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BUREAU OF RECLAMATION RESEARCH IN DESTRATIFICATION

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BUREAU OF RECLAMATION RESEARCH IN LAKE DESTRATIFICATION

by

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INTRODUCTION

The Bureau of Reclamation operates 125 storage reservoirs in the United States, with a total capacity of 229 million acre-ft (283 x 10 m^3). Capacities range from 30 million acre-ft (37 x $10^9 m^3$) in Lake Mead behind Hoover Dam to less than 1,000 acre-ft (10 x $10^6 m^3$) in several small reservoirs. A survey in 1971 showed that water quality problems associated with low dissolved oxygen existed in at least 27 of these reservoirs. Destratification is one alternative for maintenance of dissolved oxygen.

Destratification must be considered carefully, since reservoir stratification may be highly desirable when certain requirements are imposed. When a cold, high DO release is required, reaeration of only the hypolimnion may be indicated. Certain general studies may be needed to provide an adequate understanding of the hydrodynamics of reservoirs so that a rational selection of the method and/or device can be made, location of devices optimized, and operating criteria established.

Work in destratification of reservoirs was pioneered by Symons and his associates in the U.S. Public Health Service. Although their work was limited to very small impoundments, they developed a method for calculating destratification efficiency which has universal application [9]. Also, under Symons' leadership

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a survey was conducted [10] which provided general and approximate information on destratification efficiency and costs for reservoirs up to nearly 500,000 acre-ft (617 x 10^6m/^{3}) in volume.

In 1962, Koberg and Ford [7] of the Geological Survey also performed some basic work with an air-bubbling system at Lake Wohlford in California, 2,500 acre-feet (3.08 x 10^6/m^3).

The Geological Survey at Lake Cachuma in California, 205,000 acre-ft (253 x 10^6m/^{3}), met with little success because of inadequate sizing of the diffused air system [4].

Since 1968, a successful diffused-air destratification system has operated at Lake Casitas in California, 254,000 acre-ft (313 x 10^6m^3), under the direction of the Casitas Municipal Water District [2, 3]. The system was intended to maintain a minimum DO level of 1 mg/l near the municipal intake, maintain a DO level of greater than 5 mg/l in the upper zone of the reservoir to support existing aquatic life, establish a maximum allowable temperature of 64°F (18°C) in the lower zone of the reservoir, and enhance the reservoir fishery by increasing the habitable reservoir volume. Recent work at Lake Casitas is discussed later in this paper.

In recent years there has been interest in applying the concept of destratification to increasingly larger reservoirs. In 1968 the Corps of Engineers installed a 300-horsepower (224-kW) diffused-air system at Lake Allatoona in Georgia, 367,500 acre-ft (453 x 10^6m^3)[1]. In 1971, the Corps also installed a diffused-air system at Table Rock Reservior in Missouri, 2.7 million acre-ft (3,330 x 10^6m^3)[6].

CASE STUDIES

Destratification with Air Guns

Lake of the Arbuckles

The first major thrust by the Bureau of Reclamation in destratification research was at Lake of the Arbuckles in Oklahoma (figure 1), which has a capacity of 72,400 acre-ft (8.9 x $10^7 m^3$), and a surface area of 2,350 acres (950 ha).

Stream water quality data from the 1926-1961 period indicated that the reservoir would yield high quality water for M&I use. This has been borne out by operating experience since 1968. However, some form of chemical, algae, or micro-organism in the reservoir water causes a rapid depletion of chlorine when introduced at the pumping plant and the point of release from the pipeline at the regulating reservoir. Chlorination is, therefore, required at the points of water treatment. Also, copper sulfate has been used in the regulating reservoir to control aquatic weed growth.

The annual development of thermal stratification during the warm part of the season, with accompanying depletion of DO in the hypolimnion (figure 2) suggested that steps should be taken to prevent any future serious deterioration of water quality in the M&I deliveries.

It was decided that destratification should be applied to eliminate the DO depletion in the hypolimnion, provide cooler waters at and near the surface to reduce evaporation losses and control algae growth, reduce the organic content of the water, reduce objectionable tastes and odors, reduce the chlorine requirement, and reduce the costs of water treatment. An improved lake fishery would also be expected, as well as improvement in the quality of downstream releases.

