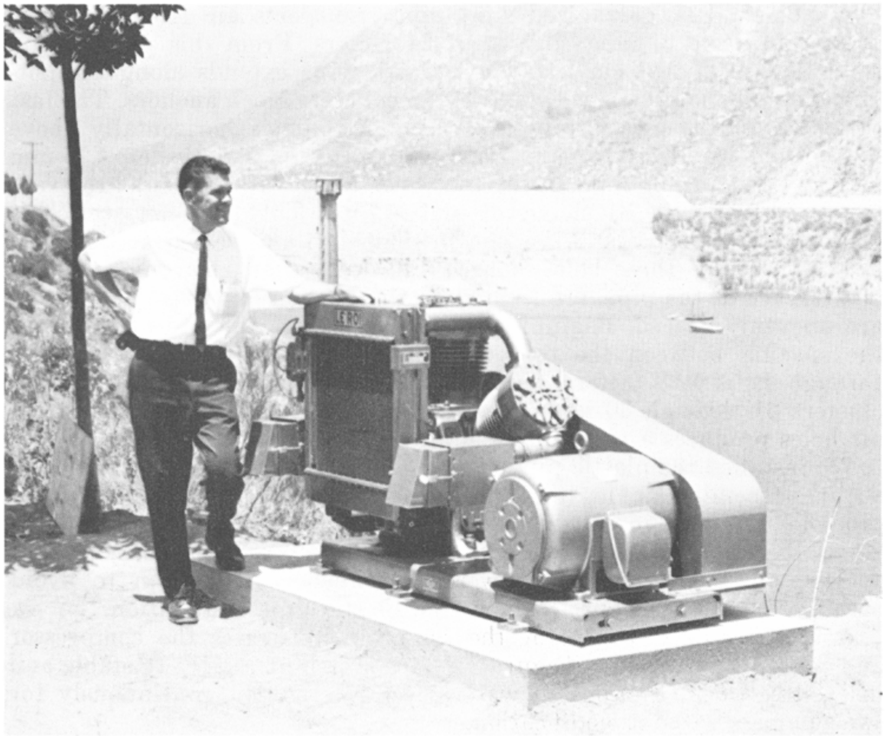

FIGURE 7. Electric compressor at El Capitan without its protective cage and control panel. Photograph by Lee W. Miller.

FIGURE 7. Electric compressor at El Capitan without its protective cage and control panel. Photograph by Lee W. Miller

FIGURE 8. El Capitan compressor in operation. Photograph by the author.

FIGURE 8. El Capitan compressor in operation. Photograph by the author

A 5.08-cm I.D. galvanized steel pipe transports air from the compressor to about a gauge height of 24 meters. From this point, a 92-meter length of 3.96-cm I.D. PVC plastic pipe extends along the bottom. The plastic pipe is weighted by 15 concrete block anchors. The last 31 meters of the plastic pipe are suspended almost horizontally above the bottom by 13 styrofoam floats and adjusted lengths of 4.75-mm polyethylene anchor rope. Thirteen sets of floats with anchors are evenly spaced along the 31 meters of plastic pipe. This 31-meter section is perforated by 90 holes, 3.175 mm in diameter, and sealed at its distal end. Clusters of three holes, spaced 120 degrees apart around the circumference of the pipe, are located on this section of pipe. The clusters are unevenly spaced. Beginning 29.6 meters from the end of the pipe, the spacing between the first six clusters is 1.54 meters, clusters 6 through 12 is 1.23 meters, clusters 12 through 21 is 0.92 meters and, clusters 21 through 30 is 0.62 meters. This non-linear arrangement of air holes produces a more uniform air release.

We installed the plastic pipe by stretching a rope across the reservoir about perpendicular to its longitudinal axis. The unweighted PVC pipe floated next to the rope. We located 13 boats and attendants along the rope. Each attendant attached a styrofoam float, cement anchor, and drop line. We lowered all anchors in unison to avoid breaking the pipe. Figure 9 shows the plastic pipe installation.

A cross-sectional profile of the reservoir illustrates the compressor and distribution system (Figure 3). This system is relatively stable and insensitive to fluctuations in water level. We used it continuously for two summers without modification.

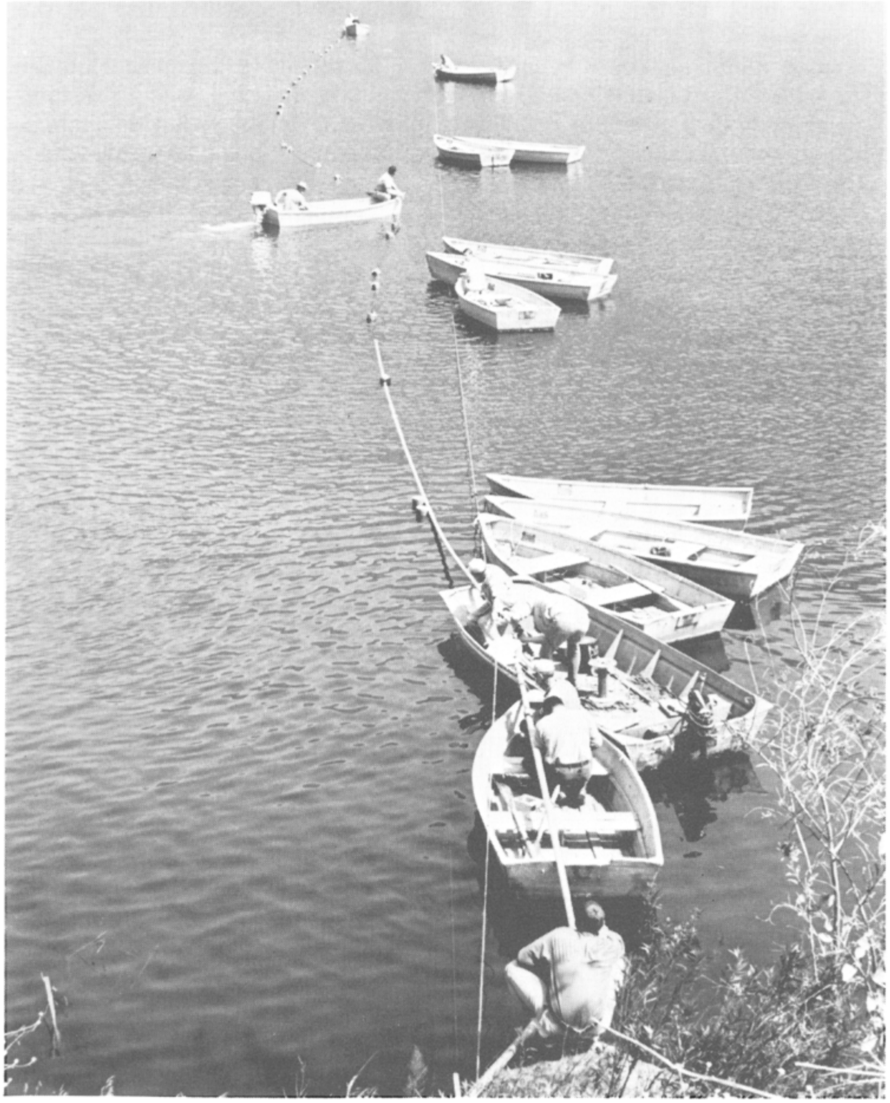

FIGURE 9. Project personnel installing the air distribution system. The iron pipe in the foreground extends to the second boat. The plastic pipe has its styrofoam floats attached, but not its anchors. Photograph by Lee W. Miller.

FIGURE 9. Project personnel installing the air distribution system. The iron pipe in the foreground extends to the second boat. The plastic pipe has its styrofoam floats attached, but not its anchors. Photograph by Lee W. Miller

The aeration system is located in a section of the reservoir that is closed to recreational use. A sturdier distribution system may be necessary to prevent damage from boat anchors where recreational use is permitted.

2.1. Operation

Aeration commenced June 10, 1965 and continued for 263 hours through June 21st. Aeration was discontinued from June 21st through July 1st. Aeration was resumed on July 1st and continued through October 4th, 1965. The June starting date was selected to coincide with the beginning of the pre-aeration study and the availability of the compressor.

During 1966, aeration extended from March 19th through October 17th, without interruption. The objective during 1966 was to accomplish the greatest possible reduction in stratification with this system. When operating, the compressor ran continuously on a 24-hour schedule during both years.

2.2. Costs

The County of San Diego purchased the compressor, control panel, and protective cage. The Utilities Department, City of San Diego and Helix Irrigation District shared the costs of installing the compressor and pipe lines, maintenance, repair, and electrical power. The U.S. Geological Survey provided the perforated PVC pipeline.

Total cost of equipment, materials, and labor to install the system was about $6,010. A breakdown of these expenditures and estimated yearly operating costs are given in Table 1. With a 10-year amortization of $6,010, at 6% interest, the annual cost was $825.

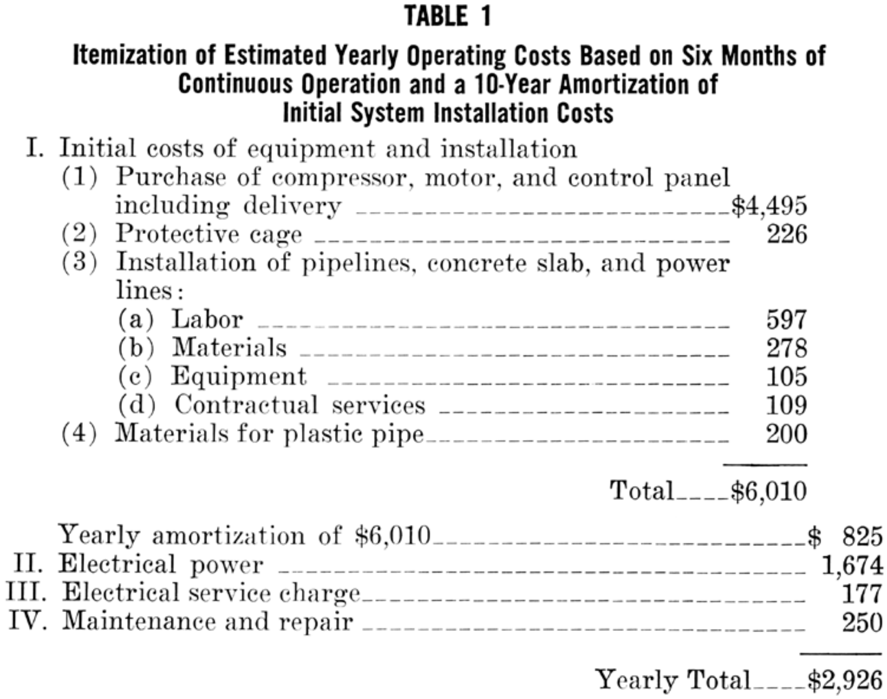

TABLE 1

Itemization of Estimated Yearly Operating Costs Based on Six Months of Continuous Operation and a 10-Year Amortization of Initial System Installation Costs

I. Initial costs of equipment and installation		
(1) Purchase of compressor, motor, and control panel including delivery	$4,495	
(2) Protective cage	226	
(3) Installation of pipelines, concrete slab, and power lines:		
(a) Labor	597	
(b) Materials	278	
(c) Equipment	105	
(d) Contractual services	109	
(4) Materials for plastic pipe	200	
Total	$6,010	
Yearly amortization of $6,010		$ 825
II. Electrical power		1,674
III. Electrical service charge		177
IV. Maintenance and repair		250
Yearly Total		$2,926

TABLE 1

Itemization of Estimated Yearly Operating Costs Based on Six Months of Continuous Operation and a 10-Year Amortization of Initial System Installation Costs

Operation costs included power consumption, electrical service charges, oil and filter changes, and routine repairs and maintenance. For continuous operation over a 30-day period, about 22,824 kilowatt-hours were consumed. Power costs were on a sliding scale and depend on the rate of consumption and size of the motor. For the above conditions, monthly power rates were about $279. The monthly electrical service charge was $29.50 additional. A 10-quart oil change was necessary every 500 hours of operation. Because the compressor was relatively new, few repairs were necessary. A head gasket blew due to inadequate anchoring of the steel pipe. The unanchored steel pipe caused unequal distribution of force on the compressor head. Adequate support of the steel pipe alleviated this problem. Minor adjustments to the drive belts and bolts were made. It is impossible to predict the repair and maintenance costs for a given compressor over a 10-year period, but for our purposes, I estimate $250 per year.

With continuous operation on a 6-month basis each year, total power consumption was about $1,674, and service charges $177. Including the $825 annual amortization of equipment and an estimated $250 for maintenance and repair over a 10-year period, the estimated annual cost of operating this destratification system was about $2,926.

Further considerations of the savings and benefits derived from this estimated annual investment are discussed in the Economics section.

3. METHODS

Chemical analysis of water samples from 0, 7, and 17 meters were made at about monthly intervals from August 1964 through September 1967. The 7 and 17 meter samples were collected with either an 8-liter Van Dorn water sampler, or a 2-liter GM water sampler from location S-1, (Figure 10) . These samples were then placed in amber, 1-liter polyethylene plastic bottles. The surface samples were generally collected by hand dipping the inverted plastic bottle to elbow length and then reversing it. Samples were taken to the City of San Diego's Alvarado Water Filtration Plant, for complete chemical analyses. Samples were generally analysed within a week, but occasionally it took longer.

Complete chemical analysis by the city chemists consisted of 41 chemical determinations. The determination and method used to derive it are shown in Table 2. Unless otherwise specified in Table 2, specific procedures are described in more detail by the American Public Health Association (1965).

Spectrophotometric determinations were made with a Beckman model B spectrophotometer with flame adapter. A Coleman photonephlometer model 17 was used for turbidity. Conductivity measurements were made with a Leeds and Northrup conductivity meter. A Beckman model K autotitrater was used for pH measurements and titration procedures.

Complete chemical analyses prior to August 1964 were either made by the City of San Diego chemists, as described, or by the Wilson Laboratory of Los Angeles. The Wilson Laboratory used the prevalent standard techniques recognized by the American Public Health Assn., but favored titrametric rather than photometric procedures. Specific methods used by the Wilson Laboratory are not available. Prior to the early 1950's, the Wilson Laboratory made the determinations. However, after this period the City of San Diego made all determinations. City of San Diego personnel made all collections prior to August 1964 with a specially designed sampler. The sampler consisted of a

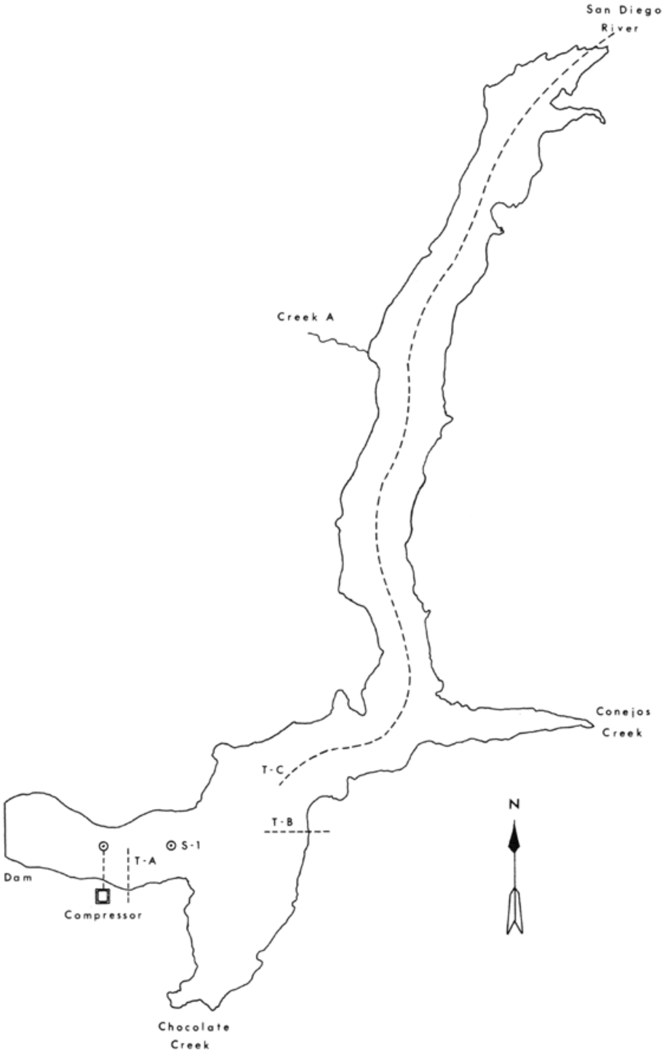

FIGURE 10. El Capitan Reservoir including sampling locations, compressor site and major tributaries. Sample site S-1 is our principal sampling location.

FIGURE 10. El Capitan Reservoir including sampling locations, compressor site and major tributaries. Sample site S-1 is our principal sampling location

TABLE 2

Chemical Analysis Performed by the City of San Diego and Method of Determination

Name of Analysis	Method of Determination
The following constituents are in mg/liter	
Silica (SiO_2)	Colorimetric molybdosilicate (410 mμ)
Iron (Fe)	Phenanthroline (510 mμ)
Aluminum (Al)	Aluminonon buffer (525 mμ)
Manganese (Mn)	Periodate (525 mμ)
Calcium (Ca)	EDTA with calcein indicator
Magnesium (Mg)	Total hardness less calcium concentration
Sodium (Na)	Flame photometric (589 mμ)
Potassium (K)	Flame photometric (768 mμ)
Carbon Dioxide (CO_2)	American Water Works Association (1950)
Carbonate (CO_3)	Phenolphthalein alkalinity × 1.2
Bicarbonate (HCO_3)	(Methyl orange alkalinity − 2 × phenolphthalein alkalinity) × 1.22
Total Alkalinity as $CaCO_3$ (TA)	Methyl orange alkalinity with pH end point of 4.4
Sulfate (SO_4)	Turbimetric method C (420 mμ)
Chloride (Cl)	Amperometric. Titration with 0.0141 N silver nitrate. 2.85 mv end-point
Nitrate (NO_3)	Brucine method B (410 mμ)
Fluoride (F)	Alizarin photometric (550 mμ)
Total Hardness (TH)	EDTA, H-3 indicator, Sol. No. 277 from Nalco Chem. Co.
Carbonate Hardness (CH) *as* $CaCO_3$	Methyl orange alkalinity (same as TA)
Non-Carbonate Hardness as $CaCO_3$ (NCH)	TH—CH
Total Residue (TR)	Method A
Turbidity (Tur.)	Standard curves with photonephlometer
Total Phosphate (TP)	Orthophosphates plus polyphosphates
Orthophosphate (OP)	Method B, stannous chloride (690 mμ)
Polyphosphate (PP)	Method C, stannous chloride (690 mμ)
The following are not in mg per liter	
Conductivity (Cond.)	Conductivity meter (micromhos)
pH	pH meter
pHs	From total residue, methyl orange and calcium hardness nomographs. Used for analyses L.I. and R.I.
Langelier Index (L.I.)	pH less pHs
Ryznar Index (R.I.)	2 pHs less pH
The following are in milligram equivalents	
	$\text{milligram equivalent} = \frac{\text{Conc. in mg/liter} \times \text{valence}}{\text{Atomic weight}}$
Calcium (rCa)	
Magnesium (rMg)	
Sodium (rNa)	
Potassium (rK)	
Carbonate (rCO_3)	
Bicarbonate ($rHCO_3$)	
Sulphate (rSO_4)	
Chloride (rCl)	
Nitrate (rNO_3)	
Fluoride (rF)	
Concentration Value (CV)	Sum of the preceding milligram equivalent values
The following is derived by using the milligram equivalent concentrations	
Percent Sodium (%Na)	$\frac{Na + K \times 100}{Na + K + Ca + Mg}$

TABLE 2
Chemical Analysis Performed by the City of San Diego and Method of Determination

metal tube of about 10 cm diameter and 40 cm length. Each end of the tube contained hinged valves that flopped open when the device was lowered. The sampler was lowered to the desired depth and jerked rapidly up and down several times before retrieval. Samples were generally taken from selected depths, but apparently composite samples from several depths were sometimes taken.

In addition to the complete chemical analyses made by the City, we made several chemical determinations at the reservoir from June 1964 through September 1965. These analyses include oxygen, pH, and alkalinity. Prior to May 1, 1965, oxygen determinations at each depth were made using the Alsterberg (ozide) modification of the Winkler Method. Thereafter, oxygen determinations were made using a Precision galvanic cell oxygen analyser and the Alsterberg method for standardization. Prior to July 1965, pH was measured using a Beckman Model G pH meter and alkalinity was estimated by methyl purple titration. Thereafter, both pH and alkalinity were measured with a Beckman Model N pH meter. A pH end-point of 4.4 was used for alkalinity. Oxygen, pH, and alkalinity samples were collected with one of the water samplers mentioned and generally from each 2-meter depth interval at location S-1, (Figure 10). Samples were either analysed on the lake or taken immediately to the shore laboratory for analysis.

Temperature-depth measurements prior to 1964 were made by City of San Diego personnel, using an unspecified resistance thermometer. From May 1964 through May 1, 1965, a Bright Radio Laboratories resistance thermometer was used. Thereafter, temperatures were taken with the Precision D. O. analyser. Temperature-depth measurements were occasionally made using a bathythermograph. We used a grid-viewer to read the temperature profile etch. The etch was made on a gold plated glass slide. The pre-1964 temperature measurements were generally made in the center of the reservoir near the dam. Measurements during 1964 and after, generally were made at location S-1, (Figure 10).

Daily surface water temperatures, minimum-maximum air temperature, rainfall and reservoir gauge height measurements were taken since 1935. Surface water temperatures were generally measured twice daily using a glass thermometer. One measurement was made at about 0700 hours near the dam, and another at about 1500 hours in the Chocolate Creek arm. Air temperatures were measured with a minimum-maximum glass thermometer. Gauge height and rainfall were measured to the nearest 0.25 mm. Measurements other than water temperature were generally made each morning at about 0700 hours at a field weather station near the base of the dam.

A 20-cm secchi disc (Welch 1948) was used for turbidity measurements.

Area-capacity values used in this report are based on surveys made in 1927 and 1956. Volume estimates for analyses involving chemical determinations prior to 1964 are based on extrapolated values between the 1927 and 1956 area-capacity values. Volume estimates used for other analyses are based on the 1956 table values.

Stability values in this report were calculated according to McEwen (1941), except that the graphical estimate described in his paper is estimated by fitting a linear regression. Regression lines are fitted to each pair of ascending and descending values. The regression line with a data point nearest the isothermal center of gravity is selected for estimating the desired value. A computer program was written to calculate stability values, heat contents, and temperature ranges.

Heat content is calculated by dividing the lake into horizontal strata. The volume of each stratum is multiplied by its average temperature. The sum of these products yields the total heat content. This sum divided by total surface area yields heat per unit area; and divided by total volume yields average temperature.

Sediment size was determined by the California Department of Water Resources laboratory using procedures described by the California Department of Water Resources (1968). They used the U.S. sieve series to estimate sediment sizes 200 microns and greater. Hydrometer tests were used to estimate sizes of 5 microns and less. Samples were collected from three transects using an Ekman dredge. Figure 10 shows the sample transects designated T-A, T-B and T-C. A sediment sample was collected from each 2-meter depth interval along each transect. Excess water was decanted and the sediment frozen for shipment to the Water Resources Laboratory in Sacramento.

Sediment percent solids, chemical oxygen demand and percent nitrogen analyses were made by the City of San Diego's Pt. Loma Sewage laboratory. They used procedures described by the American Public Health Association (1965). Samples were collected with a vertical core sampler similar to that described by Welch (1948). About the upper 5 cm of core sample was collected and taken to the laboratory. Samples were collected near the air release point (Figure 10) at selected depths.

We used a special barge to collect most of our samples. The barge was constructed of three 3.96-meter wooden boats covered by a 6.10- x 3.05-meter plywood deck, (Figure 11) . The boats were 1.22 meters apart. Trap doors permitted lowering of samplers between the boats. A 40-hp outboard with forward controls powered the barge. The craft was very stable and highly maneuverable.

Spearman's rank correlation coefficient (rho) is computed as described by Steel and Torrie (1960). A *t*-value conversion is used to calculate significance of the correlation coefficient. Isotherms, isopleths, scattergrams, and line plots were constructed with programs designed for an IBM 1620 computer with a CalComp *x-y* plotter. One scattergram program using a 407 lister is described (Fast, 1967), but the others are not. Stability, heat content, average temperature, and many other calculations were made using a computer.

All times presented in this report are in Pacific Standard Time.

FIGURE 11. Experimental barge especially designed for use at El Capitan. Photograph by Martha L. Fast.

FIGURE 11. Experimental barge especially designed for use at El Capitan. Photograph by Martha L. Fast

4. EL CAPITAN RESERVOIR DESCRIPTION AND HISTORY

El Capitan Dam impounds the intermittently flowing San Diego River. The reservoir is located about 40 kilometers east of San Diego within the Upper Sonoran life zone, (Beland, 1960). Characteristically, the surrounding terrain is steep-sided mountains of decomposed granite covered with chapparal (Figures [12] and [13]). Dam construction began during 1932 and was completed during 1934 at a cost of $5.8 million. By 1938 the reservoir filled to capacity and overflowed during 1938, 1939 and 1941. The dam is of semi-hydraulic rock embankment, with an impervious clay core. It rises 66.7 meters above the streambed and extends 7.7 meters below. The crest length is 360 meters and the foundation width at streambed is 194 meters. The crest elevation is 236.5 meters above mean sea level and the spillway is 230.5 meters above MSL. Water is drawn, or enters, through an independent wet tower with six 76-cm saucer valves for level selection. Fowler (1953) presents a more detailed physical description of this reservoir, and an interesting history of the dams and water supply system of western San Diego County.

FIGURE 12. View of El Capitan Reservoir and dam looking westward from an adjacent mountain. This view looks down the San Diego River bed. Photograph by the author.

FIGURE 12. View of El Capitan Reservoir and dam looking westward from an adjacent mountain. This view looks down the San Diego River bed. Photograph by the author

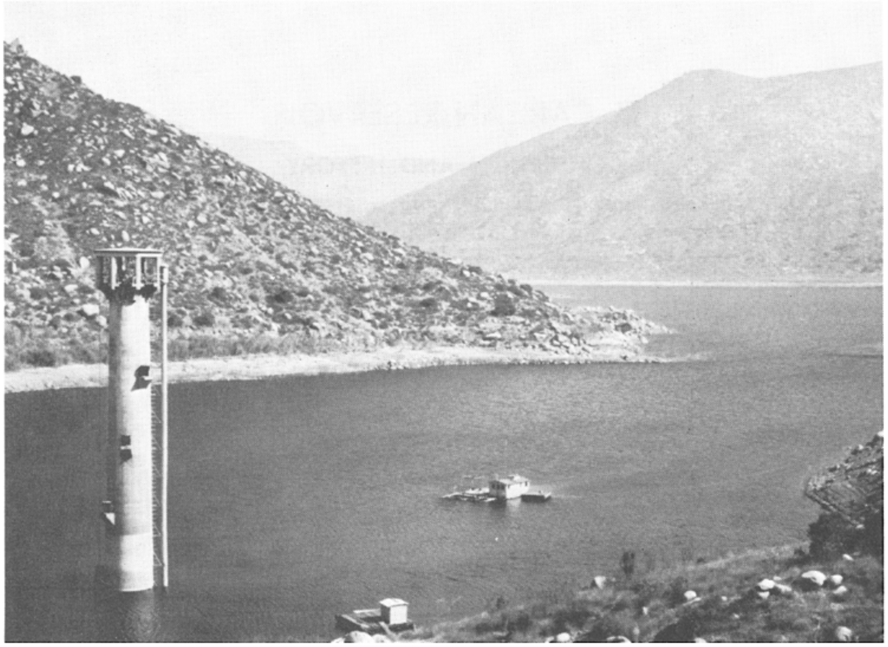

FIGURE 13. View of El Capitan Reservoir and control tower taken from the dam. Photograph by the author.

FIGURE 13. View of El Capitan Reservoir and control tower taken from the dam. Photograph by the author

The basin topography illustrates El Capitan's steep sides and reduced littoral area (Figure 14). Roelofs (1944) indicates a high slope not only limits the dimension of the littoral area but also reduces production of rooted aquatic plants. Rooted aquatics are abundant only when the water level is stable. This condition seldom occurs in El Capitan. Consequently, it appears that most of the primary production occurs in the phytoplankton.

These primary producers are numerically abundant in this reservoir. Their populations are characterized by species indicative of highly productive communities. Bluegreen algae, diatoms, and green algae predominate. Over 150 genera were recorded from 1960 through 1966, but relatively few of these commonly occurred in the counts. A more detailed description of the phytoplankton will be included in subsequent reports.

Sedimentation of the basin is relatively slight. Estimated total pre-impoundment capacity was 1.44×10^8 cubic meters. By 1956 this volume was estimated at 1.39×10^8 cubic meters, and represents a 3.5% reduction in total capacity during the ensuing 22 years.

Although total volume is diminishing slowly, the form of the depth-volume curve shows marked changes (Figure 15). Considerable quantities of sediment are transported from higher to lower levels of the reservoir by wave cut and fill erosion. This process is expedited by fluctuating water levels and loose composition of the decomposed granite substrata. Although cut and fill erosion does not reduce the total capacity of the reservoir, it does result in a reduced bottom slope and reduced maximum depth. Both these situations should increase lake fertility.

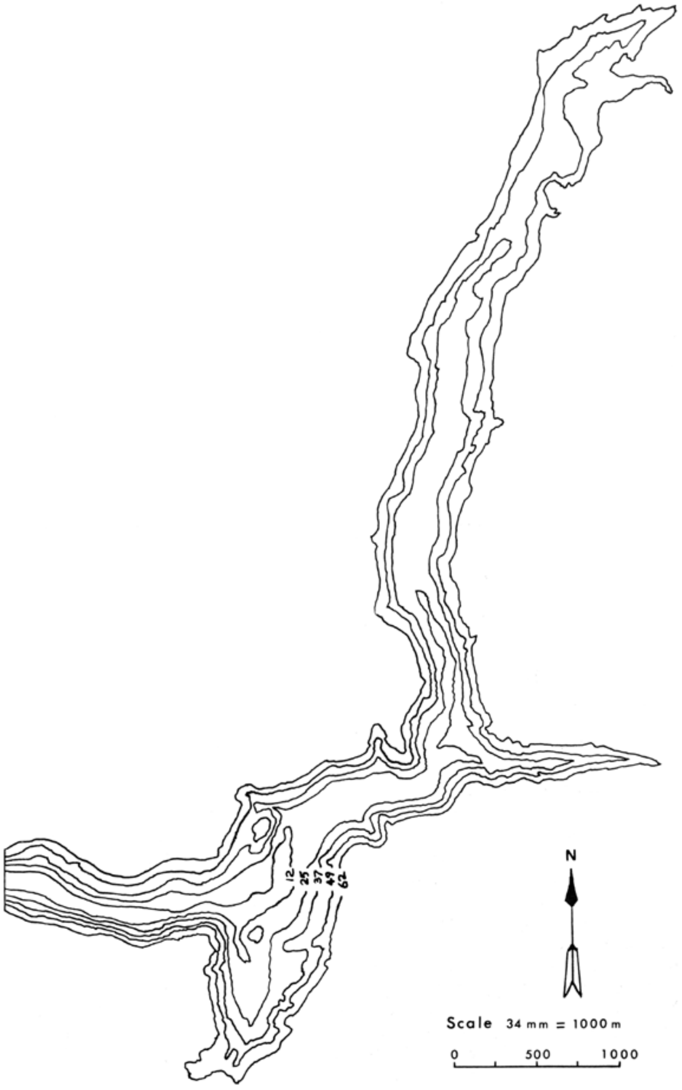

FIGURE 14. **Topographic map of El Capitan Reservoir's basin. Depth contours are in meters. This map is based on a pre-impoundment survey of the basin.**

FIGURE 14. Topographic map of El Capitan Reservoir's basin. Depth contours are in meters. This map is based on a pre-impoundment survey of the basin

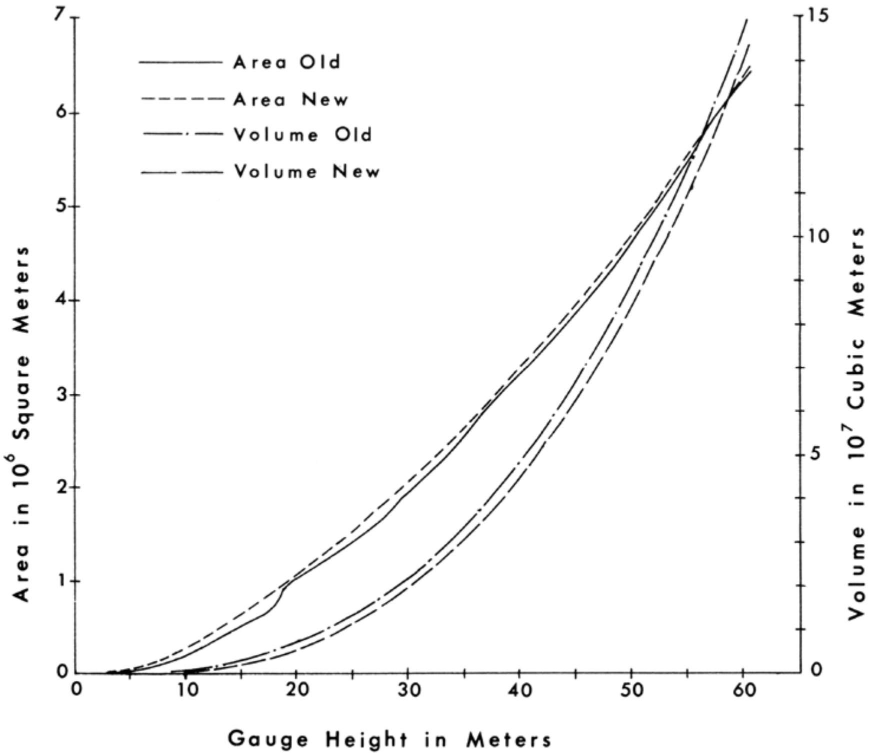

FIGURE 15. Area-Capacity curves constructed from 1927 and 1956 surveys of the lake basin.

FIGURE 15. Area-Capacity curves constructed from 1927 and 1956 surveys of the lake basin

Beland (1960) and Fast (1966a) discuss the fisheries management history of this reservoir. Although water was impounded in quantity since 1935, the reservoir was not open to fishing until 1955. The fishery consists essentially of the warmwater species: largemouth basses (Micropterus salmoides salmoides, M. salmoides floridanus, and intergrades), bluegill (Lepomis macrochirus) , green sunfish (L. cyanellus) , brown bullheads (Ictalurus nebulosus) , and channel catfish (I. punctatus) . Walleye (Stizostedion vitreum vitreum) were introduced during 1962–63. Walleye show excellent growth rates (Miller, 1967) but do not enter the creel in significant numbers. White crappie (Pomoxis annularis) are periodically abundant but have declined since 1961.

More than 300,000 largemouth bass were planted between 1956 and 1963 to correct an "out of balance" bluegill-bass fishery. The beneficial consequences of this action are dubious (Fast, 1966).

The basic limnology of El Capitan is similar to other comparable San Diego County reservoirs (Rawstron, 1964). It is a eutrophic, warm monomictic reservoir (Hutchinson, 1967) and may be termed an alkali lake, according to Moyle's (1949) classification. According to Welch's classification (1952), it is a second degree tropical lake.

Characteristically, the lake experiences one annual period of stagnation. Thermal stratification usually begins during March or April and disappears during November or December (Figure 16) . The thermocline depth appears to be influenced only slightly by the total water volume.

Surface water temperatures follow an annual cycle, reaching a maximum during the last week of July and the first week of August, and a minimum during January (Figure 17) . The yearly range in average median daily temperature is from about 11°C to 25°C. However, surface temperatures as low as 1.1°C and as high as 28.3°C are recorded.

Air temperatures follow a similar cycle but exhibit much greater daily fluctuation (Figure 18) . The range in average median temperatures is also about 11°C to 25°C, with recorded extremes of minus 7.8°C and 45.5°C.

Average weekly median air temperatures and surface water temperature appear to be very highly correlated (Figure 19) . Based on 521 observations, a correlation coefficient of .906 and a least squares line of $y = -14.86 + .92\,x$ was calculated. Where y = average median weekly surface water temperature in °C and x = average median weekly air temperatures in °C. The same least square line for degrees Fahrenheit is: $y = 5.24 + .92\,x$.

El Capitan's watershed is about 51,800 hectares. This includes upstream Cuyamaca Reservoir's watershed. Only runoff water was impounded prior to 1958. However, since then imported Colorado River water is also periodically stored in the lake (Table 3). The two sources

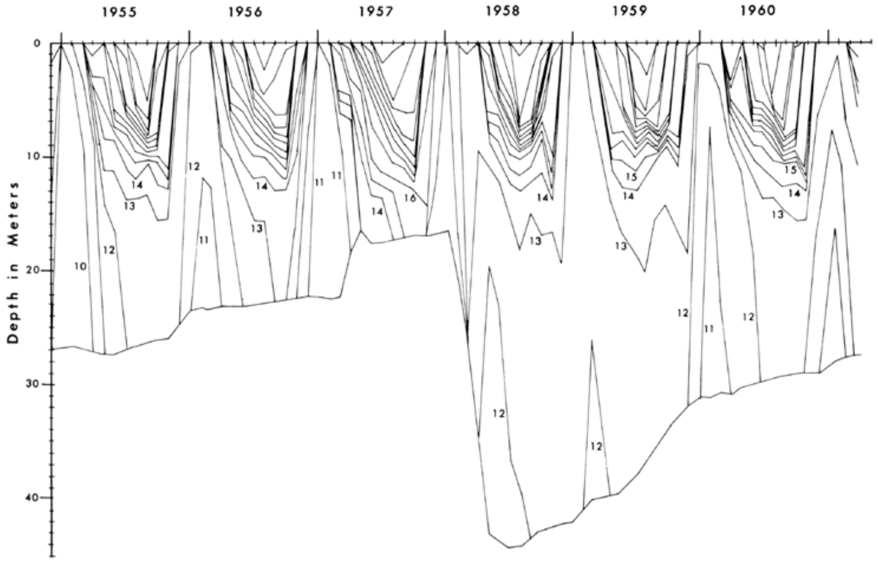

FIGURE 16. El Capitan isotherms during 1954 through 1961. Isotherms are in degrees centigrade. The reservoir stratified normally during this period.

FIGURE 16. El Capitan isotherms during 1954 through 1961. Isotherms are in degrees centigrade. The reservoir stratified normally during this period

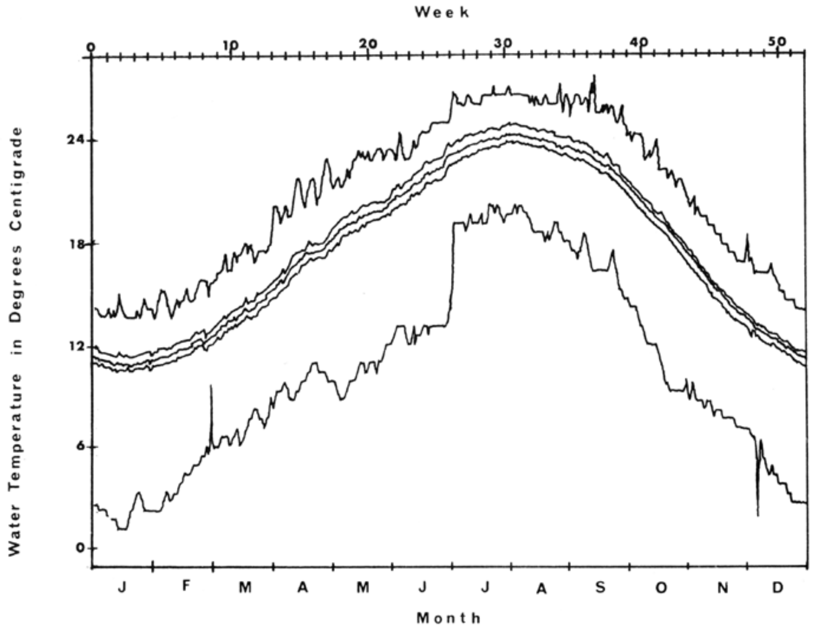

FIGURE 17. Average and extreme surface water temperatures for each day of the year based on more than 30 years of daily observations (1935–1966). From top to bottom the water temperature curves are: absolute maximum, average maximum, average median, average minimum and absolute minimum.

FIGURE 17. Average and extreme surface water temperatures for each day of the year based on more than 30 years of daily observations (1935–1966). From top to bottom the water temperature curves are: absolute maximum, average maximum, average median, average minimum and absolute minimum

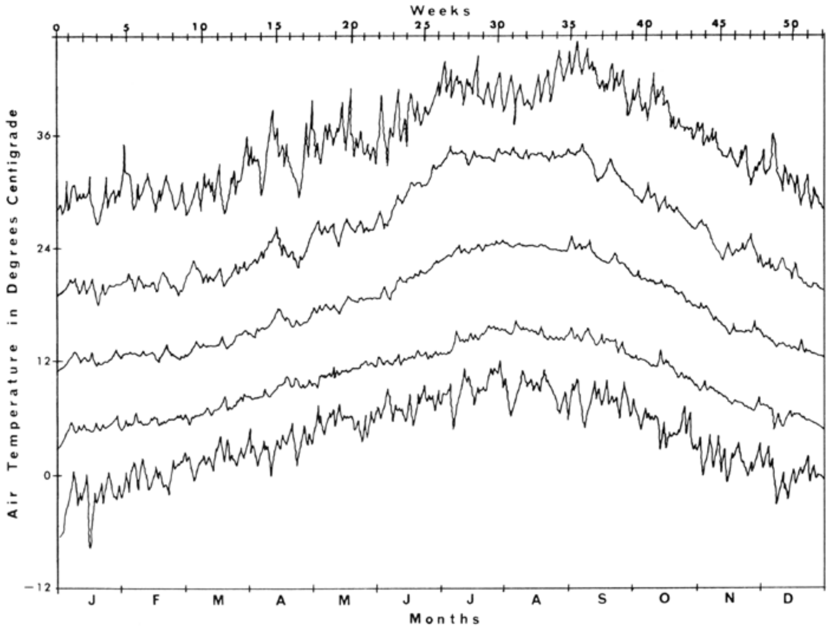

FIGURE 18. Average and extreme air temperatures for each day of the year, based on more than 30 years of daily observations (1935–1966). From top to bottom the air temperature curves are: absolute maximum, average maximum, average median, average minimum and absolute minimum.

FIGURE 18. Average and extreme air temperatures for each day of the year, based on more than 30 years of daily observations (1935–1966). From top to bottom the air temperature curves are: absolute maximum, average maximum, average median, average minimum and absolute minimum

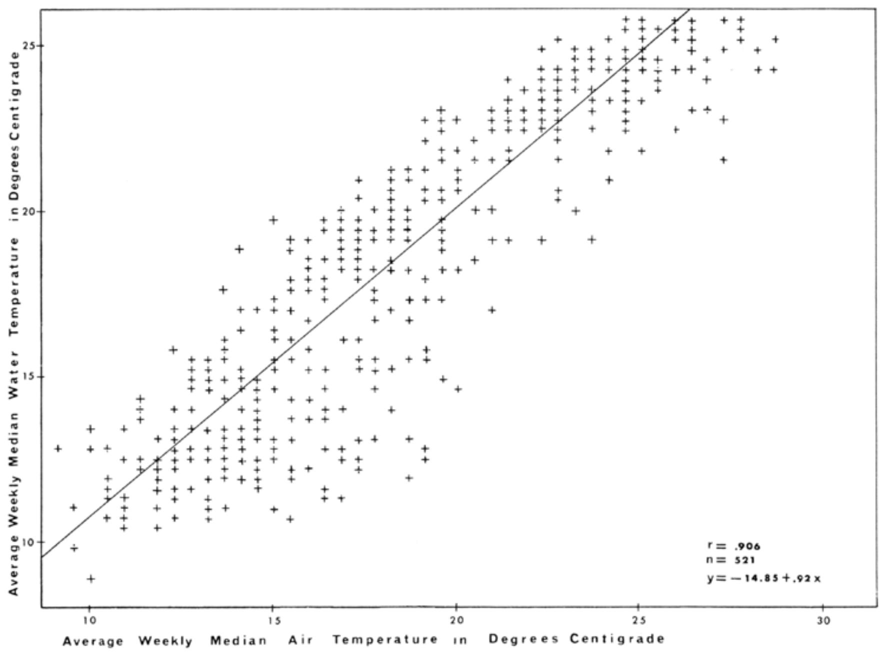

FIGURE 19. Scattergram plot and least squares lines of average median weekly surface water and air temperatures.

FIGURE 19. Scattergram plot and least squares lines of average median weekly surface water and air temperatures

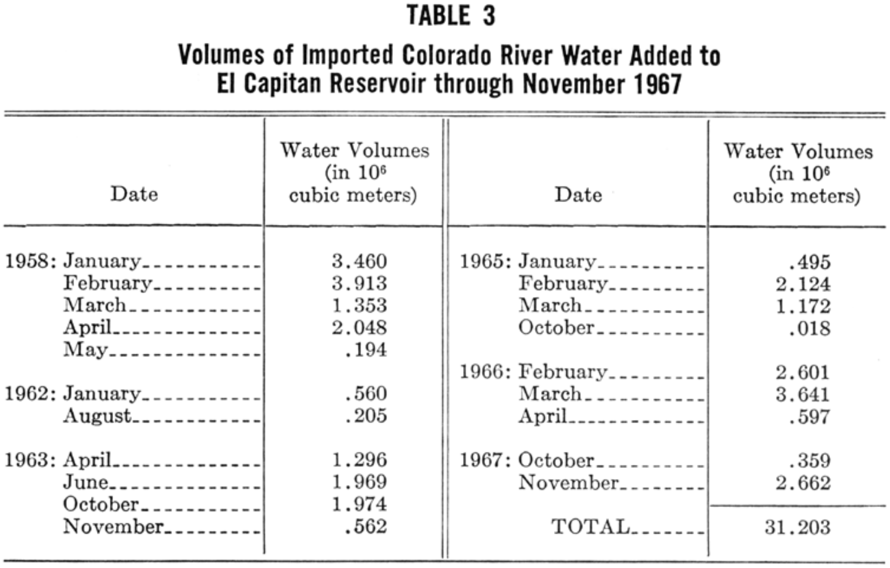

TABLE 3

Volumes of Imported Colorado River Water Added to El Capitan Reservoir through November 1967

Date	Water Volumes (in 10^6 cubic meters)	Date	Water Volumes (in 10^6 cubic meters)
1958: January	3.460	1965: January	.495
February	3.913	February	2.124
March	1.353	March	1.172
April	2.048	October	.018
May	.194		
		1966: February	2.601
1962: January	.560	March	3.641
August	.205	April	.597
1963: April	1.296	1967: October	.359
June	1.969	November	2.662
October	1.974		
November	.562	TOTAL	31.203

TABLE 3

Volumes of Imported Colorado River Water Added to El Capitan Reservoir through November 1967

of El Capitan's imported water are Colorado River water via the San Diego aqueducts, and water from San Vicente Reservoir. The ionic concentrations of these sources vary considerably; as do the relative proportions of these ions. Table 4 illustrates the ionic concentrations of: El Capitan Reservoir surface water, Colorado River water in San

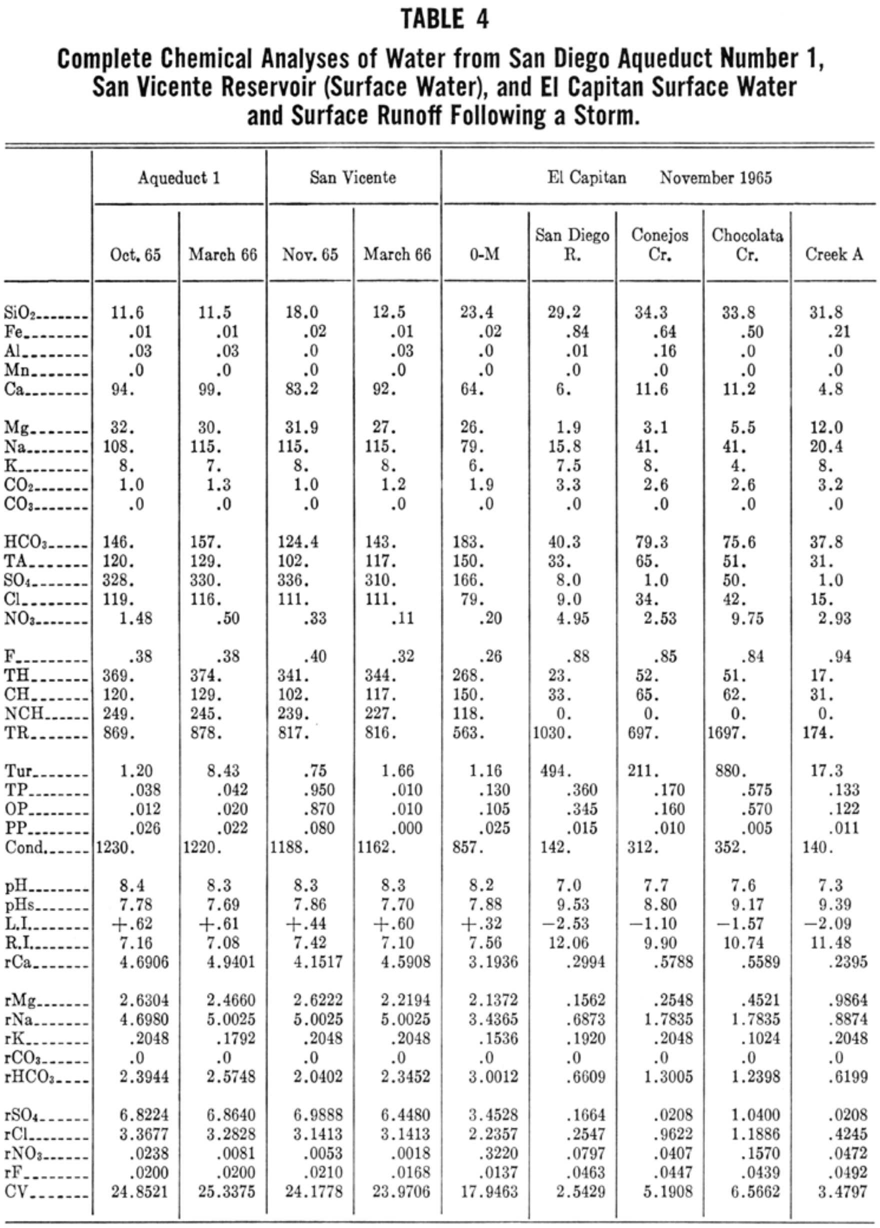

TABLE 4

Complete Chemical Analyses of Water from San Diego Aqueduct Number 1, San Vicente Reservoir (Surface Water), and El Capitan Surface Water and Surface Runoff Following a Storm.

	Aqueduct 1		San Vicente		El Capitan November 1965				
	Oct. 65	March 66	Nov. 65	March 66	0-M	San Diego R.	Conejos Cr.	Chocolata Cr.	Creek A
SiO_2	11.6	11.5	18.0	12.5	23.4	29.2	34.3	33.8	31.8
Fe	.01	.01	.02	.01	.02	.84	.64	.50	.21
Al	.03	.03	.0	.03	.0	.01	.16	.0	.0
Mn	.0	.0	.0	.0	.0	.0	.0	.0	.0
Ca	94.	99.	83.2	92.	64.	6.	11.6	11.2	4.8
Mg	32.	30.	31.9	27.	26.	1.9	3.1	5.5	12.0
Na	108.	115.	115.	115.	79.	15.8	41.	41.	20.4
K	8.	7.	8.	8.	6.	7.5	8.	4.	8.
CO_2	1.0	1.3	1.0	1.2	1.9	3.3	2.6	2.6	3.2
CO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
HCO_3	146.	157.	124.4	143.	183.	40.3	79.3	75.6	37.8
TA	120.	129.	102.	117.	150.	33.	65.	51.	31.
SO_4	328.	330.	336.	310.	166.	8.0	1.0	50.	1.0
Cl	119.	116.	111.	111.	79.	9.0	34.	42.	15.
NO_3	1.48	.50	.33	.11	.20	4.95	2.53	9.75	2.93
F	.38	.38	.40	.32	.26	.88	.85	.84	.94
TH	369.	374.	341.	344.	268.	23.	52.	51.	17.
CH	120.	129.	102.	117.	150.	33.	65.	62.	31.
NCH	249.	245.	239.	227.	118.	0.	0.	0.	0.
TR	869.	878.	817.	816.	563.	1030.	697.	1697.	174.
Tur	1.20	8.43	.75	1.66	1.16	494.	211.	880.	17.3
TP	.038	.042	.950	.010	.130	.360	.170	.575	.133
OP	.012	.020	.870	.010	.105	.345	.160	.570	.122
PP	.026	.022	.080	.000	.025	.015	.010	.005	.011
Cond.	1230.	1220.	1188.	1162.	857.	142.	312.	352.	140.
pH	8.4	8.3	8.3	8.3	8.2	7.0	7.7	7.6	7.3
pHs	7.78	7.69	7.86	7.70	7.88	9.53	8.80	9.17	9.39
L.I.	+.62	+.61	+.44	+.60	+.32	−2.53	−1.10	−1.57	−2.09
R.I.	7.16	7.08	7.42	7.10	7.56	12.06	9.90	10.74	11.48
rCa	4.6906	4.9401	4.1517	4.5908	3.1936	.2994	.5788	.5589	.2395
rMg	2.6304	2.4660	2.6222	2.2194	2.1372	.1562	.2548	.4521	.9864
rNa	4.6980	5.0025	5.0025	5.0025	3.4365	.6873	1.7835	1.7835	.8874
rK	.2048	.1792	.2048	.2048	.1536	.1920	.2048	.1024	.2048
rCO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
$rHCO_3$	2.3944	2.5748	2.0402	2.3452	3.0012	.6609	1.3005	1.2398	.6199
rSO_4	6.8224	6.8640	6.9888	6.4480	3.4528	.1664	.0208	1.0400	.0208
rCl	3.3677	3.2828	3.1413	3.1413	2.2357	.2547	.9622	1.1886	.4245
rNO_3	.0238	.0081	.0053	.0018	.3220	.0797	.0407	.1570	.0472
rF	.0200	.0200	.0210	.0168	.0137	.0463	.0447	.0439	.0492
CV	24.8521	25.3375	24.1778	23.9706	17.9463	2.5429	5.1908	6.5662	3.4797

TABLE 4

Complete Chemical Analyses of Water from San Diego Aqueduct Number 1, San Vicente Reservoir (Surface Water), and El Capitan Surface Water and Surface Runoff Following a Storm

Diego aqueduct number one, San Vicente surface water, and El Capitan runoff following heavy storms. El Capitan sample locations are illustrated in Figure 10. The zero meter (0-M) El Capitan sample is from Station 1. Table 4 illustrates the disparity in ionic concentrations from these sources. It should be noted that the concentrations of each source may also vary considerably depending on several factors; such as time of year, amount of rainfall, reservoir volumes, and depth of withdrawal from the reservoirs.

Rainfall and runoff follow an annual cycle. Figure 20 illustrates this pattern based on daily observations from 1935 through 1966. Most of the yearly rainfall occurs during December through March. Little or no rain occurs during May through October. Hence, the reservoir receives the bulk of its runoff during periods of isothermy, i.e., before strong stratification develops.

Figure 21 illustrates the moving means of monthly rainfall based on 3-month averages and the yearly total rainfall for 1935 through 1966. Although the monthly averages illustrate the monthly cycle, the yearly totals do not appear cyclic. The yearly totals coincide somewhat with fluctuations in reservoir water volume.

Large quantities of imported sediments are received periodically as a consequence of irregular, torrential runoff. Examination of some of the sediments illustrates this condition. Strata of light colored clay are interspersed with black bands of apparent organic origin. The clay strata vary greatly in thickness and appear to represent periods of high runoff, whereas the black strata apparently represent periods of low runoff. Further analyses of this stratigraphy were not made.

Dramatic changes in ionic concentrations and water volumes occurred. Some of these changes are illustrated in Figures 22 through 24. Many of the chemical constituent trends are strongly correlated with water volume trends. Table 5 illustrates the Spearman rank correlation coefficients of water volume vs. ionic concentrations.

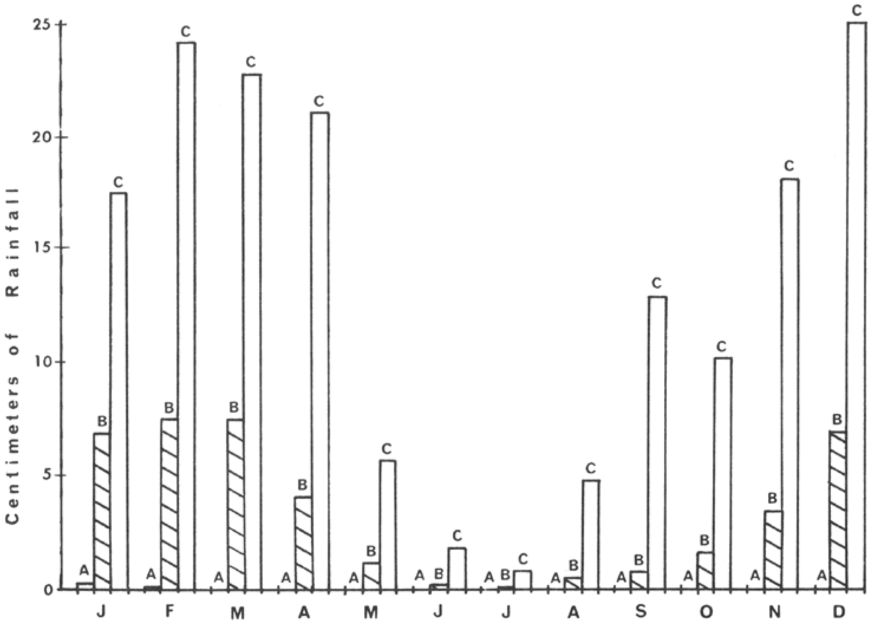

FIGURE 20. Monthly pattern of rainfall based on more than 30 years of daily observations. Absolute minimum (A), absolute maximum (C) and average rainfall totals (B) for each month are shown.

FIGURE 20. Monthly pattern of rainfall based on more than 30 years of daily observations. Absolute minimum (A), absolute maximum (C) and average rainfall totals (B) for each month are shown

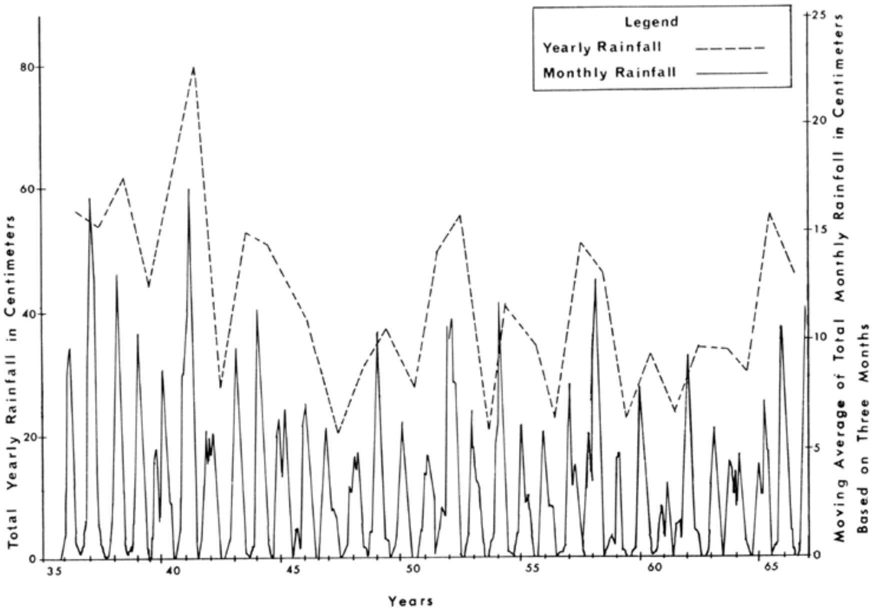

FIGURE 21. Moving means of monthly rainfall totals and total yearly rainfall from 1935 through 1967. Monthly moving means are based on three month averages.

FIGURE 21. Moving means of monthly rainfall totals and total yearly rainfall from 1935 through 1967. Monthly moving means are based on three month averages

Not apparent from either the correlation coefficient or the line graphs is the nature of the relationship between the water volume and ionic concentrations. Figures 25 through 27 illustrate scattergram plots of certain ions and water volumes. An exponential relationship is suggested by these plots, but several such transformations of the data do not add significantly to the correlation coefficient. This does not mean an exponential relationship does not exist, since it may be obscured by other concomitant processes. If ionic concentrations are allowed to approach comparable levels of equilibrium at each observed water volume, a more definitive relationship between ionic concentrations and water volume may be evident. However, water volumes often fluctuate rapidly. For any given set of chemical analyses, the water volume may have been stable for a long period, or in the process of rapid change. The degree of equilibrium for these two conditions may be quite different. These conditions, in addition to limitations of the chemical analyses, could be responsible for most of the variability in chemical concentration at a given water volume. This variation appears to be greatest at reduced water volumes. Nevertheless, a remarkably strong correlation between certain ions and water volume is evident.

In general, increased water volume results in decreased ionic concentrations. This reduction could be explained by a simple dilution effect since influent water generally has lower ionic concentrations (Table 4). However, the reasons for an increased ionic content with decreased volume are not as evident. This is especially true since reduced volumes are primarily a function of water withdrawals, rather

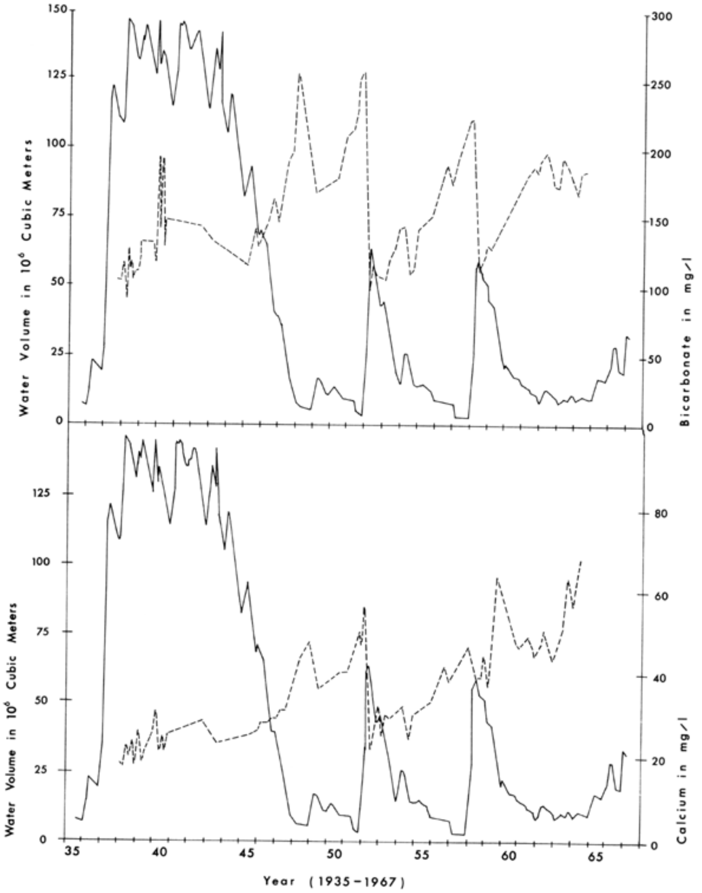

FIGURE 22. Line plots of El Capitan calcium and bicarbonate concentrations and water volumes. Water volume is the solid line.