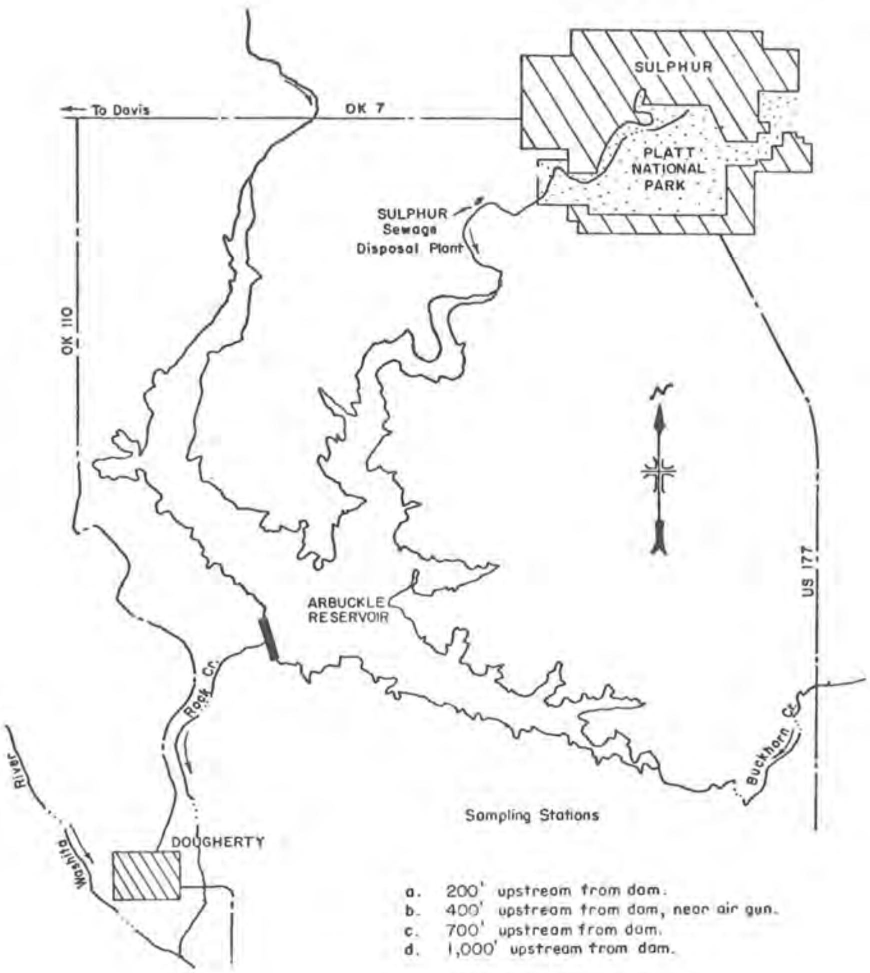


FIGURE I MAP OF LAKE OF THE ARBUCKLES

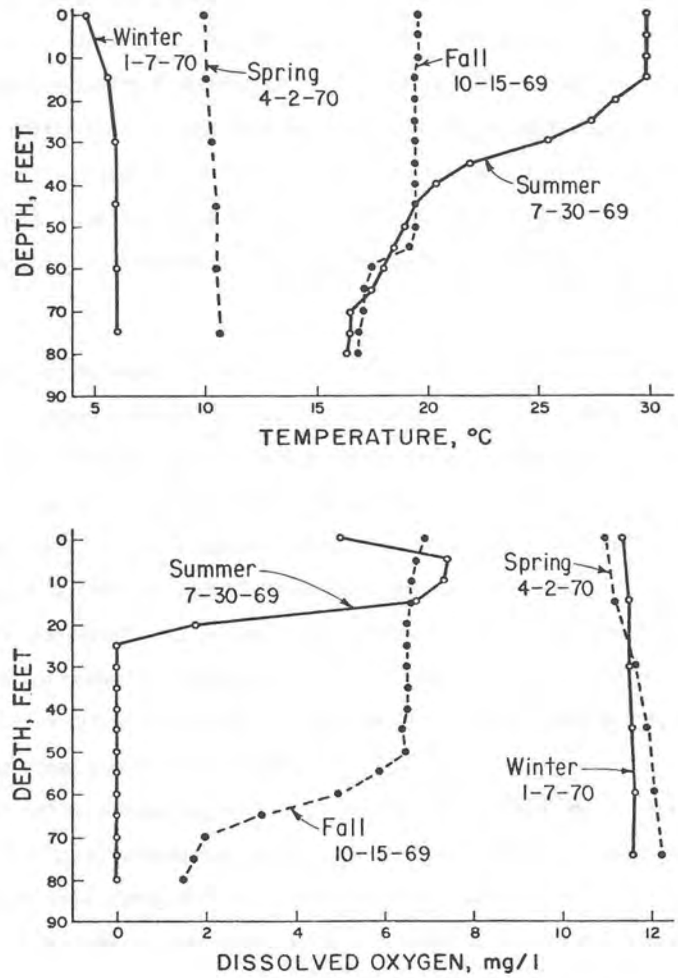
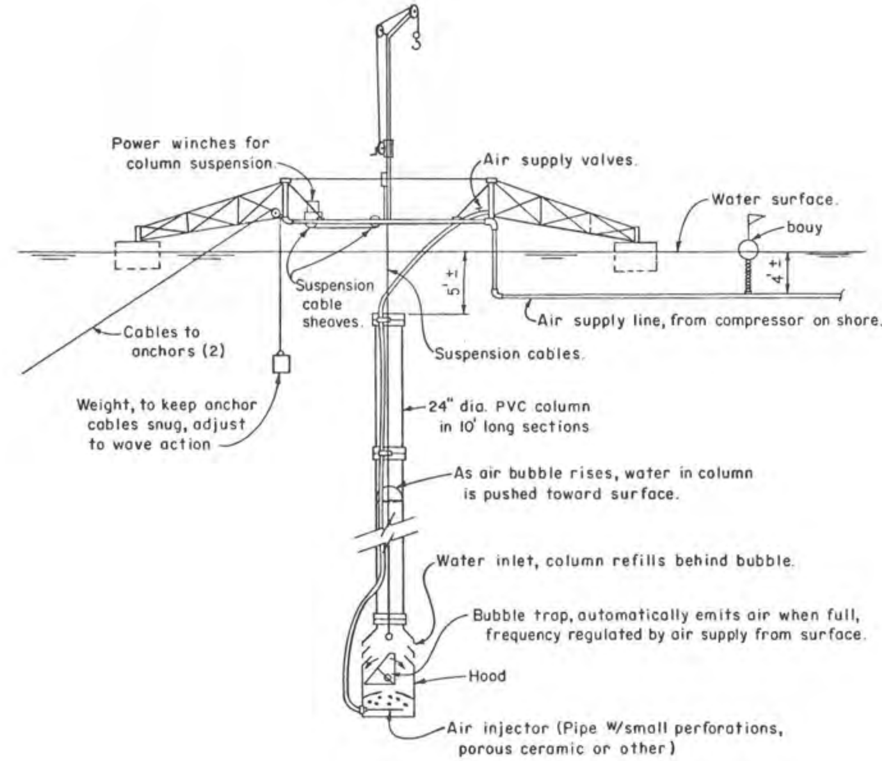