FIGURE 22. Line plots of El Capitan calcium and bicarbonate concentrations and water volumes. Water volume is the solid line

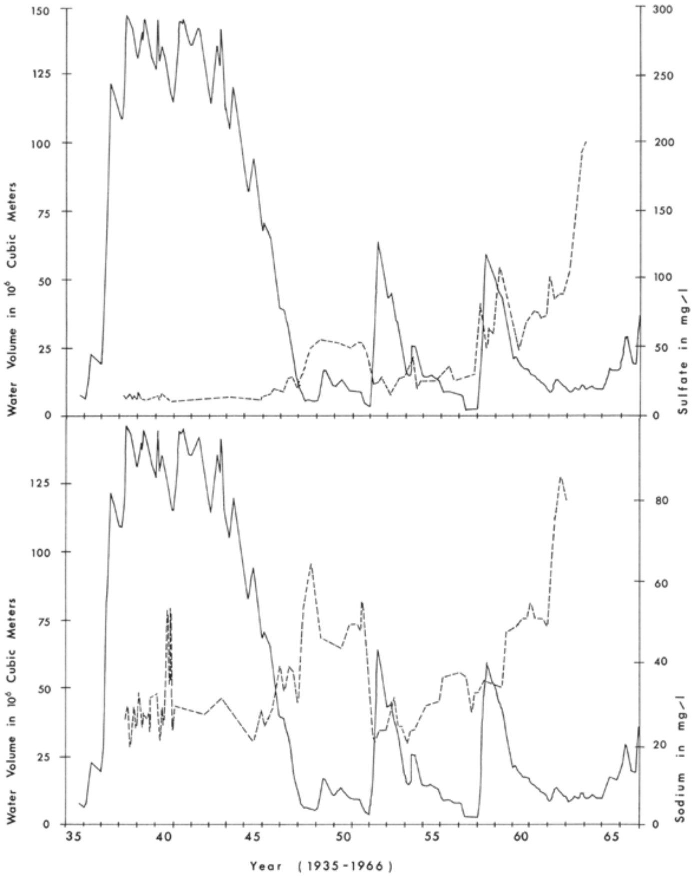

FIGURE 23. Line plots of El Capitan sodium and sulfate concentrations and water volumes. Water volume is the solid line.

FIGURE 23. Line plots of El Capitan sodium and sulfate concentrations and water volumes. Water volume is the solid line

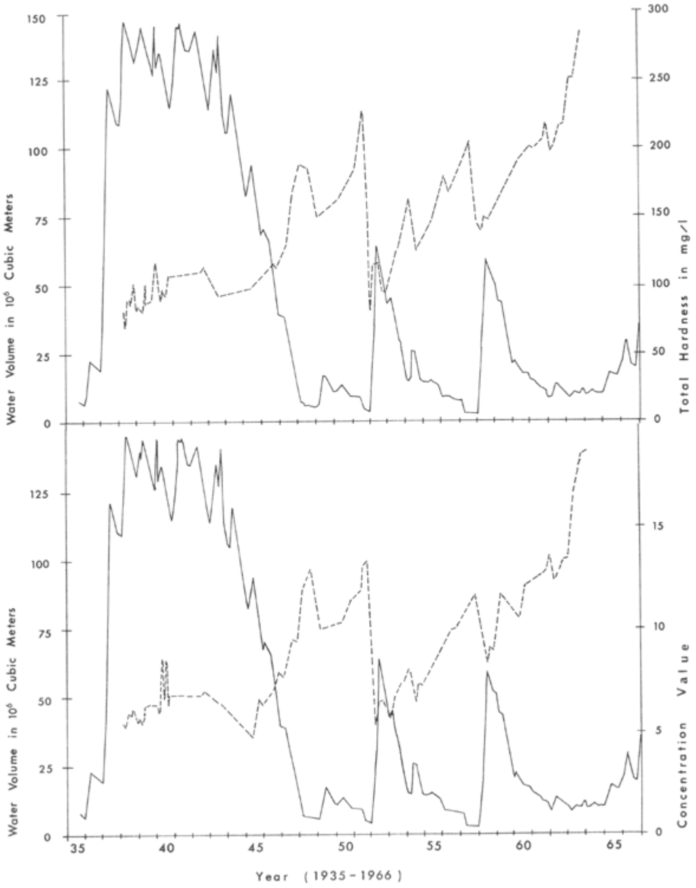

FIGURE 24. Line plots of El Capitan total hardness, concentration value and water volumes. Water volume is the solid line.

FIGURE 24. Line plots of El Capitan total hardness, concentration value and water volumes. Water volume is the solid line

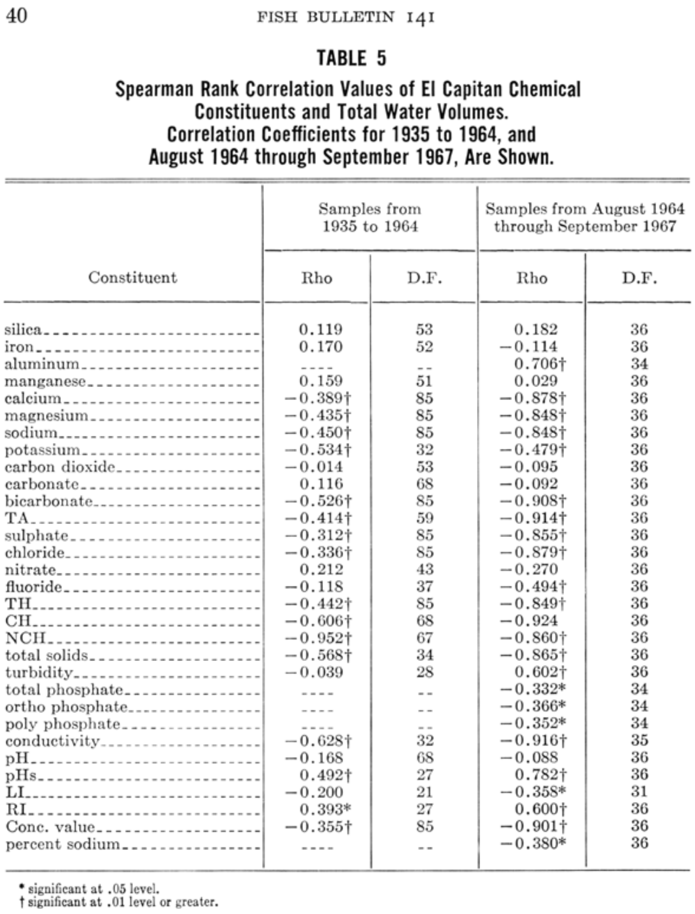

TABLE 5

Spearman Rank Correlation Values of El Capitan Chemical Constituents and Total Water Volumes. Correlation Coefficients for 1935 to 1964, and August 1964 through September 1967, Are Shown.

Constituent	Samples from 1935 to 1964		Samples from August 1964 through September 1967	
	Rho	D.F.	Rho	D.F.
silica	0.119	53	0.182	36
iron	0.170	52	−0.114	36
aluminum	----	--	0.706†	34
manganese	0.159	51	0.029	36
calcium	−0.389†	85	−0.878†	36
magnesium	−0.435†	85	−0.848†	36
sodium	−0.450†	85	−0.848†	36
potassium	−0.534†	32	−0.479†	36
carbon dioxide	−0.014	53	−0.095	36
carbonate	0.116	68	−0.092	36
bicarbonate	−0.526†	85	−0.908†	36
TA	−0.414†	59	−0.914†	36
sulphate	−0.312†	85	−0.855†	36
chloride	−0.336†	85	−0.879†	36
nitrate	0.212	43	−0.270	36
fluoride	−0.118	37	−0.494†	36
TH	−0.442†	85	−0.849†	36
CH	−0.606†	68	−0.924	36
NCH	−0.952†	67	−0.860†	36
total solids	−0.568†	34	−0.865†	36
turbidity	−0.039	28	0.602†	36
total phosphate	----	--	−0.332*	34
ortho phosphate	----	--	−0.366*	34
poly phosphate	----	--	−0.352*	34
conductivity	−0.628†	32	−0.916†	35
pH	−0.168	68	−0.088	36
pHs	0.492†	27	0.782†	36
LI	−0.200	21	−0.358*	31
RI	0.393*	27	0.600†	36
Conc. value	−0.355†	85	−0.901†	36
percent sodium	----	--	−0.380*	36

* significant at .05 level.
† significant at .01 level or greater.

TABLE 5
Spearman Rank Correlation Values of El Capitan Chemical Constituents and Total Water Volumes. Correlation Coefficients for 1935 to 1964, and August 1964 through September 1967, Are Shown

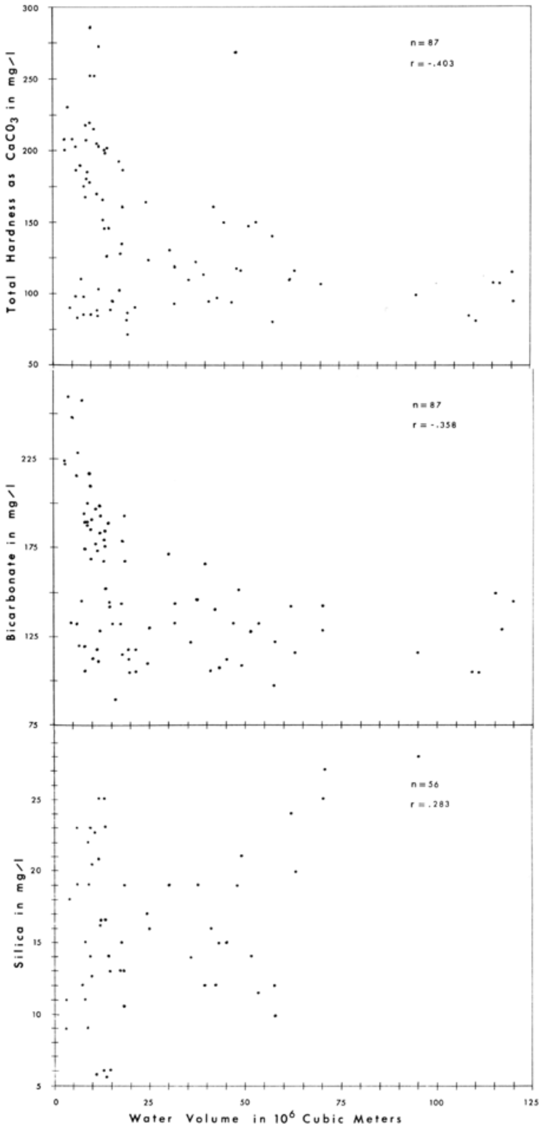

FIGURE 25. **Scattergram plots of El Capitan total hardness, bicarbonate and silica concentrations vs. water volumes from 1935 through 1964.**

FIGURE 25. Scattergram plots of El Capitan total hardness, bicarbonate and silica concentrations vs. water volumes from 1935 through 1964

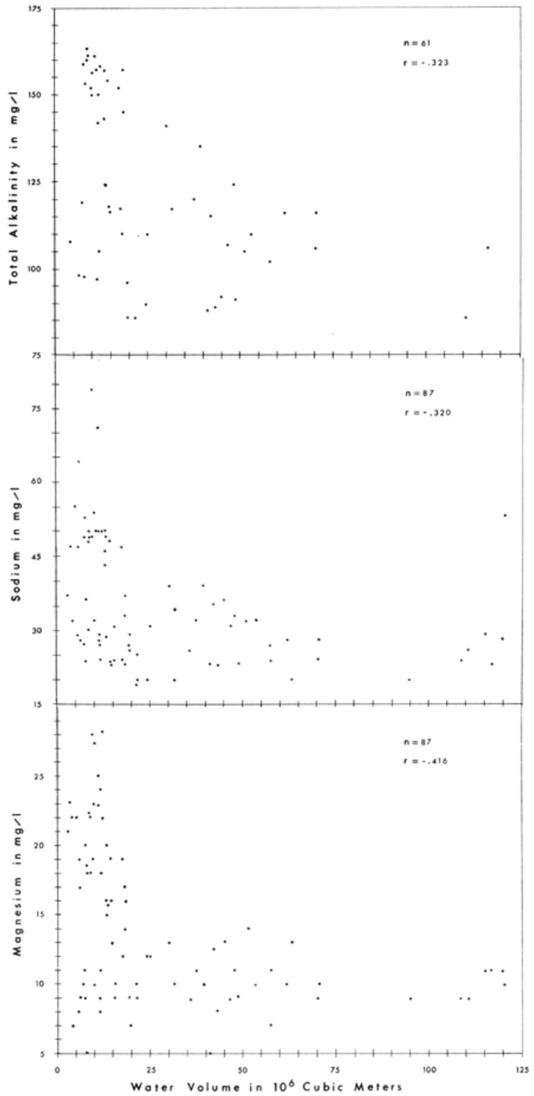

FIGURE 26. Scattergram plots of El Capitan total alkalinity, sodium and magnesium concentrations vs. water volumes from 1935 through 1964.

FIGURE 26. Scattergram plots of El Capitan total alkalinity, sodium and magnesium concentrations vs. water volumes from 1935 through 1964

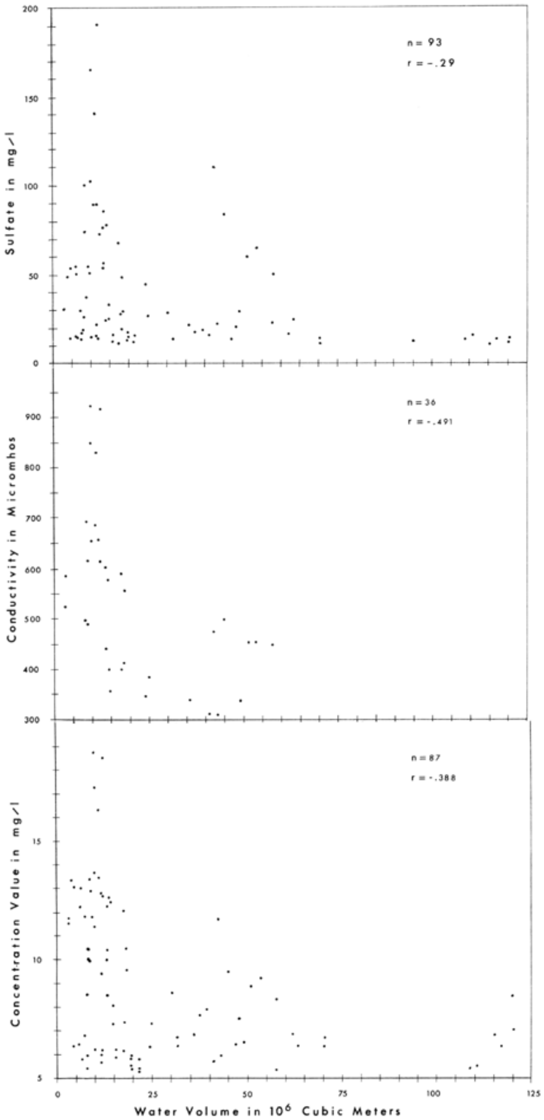

FIGURE 27. Scattergram plots of El Capitan sulfate, conductivity and concentration values vs. water volumes from 1935 through 1964.

FIGURE 27. Scattergram plots of El Capitan sulfate, conductivity and concentration values vs. water volumes from 1935 through 1964

than evaporation. Three processes that probably account in part for observed increases in concentrations with decreased volume are: (i) Epilimnion withdrawal. During stratified conditions there is a considerable vertical disparity between certain ions. Higher concentrations of certain undesirable ions often exist in the hypolimnion. Consequently, water is almost always withdrawn from the epilimnion. This process causes an increase in the average concentration of stratified constituents as a function of decreased water volume. Epilimnion withdrawal should not greatly affect ions that do not show vertical stratification. Epilimnion withdrawal may result in the long term accumulation of certain ions and account in part for the gradual eutrophication witnessed in most lakes, (ii) Evaporation. Although evaporation concentrates dissolved substances, I doubt if it explains all the observed changes. More water is generally withdrawn than evaporates. About 130 cm of water evaporates annually from El Capitan Reservoir, and (iii) Ionic equilibrium between lake basin and water. The deeper bottom area of El Capitan is covered by fine, colloidal silt and sludge. This material has a high organic content relative to shallower areas (Table 6 and Figure 28). The shallow bottom areas are mostly coarse sand and gravel.

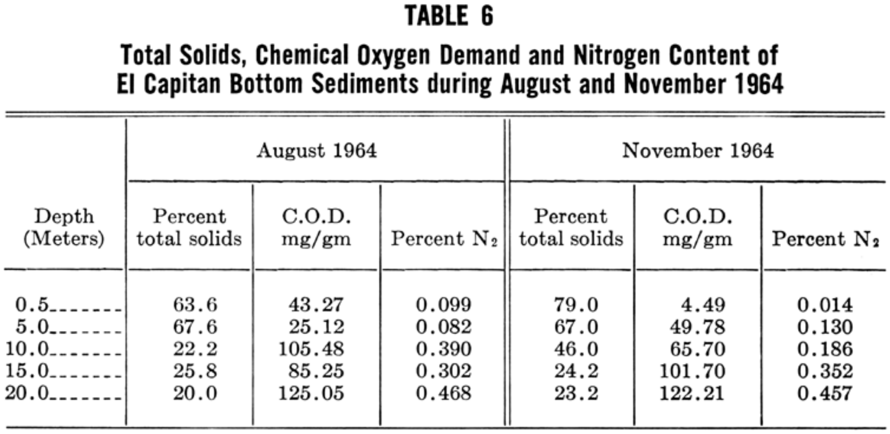

TABLE 6

Total Solids, Chemical Oxygen Demand and Nitrogen Content of El Capitan Bottom Sediments during August and November 1964

Depth (Meters)	August 1964			November 1964		
	Percent total solids	C.O.D. mg/gm	Percent N_2	Percent total solids	C.O.D. mg/gm	Percent N_2
0.5	63.6	43.27	0.099	79.0	4.49	0.014
5.0	67.6	25.12	0.082	67.0	49.78	0.130
10.0	22.2	105.48	0.390	46.0	65.70	0.186
15.0	25.8	85.25	0.302	24.2	101.70	0.352
20.0	20.0	125.05	0.468	23.2	122.21	0.457

TABLE 6

Total Solids, Chemical Oxygen Demand and Nitrogen Content of El Capitan Bottom Sediments during August and November 1964

The lake basin and water strive to reach an ionic equilibrium. This equilibrium is probably never attained. The nature and degree of the equilibrium is probably a function of thermal stratification, total water volume, and ratio of total sludge area to total volume.

Although ions are exchanged between the water and gravel sediments, the rate of exchange may be greatest over the sludge area. Thermal stratification seals off much of the water from contact with the sludge. Stratification reduces contact by causing discontinuous circulation and reduced water flow over the sediments. This situation may limit the rate of ion exchange. Essentially only the hypolimnion is in contact with the sludge.

Water volume should influence the equilibrium since the relative epilimnion volume decreases as total volume increases. Figure 29 illustrates this relationship if we assume a constant epilimnion depth of

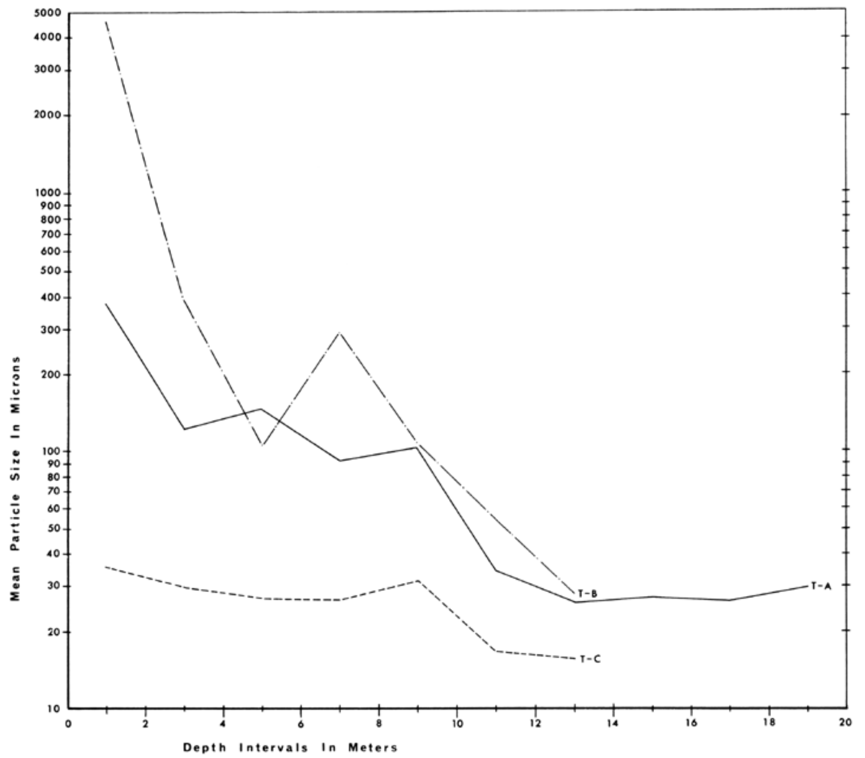

FIGURE 28. Mean particle diameter of sediments collected from El Capitan transects A, B and C. Figure 9 illustrates these transect locations. Particle size scale is logarithmic.

FIGURE 28. Mean particle diameter of sediments collected from El Capitan transects A, B and C. Figure 9 illustrates these transect locations. Particle size scale is logarithmic

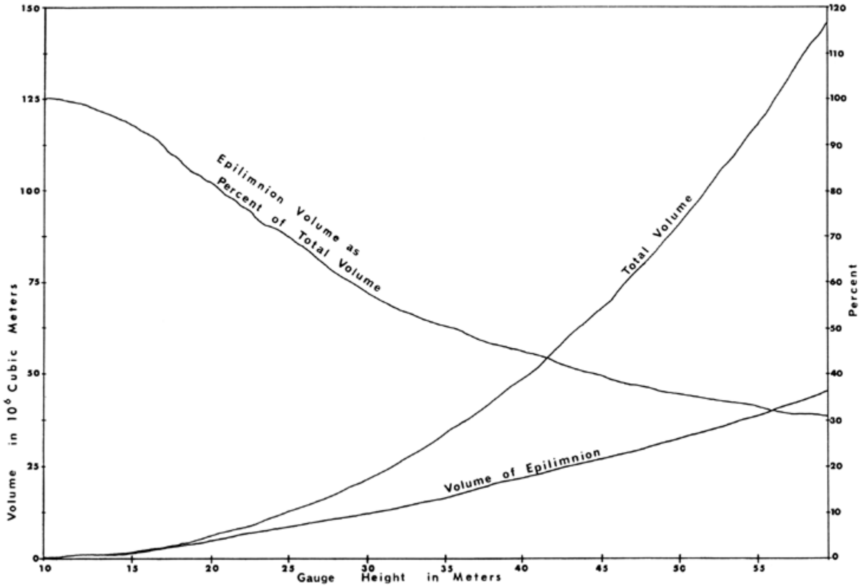

FIGURE 29. Change in epilimnion volume as percent of total volume, as total volume increases from zero to maximum capacity.

FIGURE 29. Change in epilimnion volume as percent of total volume, as total volume increases from zero to maximum capacity

about 8 meters. Epilimnion volume decreases from 100% to 31% of total volume as total water volume increases from 0 to maximum capacity.

On the other hand, Mortimer (1941, 1942) demonstrates that the diffusion of certain ions from the mud is increased by stratification and hypolimnion oxygen depletion.

Probably the most important factor influencing ionic concentrations is the ratio of total sludge area to total water volume. The sludge area is a function of time and water depth. Fine colloidal particles settle out below the level of wave and current action to form the sludge zone. This zone generally starts at about 8 meters, if water levels are static, and coincides with the metalimnion depth. Changes in water level affect the size of this zone.

A relatively small ratio exists between sludge area and water volume at high water volumes. The sludge area may cover the entire bottom if water is withdrawn rapidly, or if the volume is much reduced.

As the ratio of sludge area to water volume increases, the rate of ion transfer should increase. Maximum transfer should occur at reduced water volumes where sludge covers the entire bottom and the ratio is greatest.

5. EFFECTS OF ARTIFICIAL DESTRATIFICATION ON THE CHEMICAL-PHYSICAL REGIME OF EL CAPITAN RESERVOIR

5.1. Introduction

The study of El Capitan commenced during May 1964. This year was a control period. Many lake parameters were measured without altering the natural cycle of stratification. El Capitan was aerated during 1965 and 1966. Aeration began June 10, 1965. The lake stratified strongly by this date. The reservoir was aerated continuously from June 10th through June 21st. A steady state condition existed then. Compressor operation was discontinued from June 21st through July 1, to observe the rate of restratification. The compressor was started for the second time July 1st and it ran continuously through October 4, 1965. Aeration was discontinued from October, 1965 until March 19, 1966. By March 19th the lake started to stratify. The compressor ran continuously from March 19th through October 17, 1966. The year 1967 was a second control period. The lake stratified normally and we did not alter that condition.

Hence, we have one year of pre-aeration observations, two years of aeration observations and one year of post-aeration observations.

5.2. Temperature

A lake's temperature regime is probably its most important parameter. Yearly and seasonal extremes and the distribution of heat within the water at any given time reveal much about the condition of the lake. Indeed, the kind and extent of life may be determined by its temperature regime.

Isotherms from December 1954 through March 1961 are illustrated in Figure 16. Although maximum depth and water volume fluctuated greatly, seasonal stratification and the limits of the epilimnion were quite uniform. In general, stratification commenced during March. With stable water levels during summer, the metalimnion depth deepened as the metalimnion and hypolimnion were eroded by the epilimnion. Concomitant with this erosion was the heating of the epilimnion in the spring and summer and its cooling in the fall. Complete mixing generally occurred in November. The uniformity of this process was witnessed by the similarity in metalimnion formation and depth during 1958 as compared to previous years. The reservoir volume and depth during 1958 were more than double those of the preceding years.

Isotherms for May 1964 through September 1967 illustrate the effects of artificial destratification on the temperature profiles (Figure 30) . Isotherms during 1964 illustrate the normal cycle of stratification (Figure 31) , with gradual thermocline deepening preceding the fall overturn.

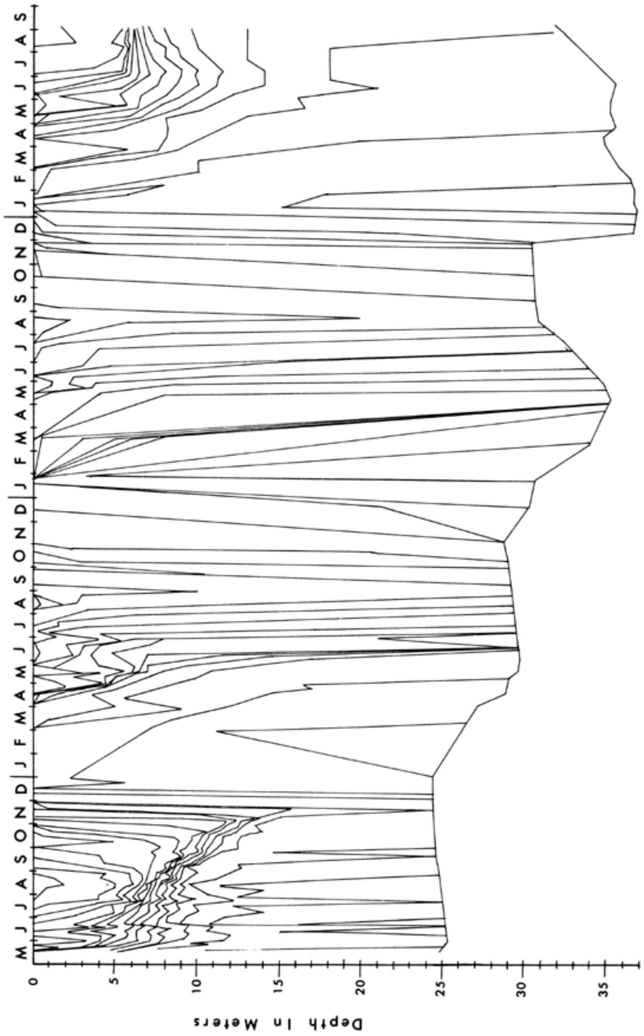

FIGURE 30. El Capitan isotherms in °C from May 1964 through September 1967. The reservoir stratified normally during 1964 and 1967. We destratified it during 1965 and 1966.

FIGURE 30. El Capitan isotherms in °C from May 1964 through September 1967. The reservoir stratified normally during 1964 and 1967. We destratified it during 1965 and 1966

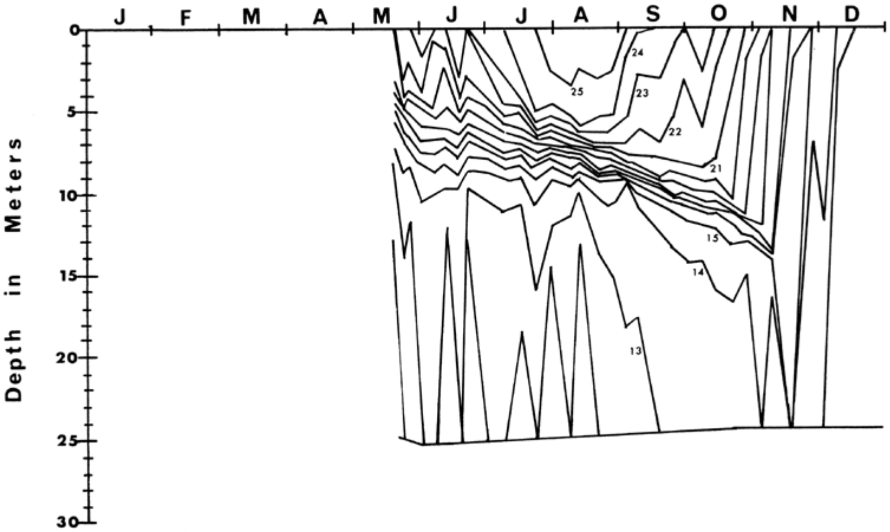

FIGURE 31. El Capitan isotherms in °C during 1964. We did not aerate this year.

FIGURE 31. El Capitan isotherms in °C during 1964. We did not aerate this year

Isotherms during 1965 and 1966 (Figures 32 , 33) illustrate another story. Normal stratification commenced during March 1965 and extended into June. Destratification commenced June 10, 1965. The isotherms reflect the abrupt changes caused by this action. They illustrate the elimination of the metalimnion and hypolimnion and the considerable heating of lower lake depths during the summer. They also show gradual cooling during the fall, rather than the abrupt changes caused by fall overturn.

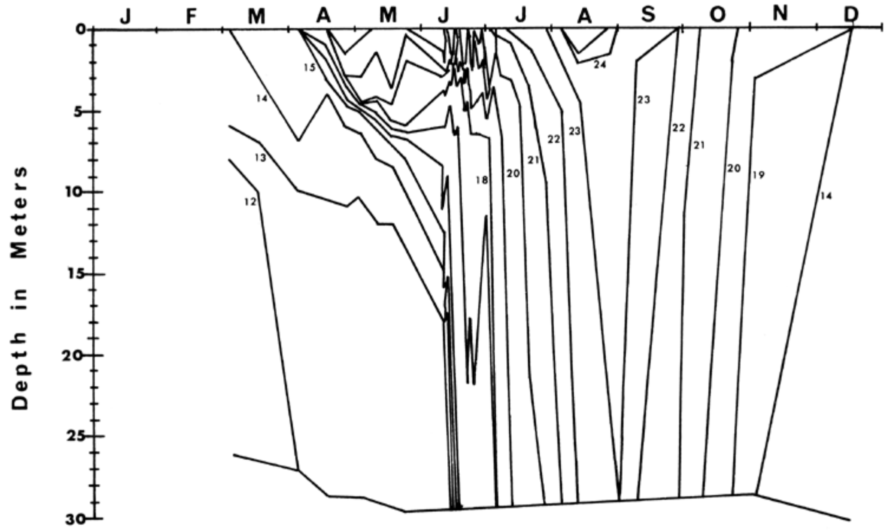

FIGURE 32. El Capitan isotherms in °C during 1965. We aerated from June 10th through June 21st, and from July 1st through October 4th.

FIGURE 32. El Capitan isotherms in °C during 1965. We aerated from June 10th through June 21st, and from July 1st through October 4th

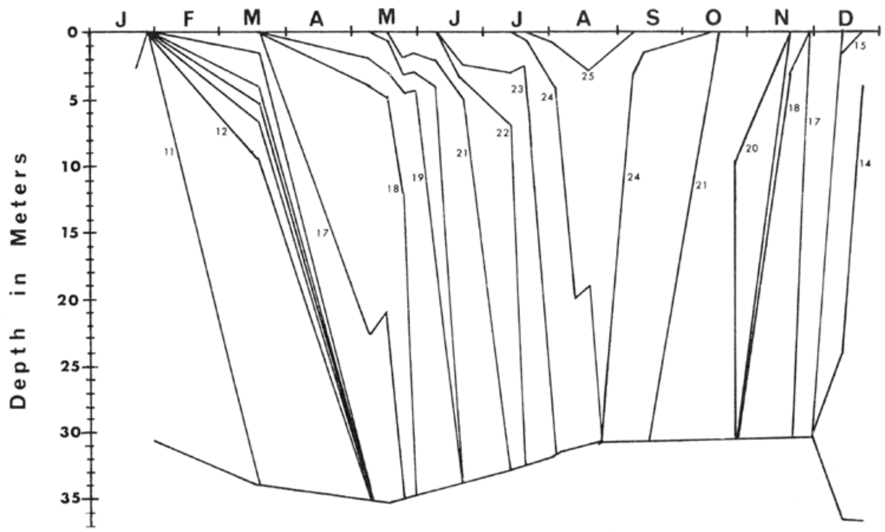

FIGURE 33. El Capitan isotherms in °C during 1966. We aerated from March 19th through October 17th.

FIGURE 33. El Capitan isotherms in °C during 1966. We aerated from March 19th through October 17th

Temperatures during the winter of 1965–66 are comparable to other years and apparently weren't influenced by the summer events of 1965. A metalimnion formed by early March 1966. Air injection was started March 19th and continued through October 17, 1966. The metalimnion disappeared rapidly and did not reappear until March 1967. The 1966 isotherms are similar to 1965's after destratification. They illustrate the gradual warming and cooling at all depths. Thermal barriers to biotic distribution appear minimal.

Isotherms for 1967 appear similar to 1964 and before (Figure 34) . We did not aerate during 1967 and stratification developed normally. However, the gradual metalimnion deepening was not observed. On the contrary, the metalimnion depth became shallower during the summer. This was caused by epilimnion withdrawal. As a result of stratification and hypolimnion stagnation, good quality water remained only in the epilimnion. Water for domestic purposes was withdrawn from the epilimnion and this reduced its total volume faster than it eroded the metalimnion and hypolimnion. Epilimnion water quality deteriorated rapidly and an avalanche of consumer complaints (about 400 a day) by the end of September caused the water managers to discontinue using this source.

The initial effects of air injection on the temperature profiles during 1965 are illustrated in Figure 35. The June 10th profile shows the temperature-depth distribution prior to air injection. A well developed metalimnion started at about 7 meters and extended to about 11 meters. The surface temperature was about 19°C and the bottom temperature about 13°C. On June 12th, after 2 days of air injection, the "classical" profile was much distorted. There were essentially two restricted metalimnions, one at about 3 meters and the other at about 16 meters. The zone between these depths was nearly uniform in temperature.

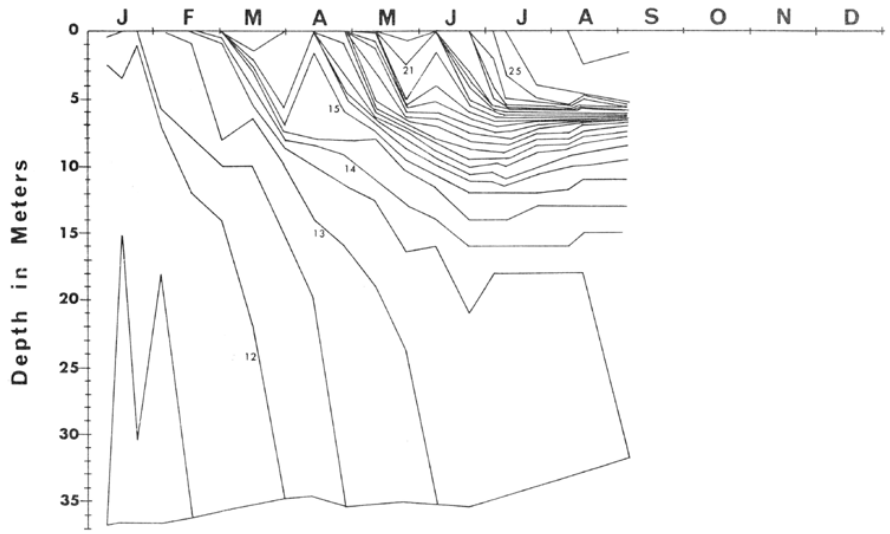

FIGURE 34. El Capitan isotherms in °C during 1967. We did not aerate this year.

FIGURE 34. EI Capitan isotherms in °C during 1967. We did not aerate this year

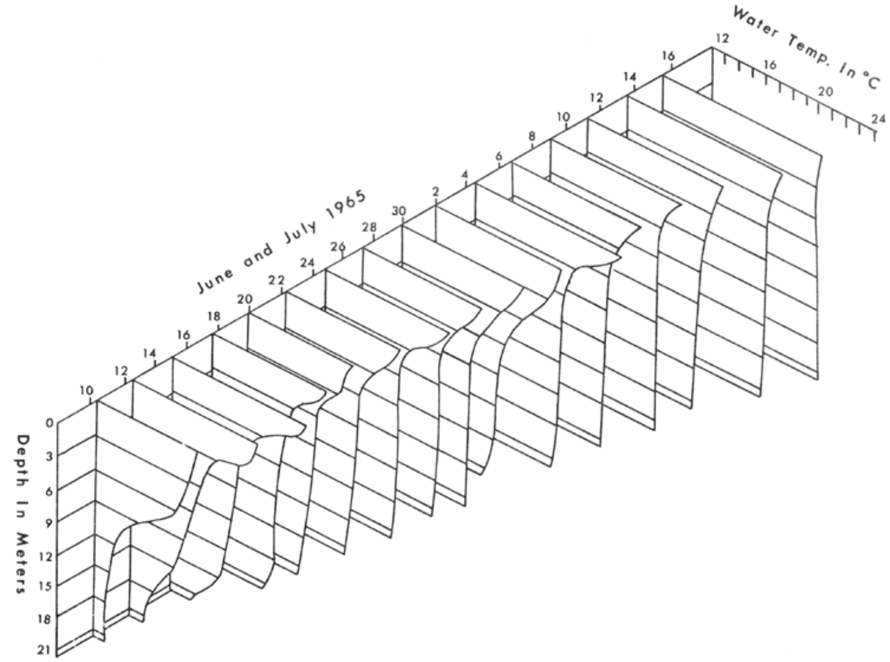

FIGURE 35. Changes in the temperature-depth profiles during June and July 1965.

FIGURE 35. Changes in the temperature-depth profiles during June and July 1965

This zone reflects the nature of the mixing process. As hypolimnion water is upwelled and mixes with epilimnion water, intermediate mixtures are formed. These mixtures seek a level of isodensity and initially flow into the metalimnion. The metalimnion increases its volume and becomes more uniform. Consequently, the metalimnion loses its integrity, per se. This intermediate zone of mixed water increases in volume as the former epilimnion and hypolimnion are reduced through mixing.

The lake approached a steady state thermal condition by June 20, 1965.

The water was essentially isothermal from about 4 meters down. A temperature cline existed above that depth and was maintained by the net influx of heat. Although mixing by aeration continued, the rate of mixing was less than the influx of heat energy from the sun and atmosphere. Mixing efficiency is greatest during maximum stratification and approaches zero as the water approaches an isothermal condition (Koberg and Ford, 1965). Hence, complete mixing during the spring is thwarted by reduced mixing efficiency as the lake approaches isothermy, and a net inflow of heat energy. During late summer and fall, mixing is assisted by a net outflow of heat energy. This heat energy is lost essentially at the lake surface and the surface water during later summer and fall is cooled. As it cools, it sinks and mixes with deeper, warmer water. This process will maintain the lake in an isothermal condition until the following spring when a net influx of heat again occurs. Air injection was discontinued June 21, 1965 to observe the rate of restratification. On this date, about 2.5°C difference between surface and bottom existed. On July 1st, after 10 days of restratification, about a 5°C difference existed. Air injection was again started July 1st and continued until October 4th. By July 11th, the lake was almost isothermal. Less than a 1°C difference existed. By the end of July this difference was further reduced. It was reduced primarily because the net flow of heat to the lake was reduced and eventually reversed. Concomitant with the mixing and trend toward isothermy the entire water is gradually warmed. By July 15th all depths were warmer than the warmest water on June 10th.

During normal stratified years, surface temperatures reach minimum values of about 11.5°C generally in January and maximums of about 25.5°C during late July or early August (Figure 36) . The average difference between these extremes is about 14°C. Bottom temperatures follow a similar cycle with minimum values of about 11.0°C during January and maximums of about 13.5°C during November. The maximum bottom temperature was observed at the fall turnover. During destratified years, this cycle was altered drastically (Figure 37) . During 1965 and 1966 the summer bottom temperature almost equaled the surface temperature. This represents an average increase of about 10.5°C over the normal yearly maximum bottom temperature. A high of about 23.0°C was observed during 1965, and a high of about 24.5°C during 1966. The 1966 maximum was probably greater than 1965's because aeration was started earlier during 1966. However, normal climatic fluctuations might account for this difference.

Although increased bottom temperature may be beneficial in certain situations, it may also be a liability. Elevated bottom temperature may preclude the establishment or continuance of year-round coldwater fisheries. Most coldwater fishes are stressed or killed by water temperatures above 24.5°C. Water temperature of more than 21°C are generally considered undesirable. Artificial destratification may increase

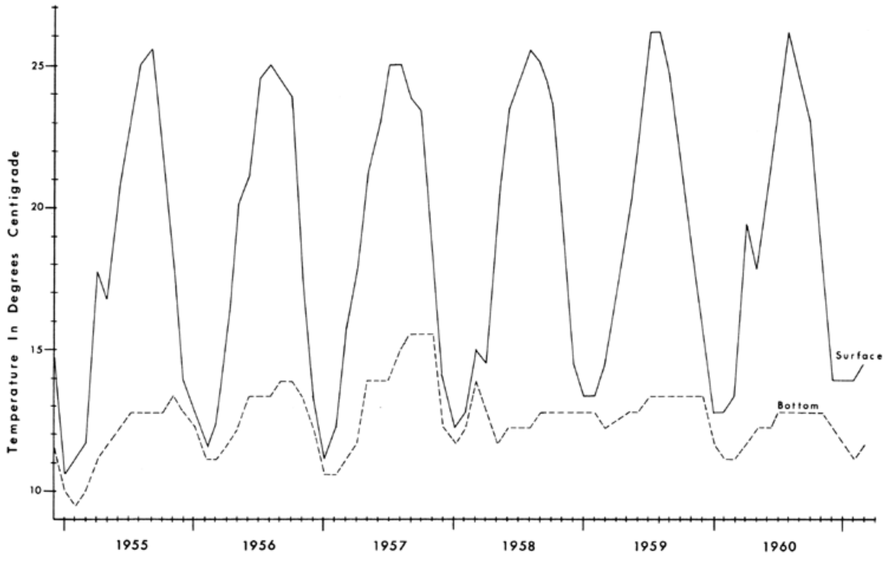

FIGURE 36. El Capitan surface and bottom temperatures from 1954 through 1961.

FIGURE 36. EI Capitan surface and bottom temperatures from 1954 through 1961

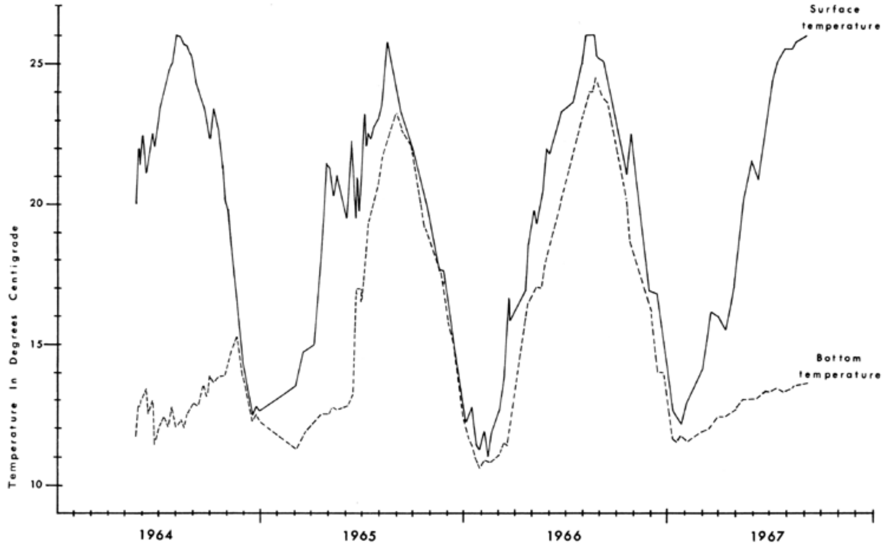

FIGURE 37. El Capitan surface and bottom temperatures from May 1964 through September 1967.

FIGURE 37. EI Capitan surface and bottom temperatures from May 1964 through September 1967

the minimum temperature in the lake to greater than 25°C. Highs of 23°C and 24.5°C were observed at El Capitan.

Increased metabolic potential of zoobenthos is afforded by increased temperature and oxygen concentration. The great increase in bottom temperature, coupled with a shift from anaerobic to aerobic conditions, should have a profound influence on the processes in the lower levels of the lake. Chemical reactions alone are theoretically doubled by every

10°C increase in temperature. Aerobic and facultative anaerobic zoobenthos have invaded this region in quantity (Fast, 1966b) and apparently are benefited by the rich organic natures of the profoundal sediment (Table 6).

Although bottom temperatures are elevated drastically by forced circulation, surface temperatures are only slightly affected (Figure 38) . Surface temperatures during aeration are generally lower in the spring and summer and higher during the fall (Koberg and Ford, 1965).

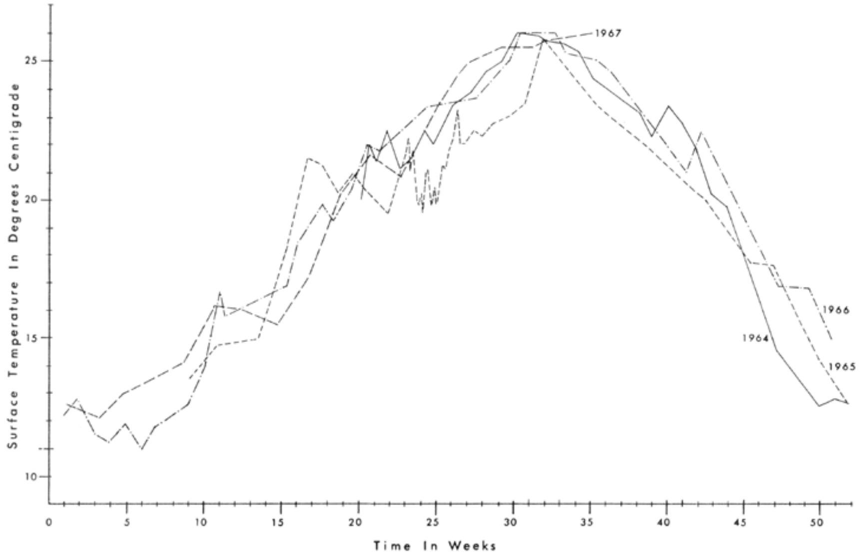

FIGURE 38. El Capitan surface temperatures from May 1964 through September 1967.

FIGURE 38. EI Capitan surface temperatures from May 1964 through September 1967

This situation accounts for the reduced annual evaporation rates described by Koberg (1964); Koberg and Ford (1965). The aeration system and wind distribute heat throughout the lake. Formerly it was distributed mostly within the epilimnion by the wind. There is a time lag between absorption and distribution to the deeper levels of the lake. This lag might account in part for the lowered surface temperatures in the spring and summer. As expected, the mean lake temperature is elevated by artificial destratification. Average maximum water temperature during stratified years is about 22.5°C (Figures 39 and 40). The maximum for any given year is affected greatly by total water volume and the depth of water withdrawal. At higher water volumes, the hypolimnion accounts for a relatively greater percentage of the total volume (Figures 16 and 29). However, total volume and percentage volume of the hypolimnion apparently do not have much effect on the epilimnion temperature, although the average lake temperature is lower at higher water volumes.

The maximum average water temperature during 1965 was about 23.8°C, and about 25.2°C during 1966. The 1966 average was probably greater than the 1965 because aeration was started later during 1965. The average maximum temperature for the two destratified years was 24.5°C or about 2.0°C greater than for stratified years. This represents a considerable increase in the heat budget of the lake due to forced circulation.

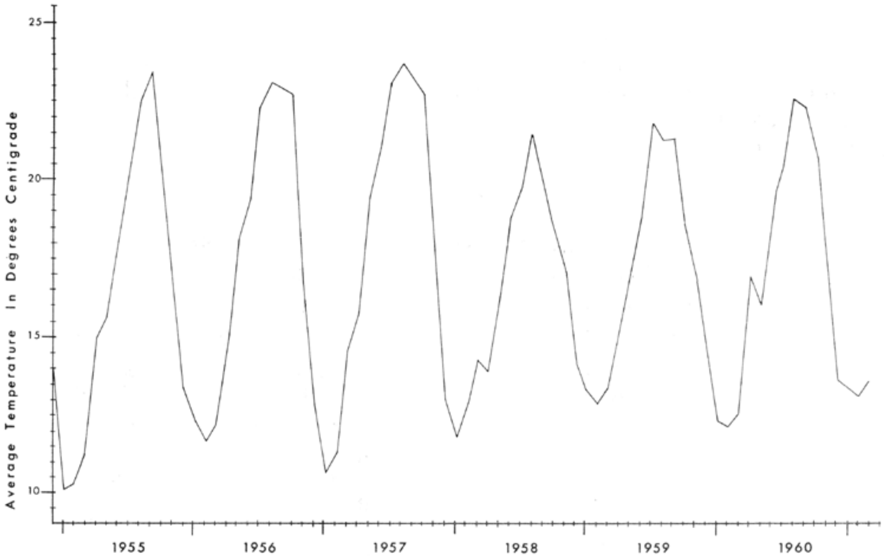

FIGURE 39. El Capitan average temperatures from 1954 through 1961.

FIGURE 39. EI Capitan average temperatures from 1954 through 1961

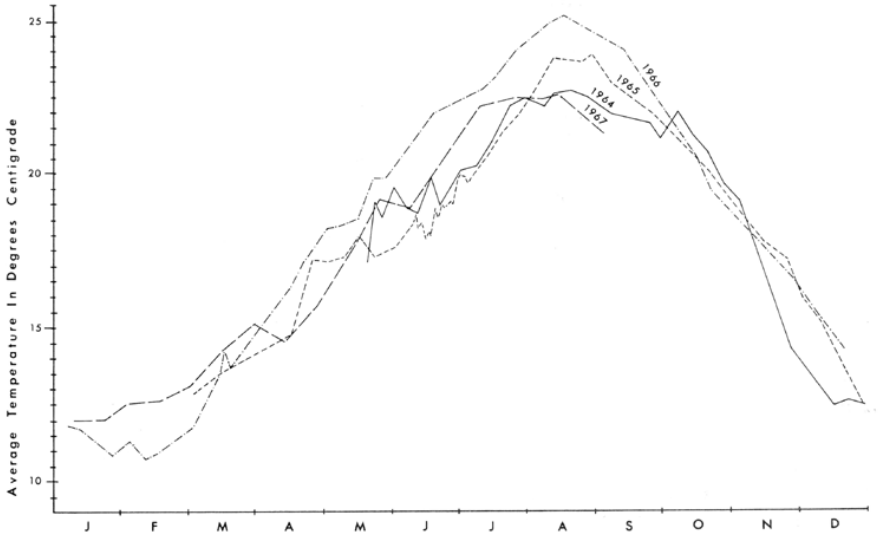

FIGURE 40. El Capitan average temperatures from May 1964 through September 1967.

FIGURE 40. EI Capitan average temperatures from May 1964 through September 1967

5.3. Heat Budget

Heat budgets are generally expressed as calories per cm^2 (Hutchinson, 1957; Welch, 1952). This convention may be applicable to lakes with stable water levels; however, this unit of measure apparently cannot be used to compare lakes of different sizes, nor yearly values of a fluctuating reservoir. Table 7 illustrates minimum and maximum heat content values and corresponding water volumes for El Capitan Reservoir. The heat content is expressed both as calories/cm^2 above 0.0°C and calories/m^3 above 0.0°C. The total caloric content of the lake is divided by total surface area in square centimeters and by total volume in cubic meters to estimate the corresponding values. Both yearly maximum and minimums for January 1955 through February 1961 are presented. Yearly maximums for 1964 through 1967 are shown.

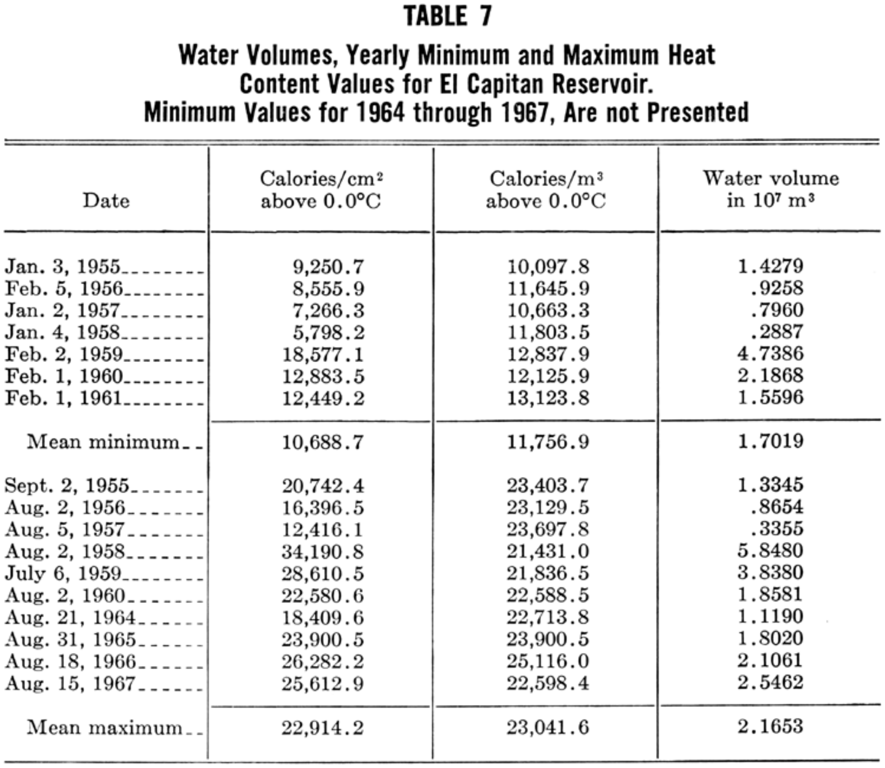

TABLE 7

Water Volumes, Yearly Minimum and Maximum Heat Content Values for El Capitan Reservoir. Minimum Values for 1964 through 1967, Are not Presented

Date	Calories/cm^2 above 0.0°C	Calories/m^3 above 0.0°C	Water volume in 10^7 m^3
Jan. 3, 1955	9,250.7	10,097.8	1.4279
Feb. 5, 1956	8,555.9	11,645.9	.9258
Jan. 2, 1957	7,266.3	10,663.3	.7960
Jan. 4, 1958	5,798.2	11,803.5	.2887
Feb. 2, 1959	18,577.1	12,837.9	4.7386
Feb. 1, 1960	12,883.5	12,125.9	2.1868
Feb. 1, 1961	12,449.2	13,123.8	1.5596
Mean minimum	10,688.7	11,756.9	1.7019
Sept. 2, 1955	20,742.4	23,403.7	1.3345
Aug. 2, 1956	16,396.5	23,129.5	.8654
Aug. 5, 1957	12,416.1	23,697.8	.3355
Aug. 2, 1958	34,190.8	21,431.0	5.8480
July 6, 1959	28,610.5	21,836.5	3.8380
Aug. 2, 1960	22,580.6	22,588.5	1.8581
Aug. 21, 1964	18,409.6	22,713.8	1.1190
Aug. 31, 1965	23,900.5	23,900.5	1.8020
Aug. 18, 1966	26,282.2	25,116.0	2.1061
Aug. 15, 1967	25,612.9	22,598.4	2.5462
Mean maximum	22,914.2	23,041.6	2.1653

TABLE 7

Water Volumes, Yearly Minimum and Maximum Heat Content Values for EI Capitan Reservoir. Minimum Values for 1964 through 1967, Are not Presented

It is apparent from Table 7 that the per unit area heat content values are influenced to a great extent by water volumes. The yearly minimum heat content as cal./cm^2 during 1959, when the volume was large, is actually greater than the maximums as cal./cm^2 during 1956, 1957 and 1964. The heat content expressed in calories per unit volume is influenced to a much less extent by water volumes.

Heat content per unit area is influenced greatly by water volumes, because the surface area—water volume curve is not linear.

Water volume increases relatively more than surface area per unit change in depth. This trend causes an apparent increase in the heat content per unit area as water volume increases, even though the average temperature remains constant. For El Capitan the ratio of surface area in hectares to volume in cubic meters at about 62 meters gauge height is 1.06 X 10^5. At about 31 meters height, this ratio is 2.28 X 10^5. Therefore, if we compute the heat capacity per cm^2 of El Capitan under isothermal conditions with gauge height 31 meters, this value will be more than twice the heat capacity per cm^2 at gauge height 62 meters. Heat content as calories/m^3 would give the same value regardless of gauge height if the lake is isothermal at a given temperature. Intuitively, I prefer a heat per unit volume measure. Heat is distributed in three dimensional space, not two.

Because of the relative consistency of heat contents per unit volume of El Capitan, I feel this is a better measure of the annual heat budget. Although considerable variation occurs in yearly heat contents as cal/m^3, this unit of measure is not as sensitive to total volume changes as calories/cm^2. The annual heat budget of a cm^2 column of water, equal to observed reservoir depths, may give a reasonable estimate of the heat budget. However, this method tends to give undue weight to the deeper depths in the lake which represent only a small fraction of total volume.

Aeration during 1965 and 1966 apparently caused an increase in the heat budget. A maximum of 25,116.0 cal/m^3 above 0.0°C occurred during 1966, and a maximum of 23,900.5 cal/m^3 above 0.0°C occurred during 1965. The 1966 maximum is the greatest observed during the 10 years and the 1965 maximum is the second greatest. The high value during 1966, as compared to 1965, can possibly be attributed to the longer period of destratification during 1966.

Artificial destratification apparently increases the heat budget by distributing the heat to greater depths. Prior to forced circulation, heat is distributed essentially within the epilimnion by wind driven currents. The maximum epilimnion temperature is limited essentially by energy exchange processes at the surface. After destratification, energy is distributed to all depths. In addition, the maximum surface temperature of stratified periods is equaled or approached.

5.4. Stability

Schmidt (1915) describes stability as the energy required to change a thermally stratified lake to one of equal temperature throughout. He calculates this energy as that necessary to lift the entire water mass from its center of gravity under isothermal conditions to its center of gravity under stratified conditions. Stability is zero when the lake is isothermal and reaches a maximum value when the lake is well stratified.

McEwen (1941) presents a graphical method for calculating stability per unit area. Symons and Robeck (1966) also describe a method of calculating stability and use this technique to evaluate the efficiencies of destratification systems. The efficiency of a given system may be calculated as the change in lake stability divided by the energy expended by the destratification system to cause the observed change. Theoretically, this procedure may appear sound, but in practice it has limited application. Figure 41 illustrates El Capitan's stability as kilogram-meters per hectare and water volume in cubic meters from December 1954 through March 1961. The lake stratified normally during

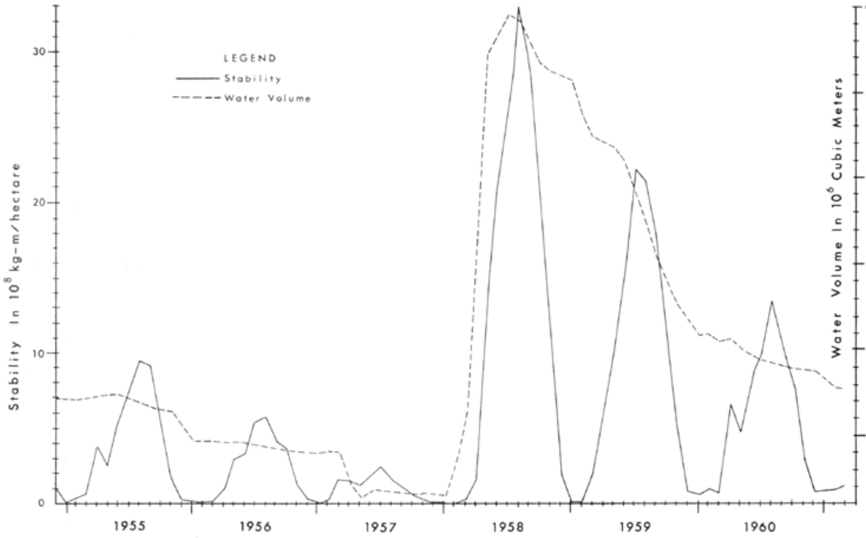

FIGURE 41. El Capitan stability and water volume from 1954 through 1961.

FIGURE 41. EI Capitan stability and water volume from 1954 through 1961

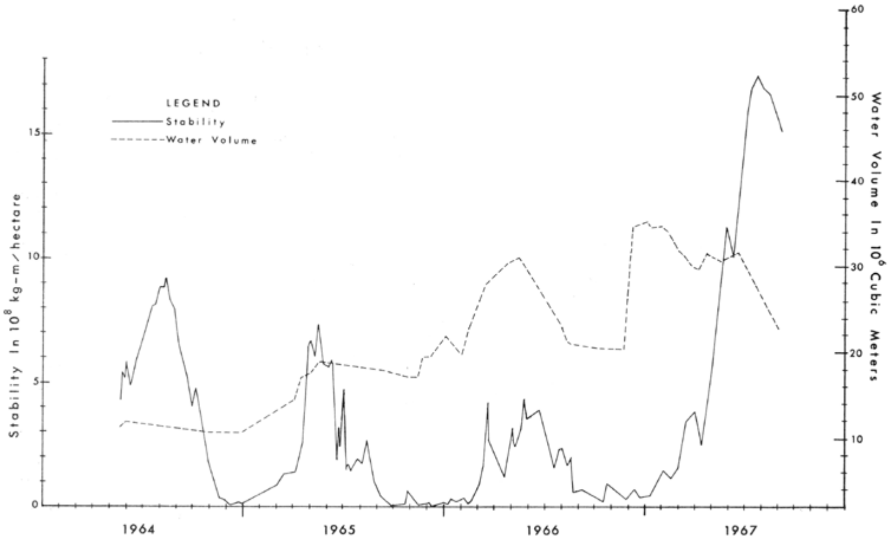

FIGURE 42. El Capitan stability and water volume from May 1964 through September 1967.

FIGURE 42. EI Capitan stability and water volume from May 1964 through September 1967

this period (Figure 16). It is evident from Figure 42 that stability is influenced considerably by maximum water volume. I have also calculated stability as kg-m/m^3 and as kg-m, but found essentially the same situation, although it is not as pronounced as for kg-m/hectare. Most authors use stability per unit area. In addition to the problem of different volumes, the seasonal cycle of stratification will distort the observed efficiency of a given destratification system. During the spring and early summer there is a net influx of heat energy. This influx tends to work against the forced circulation system. It may prevent complete destratification during this period, as we observed during the spring and summer of both 1965 and 1966. It may also indicate a lower efficiency if compared with later summer or fall destratifications, as there is a net outflow of heat during the late summer and fall. This condition tends to perpetuate an isothermal condition, and will indicate a greater efficiency value if the lake is destratified during this period, as compared to spring and early summer.

Figure 42 illustrates El Capitan stabilities and water volumes during 1964 through 1967. Again, stability is shown to be greatly influenced by water volumes. Although the lake stratified normally during both 1964 and 1967 (Figure 30) the 1967 stability values are much greater. This is essentially a function of increased water volume during 1967.

Although water volume and season have an overbearing effect on stability, the influence of the aeration system is evident during 1965 and 1966. Even though water volumes increased during 1964 to 1965, the stabilities after June 1965 are much less compared to 1964. This same effect is evident for 1966. Although water volume had more than tripled by 1966, stabilities are much less than during 1964. The lower stabilities during 1966, compared to 1965, are attributed to a longer period of destratification during 1966.

If thermal stratification is eliminated, stability will be zero regardless of how it is expressed. We did not completely eliminate stratification because our aeration system was not large enough to completely disperse all the heat absorbed during the spring and summer at the same rate it was absorbed. Likewise, although our system may be able to disperse all the energy absorbed during a given 24-hour period, there may be times during this period when the rate of absorption is greater than the mixing rate. This condition may occur during the daylight hours. We generally measured temperature between 1000 and 1400 hours. Only a few degrees temperature difference between the surface and bottom may result in a relatively large stability value.

If stability changes can be expressed as a function of both water volumes and energy exchange processes, it should be a good method of evaluating aeration systems and techniques. Although forced circulation definitely reduces stability, our techniques for calculating efficiencies based on stability changes are not refined enough to give valid comparisons. Some multivariant formula is undoubtedly needed. This formula should consider the principle energy exchange processes of the lake.

5.5. Oxygen

Dissolved oxygen is probably the second most important lake parameter. Its seasonal and depth distributions indicate a great deal about the conditions of life in the lake. It indicates the organic richness of the lake and restrictions to animal distributions. It also indicates the kind of decomposition taking place and the quality of drinking water.

El Capitan is organically rich and normally develops an oxygen deficit below the metalimnion. During June 1964, an oxygen deficit existed from the 9-meter depth to the bottom (Figure 43) . During 1965, an oxygen deficit developed early, but cold, aerated surface run-off recharged the hypolimnion with oxygen before we began aeration. The 1964 and 1967 isopleths are relatively uniform and do not show the

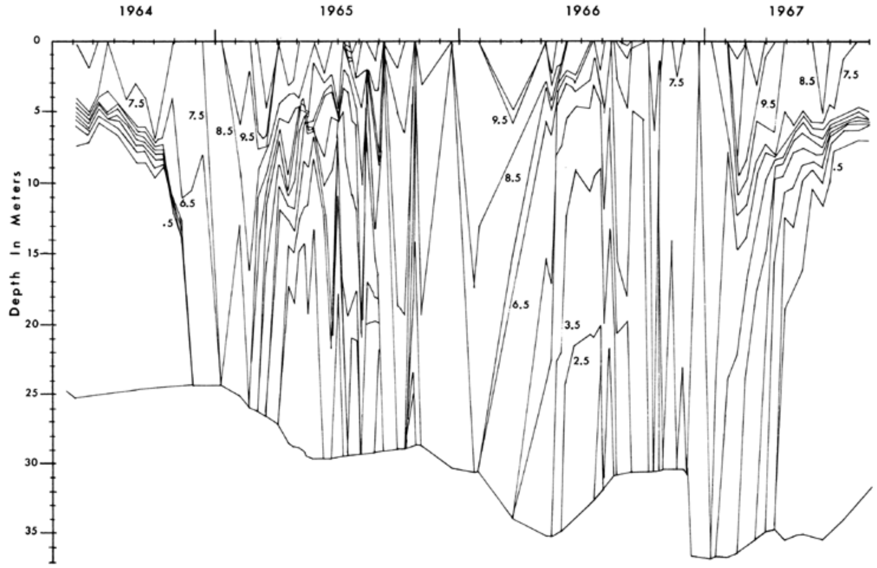

FIGURE 43. El Capitan isopleths from May 1964 through September 1967. Isopleths are in mg/l. oxygen.

FIGURE 43. El Capitan isopleths from May 1964 through September 1967. Isopleths are in mg/I. oxygen

considerable oscillations observed during air injection. These fluctuations are probably attributed mostly to phytoplankton activity, bacterial decomposition, and oxidation of organic and inorganic materials. Increased bottom temperatures and rates of flow over the organically rich sediments undoubtedly contribute to those oscillations. During normal stratified years, most biota is limited to the zone above the metalimnion. After destratification, oxygen is generally plentiful at all depths (Figure 44) . High oxygen concentrations in the deeper areas permit wider fish and invertebrate forage organism distribution. It also changes organic decomposition from anaerobic to aerobic and many of the compounds causing taste and odor problems in drinking water are oxidized.

Figure 45 illustrates the oxygen-depth profiles during comparable periods of 1964 and 1965. Aeration was not attempted during 1964. Figure 45-A illustrates the oxygen profiles during June 10, 1965 before aeration began, and the same period of 1964. These profiles are essentially similar and illustrate low oxygen concentrations below the metalimnion. After 11 days of aerating, the oxygen profile is illustrated by Figure 45-B. Oxygen is now distributed to all depths, but is most concentrated near the surface. We discontinued aeration June 21, 1965 to observe the rate of restratification. After 10 days of restratification, an oxygen deficit again developed and the oxygen profile was approaching a pre-aeration configuration (Figure 45-C). July 1st we commenced aeration again and ran our aerator continuously until October 4, 1965. Figure 45-D illustrates the oxygen profiles during September 1964 and 1965. Although oxygen is plentiful and uniform at all depths during 1965, its surface concentration is much less than during 1964. This indicates the accelerated oxidation rate that apparently occurs during forced circulation. This is particularly notable since oxygen recharge from the atmosphere, injected air and aquatic plants, should be much greater during aeration than during stratified periods.

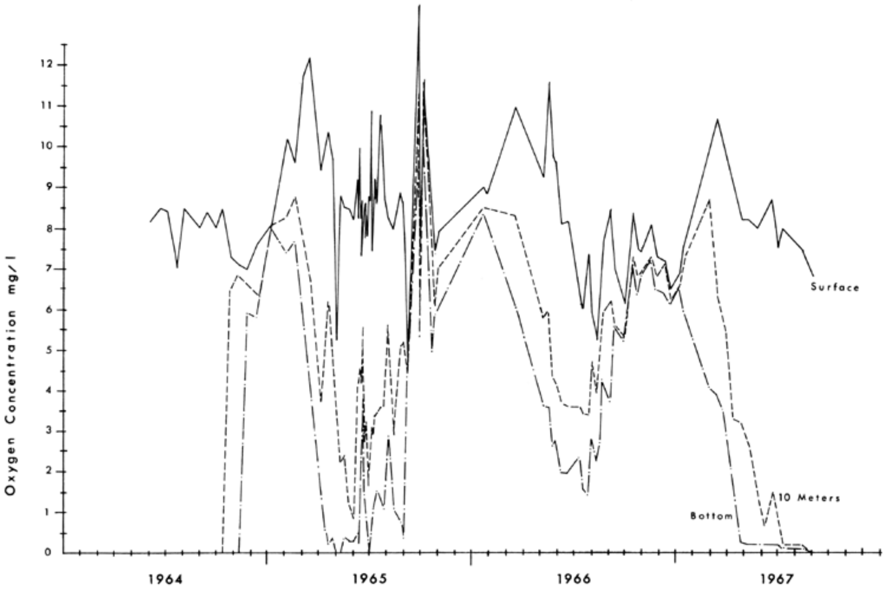

FIGURE 44. El Capitan oxygen concentrations at the surface, 10 meters depth and the bottom, from May 1964 through September 1967.

FIGURE 44. El Capitan oxygen concentrations at the surface, 10 meters depth and the bottom, from May 1964 through September 1967

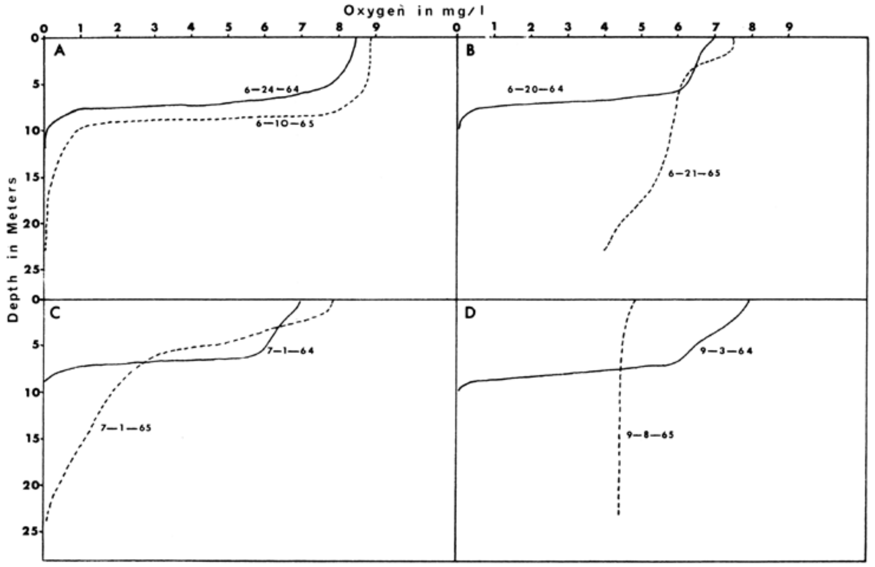

FIGURE 45. Oxygen concentrations during comparable periods of 1964 and 1965. We aerated from June 10th through June 21st, 1965, and from July 1st through October 4th, 1965.

FIGURE 45. Oxygen concentrations during comparable periods of 1964 and 1965. We aerated from June 10th through June 21st, 1965, and from July 1st through October 4th, 1965

5.6. Chemistry

Certain ion concentrations and physical water characteristics show pronounced differences as a result of stratification and hypolimnion oxygen depletion. These differences are especially noticeable with iron (Fe), manganese (Mn), carbon dioxide (CO_2), bicarbonate (HCO_3), total alkalinity (TA), total hardness (TH), total solids (TS), and conductivity (Cond.). Many other ions do not appear to be specially affected by stratification. Many show erratic differences. Some of these erratic changes may be real, but others may be due to sampling or analytical error.

The appendix gives a listing of El Capitan chemical analyses run by utilities department chemists between August 1964 and September 1967. Generally three samples were collected each month. Sample depths of 0, 7 and 17 meters were selected to determine the effects of stratification on the vertical distribution of each chemical. The surface (0 m) and 17 meters depth samples are most useful in this respect. The 7 meters sample may be located above or below the summertime oxygen deficit, depending on whether it is early or late summer, and if the lake is stratified.

Iron and manganese are especially important to water quality. The U.S. Public Health Service (1962) advised a combined concentration limit of 0.3 mg/l for potable water. During August 1964 (appendix) the El Capitan concentrations were 0.02, 0.65, and 1.46 mg/l at 0, 7 and 17 meters respectively. The 7 and 17 meters concentrations exceed that recommended for drinking water. Following destratification the concentrations during August 1965 and 1966 are below 0.3 mg/l at all depths. Several other researchers indicate a reduction in iron and manganese concentrations following destratification.

Most, but not all depth concentration differences are reduced or eliminated by aeration.

Although we did not analyze for hydrogen sulfide, artificial destratification limits this substance. Seventeen-meter water samples during the summer 1964, were clear when first collected. After they set a few minutes they turned a milky white color due to elemental sulfur formation. The samples had a pronounced rotten egg odor, attesting to high hydrogen sulfide concentrations. I did not detect these odors during either 1965 or 1966. Aeration prevented the accumulation of this substance. The rotten egg odor again became pronounced during the summer, 1967, following several months of hypolimnion stagnation. The 1967 levels did not appear to be as high as 1964's, due in part to greater water volume and the persistence of higher oxygen concentrations until late summer.

Figures 46 through 49 illustrate the concentrations at 0, 7 and 17 meters of several chemicals during the study period. Not all are noticeably affected by the thermal properties of the water. However, several show a strong correlation between water volume and their concentration. Figures 50 through 52 illustrate scattergram plots of this relationship for several of the chemicals. Table 5 shows the rank correlation value for these chemical constituents and water volumes from August 1964 through September 1967.

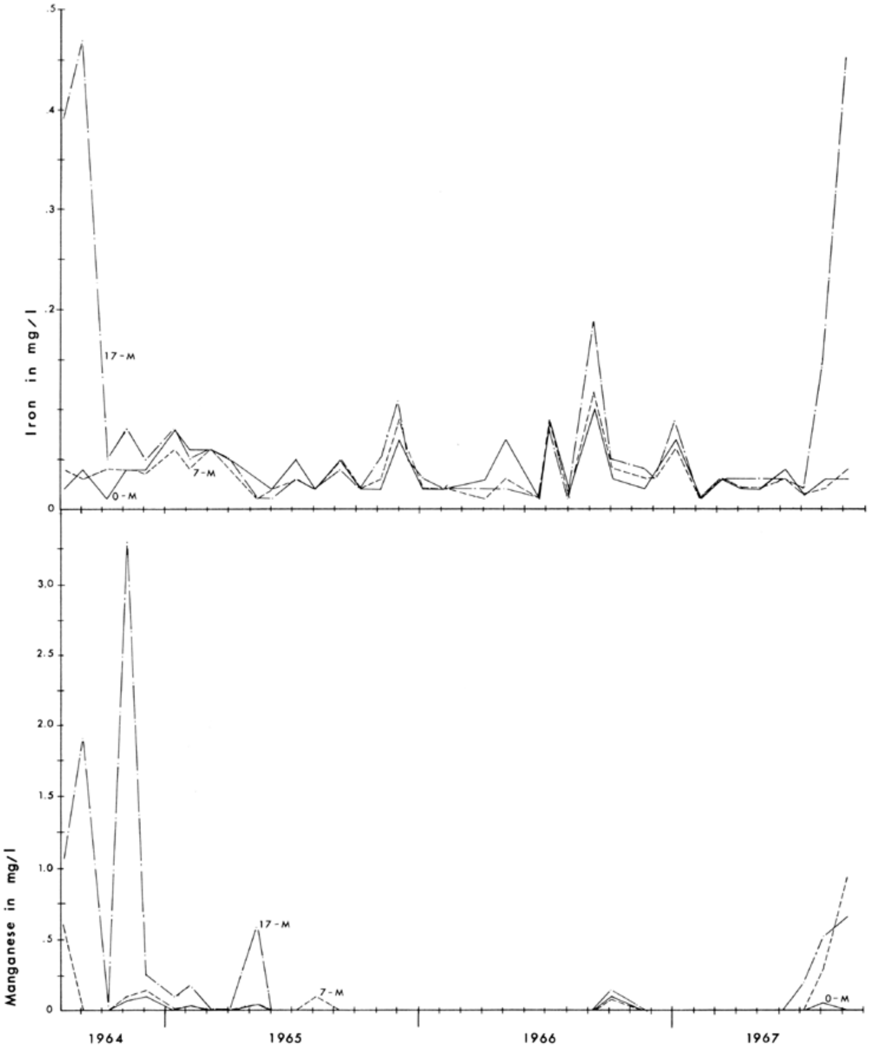

FIGURE 46. Iron and manganese concentrations at 0, 7 and 17 meters depths from August 1964 through September 1967.

FIGURE 46. Iron and manganese concentrations at 0, 7 and 17 meters depths from August 1964 through September 1967

A negative correlation between water volume and certain chemical concentrations is evident. This relationship is discussed earlier in this paper. Whereas an exponential relationship is suggested for these analyses made prior to 1964, a linear relationship appears to exist during 1964–67. This may be due in part to a smaller variation in water volume compared to that of the earlier period. Improved analytical technique may also be responsible for this apparent difference.

of the three factors suggested to account for the relationship between water volume and ion concentration, only the ratio of sludge area to water volume, and evaporation appear significant here. Any differences caused by stratification are not readily apparent.

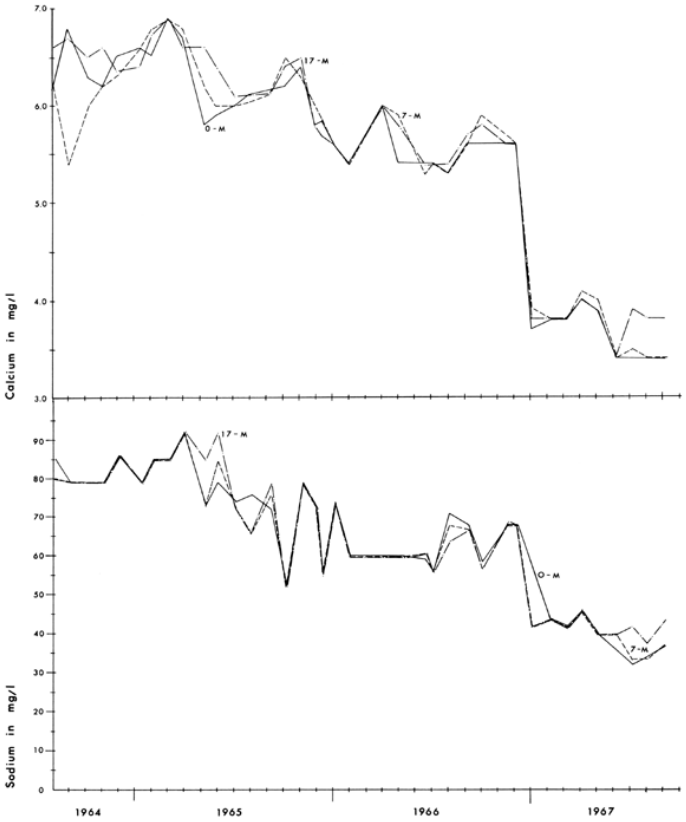

FIGURE 47. Calcium and sodium concentrations at 0, 7 and 17 meters depths from August 1964 through September 1967.

FIGURE 47. Calcium and sodium concentrations at 0, 7 and 17 meters depths from August 1964 through September 1967

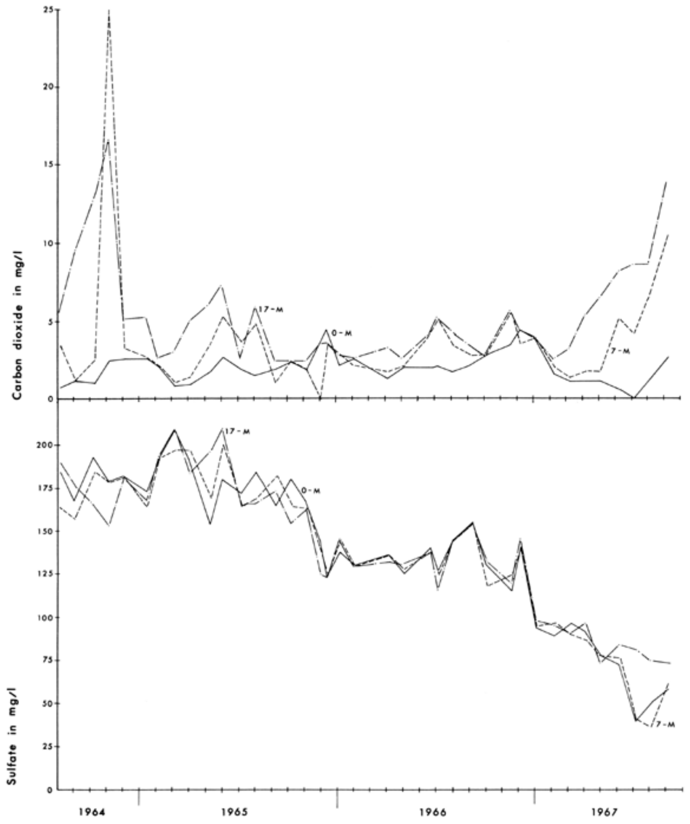

FIGURE 48. Carbon dioxide and sulfate concentrations at 0, 7 and 17 meters depths from August 1964 through September 1967.

FIGURE 48. Carbon dioxide and sulfate concentrations at 0, 7 and 17 meters depths from August 1964 through September 1967

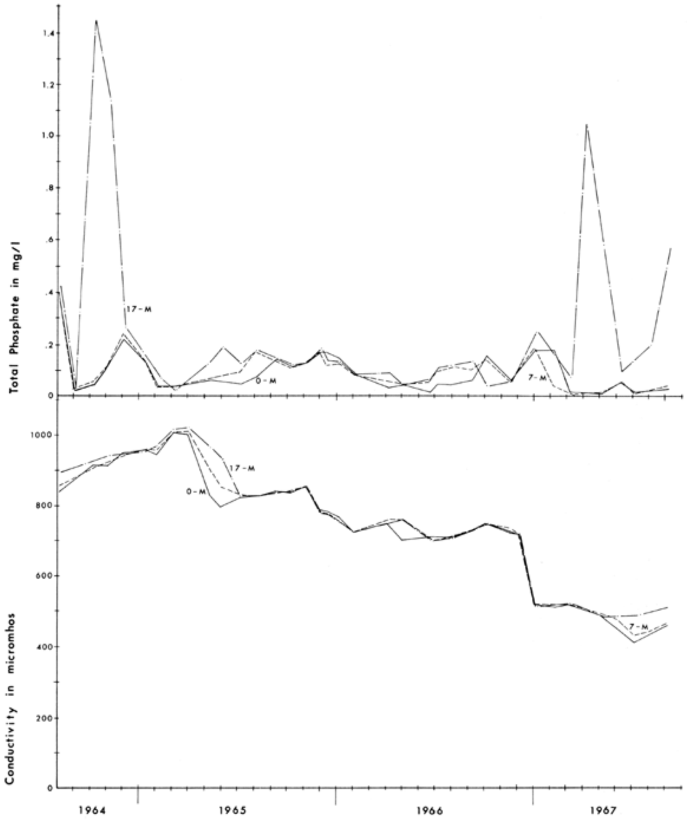

FIGURE 49. Total phosphate and conductivity values at 0, 7 and 17 meters depths from August 1964 through September 1967.

FIGURE 49. Total phosphate and conductivity values at 0, 7 and 17 meters depths from August 1964 through September 1967

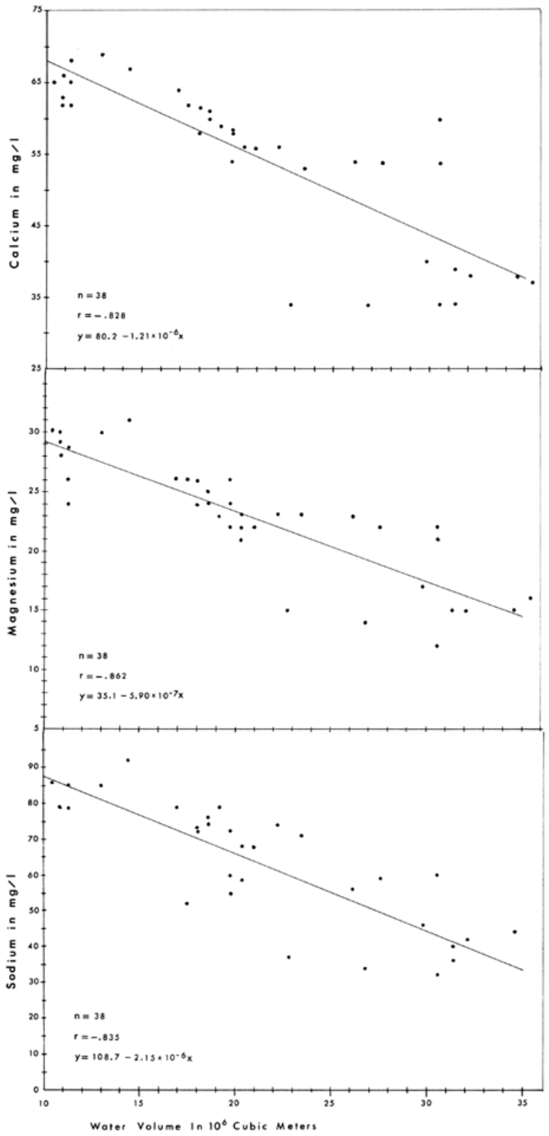

FIGURE 50. Scattergram plots of surface calcium, magnesium and sodium values vs. water volumes at El Capitan from August 1964 through September 1967. The least-squares regression line is also shown.

FIGURE 50. Scattergram plots of surface calcium, magnesium and sodium values vs. water volumes at El Capitan from August 1964 through September 1967. The least-squares regression line is also shown

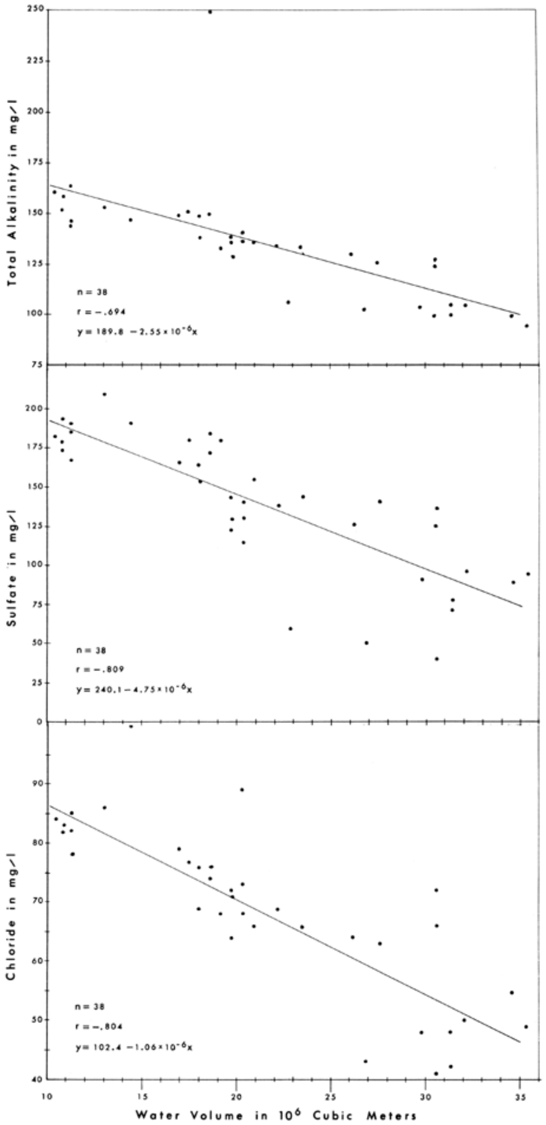

FIGURE 51. Scattergram plots of surface total alkalinity, sulfate, and chloride values vs. water volumes at El Capitan from August 1964 through September 1967. The least-squares regression line is also shown.

FIGURE 51. Scattergram plots of surface total alkalinity, sulfate, and chloride values vs. water volumes at El Capitan from August 1964 through September 1967. The least-squares regression line is also shown

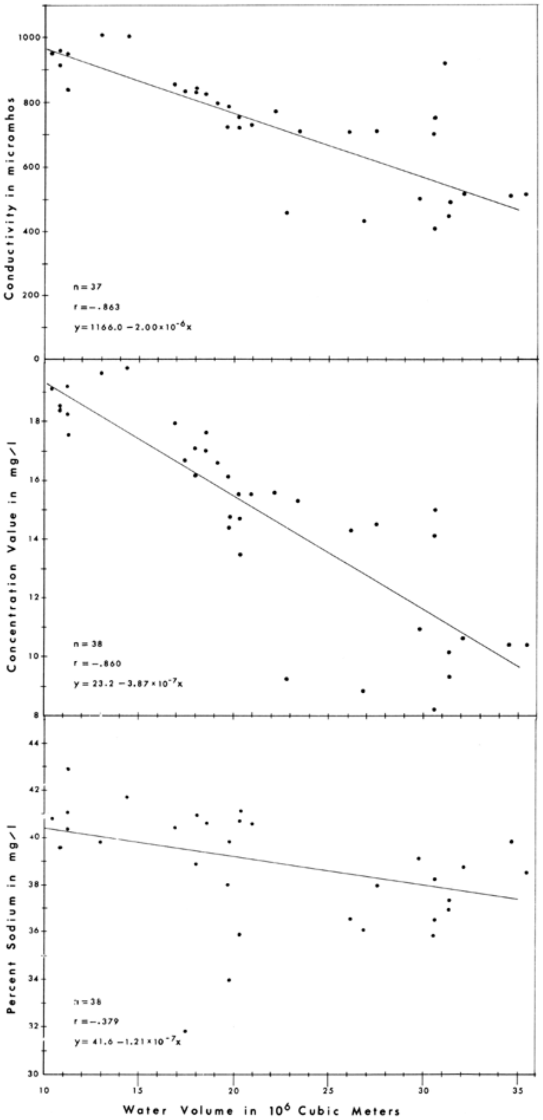

FIGURE 52. Scattergram plots of surface conductivity, concentration value and percent sodium values vs. water volumes at El Capitan from August 1964 through September 1967. The least-squares regression line is also shown.

FIGURE 52. Scattergram plots of surface conductivity, concentration value and percent sodium values vs. water volumes at El Capitan from August 1964 through September 1967. The least-squares regression line is also shown

6. FISHERIES BENEFITS FROM AIR INJECTION

From the fisheries management standpoint, the most appropriate method of aerating depends ultimately on the: (i) specific limnology of the lake under consideration, (ii) relative importance of changes caused by the aeration system, and (iii) desired fisheries management program. These factors, in addition to other multiple use conditions, must be considered simultaneously.

Changes caused by a given aeration system will conflict at times, with different interest group goals. Aeration by destratification may be most beneficial to a warmwater fishery, but preclude the establishment or continuance of a year-around coldwater fishery. Hypolimnion aeration may be most beneficial to a year-around trout fishery, but not reduce evaporation. Destratification may result in a significant savings in evaporation, but eliminate a coldwater fishery potential and cause undesirable algae growth. Consequently, an overall and somewhat subjective appraisal of any situation should be made before deciding to install an aeration system. Water managers with the best of intentions may be discouraged because their "bubbler" is not a panacea for all that ails their lake. Aeration of a shallow lake with a reduced hypolimnion, or none at all, could have essentially no ecological effect. However, in all reservoirs thus far aerated, the results are generally beneficial in all measured aspects and are financially profitable.

Fishery management benefits from air injection should be considered under two main categories: (i) Aeration with Thermal Destratification, and (ii) Aeration without Destratification. Although the benefits from either category may be similar for a given lake situation, the potentials of each category are unique and justify separate consideration.

6.1. Aeration With Destratification

Any of several techniques previously discussed may be used to artificially destratify and aerate a lake. Each method consists essentially of mixing hypolimnion water with surface water. The resultant mixture is aerated by contact with injected air, the atmosphere and aquatic plants. Although the summer surface temperature may be lowered slightly by continuous mixing, the bottom temperatures will approach, or equal, the surface temperature. This may be beneficial to warmwater fishes, but disastrous to coldwater fishes.

We do not understand all the fishery consequences of artificial destratification. However, we measured and observed some effects and inferred others. We observed the effects on the vertical distribution of fishes (L. W. Miller, unpublished data). During the summer, 1964, the oxygen deficit associated with stratification limited all fish species to the epilimnion. Their vertical distribution extended deeper after the natural fall overturn and remained deep until thermal stratification commenced in the spring, 1965. Mayhew (1963) found a similar distribution pattern in Red Haw Lake, Iowa. He concluded this cycle adversely affected fish growth and angler success. Growth checks and retarded growth rates are indicated. He suggests extreme stratification limits bluegill growth rates. Angler success is partly reduced by anglers fishing below the metalimnion.

Red Haw Lake has a pronounced oxygen deficit starting in the metalimnion during the summer and fish are not present in the hypolimnion. Horak and Tanner (1964) observed similar depth distribution patterns in Horsetooth Reservoir, Colorado. This reservoir supports coldwater fish year around. They conclude fish are limited to the epilimnion of this lake by the temperature barrier, since oxygen is not limiting below the metalimnion.

El Capitan stratification during the spring, 1965, again compressed fish distributions into the epilimnion. After artificial destratification during the summer, 1965, their distributions were deepened and approximated their winter distribution patterns. Fish species do not all capitalize equally on the increased living space available to them. Channel catfish and threadfin shad (Dorosoma petenense) extend their distributions ubiquitously after destratification. Walleye distribution is significantly deeper after destratification (Miller, 1967), but does not extend as deep as the catfish or shad.

We can infer some consequences of increasing available living space. Intuitively, I expect this change is beneficial.

Space may be a prime factor limiting a fish population. Destratification increases the available space and thus may allow the population to increase. Expanding fish populations generally provide good fishing. Expanding fish populations occur in new impoundments, following chemical treatment to control fish populations in existing impoundments, and in some fluctuating reservoirs.

Food density is another important factor that may limit a fish population. Destratification increases the depth distribution of benthic forage organisms and also appears to increase their total biomass (Fast, 1966[b] and unpublished data). Most benthic invertebrates are limited to the littoral zone during stratified periods. After artificial destratification, most extend their distribution uniformly to all depths. Benthic feeding fishes such as catfish, bullheads, and carp should benefit most from increased density and distribution of zoobenthos forage.

Zooplankters are also limited to the epilimnion by stratified conditions. Prior to artificial destratification, essentially all zooplankters are confined to the zone above the oxygen deficit. After destratification, their distribution extends to the bottom of the lake (Fast, unpublished data).

Artificial destratification may prevent fish kills. Kills due to epilimnion drawdown will be prevented by continuous destratification. Such fish kills may be caused by water managers withdrawing large quantities of water selectively from the epilimnion, due to poor water quality at greater depths. If this water is not replaced, the epilimnion volume may be reduced greatly relative to the hypolimnion volume. A strong wind, or the fall turnover may rapidly mix the diminished epilimnion with the stagnant deep water. The oxygen content throughout the lake may be drastically reduced and suffocate the fish. In addition to the oxygen deficit threat, an algae bloom may develop after mixing.

The decaying algae may also reduce the oxygen concentration enough to cause fish suffocation.

Continuous destratification may reduce fish kills by limiting the intensity and frequency of algae blooms. Algae blooms in Lake Wohlford appear to be damped by destratification (Fast, 1966[b]). In addition to preventing the blooms, diffuse aeration may add enough oxygen directly to the water to carry fish through critical periods should a bloom occur.

Aeration may prevent fish winter kills (Woods, 1961; Rasmussen, 1960; Schmitz, 1958). However, some investigators have not been successful (Patriache, 1961). Fish winter kills often occur in ice-covered lakes if oxygen concentrations below the ice are reduced. Oxygen in these lakes comes mostly from photosynthesis of submerged aquatic plants. If photosynthesis is inhibited by low light intensities, oxygen is depleted by respiration and decay of organic materials. Light is often limited by cloudy weather or snow-covered ice.

Water is at maximum density at 3.98°C. Water above or below this temperature is less dense. Hence, water under an ice-covered lake will exhibit inverse stratification. The coldest water, at 0°C is just under the ice and the warmest, at 3.98°C or less is on the bottom.

Warm bottom water is lifted to the surface and melts the ice if air is injected along the bottom of an ice-covered lake. Rasmussen (1960) melted about 50 cm.of ice with about 60 cm of snow cover by injecting air in Soda Lake, Wyoming.

Although artificial mixing can assist several types of chemical dispersion, its use to eliminate unwanted fish populations is promising. Thermal stratification inhibits the dispersal of some types of fish toxicants. (Clemens and Martin, 1952; Hooper and Grzenda, 1955).

Air injection could be used to distribute rotenone in a reservoir. The toxicant could be applied either directly at the air discharge location or at several locations in the lake. Forced circulation may mix the compound uniformly throughout the lake and thereby eliminate pockets of low concentration.

Destratification may be used in post-treatment rehabilitation of the lake. Continued air injection should reduce detoxification time. Rotenone is detoxified rapidly by increased temperature and concentrations of oxygen and light. Lake circulation results in an increased heat content. The bottom temperature approaches the surface temperature and the total heat content of the lake is much greater. Because of uniform temperature, the entire lake should detoxify at about the same time. Artificial destratification adds oxygen to the water and brings deep water in contact with surface light. These conditions and the increased heat content should reduce detoxification time.

A portable air injection system could be used to assist lake rehabilitation operations. The device could be moved from lake to lake as needed.

Long term destratification may reduce or reverse the natural eutrophication process. Under normal stratified conditions, certain ions will concentrate in the hypolimnion. Water withdrawals during this period are generally made from the epilimnion. Due to this practice, a lake may accumulate certain ions in the hypolimnion during 7 months of each year. During the winter, the lake is well mixed and all ions will tend to be removed nonselectively. Intuitively, I expect the yearly period of stratification to result in the accumulation of nutrients and gradual eutrophication of the lake.

If the lake is never allowed to stratify and thereby approximates the winter mixed condition, ions should be removed nonselectively. Under these conditions the lake water should tend toward the ionic content of its water sources. This state would never be attained, however, because of ionic diffusion from the bottom sediments. If ion transfer from the bottom and water retention time are low, destratification may retard eutrophication due to this process.

During normal stratified conditions, organic material settles in the profoundal zone. Accumulation of this material is assisted by anaerobic conditions since the rate of decomposition is much slower by anaerobiosis. The accumulation of this organic material in the lake enhances eutrophication. Artificial destratification should reduce the rate of organic sedimentation and thus retard eutrophication by this process. Destratification eliminates anaerobic conditions at the water and mudwater interface. This should increase the rate of organic decomposition and oxidation and reduce the accumulation of organic sediments. In addition, destratification will increase the bottom temperatures greatly. The destratified bottom temperature may be 10°C warmer than stratified bottom temperatures. Theoretically, the shift from anaerobic to aerobic decomposition and increased temperatures should more than double the rate of organic decomposition. This may not only reduce the rate of organic sedimentation, but oxidize and remove quantities of accumulated organic material.

Artificial destratification may result in the more efficient utilization of nutrients through autofertilization. Under normal stratified conditions nutrients are often lost to the ecosystem during long periods. Destratification may decrease the turn around time for these nutrients and thereby increase the overall productivity and efficiency of the food web. This possibility is evidenced by an increased zoobenthos total biomass and density (Fast, 1966b) without an apparent commensurate increase in net primary productivity (Fast, unpublished data).

6.2. Aeration Without Destratification

Bernhardt's (1967) hypolimnion aeration system described in this bulletin is the only tested method that I know of for aerating the hypolimnion without destratifying the lake. This new and unique technique holds much promise for management of coldwater and potential coldwater fisheries.

Using the hypolimnion aerator, the stagnant hypolimnion water may be aerated without mixing it with the epilimnion or metalimnion. In many situations this is desirable from the fisheries management standpoint, as well as domestic water management's.

By aerating without mixing, most of the fishery benefits discussed under Aeration by Destratification should be realized, with the additional benefit of not increasing the heat budget and minimum water temperatures. By using a hypolimnion aerator, many otherwise strictly warmwater fisheries may be transformed into two story lakes that support year around warmwater and coldwater fisheries. If this is the case, it may be possible to economically plant fry, fingerlings and/or sub-catchable trout in these lakes and let the lake, rather than the hatchery supply the nutrition to produce catchable size trout. It is presently impossible to do this in most stratified eutrophic lakes since the trout would not put on enough growth to attain catchable size before the advent of lethal epilimnion temperatures, or lethal hypolimnion oxygen concentrations. In destratified lakes, the entire lake may attain lethal temperatures.

Hypolimnion aeration is beneficial to water managers since it provides cold, oxygenated water which is essential for many domestic uses. However, because hypolimnion aeration does not mix the entire water mass, there will not be a reduction in yearly evaporation by this method. This is probably the only potentially deleterious consequence of this technique, but this will not be a significant factor in many lake situations. Even if it is, the other benefits may more than compensate for the loss of evaporation savings.

7. ECONOMIC BENEFITS

A complete monetary evaluation of any ecological change is difficult, especially if some consequences of the change are difficult or impossible to measure. Artificial aeration is a gross ecological alteration of the lake habitat and consequently affects essentially every process in the lake. The consequences of aeration vary as functions of method used and lake type. Furthermore, certain alterations may be considered very important in one lake situation, but not so important in another. Certain domestic water managers exclude all recreational use of their water supply. They do not care about the fishery benefits of aeration, but might be very interested in its effects on water quality and evaporation savings. The converse may be true in strictly recreational lakes. In most multiple use situations both water quality and fishery consequences are of major importance. As our population and recreational needs increase, continued emphasis is placed on the development of multiple use reservoirs. The greatest overall benefits from aeration are realized in these impoundments.

Although many of the fishery benefits are difficult to evaluate except esthetically, I assume *a priori* that changes in the fishery will eventually be manifested in the local economy of most lakes. Increased fish forage, expanded fish population size, decreased fish kills and other possible fishery benefits from aeration should increase fishing quality. This in turn should increase patronage and become a financial asset.

Establishment of a new fishery in a reservoir, such as a year-around trout fishery, is easier to evaluate. In many areas such as southern California, few lakes maintain year-around coldwater fisheries. Summer trout fishing is essentially non-existent. If by hypolimnion aeration or some other aeration technique, a summer trout fishery could be established, I would expect a very profitable return.

It is easiest to evaluate monetarily certain water quality improvements. These include improvements in taste and odor, reduced chlorine dosage, chemical dispersion, and reduced evaporation rates.

Aeration has reduced or eliminated many cases of extreme taste and odor caused by thermal stratification and stagnation (Nickerson, 1961; Ogborn, 1966; Ford, 1963). In some cases, alternate sources of water are sought because of the intensity of the problem. The taste and odor are often caused by increased hydrogen sulfide, iron, and manganese concentrations. These elements are oxidized to acceptable levels by aeration.

Water managers employing aeration equipment to reduce their taste and odor problems considered this both economically feasible and superior to other methods of combating the problem.

Concomitant with oxidation of anoxious substances and improvements in taste and odor is a reduction in the chlorine demand (Koberg and Ford, 1965; Ford, 1963). Diffuse aeration of Lake Wohlford reduces their breakpoint chlorine demand from about 12 mg/l to about 7 mg/l.

Chlorine savings alone saved the water managers about $6,000 annually, (Jim Burns, personal communication). In addition, they estimated about $10,000 worth of extra chlorination equipment would have been needed if this reduction by aeration had not been achieved. They estimate an annual operating cost of about $2,300 for their aeration system. This includes amortization of their system's hardware, yearly power consumption and compressor maintenance. They achieved additional savings in evaporation, and consumer complaints dropped off. The aeration system at this lake resulted in a direct savings to the water managers from the standpoint of water quality control alone.

Forced circulation can be used economically to disperse chemicals within a reservoir. Riddick (1957) dispersed lime using a floating aerator. This method of dispersal proved economically superior to other methods of application. He added lime to Indian Brook Reservoir to increase the coagulating properties of the raw water and reduce corrosion. He also observed a reduction in iron concentration, reduction in color and a numeric increase in certain zooplankters.

Ogborn (1966) dispersed alum using a plastic hose distribution system. He installed this system in two Johnstown, Pennsylvania domestic water reservoirs to improve taste and odor. He eliminated the taste and odor problem, but caused an increase in turbidity attributed to biodegradation of the bottom sediments. He used this system to apply alum, and after 24 hours reservoir transparency changed from muddy to "crystal clear". Copper sulfate, rotenone, and other chemicals may be economically dispersed using an aeration system.

Koberg (1964) estimates a 5% annual reduction in evaporation at Lake Wohlford due to artificial destratification. He estimates a 4.1% reduction during 1965 and a 6.5% reduction during 1966 at El Capitan Reservoir (personal communication). We destratified El Capitan beginning in June 1965 and March 1966.

Assuming aeration reduced evaporation by 6.5% during 1966, this saved about 2.36×10^5 cubic meters of water, (about 192 acre-feet). At $40.50 per 1,000 cubic meters ($50 per acre-foot), this saved about $9,600 of water from evaporating. The yearly cost of operating our diffuse aeration system at El Capitan is about $3,000 (Table 1). Savings from evaporation reduction alone more than paid for our system.

Figure 53 is a nomograph for estimating savings from reduced evaporation rates. Each regression line represents evaporation rate prior to destratification. Savings due to reduced evaporation is based on an estimated 4% annual reduction and water costs of $40.50 per 1,000 cubic meters. A reduction of more than 4% annually should be realized from large, deep reservoirs. Table 8 illustrates estimated evaporation rates for several San Diego County reservoirs. The surface area necessary to just pay for the yearly operation and maintenance of a diffuse aeration system (about $3,000) is defined as the compensation area. This assumes a reduction in evaporation of only 4% and water costs of $40.50 per 1,000 cubic meters.

Artificial circulation of ice-covered waters may be profitable. By circulating these inversely stratified waters, ice cover may be removed for navigational purposes. A diffuse air injector removed about 60 cm

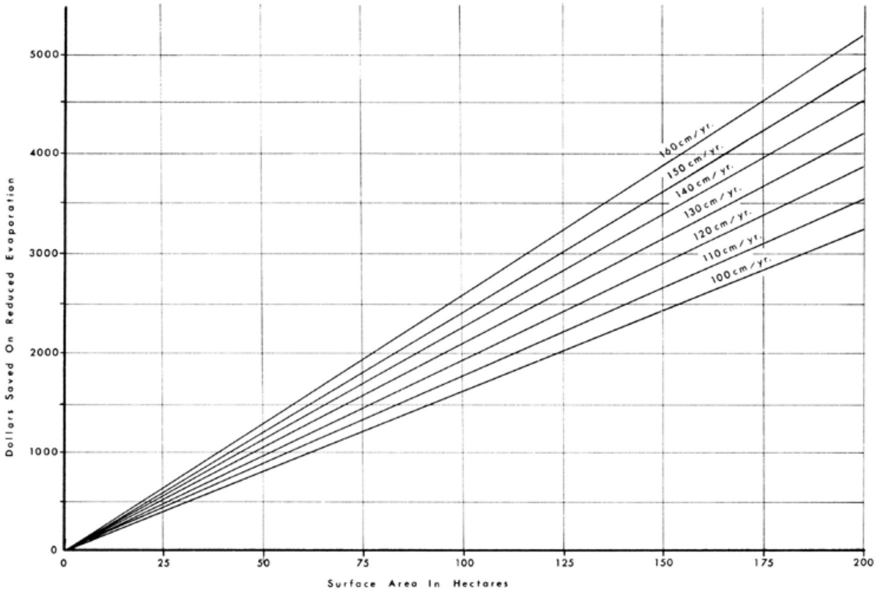

FIGURE 53. Nomograph illustrating the relationship between evaporation savings, surface area and evaporation rates. Savings are based on a 4% reduction in evaporation and water costs of $40.50 per 1000 cubic meters, (i.e. $50 per acre-foot).

FIGURE 53. Nomograph illustrating the relationship between evaporation savings, surface area and evaporation rates. Savings are based on a 4% reduction in evaporation and water costs of $40.50 per 1000 cubic meters, (i.e. $50 per acre-foot)

TABLE 8

Yearly Evaporation Rates for the 1966–67 Water Year and Compensation Areas for Several San Diego County Reservoirs. Compensation Areas Are Based on 4% Reduction in Evaporation Rates and Water Costs of $40.50 Per 1000 Cubic Meters ($50 Per Acre-Foot).

Reservoir	Evaporation in centimeters	Compensation area in hectares	Reservoir	Evaporation in centimeters	Compensation area in hectares
Barrett	87.4	213	Morena	142.6	128
Murray	110.0	168	Miramar	146.5	125
San Dieguito	114.8	160	Sutherland	149.4	123
San Vicente	118.2	156	Hodges	151.3	121
El Capitan	132.0	138			
Lower Otay	136.0	134	Mean =	128.8	147

TABLE 8

Yearly Evaporation Rates for the 1966–67 Water Year and Compensation Areas for Several San Diego County Reservoirs. Compensation Areas Are Based on 4% Reduction in Evaporation Rates and Water Costs of $40.50 Per 1000 Cubic Meters ($50 Per Acre-Foot)

of ice from Babine Lake, British Columbia (Engineering News-Record, 1966). Even during the coldest months, an open stretch of water about 3000 meters long is kept open to Copper Island. This permits access to year-round mining operations on Copper Island that might otherwise be limited to only ice-free months.

Artificial circulation can be used to keep harbors ice free. It may be more economical to de-ice a harbor than to remove the boats for the winter.

Artificial aeration and circulation, either by destratification or hypolimnion aeration, may be financially profitable. Many studies demonstrate this without a doubt. Use of aeration equipment is spreading as water manipulators become aware of its potential. Eventually, I expect to see most of our major reservoir systems employing aeration devices. They will be as commonplace as spillways, if not as useful.

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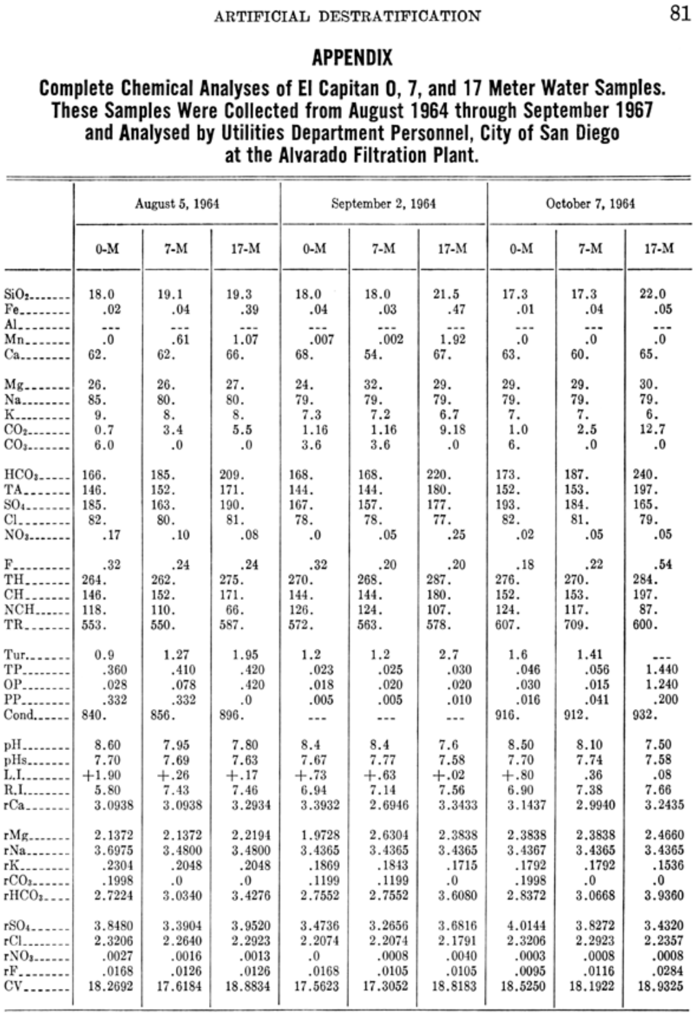
APPENDIX



APPENDIX

Complete Chemical Analyses of El Capitan 0, 7, and 17 Meter Water Samples. These Samples Were Collected from August 1964 through September 1967 and Analysed by Utilities Department Personnel, City of San Diego at the Alvarado Filtration Plant.

	August 5, 1964			September 2, 1964			October 7, 1964		
	0-M	7-M	17-M	0-M	7-M	17-M	0-M	7-M	17-M
SiO_2	18.0	19.1	19.3	18.0	18.0	21.5	17.3	17.3	22.0
Fe	.02	.04	.39	.04	.03	.47	.01	.04	.05
Al	---	---	---	---	---	---	---	---	---
Mn	.0	.61	1.07	.007	.002	1.92	.0	.0	.0
Ca	62.	62.	66.	68.	54.	67.	63.	60.	65.
Mg	26.	26.	27.	24.	32.	29.	29.	29.	30.
Na	85.	80.	80.	79.	79.	79.	79.	79.	79.
K	9.	8.	8.	7.3	7.2	6.7	7.	7.	6.
CO_2	0.7	3.4	5.5	1.16	1.16	9.18	1.0	2.5	12.7
CO_3	6.0	.0	.0	3.6	3.6	.0	6.	.0	.0
HCO_3	166.	185.	209.	168.	168.	220.	173.	187.	240.
TA	146.	152.	171.	144.	144.	180.	152.	153.	197.
SO_4	185.	163.	190.	167.	157.	177.	193.	184.	165.
Cl	82.	80.	81.	78.	78.	77.	82.	81.	79.
NO_3	.17	.10	.08	.0	.05	.25	.02	.05	.05
F	.32	.24	.24	.32	.20	.20	.18	.22	.54
TH	264.	262.	275.	270.	268.	287.	276.	270.	284.
CH	146.	152.	171.	144.	144.	180.	152.	153.	197.
NCH	118.	110.	66.	126.	124.	107.	124.	117.	87.
TR	553.	550.	587.	572.	563.	578.	607.	709.	600.
Tur	0.9	1.27	1.95	1.2	1.2	2.7	1.6	1.41	---
TP	.360	.410	.420	.023	.025	.030	.046	.056	1.440
OP	.028	.078	.420	.018	.020	.020	.030	.015	1.240
PP	.332	.332	.0	.005	.005	.010	.016	.041	.200
Cond.	840.	856.	896.	---	---	---	916.	912.	932.
pH	8.60	7.95	7.80	8.4	8.4	7.6	8.50	8.10	7.50
pHs	7.70	7.69	7.63	7.67	7.77	7.58	7.70	7.74	7.58
L.I.	+1.90	+.26	+.17	+.73	+.63	+.02	+.80	.36	.08
R.I.	5.80	7.43	7.46	6.94	7.14	7.56	6.90	7.38	7.66
rCa	3.0938	3.0938	3.2934	3.3932	2.6946	3.3433	3.1437	2.9940	3.2435
rMg	2.1372	2.1372	2.2194	1.9728	2.6304	2.3838	2.3838	2.3838	2.4660
rNa	3.6975	3.4800	3.4800	3.4365	3.4365	3.4365	3.4367	3.4365	3.4365
rK	.2304	.2048	.2048	.1869	.1843	.1715	.1792	.1792	.1536
rCO_3	.1998	.0	.0	.1199	.1199	.0	.1998	.0	.0
$rHCO_3$	2.7224	3.0340	3.4276	2.7552	2.7552	3.6080	2.8372	3.0668	3.9360
rSO_4	3.8480	3.3904	3.9520	3.4736	3.2656	3.6816	4.0144	3.8272	3.4320
rCl	2.3206	2.2640	2.2923	2.2074	2.2074	2.1791	2.3206	2.2923	2.2357
rNO_3	.0027	.0016	.0013	.0	.0008	.0040	.0003	.0008	.0008
rF	.0168	.0126	.0126	.0168	.0105	.0105	.0095	.0116	.0284
CV	18.2692	17.6184	18.8834	17.5623	17.3052	18.8183	18.5250	18.1922	18.9325

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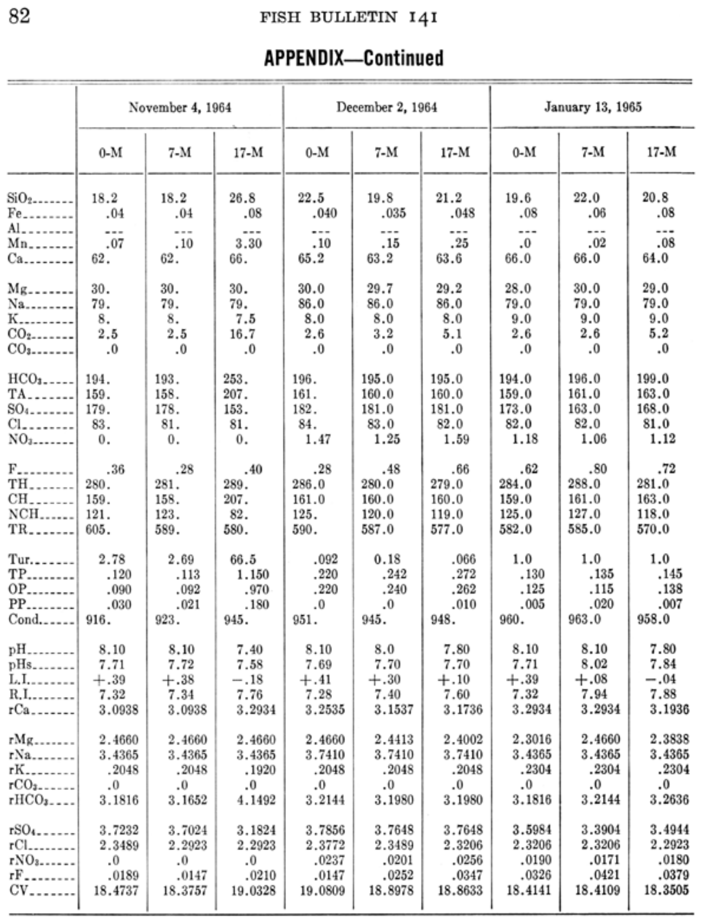
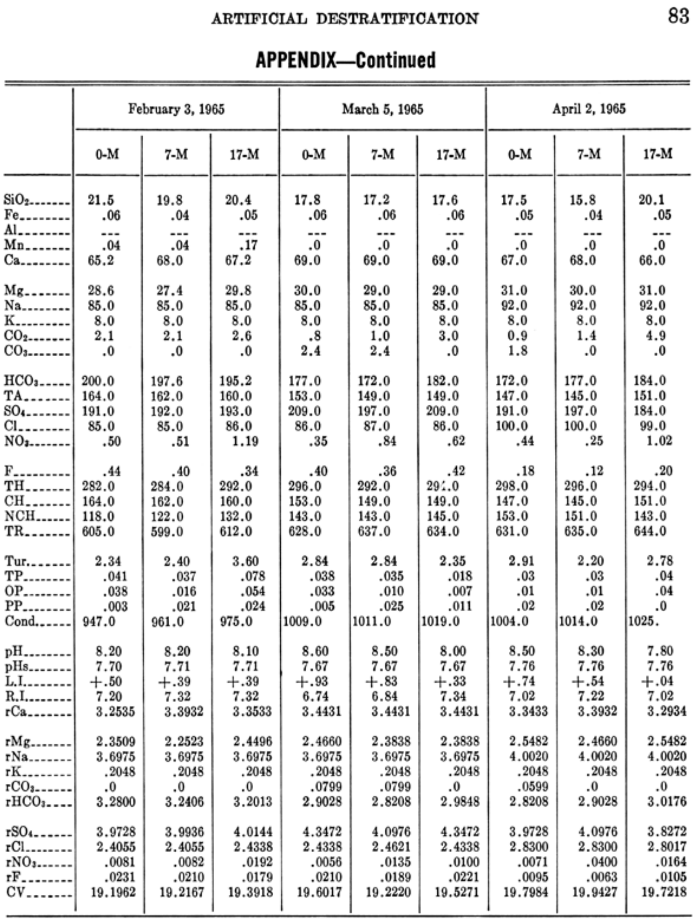


APPENDIX—Continued

	November 4, 1964			December 2, 1964			January 13, 1965		
	0-M	7-M	17-M	0-M	7-M	17-M	0-M	7-M	17-M
SiO_2	18.2	18.2	26.8	22.5	19.8	21.2	19.6	22.0	20.8
Fe	.04	.04	.08	.040	.035	.048	.08	.06	.08
Al	---	---	---	---	---	---	---	---	---
Mn	.07	.10	3.30	.10	.15	.25	.0	.02	.08
Ca	62.	62.	66.	65.2	63.2	63.6	66.0	66.0	64.0
Mg	30.	30.	30.	30.0	29.7	29.2	28.0	30.0	29.0
Na	79.	79.	79.	86.0	86.0	86.0	79.0	79.0	79.0
K	8.	8.	7.5	8.0	8.0	8.0	9.0	9.0	9.0
CO_2	2.5	2.5	16.7	2.6	3.2	5.1	2.6	2.6	5.2
CO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
HCO_3	194.	193.	253.	196.	195.0	195.0	194.0	196.0	199.0
TA	159.	158.	207.	161.	160.0	160.0	159.0	161.0	163.0
SO_4	179.	178.	153.	182.	181.0	181.0	173.0	163.0	168.0
Cl	83.	81.	81.	84.	83.0	82.0	82.0	82.0	81.0
NO_3	0.	0.	0.	1.47	1.25	1.59	1.18	1.06	1.12
F	.36	.28	.40	.28	.48	.66	.62	.80	.72
TH	280.	281.	289.	286.0	280.0	279.0	284.0	288.0	281.0
CH	159.	158.	207.	161.0	160.0	160.0	159.0	161.0	163.0
NCH	121.	123.	82.	125.	120.0	119.0	125.0	127.0	118.0
TR	605.	589.	580.	590.	587.0	577.0	582.0	585.0	570.0
Tur.	2.78	2.69	66.5	.092	0.18	.066	1.0	1.0	1.0
TP	.120	.113	1.150	.220	.242	.272	.130	.135	.145
OP	.090	.092	.970	.220	.240	.262	.125	.115	.138
PP	.030	.021	.180	.0	.0	.010	.005	.020	.007
Cond.	916.	923.	945.	951.	945.	948.	960.	963.0	958.0
pH	8.10	8.10	7.40	8.10	8.0	7.80	8.10	8.10	7.80
pHs	7.71	7.72	7.58	7.69	7.70	7.70	7.71	8.02	7.84
L.I.	+.39	+.38	−.18	+.41	+.30	+.10	+.39	+.08	−.04
R.I.	7.32	7.34	7.76	7.28	7.40	7.60	7.32	7.94	7.88
rCa	3.0938	3.0938	3.2934	3.2535	3.1537	3.1736	3.2934	3.2934	3.1936
rMg	2.4660	2.4660	2.4660	2.4660	2.4413	2.4002	2.3016	2.4660	2.3838
rNa	3.4365	3.4365	3.4365	3.7410	3.7410	3.7410	3.4365	3.4365	3.4365
rK	.2048	.2048	.1920	.2048	.2048	.2048	.2304	.2304	.2304
rCO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
$rHCO_3$	3.1816	3.1652	4.1492	3.2144	3.1980	3.1980	3.1816	3.2144	3.2636
rSO_4	3.7232	3.7024	3.1824	3.7856	3.7648	3.7648	3.5984	3.3904	3.4944
rCl	2.3489	2.2923	2.2923	2.3772	2.3489	2.3206	2.3206	2.3206	2.2923
rNO_3	.0	.0	.0	.0237	.0201	.0256	.0190	.0171	.0180
rF	.0189	.0147	.0210	.0147	.0252	.0347	.0326	.0421	.0379
CV	18.4737	18.3757	19.0328	19.0809	18.8978	18.8633	18.4141	18.4109	18.3505

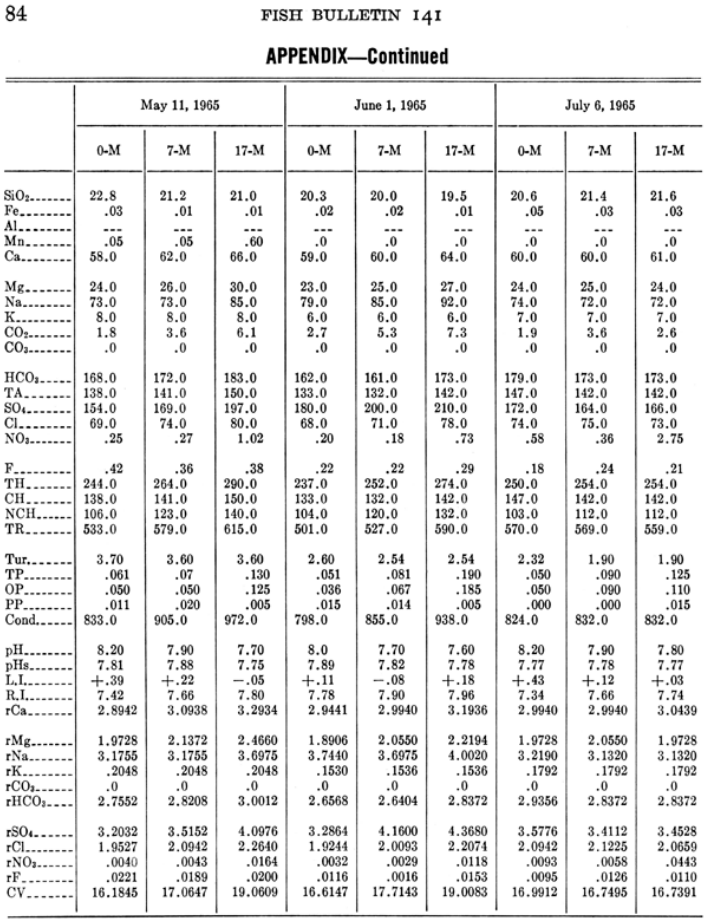
APPENDIX—Cont'd.



APPENDIX—Continued

	February 3, 1965			March 5, 1965			April 2, 1965		
	0-M	7-M	17-M	0-M	7-M	17-M	0-M	7-M	17-M
SiO$_2$	21.5	19.8	20.4	17.8	17.2	17.6	17.5	15.8	20.1
Fe	.06	.04	.05	.06	.06	.06	.05	.04	.05
Al	---	---	---	---	---	---	---	---	---
Mn	.04	.04	.17	.0	.0	.0	.0	.0	.0
Ca	65.2	68.0	67.2	69.0	69.0	69.0	67.0	68.0	66.0
Mg	28.6	27.4	29.8	30.0	29.0	29.0	31.0	30.0	31.0
Na	85.0	85.0	85.0	85.0	85.0	85.0	92.0	92.0	92.0
K	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
CO$_2$	2.1	2.1	2.6	.8	1.0	3.0	0.9	1.4	4.9
CO$_3$	.0	.0	.0	2.4	2.4	.0	1.8	.0	.0
HCO$_3$	200.0	197.6	195.2	177.0	172.0	182.0	172.0	177.0	184.0
TA	164.0	162.0	160.0	153.0	149.0	149.0	147.0	145.0	151.0
SO$_4$	191.0	192.0	193.0	209.0	197.0	209.0	191.0	197.0	184.0
Cl	85.0	85.0	86.0	86.0	87.0	86.0	100.0	100.0	99.0
NO$_3$	.50	.51	1.19	.35	.84	.62	.44	.25	1.02
F	.44	.40	.34	.40	.36	.42	.18	.12	.20
TH	282.0	284.0	292.0	296.0	292.0	294.0	298.0	296.0	294.0
CH	164.0	162.0	160.0	153.0	149.0	149.0	147.0	145.0	151.0
NCH	118.0	122.0	132.0	143.0	143.0	145.0	153.0	151.0	143.0
TR	605.0	599.0	612.0	628.0	637.0	634.0	631.0	635.0	644.0
Tur	2.34	2.40	3.60	2.84	2.84	2.35	2.91	2.20	2.78
TP	.041	.037	.078	.038	.035	.018	.03	.03	.04
OP	.038	.016	.054	.033	.010	.007	.01	.01	.04
PP	.003	.021	.024	.005	.025	.011	.02	.02	.0
Cond	947.0	961.0	975.0	1009.0	1011.0	1019.0	1004.0	1014.0	1025.
pH	8.20	8.20	8.10	8.60	8.50	8.00	8.50	8.30	7.80
pHs	7.70	7.71	7.71	7.67	7.67	7.67	7.76	7.76	7.76
L.I.	+.50	+.39	+.39	+.93	+.83	+.33	+.74	+.54	+.04
R.I.	7.20	7.32	7.32	6.74	6.84	7.34	7.02	7.22	7.02
rCa	3.2535	3.3932	3.3533	3.4431	3.4431	3.4431	3.3433	3.3932	3.2934
rMg	2.3509	2.2523	2.4496	2.4660	2.3838	2.3838	2.5482	2.4660	2.5482
rNa	3.6975	3.6975	3.6975	3.6975	3.6975	3.6975	4.0020	4.0020	4.0020
rK	.2048	.2048	.2048	.2048	.2048	.2048	.2048	.2048	.2048
rCO$_3$	.0	.0	.0	.0799	.0799	.0	.0599	.0	.0
rHCO$_3$	3.2800	3.2406	3.2013	2.9028	2.8208	2.9848	2.8208	2.9028	3.0176
rSO$_4$	3.9728	3.9936	4.0144	4.3472	4.0976	4.3472	3.9728	4.0976	3.8272
rCl	2.4055	2.4055	2.4338	2.4338	2.4621	2.4338	2.8300	2.8300	2.8017
rNO$_3$	.0081	.0082	.0192	.0056	.0135	.0100	.0071	.0400	.0164
rF	.0231	.0210	.0179	.0210	.0189	.0221	.0095	.0063	.0105
CV	19.1962	19.2167	19.3918	19.6017	19.2220	19.5271	19.7984	19.9427	19.7218

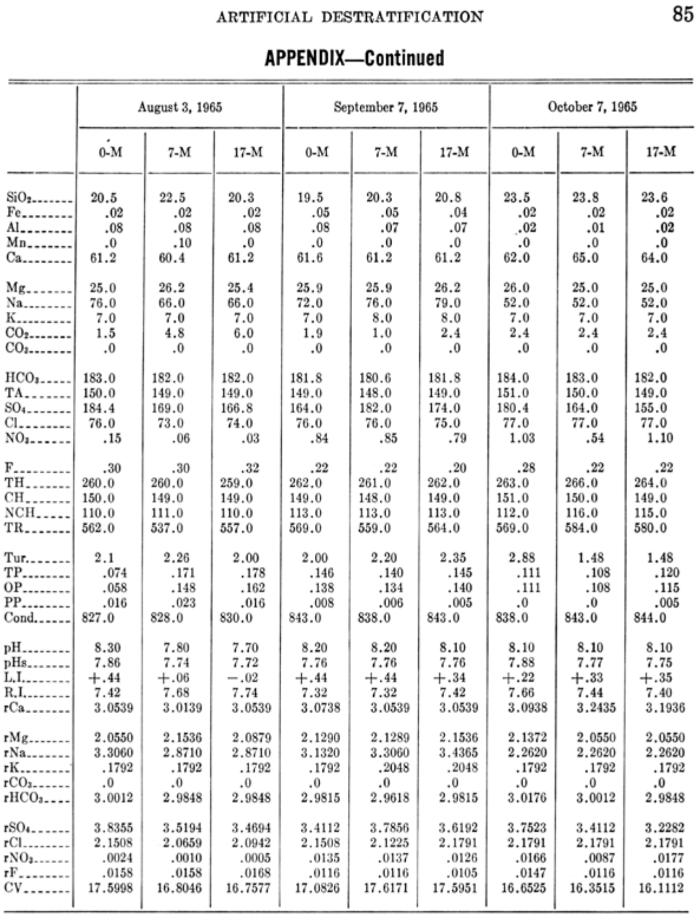
APPENDIX—Cont'd.



APPENDIX—Continued

	May 11, 1965			June 1, 1965			July 6, 1965		
	0-M	7-M	17-M	0-M	7-M	17-M	0-M	7-M	17-M
SiO_2	22.8	21.2	21.0	20.3	20.0	19.5	20.6	21.4	21.6
Fe	.03	.01	.01	.02	.02	.01	.05	.03	.03
Al	---	---	---	---	---	---	---	---	---
Mn	.05	.05	.60	.0	.0	.0	.0	.0	.0
Ca	58.0	62.0	66.0	59.0	60.0	64.0	60.0	60.0	61.0
Mg	24.0	26.0	30.0	23.0	25.0	27.0	24.0	25.0	24.0
Na	73.0	73.0	85.0	79.0	85.0	92.0	74.0	72.0	72.0
K	8.0	8.0	8.0	6.0	6.0	6.0	7.0	7.0	7.0
CO_2	1.8	3.6	6.1	2.7	5.3	7.3	1.9	3.6	2.6
CO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
HCO_3	168.0	172.0	183.0	162.0	161.0	173.0	179.0	173.0	173.0
TA	138.0	141.0	150.0	133.0	132.0	142.0	147.0	142.0	142.0
SO_4	154.0	169.0	197.0	180.0	200.0	210.0	172.0	164.0	166.0
Cl	69.0	74.0	80.0	68.0	71.0	78.0	74.0	75.0	73.0
NO_3	.25	.27	1.02	.20	.18	.73	.58	.36	2.75
F	.42	.36	.38	.22	.22	.29	.18	.24	.21
TH	244.0	264.0	290.0	237.0	252.0	274.0	250.0	254.0	254.0
CH	138.0	141.0	150.0	133.0	132.0	142.0	147.0	142.0	142.0
NCH	106.0	123.0	140.0	104.0	120.0	132.0	103.0	112.0	112.0
TR	533.0	579.0	615.0	501.0	527.0	590.0	570.0	569.0	559.0
Tur.	3.70	3.60	3.60	2.60	2.54	2.54	2.32	1.90	1.90
TP	.061	.07	.130	.051	.081	.190	.050	.090	.125
OP	.050	.050	.125	.036	.067	.185	.050	.090	.110
PP	.011	.020	.005	.015	.014	.005	.000	.000	.015
Cond.	833.0	905.0	972.0	798.0	855.0	938.0	824.0	832.0	832.0
pH	8.20	7.90	7.70	8.0	7.70	7.60	8.20	7.90	7.80
pHs	7.81	7.88	7.75	7.89	7.82	7.78	7.77	7.78	7.77
L.I.	+.39	+.22	−.05	+.11	−.08	+.18	+.43	+.12	+.03
R.I.	7.42	7.66	7.80	7.78	7.90	7.96	7.34	7.66	7.74
rCa	2.8942	3.0938	3.2934	2.9441	2.9940	3.1936	2.9940	2.9940	3.0439
rMg	1.9728	2.1372	2.4660	1.8906	2.0550	2.2194	1.9728	2.0550	1.9728
rNa	3.1755	3.1755	3.6975	3.7440	3.6975	4.0020	3.2190	3.1320	3.1320
rK	.2048	.2048	.2048	.1530	.1536	.1536	.1792	.1792	.1792
rCO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
$rHCO_3$	2.7552	2.8208	3.0012	2.6568	2.6404	2.8372	2.9356	2.8372	2.8372
rSO_4	3.2032	3.5152	4.0976	3.2864	4.1600	4.3680	3.5776	3.4112	3.4528
rCl	1.9527	2.0942	2.2640	1.9244	2.0093	2.2074	2.0942	2.1225	2.0659
rNO_3	.0040	.0043	.0164	.0032	.0029	.0118	.0093	.0058	.0443
rF	.0221	.0189	.0200	.0116	.0016	.0153	.0095	.0126	.0110
CV	16.1845	17.0647	19.0609	16.6147	17.7143	19.0083	16.9912	16.7495	16.7391

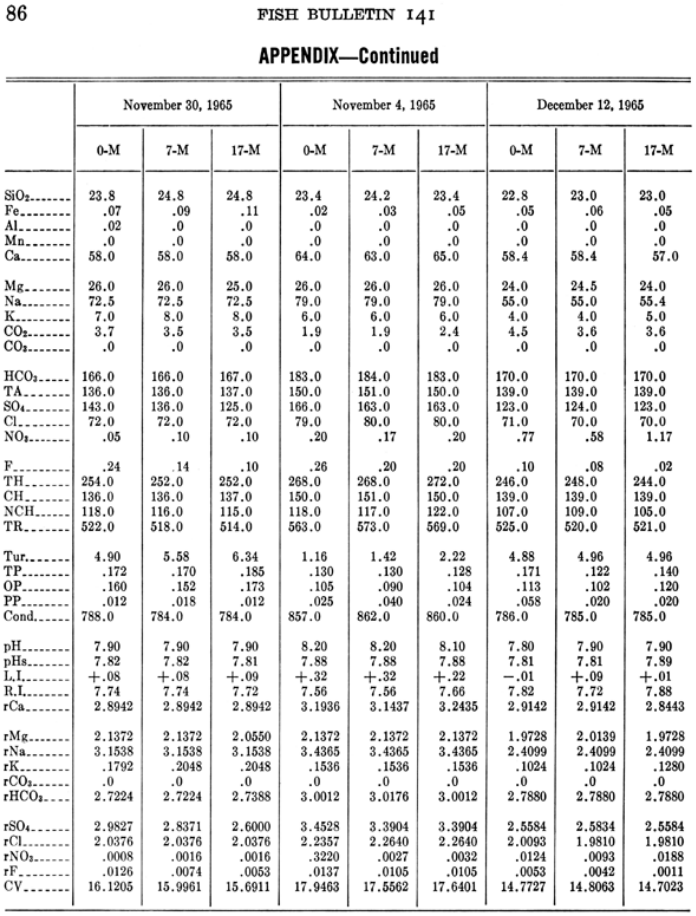
APPENDIX—Cont'd.



APPENDIX—Continued

	August 3, 1965			September 7, 1965			October 7, 1965		
	0-M	7-M	17-M	0-M	7-M	17-M	0-M	7-M	17-M
SiO_2	20.5	22.5	20.3	19.5	20.3	20.8	23.5	23.8	23.6
Fe	.02	.02	.02	.05	.05	.04	.02	.02	.02
Al	.08	.08	.08	.08	.07	.07	.02	.01	.02
Mn	.0	.10	.0	.0	.0	.0	.0	.0	.0
Ca	61.2	60.4	61.2	61.6	61.2	61.2	62.0	65.0	64.0
Mg	25.0	26.2	25.4	25.9	25.9	26.2	26.0	25.0	25.0
Na	76.0	66.0	66.0	72.0	76.0	79.0	52.0	52.0	52.0
K	7.0	7.0	7.0	7.0	8.0	8.0	7.0	7.0	7.0
CO_2	1.5	4.8	6.0	1.9	1.0	2.4	2.4	2.4	2.4
CO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
HCO_3	183.0	182.0	182.0	181.8	180.6	181.8	184.0	183.0	182.0
TA	150.0	149.0	149.0	149.0	148.0	149.0	151.0	150.0	149.0
SO_4	184.4	169.0	166.8	164.0	182.0	174.0	180.4	164.0	155.0
Cl	76.0	73.0	74.0	76.0	76.0	75.0	77.0	77.0	77.0
NO_3	.15	.06	.03	.84	.85	.79	1.03	.54	1.10
F	.30	.30	.32	.22	.22	.20	.28	.22	.22
TH	260.0	260.0	259.0	262.0	261.0	262.0	263.0	266.0	264.0
CH	150.0	149.0	149.0	149.0	148.0	149.0	151.0	150.0	149.0
NCH	110.0	111.0	110.0	113.0	113.0	113.0	112.0	116.0	115.0
TR	562.0	537.0	557.0	569.0	559.0	564.0	569.0	584.0	580.0
Tur	2.1	2.26	2.00	2.00	2.20	2.35	2.88	1.48	1.48
TP	.074	.171	.178	.146	.140	.145	.111	.108	.120
OP	.058	.148	.162	.138	.134	.140	.111	.108	.115
PP	.016	.023	.016	.008	.006	.005	.0	.0	.005
Cond	827.0	828.0	830.0	843.0	838.0	843.0	838.0	843.0	844.0
pH	8.30	7.80	7.70	8.20	8.20	8.10	8.10	8.10	8.10
pHs	7.86	7.74	7.72	7.76	7.76	7.76	7.88	7.77	7.75
L.I.	+.44	+.06	−.02	+.44	+.44	+.34	+.22	+.33	+.35
R.I.	7.42	7.68	7.74	7.32	7.32	7.42	7.66	7.44	7.40
rCa	3.0539	3.0139	3.0539	3.0738	3.0539	3.0539	3.0938	3.2435	3.1936
rMg	2.0550	2.1536	2.0879	2.1290	2.1289	2.1536	2.1372	2.0550	2.0550
rNa	3.3060	2.8710	2.8710	3.1320	3.3060	3.4365	2.2620	2.2620	2.2620
rK	.1792	.1792	.1792	.1792	.2048	.2048	.1792	.1792	.1792
rCO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
$rHCO_3$	3.0012	2.9848	2.9848	2.9815	2.9618	2.9815	3.0176	3.0012	2.9848
rSO_4	3.8355	3.5194	3.4694	3.4112	3.7856	3.6192	3.7523	3.4112	3.2282
rCl	2.1508	2.0659	2.0942	2.1508	2.1225	2.1791	2.1791	2.1791	2.1791
rNO_3	.0024	.0010	.0005	.0135	.0137	.0126	.0166	.0087	.0177
rF	.0158	.0158	.0168	.0116	.0116	.0105	.0147	.0116	.0116
CV	17.5998	16.8046	16.7577	17.0826	17.6171	17.5951	16.6525	16.3515	16.1112

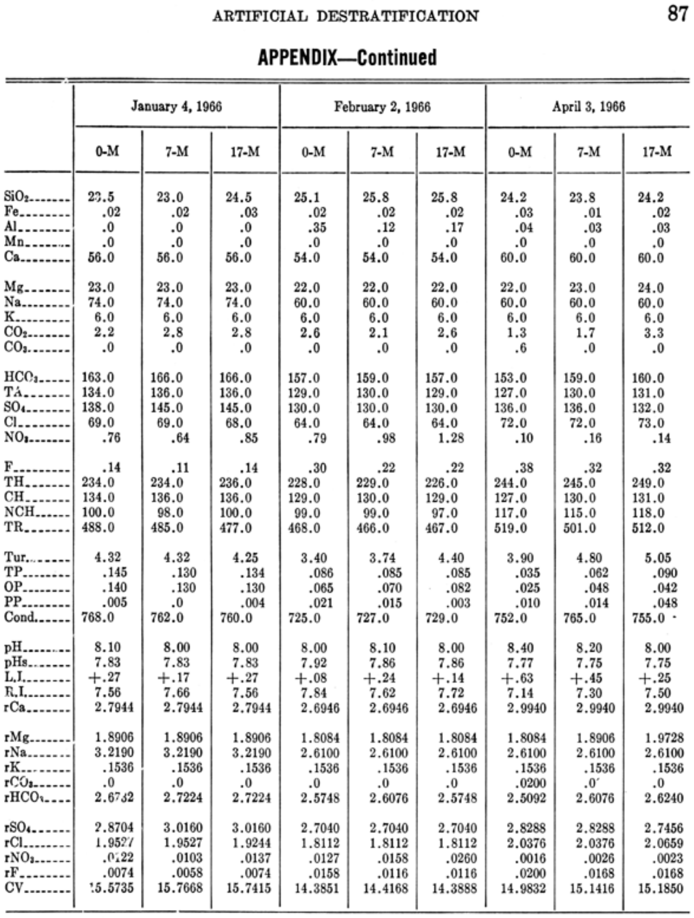
APPENDIX—Cont'd.



APPENDIX—Continued

	November 30, 1965			November 4, 1965			December 12, 1965		
	0-M	7-M	17-M	0-M	7-M	17-M	0-M	7-M	17-M
SiO_2	23.8	24.8	24.8	23.4	24.2	23.4	22.8	23.0	23.0
Fe	.07	.09	.11	.02	.03	.05	.05	.06	.05
Al	.02	.0	.0	.0	.0	.0	.0	.0	.0
Mn	.0	.0	.0	.0	.0	.0	.0	.0	.0
Ca	58.0	58.0	58.0	64.0	63.0	65.0	58.4	58.4	57.0
Mg	26.0	26.0	25.0	26.0	26.0	26.0	24.0	24.5	24.0
Na	72.5	72.5	72.5	79.0	79.0	79.0	55.0	55.0	55.4
K	7.0	8.0	8.0	6.0	6.0	6.0	4.0	4.0	5.0
CO_2	3.7	3.5	3.5	1.9	1.9	2.4	4.5	3.6	3.6
CO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
HCO_3	166.0	166.0	167.0	183.0	184.0	183.0	170.0	170.0	170.0
TA	136.0	136.0	137.0	150.0	151.0	150.0	139.0	139.0	139.0
SO_4	143.0	136.0	125.0	166.0	163.0	163.0	123.0	124.0	123.0
Cl	72.0	72.0	72.0	79.0	80.0	80.0	71.0	70.0	70.0
NO_3	.05	.10	.10	.20	.17	.20	.77	.58	1.17
F	.24	.14	.10	.26	.20	.20	.10	.08	.02
TH	254.0	252.0	252.0	268.0	268.0	272.0	246.0	248.0	244.0
CH	136.0	136.0	137.0	150.0	151.0	150.0	139.0	139.0	139.0
NCH	118.0	116.0	115.0	118.0	117.0	122.0	107.0	109.0	105.0
TR	522.0	518.0	514.0	563.0	573.0	569.0	525.0	520.0	521.0
Tur.	4.90	5.58	6.34	1.16	1.42	2.22	4.88	4.96	4.96
TP	.172	.170	.185	.130	.130	.128	.171	.122	.140
OP	.160	.152	.173	.105	.090	.104	.113	.102	.120
PP	.012	.018	.012	.025	.040	.024	.058	.020	.020
Cond.	788.0	784.0	784.0	857.0	862.0	860.0	786.0	785.0	785.0
pH	7.90	7.90	7.90	8.20	8.20	8.10	7.80	7.90	7.90
pHs	7.82	7.82	7.81	7.88	7.88	7.88	7.81	7.81	7.89
L.I.	+.08	+.08	+.09	+.32	+.32	+.22	−.01	+.09	+.01
R.I.	7.74	7.74	7.72	7.56	7.56	7.66	7.82	7.72	7.88
rCa	2.8942	2.8942	2.8942	3.1936	3.1437	3.2435	2.9142	2.9142	2.8443
rMg	2.1372	2.1372	2.0550	2.1372	2.1372	2.1372	1.9728	2.0139	1.9728
rNa	3.1538	3.1538	3.1538	3.4365	3.4365	3.4365	2.4099	2.4099	2.4099
rK	.1792	.2048	.2048	.1536	.1536	.1536	.1024	.1024	.1280
rCO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
$rHCO_3$	2.7224	2.7224	2.7388	3.0012	3.0176	3.0012	2.7880	2.7880	2.7880
rSO_4	2.9827	2.8371	2.6000	3.4528	3.3904	3.3904	2.5584	2.5834	2.5584
rCl	2.0376	2.0376	2.0376	2.2357	2.2640	2.2640	2.0093	1.9810	1.9810
rNO_3	.0008	.0016	.0016	.3220	.0027	.0032	.0124	.0093	.0188
rF	.0126	.0074	.0053	.0137	.0105	.0105	.0053	.0042	.0011
CV	16.1205	15.9961	15.6911	17.9463	17.5562	17.6401	14.7727	14.8063	14.7023

APPENDIX—Cont'd.



APPENDIX—Continued

	January 4, 1966			February 2, 1966			April 3, 1966		
	0-M	7-M	17-M	0-M	7-M	17-M	0-M	7-M	17-M
SiO_2	23.5	23.0	24.5	25.1	25.8	25.8	24.2	23.8	24.2
Fe	.02	.02	.03	.02	.02	.02	.03	.01	.02
Al	.0	.0	.0	.35	.12	.17	.04	.03	.03
Mn	.0	.0	.0	.0	.0	.0	.0	.0	.0
Ca	56.0	56.0	56.0	54.0	54.0	54.0	60.0	60.0	60.0
Mg	23.0	23.0	23.0	22.0	22.0	22.0	22.0	23.0	24.0
Na	74.0	74.0	74.0	60.0	60.0	60.0	60.0	60.0	60.0
K	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
CO_2	2.2	2.8	2.8	2.6	2.1	2.6	1.3	1.7	3.3
CO_3	.0	.0	.0	.0	.0	.0	.6	.0	.0
HCO_3	163.0	166.0	166.0	157.0	159.0	157.0	153.0	159.0	160.0
TA	134.0	136.0	136.0	129.0	130.0	129.0	127.0	130.0	131.0
SO_4	138.0	145.0	145.0	130.0	130.0	130.0	136.0	136.0	132.0
Cl	69.0	69.0	68.0	64.0	64.0	64.0	72.0	72.0	73.0
NO_3	.76	.64	.85	.79	.98	1.28	.10	.16	.14
F	.14	.11	.14	.30	.22	.22	.38	.32	.32
TH	234.0	234.0	236.0	228.0	229.0	226.0	244.0	245.0	249.0
CH	134.0	136.0	136.0	129.0	130.0	129.0	127.0	130.0	131.0
NCH	100.0	98.0	100.0	99.0	99.0	97.0	117.0	115.0	118.0
TR	488.0	485.0	477.0	468.0	466.0	467.0	519.0	501.0	512.0
Tur	4.32	4.32	4.25	3.40	3.74	4.40	3.90	4.80	5.05
TP	.145	.130	.134	.086	.085	.085	.035	.062	.090
OP	.140	.130	.130	.065	.070	.082	.025	.048	.042
PP	.005	.0	.004	.021	.015	.003	.010	.014	.048
Cond	768.0	762.0	760.0	725.0	727.0	729.0	752.0	765.0	755.0
pH	8.10	8.00	8.00	8.00	8.10	8.00	8.40	8.20	8.00
pHs	7.83	7.83	7.83	7.92	7.86	7.86	7.77	7.75	7.75
L.I.	+.27	+.17	+.27	+.08	+.24	+.14	+.63	+.45	+.25
R.I.	7.56	7.66	7.56	7.84	7.62	7.72	7.14	7.30	7.50
rCa	2.7944	2.7944	2.7944	2.6946	2.6946	2.6946	2.9940	2.9940	2.9940
rMg	1.8906	1.8906	1.8906	1.8084	1.8084	1.8084	1.8084	1.8906	1.9728
rNa	3.2190	3.2190	3.2190	2.6100	2.6100	2.6100	2.6100	2.6100	2.6100
rK	.1536	.1536	.1536	.1536	.1536	.1536	.1536	.1536	.1536
rCO_3	.0	.0	.0	.0	.0	.0	.0200	.0	.0
$rHCO_3$	2.6732	2.7224	2.7224	2.5748	2.6076	2.5748	2.5092	2.6076	2.6240
rSO_4	2.8704	3.0160	3.0160	2.7040	2.7040	2.7040	2.8288	2.8288	2.7456
rCl	1.9527	1.9527	1.9244	1.8112	1.8112	1.8112	2.0376	2.0376	2.0659
rNO_3	.0122	.0103	.0137	.0127	.0158	.0260	.0016	.0026	.0023
rF	.0074	.0058	.0074	.0158	.0116	.0116	.0200	.0168	.0168
CV	15.5735	15.7668	15.7415	14.3851	14.4168	14.3888	14.9832	15.1416	15.1850

APPENDIX—Cont'd.

APPENDIX—Continued

	May 2, 1966			June 20, 1966			July 5, 1966		
	0-M	7-M	17-M	0-M	7-M	17-M	0-M	7-M	17-M
SiO_2	26.0	26.2	24.0	17.5	18.7	18.9	23.2	24.3	24.1
Fe	.07	.03	.02	.01	.01	.01	.09	.09	.08
Al	.02	.04	.01	.02	.02	.02	.02	.02	.02
Mn	.0	.0	.0	.0	.0	.0	.0	.0	.0
Ca	54.0	59.0	58.0	54.0	53.0	54.0	54.0	54.0	54.0
Mg	21.0	23.0	23.0	22.0	21.0	21.0	23.0	21.0	21.0
Na	60.0	60.0	60.0	59.0	61.0	61.0	56.0	56.0	56.0
K	5.0	5.0	5.0	7.4	7.6	7.6	8.0	8.0	8.0
CO_2	2.0	2.1	2.6	2.0	4.1	4.1	2.1	5.1	5.2
CO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
HCO_3	153.0	159.0	159.0	154.0	154.0	154.0	159.0	154.0	156.0
TA	125.0	130.0	130.0	126.0	126.0	126.0	130.0	126.0	128.0
SO_4	125.0	128.0	131.0	140.0	138.0	138.0	126.0	125.0	116.0
Cl	66.0	71.0	71.0	63.0	64.0	66.0	64.0	65.0	65.0
NO_3	.03	.11	.12	.03	.04	.06	.22	.08	.07
F	.10	.30	.10	.23	.23	.23	.14	.22	.22
TH	221.0	238.0	242.0	224.0	222.0	222.0	228.0	222.0	224.0
CH	125.0	130.0	130.0	126.0	126.0	126.0	130.0	126.0	128.0
NCH	96.0	108.0	112.0	98.0	96.0	96.0	98.0	96.0	96.0
TR	487.0	536.0	560.0	475.0	464.0	469.0	487.0	481.0	471.0
Tur.	4.35	4.95	3.00	4.30	3.40	3.10	4.60	4.70	4.70
TP	.045	.045	.042	.015	.057	.071	.050	.097	.112
OP	.031	.016	.015	.013	.054	.067	.045	.093	.108
PP	.014	.029	.027	.002	.003	.004	.005	.004	.004
Cond.	703.0	762.0	768.0	711.0	709.0	710.0	711.0	706.0	705.0
pH	8.10	8.10	8.00	8.10	7.80	7.80	8.10	7.70	7.70
pHs	7.89	7.84	7.85	7.81	7.81	7.81	7.79	7.81	7.80
L.I.	+.21	+.26	+.15	+.29	−.01	−.01	+.31	−.11	−.10
R.I.	7.68	7.58	7.70	7.52	7.82	7.82	7.48	7.92	7.90
rCa	2.6946	2.9441	2.8942	2.6946	2.6447	2.6946	2.6946	2.6946	2.6946
rMg	1.7262	1.8906	1.8906	1.8084	1.7262	1.7262	1.8906	1.7262	1.7262
rNa	2.6100	2.6100	2.6100	2.5665	2.6535	2.6535	2.4360	2.4360	2.4360
rK	.1280	.1280	.1280	.1894	.1946	.1946	.2048	.2048	.2048
rCO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
$rHCO_3$	2.5092	2.6076	2.6076	2.5256	2.5256	2.5256	2.6076	2.5256	2.5584
rSO_4	2.6000	2.6624	2.7248	2.9120	2.8704	2.8704	2.6208	2.6000	2.4128
rCl	1.8678	2.0093	2.0093	1.7829	1.8112	1.8678	1.8112	1.8395	1.8395
rNO_3	.0005	.0018	.0019	.0005	.0006	.0010	.0029	.0005	.0011
rF	.0053	.0158	.0053	.0121	.0121	.0121	.0074	.0116	.0116
CV	14.1416	14.8696	14.8717	14.4920	14.4389	14.5458	14.2759	14.0388	13.8850

APPENDIX—Cont'd.

APPENDIX—Continued

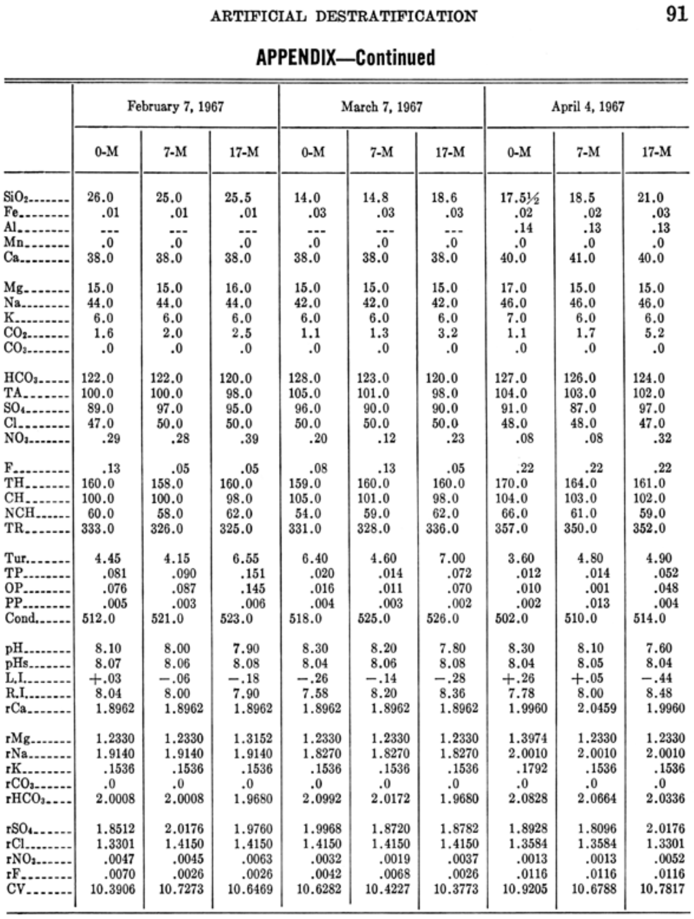
	August 1, 1966			September 6, 1966			October 3, 1966		
	0-M	7-M	17-M	0-M	7-M	17-M	0-M	7-M	17-M
SiO_2	19.3	20.0	19.4	20.3	19.9	19.9	19.0	20.5	21.0
Fe	.02	.01	.01	.10	.12	.19	.03	.04	.05
Al	.02	.03	.03	.02	.03	.05	.07	.08	.07
Mn	.0	.0	.0	.0	.0	.0	.10	.09	.14
Ca	53.0	53.0	54.0	56.0	56.0	57.0	56.0	59.0	58.0
Mg	23.0	23.0	22.0	22.0	23.0	26.0	23.0	22.0	23.0
Na	71.0	68.0	64.0	68.0	67.0	67.0	58.5	57.0	57.0
K	6.0	7.0	7.0	7.0	7.0	7.0	7.3	7.3	7.5
CO_2	1.7	3.4	4.3	2.2	2.7	3.4	2.8	2.8	2.8
CO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
HCO_3	162.0	163.0	161.0	166.0	165.0	163.0	168.0	168.0	168.0
TA	133.0	134.0	132.0	136.0	135.0	134.0	138.0	138.0	138.0
SO_4	144.0	145.0	144.0	155.0	155.0	155.0	130.0	118.0	133.0
Cl	66.0	66.0	65.0	66.0	66.0	68.0	68.0	75.0	75.0
NO_3	.05	.03	.08	.03	.03	.10	.19	.17	.16
F	.08	.18	.13	.13	.22	.17	.22	.14	.14
TH	228.0	226.0	226.0	234.0	233.0	232.0	238.0	238.0	242.0
CH	133.0	134.0	132.0	136.0	135.0	134.0	138.0	138.0	138.0
NCH	95.0	92.0	94.0	98.0	98.0	98.0	100.0	100.0	104.0
TR	464.0	477.0	465.0	527.0	500.0	516.0	522.0	516.0	512.0
Tur	3.46	4.10	3.10	4.20	4.10	6.40	4.50	5.70	6.10
TP	.047	.115	.125	.065	.102	.135	.160	.144	.091
OP	.030	.105	.114	.046	.081	.132	.145	.142	.075
PP	.017	.010	.011	.019	.021	.003	.015	.002	.016
Cond	710.0	715.0	713.0	730.0	734.0	734.0	751.0	751.0	755.0
pH	8.20	7.90	7.80	8.10	8.00	7.90	8.00	8.00	8.00
pHs	7.81	7.80	7.80	7.79	7.78	7.77	7.83	7.81	7.81
L.I.	+.29	+.10	.0	+.31	+.22	+.13	+.17	+.19	+.19
R.I.	7.42	7.70	7.80	7.48	7.56	7.64	7.64	7.62	7.62
rCa	2.6447	2.6447	2.6946	2.7944	2.7944	2.8443	2.7944	2.9441	2.8942
rMg	1.8906	1.8906	1.8084	1.8084	1.8906	2.1372	1.8906	1.8084	1.8906
rNa	3.0842	2.9667	2.7623	2.9537	2.9102	2.8928	2.5665	2.4882	2.4882
rK	.1536	.2556	.1864	.1951	.1853	.1846	.0589	.1869	.1920
rCO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
$rHCO_3$	2.6568	2.6732	2.6404	2.7224	2.7060	2.6732	2.7552	2.7552	2.7552
rSO_4	2.9952	3.0160	2.9952	3.2240	3.2240	3.2240	2.7040	2.4544	2.7664
rCl	1.8678	1.8678	1.8395	1.8678	1.8678	1.9244	1.9244	2.1225	2.1225
rNO_3	.0008	.0005	.0013	.0005	.0005	.0016	.0031	.0027	.0026
rF	.0042	.0096	.0069	.0069	.0115	.0089	.0116	.0074	.0074
CV	15.2979	15.3247	14.9350	15.5732	15.5903	15.8910	14.7087	14.7698	15.1191

APPENDIX—Cont'd.

APPENDIX—Continued

	November 18, 1966			December 5, 1966			January 2, 1967		
	0-M	7-M	17-M	0-M	7-M	17-M	0-M	7-M	17-M
SiO_2	20.3	20.6	20.1	23.0	24.0	24.0	25.3	23.8	22.7
Fe	.02	.03	.04	.04	.03	.03	.07	.06	.09
Al	.02	.03	.03	.02	.01	.03	.07	.04	.03
Mn	.0	.0	.0	.0	.0	.0	.0	.0	.0
Ca	56.0	57.0	56.0	56.0	56.0	56.0	37.0	39.2	38.0
Mg	22.0	24.0	23.0	21.0	21.0	23.0	16.0	15.0	15.0
Na	68.0	68.0	69.0	68.0	68.0	68.0	42.0	42.0	42.0
K	8.0	8.0	8.0	8.0	8.0	8.0	6.0	6.0	6.0
CO_2	3.5	5.6	5.6	4.4	3.5	4.4	3.9	3.9	3.9
CO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
HCO_3	171.0	170.0	171.0	166.0	167.0	168.0	116.0	116.0	116.0
TA	140.0	139.0	140.0	136.0	137.0	138.0	95.0	95.0	95.0
SO_4	115.0	125.0	120.0	140.0	140.0	145.0	94.0	95.0	98.0
Cl	89.0	86.0	85.0	73.0	74.0	73.0	49.0	46.0	49.0
NO_3	.16	.14	.16	.11	.07	.25	.35	.26	.35
F	.13	.08	.08	.19	.13	.19	.31	.22	.20
TH	232.0	240.0	234.0	226.0	227.0	234.0	157.0	159.0	157.0
CH	140.0	139.0	140.0	136.0	137.0	138.0	95.0	95.0	95.0
NCH	92.0	101.0	94.0	90.0	90.0	96.0	62.0	64.0	62.0
TR	508.0	486.0	489.0	473.0	470.0	471.0	359.0	361.0	354.0
Tur	4.10	5.00	5.10	4.00	3.95	4.40	3.50	3.60	3.68
TP	.064	.058	.058	.105	.090	.090	.180	.190	.252
OP	.058	.047	.053	.100	.090	.090	.177	.185	.180
PP	.006	.011	.005	.005	.000	.000	.003	.005	.072
Cond	723.0	737.0	735.0	720.0	723.0	726.0	518.0	524.0	521.0
pH	7.90	7.70	7.70	7.80	7.90	7.80	7.70	7.70	7.70
pHs	7.82	7.82	7.81	7.83	7.83	7.83	8.11	7.78	8.08
L.I.	+.12	−.12	−.11	−.03	+.07	−.03	−.41	−.08	−.38
R.I.	7.77	7.94	7.92	7.86	7.76	7.86	8.52	7.86	8.46
rCa	2.7944	2.8443	2.7944	2.7944	2.7944	2.7944	1.8463	1.9461	1.8762
rMg	1.8084	1.9728	1.8906	1.7262	1.7262	1.8906	1.3152	1.2330	1.2338
rNa	2.9580	2.9580	3.0015	2.9580	2.9580	2.9580	1.8270	1.8270	1.8270
rK	.2048	.2048	.2048	.2048	.2048	.2048	.1536	.1536	.1536
rCO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
$rHCO_3$	2.8044	2.7880	2.8044	2.7224	2.7388	2.7552	1.9024	1.9024	1.9008
rSO_4	2.3920	2.6000	2.4960	2.9120	2.9120	3.0160	1.9552	1.9760	2.0384
rCl	2.5187	2.4338	2.4055	2.0659	2.0942	2.0659	1.3867	1.3018	1.3867
rNO_3	.0026	.0022	.0026	.0018	.0011	.0039	.0056	.0042	.0056
rF	.0068	.0042	.0042	.0097	.0070	.0097	.0163	.0116	.0105
CV	15.4901	15.8081	15.6040	15.4952	15.4365	15.6985	10.4083	10.3557	10.4318

APPENDIX—Cont'd.



APPENDIX—Continued

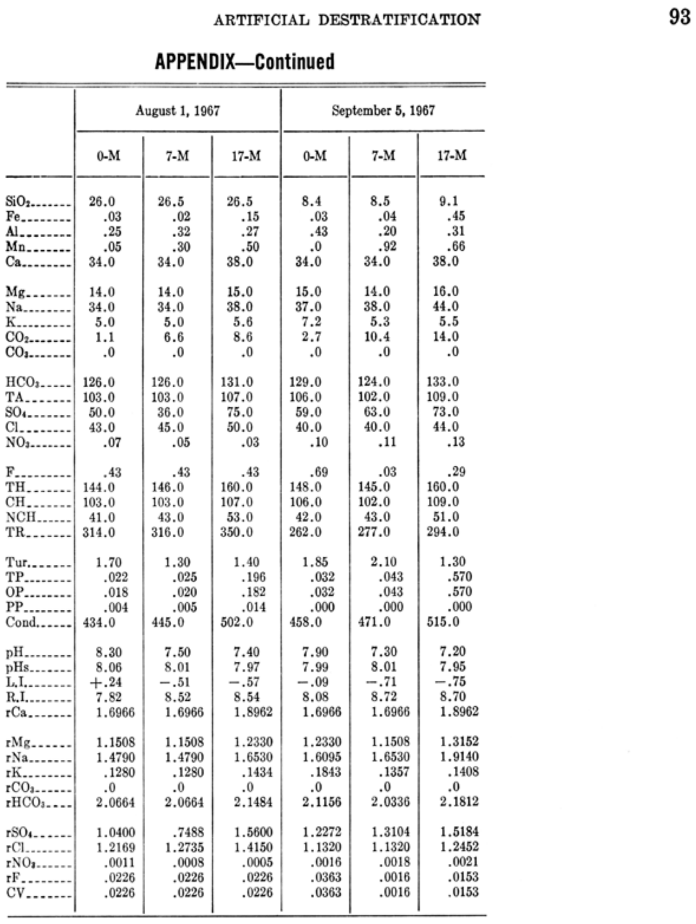
	February 7, 1967			March 7, 1967			April 4, 1967		
	0-M	7-M	17-M	0-M	7-M	17-M	0-M	7-M	17-M
SiO_2	26.0	25.0	25.5	14.0	14.8	18.6	17.5½	18.5	21.0
Fe	.01	.01	.01	.03	.03	.03	.02	.02	.03
Al	---	---	---	---	---	---	.14	.13	.13
Mn	.0	.0	.0	.0	.0	.0	.0	.0	.0
Ca	38.0	38.0	38.0	38.0	38.0	38.0	40.0	41.0	40.0
Mg	15.0	15.0	16.0	15.0	15.0	15.0	17.0	15.0	15.0
Na	44.0	44.0	44.0	42.0	42.0	42.0	46.0	46.0	46.0
K	6.0	6.0	6.0	6.0	6.0	6.0	7.0	6.0	6.0
CO_2	1.6	2.0	2.5	1.1	1.3	3.2	1.1	1.7	5.2
CO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
HCO_3	122.0	122.0	120.0	128.0	123.0	120.0	127.0	126.0	124.0
TA	100.0	100.0	98.0	105.0	101.0	98.0	104.0	103.0	102.0
SO_4	89.0	97.0	95.0	96.0	90.0	90.0	91.0	87.0	97.0
Cl	47.0	50.0	50.0	50.0	50.0	50.0	48.0	48.0	47.0
NO_3	.29	.28	.39	.20	.12	.23	.08	.08	.32
F	.13	.05	.05	.08	.13	.05	.22	.22	.22
TH	160.0	158.0	160.0	159.0	160.0	160.0	170.0	164.0	161.0
CH	100.0	100.0	98.0	105.0	101.0	98.0	104.0	103.0	102.0
NCH	60.0	58.0	62.0	54.0	59.0	62.0	66.0	61.0	59.0
TR	333.0	326.0	325.0	331.0	328.0	336.0	357.0	350.0	352.0
Tur.	4.45	4.15	6.55	6.40	4.60	7.00	3.60	4.80	4.90
TP	.081	.090	.151	.020	.014	.072	.012	.014	.052
OP	.076	.087	.145	.016	.011	.070	.010	.001	.048
PP	.005	.003	.006	.004	.003	.002	.002	.013	.004
Cond.	512.0	521.0	523.0	518.0	525.0	526.0	502.0	510.0	514.0
pH	8.10	8.00	7.90	8.30	8.20	7.80	8.30	8.10	7.60
pHs	8.07	8.06	8.08	8.04	8.06	8.08	8.04	8.05	8.04
L.I.	+.03	−.06	−.18	−.26	−.14	−.28	+.26	+.05	−.44
R.I.	8.04	8.00	7.90	7.58	8.20	8.36	7.78	8.00	8.48
rCa	1.8962	1.8962	1.8962	1.8962	1.8962	1.8962	1.9960	2.0459	1.9960
rMg	1.2330	1.2330	1.3152	1.2330	1.2330	1.2330	1.3974	1.2330	1.2330
rNa	1.9140	1.9140	1.9140	1.8270	1.8270	1.8270	2.0010	2.0010	2.0010
rK	.1536	.1536	.1536	.1536	.1536	.1536	.1792	.1536	.1536
rCO_3	.0	.0	.0	.0	.0	.0	.0	.0	.0
$rHCO_3$	2.0008	2.0008	1.9680	2.0992	2.0172	1.9680	2.0828	2.0664	2.0336
rSO_4	1.8512	2.0176	1.9760	1.9968	1.8720	1.8782	1.8928	1.8096	2.0176
rCl	1.3301	1.4150	1.4150	1.4150	1.4150	1.4150	1.3584	1.3584	1.3301
rNO_3	.0047	.0045	.0063	.0032	.0019	.0037	.0013	.0013	.0052
rF	.0070	.0026	.0026	.0042	.0068	.0026	.0116	.0116	.0116
CV	10.3906	10.7273	10.6469	10.6282	10.4227	10.3773	10.9205	10.6788	10.7817

APPENDIX—Cont'd.

APPENDIX—Continued

	May 2, 1967			June 6, 1967			July 6, 1967		
	0-M	7-M	17-M	0-M	7-M	17-M	0-M	7-M	17-M
SiO_2	16.0	14.6	17.6	20.4	18.5	18.6	20.0	19.5	18.8
Fe	.02	.02	.03	.04	.03	.03	.013	.013	.02
Al	.10	.09	.09	.10	.06	.06	.02	.01	.08
Mn	.0	.0	.0	.0	.0	.0	.0	.0	.20
Ca	39.0	40.0	39.0	34.0	36.0	34.0	34.0	35.0	39.0
Mg	15.0	16.0	15.0	15.0	15.0	15.0	12.0	13.0	15.0
Na	40.0	40.0	40.0	36.0	38.0	40.0	32.0	34.0	42.0
K	6.0	6.0	6.0	6.0	6.5	7.0	4.2	4.4	5.1
CO_2	1.1	1.7	6.4	0.6	5.1	8.1	.0	4.1	8.6
CO_3	.0	.0	.0	1.2	.0	.0	3.6	.0	.0
HCO_3	128.0	127.0	122.0	117.0	122.0	122.0	115.0	123.0	130.0
TA	105.0	104.0	100.0	100.0	100.0	100.0	100.0	101.0	107.0
SO_4	77.5	77.5	73.0	72.0	77.0	84.0	40.0	41.0	81.0
Cl	48.0	49.0	47.0	42.0	44.0	46.0	41.0	47.0	50.0
NO_3	.06	.08	.24	.02	.03	.04	.09	.03	.06
F	.05	.05	.05	.05	.05	.05	.13	.13	.10
TH	160.0	166.0	160.0	149.0	154.0	156.0	136.0	142.0	160.0
CH	105.0	104.0	100.0	100.0	100.0	100.0	100.0	101.0	107.0
NCH	55.0	62.0	60.0	49.0	54.0	56.0	36.0	41.0	53.0
TR	314.0	322.0	318.0	292.0	304.0	321.0	284.0	386.0	334.0
Tur.	2.00	2.00	3.90	2.60	2.70	3.50	3.10	3.20	4.10
TP	.010	.006	.030	.054	.055	.093	.016	.010	.145
OP	.005	.004	.025	.049	.055	.093	.014	.008	.140
PP	.005	.002	.005	.005	.000	.000	.002	.002	.005
Cond.	490.0	500.0	489.0	499.0	476.0	490.0	410.0	435.0	494.0
pH	8.30	8.10	7.50	8.50	7.60	7.40	8.60	7.70	7.40
pHs	7.95	7.94	7.97	8.01	7.98	8.02	8.00	8.04	7.95
L.I.	+.36	+.16	−.47	+.49	−.38	−.62	+.60	−.34	−.55
R.I.	7.60	7.78	8.44	7.52	8.36	8.64	7.40	8.38	8.50
rCa	1.9461	1.9960	1.9461	1.6966	1.7964	1.6966	1.6966	1.7465	1.9461
rMg	1.2330	1.3152	1.2330	1.2330	1.2330	1.2330	.9864	1.0686	1.2330
rNa	1.7400	1.7400	1.7400	1.5660	1.6530	1.7400	1.3920	1.4790	1.8270
rK	.1536	.1536	.1536	.1536	.1664	.1792	.1075	.1126	.1306
rCO_3	.0	.0	.0	.0400	.0	.0	.1199	.0	.0
rHCO_2	2.0992	2.0828	2.0008	1.9188	2.0008	2.0008	1.8860	2.0172	2.1320
rSO_4	1.6120	1.6120	1.5184	1.4976	1.6016	1.7472	.8320	.8528	1.6848
rCl	1.3584	1.3867	1.3301	1.1886	1.2452	1.3018	1.1603	1.3301	1.4150
rNO_3	.0010	.0012	.0039	.0003	.0005	.0006	.0014	.0005	.0010
rF	.0026	.0026	.0026	.0026	.0026	.0026	.0069	.0069	.0053
CV	10.1459	10.2901	9.9285	9.2971	9.6995	9.9018	8.1890	8.6142	10.3748

APPENDIX—Cont'd.



APPENDIX—Continued

	August 1, 1967			September 5, 1967		
	0-M	7-M	17-M	0-M	7-M	17-M
SiO_2	26.0	26.5	26.5	8.4	8.5	9.1
Fe	.03	.02	.15	.03	.04	.45
Al	.25	.32	.27	.43	.20	.31
Mn	.05	.30	.50	.0	.92	.66
Ca	34.0	34.0	38.0	34.0	34.0	38.0
Mg	14.0	14.0	15.0	15.0	14.0	16.0
Na	34.0	34.0	38.0	37.0	38.0	44.0
K	5.0	5.0	5.6	7.2	5.3	5.5
CO_2	1.1	6.6	8.6	2.7	10.4	14.0
CO_3	.0	.0	.0	.0	.0	.0
HCO_3	126.0	126.0	131.0	129.0	124.0	133.0
TA	103.0	103.0	107.0	106.0	102.0	109.0
SO_4	50.0	36.0	75.0	59.0	63.0	73.0
Cl	43.0	45.0	50.0	40.0	40.0	44.0
NO_3	.07	.05	.03	.10	.11	.13
F	.43	.43	.43	.69	.03	.29
TH	144.0	146.0	160.0	148.0	145.0	160.0
CH	103.0	103.0	107.0	106.0	102.0	109.0
NCH	41.0	43.0	53.0	42.0	43.0	51.0
TR	314.0	316.0	350.0	262.0	277.0	294.0
Tur.	1.70	1.30	1.40	1.85	2.10	1.30
TP	.022	.025	.196	.032	.043	.570
OP	.018	.020	.182	.032	.043	.570
PP	.004	.005	.014	.000	.000	.000
Cond.	434.0	445.0	502.0	458.0	471.0	515.0
pH	8.30	7.50	7.40	7.90	7.30	7.20
pHs	8.06	8.01	7.97	7.99	8.01	7.95
L.I.	+.24	−.51	−.57	−.09	−.71	−.75
R.I.	7.82	8.52	8.54	8.08	8.72	8.70
rCa	1.6966	1.6966	1.8962	1.6966	1.6966	1.8962
rMg	1.1508	1.1508	1.2330	1.2330	1.1508	1.3152
rNa	1.4790	1.4790	1.6530	1.6095	1.6530	1.9140
rK	.1280	.1280	.1434	.1843	.1357	.1408
rCO_3	.0	.0	.0	.0	.0	.0
$rHCO_3$	2.0664	2.0664	2.1484	2.1156	2.0336	2.1812
rSO_4	1.0400	.7488	1.5600	1.2272	1.3104	1.5184
rCl	1.2169	1.2735	1.4150	1.1320	1.1320	1.2452
rNO_3	.0011	.0008	.0005	.0016	.0018	.0021
rF	.0226	.0226	.0226	.0363	.0016	.0153
CV	.0226	.0226	.0226	.0363	.0016	.0153

APPENDIX—Cont'd.

GLOSSARY

A few of the technical terms used in this bulletin are listed here. For further assistance, you may consult Odum (1959), Ruttner (1963), Lagler (1956), Welch (1948, 1952), Hutchinson (1957, 1967), or A Handbook of Chemistry and Physics.

Aerobe (aerobic). Organism that requires the presence of free oxygen to carry on its life processes.

Anaerobe (anaerobic). Organism that may thrive in the absence of free oxygen.

Benthic. The shore and bottom region.

Calorie. That quantity of heat necessary to raise 1 milliliter of water at 0.0°C to 1°C. Also called gram-calorie. 1000 calories = 1 kilogram calorie.

Coldwater Fishery. A fishery consisting of fish requiring cold water, generally below 70°F. Trout and salmon are typical coldwater fishes.

Ecology. The study of living organisms and their interaction with the environment.

Epilimnion. The warmwater volume of a stratified lake. Generally circulated by the wind, lacks thermal stratification and oxygen concentrations near saturation. Located above the metalimnion.

Eutrophic. Water characterized by a high organic and nutrient content. Eutrophic lakes develop an oxygen deficit in or below the metalimnion.

Heat Budget. The change in heat content during the year. May be expressed as difference between the maximum and minimum values per unit area or unit volume.

Hypolimnion. The coldwater volume of a stratified lake located below the epilimnion and metalimnion. Temperatures are almost homogeneous throughout. Oxygen is usually absent in the hypolimnion of eutrophic lakes sometime during their stratified period.

Ion. An electrically charged atom, or group of atoms.

Lake. A large body of water that characteristically stratifies during summer.

Limnetic Zone. The open water zone of the lake away from the shore and bottom.

Littoral Zone. The shoreward area of the lake. Shallow water zone characterized by rooted aquatic plants.

Metalimnion. A layer of water between the epilimnion and hypolimnion. A transition zone that generally has a temperature gradient of 1°C/meter or greater. Also called the thermocline.

Monomictic. A lake that does not develop inverse stratification during the winter, (no ice cover) but does stratify during the summer. Has a fall overturn, but not a spring overturn.

Pelagic Zone. Open water area of the sea. Analogous to limnetic zone of lakes.

Phytoplankton. Plant portion of plankton.

Plankton. Small organisms that live in the open water and are carried by the water currents. May possess some means of locomotion.

Primary Production. Generally the fixing of carbon dioxide and water into organic compounds by plants.

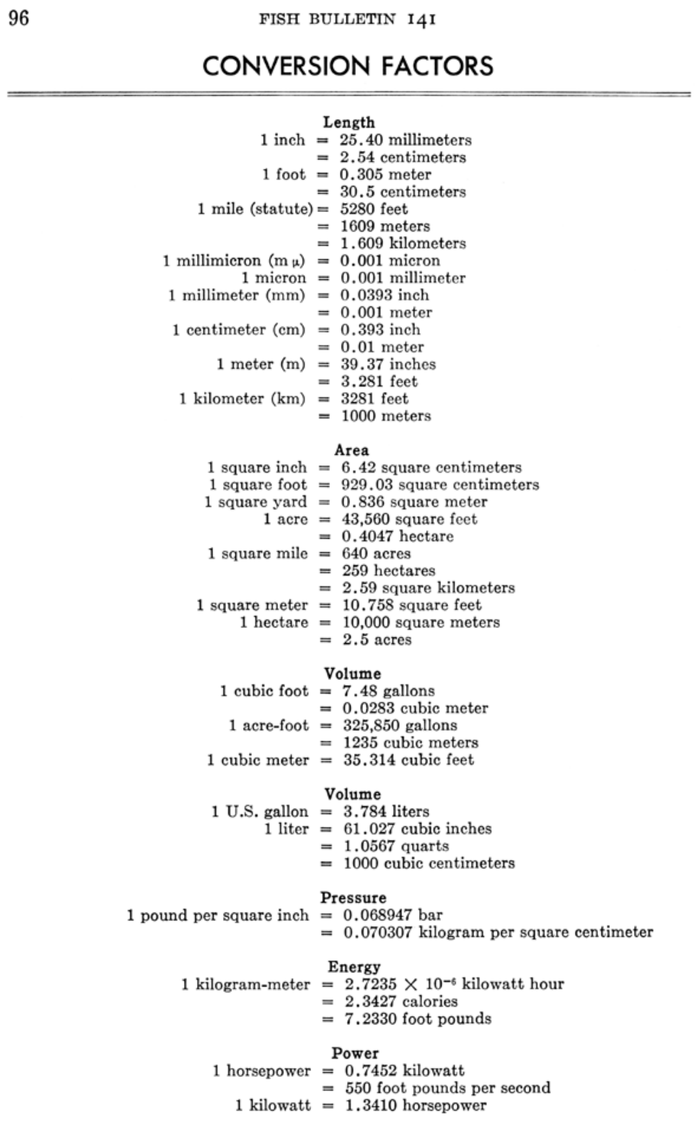
Profundal Zone. The deep water benthic area beyond the depth of effective light penetration. The bottom of the hypolimnion.

Warmwater Fishery. A fishery consisting of fishes that tolerate warm water of 75°F or greater. Bass, bluegill, catfish and bullheads are typical warmwater fishes.

Zoobenthos. Animals living on the bottom of the lake.

Zooplankton. Animal portion of the plankton.

CONVERSION FACTORS



96 FISH BULLETIN 141

CONVERSION FACTORS

Length

1 inch = 25.40 millimeters
= 2.54 centimeters
1 foot = 0.305 meter
= 30.5 centimeters
1 mile (statute) = 5280 feet
= 1609 meters
= 1.609 kilometers
1 millimicron ($m\mu$) = 0.001 micron
1 micron = 0.001 millimeter
1 millimeter (mm) = 0.0393 inch
= 0.001 meter
1 centimeter (cm) = 0.393 inch
= 0.01 meter
1 meter (m) = 39.37 inches
= 3.281 feet
1 kilometer (km) = 3281 feet
= 1000 meters

Area

1 square inch = 6.42 square centimeters
1 square foot = 929.03 square centimeters
1 square yard = 0.836 square meter
1 acre = 43,560 square feet
= 0.4047 hectare
1 square mile = 640 acres
= 259 hectares
= 2.59 square kilometers
1 square meter = 10.758 square feet
1 hectare = 10,000 square meters
= 2.5 acres

Volume

1 cubic foot = 7.48 gallons
= 0.0283 cubic meter
1 acre-foot = 325,850 gallons
= 1235 cubic meters
1 cubic meter = 35.314 cubic feet

Volume

1 U.S. gallon = 3.784 liters
1 liter = 61.027 cubic inches
= 1.0567 quarts
= 1000 cubic centimeters

Pressure

1 pound per square inch = 0.068947 bar
= 0.070307 kilogram per square centimeter

Energy

1 kilogram-meter = 2.7235×10^{-6} kilowatt hour
= 2.3427 calories
= 7.2330 foot pounds

Power

1 horsepower = 0.7452 kilowatt
= 550 foot pounds per second
1 kilowatt = 1.3410 horsepower

CONVERSION FACTORS

CONVERSION FACTORS—Continued

Degrees Centigrade to Degrees Fahrenheit

$$°F = \frac{9}{5}\,°C + 32.0$$

Degrees Fahrenheit to Degrees Centigrade

$$°C = \frac{5}{9}\,(°F - 32.0)$$

Standard Notation of Numeric Values

Throughout this report very large and very small values are often expressed in the form: 4.23×10^{y}, where y is some power of 10. For convenience, y can be thought of as a positioner of the decimal point. If y is positive, the decimal point will shift y places to the right.

If y is negative, the decimal point will shift y positions to the left. If y is 0, the decimal remains where it is.

Examples are:

$4.23 \times 10^{8} = 423{,}000{,}000$

$4.23 \times 10^{-1} = 0.423$

$1.22 \times 10^{-4} = 0.000122$

$-3.15 \times 10^{-2} = -0.0315$

$-7.19 \times 10^{0} = -7.19$

$-8.88 \times 10^{3} = -8{,}880$

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CONVERSION FACTORS—Cont'd.