FIGURE 2 TEMPERATURE AND DISSOLVED OXYGEN PROFILES IN LAKE OF THE ARBUCKLES BEFORE DESTRATIFICATION

To accomplish the destratification, the Bureau's Southwest Region designed and constructed a type of "air gun" for testing. The air gun consists of a vertical tube with a chamber at the bottom which intermittently releases large air bubbles. The rising bubbles fit snugly in the tube and act as a piston which forces water out above the bubble and draws water from the lower part of the reservoir into the tube. Thus, the reservoir water is continuously circulated and the oxygen-depleted bottom waters are brought to the surface for reaeration from the atmosphere.

The air gun (figure 3) is constructed of a 2-ft (0.6-m), diameter polyvinyl chloride (PVC) pipe and is supported from a floating, anchored barge. Air is supplied from a compressor on shore to the diffuser which produces small bubbles that rise 4 to 5 ft (1.2 to 1.5 m) into a bubble trap. The small bubbles accumulate in the bubble trap which periodically dumps a single large bubble into the vertical tube. Some oxygenation takes place by transfer of oxygen from the bubbles to the water, but the major effect is circulation and reaeration from the atmosphere. The device, tested at Lake of the Arbuckles during the summer of 1973, showed an estimated pumping capacity of 30 ft^3/s (0.8 m^3/s) or 60 acre-ft per day (74 x 10 m^3/day), withdrawing water from a depth of about 57 feet (17.4 m), which was about 10 feet (3 m) from the bottom of the lake. Temperature, dissolved oxygen, conductivity, iron, phosphorus, ammonia nitrogen, phytoplankton, zooplankton, and the effects on fish growth were studied by the Oklahoma Cooperative Fishery Unit at Oklahoma State University.

The results of testing during 1973 indicated an overall destratification efficiency of 0.3 percent, using a gasoline-engine driven compressor part of the time. The electric compressor was considerably more efficient than the gasoline compressor, and calculations suggested that an overall destratification efficiency of about 1.1 percent could have been obtained if the electric compressor had been used exclusively. This latter value compares



DRAWING 3 DRAWING OF LAKE OF THE ARBUCKLES AIR-GUN

closely with efficiencies obtained with this type of device at other locations, including many very small impoundments.

Data were not available for computation of the reoxygenating efficiency of the air gun, primarily because the amount of oxygen utilized during the test period was unknown. Other air-gun devices have given an efficiency of about 1 to 2 pounds (0.5 to 1 kg) of oxygen per kilowatt-hour, and there is no reason to believe that the Arbuckle device would not perform similarly. There was a very apparent effect in the immediate vicinity of the device, as evidenced by increased oxygen concentrations at all depths above the device. There was also some indication of a very slight (less than 0.1 mg/l) increase in DO within the hypolimnion throughout the areal extent of the reservoir.

Destratification with Diffused Air

Flaming Gorge Reservoir

In 1972, small-scale pilot tests were conducted at Flaming Gorge Dam in Utah (figure 4) to determine the feasibility of using destratification as a method of controlling the temperature of releases through the powerplant.

During the years required to fill Flaming Gorge Reservoir to near-maximum operating levels, the tailwater fishery has followed a pattern of development previously noted on other large reservoirs with single-level release facilities. With low-level diversions in operation during filling of the dead storage pool, little change occurred in the quality of releases. As the reservoir reached intermediate levels, silt was retained in the reservoir, summer release temperatures were controlled to a 50° to 55°F (10° to 13°C) range, and an ideal trout habitat was created downstream. As the reservoir continued to rise toward upper operational levels with penstock entrances at considerable depth, summer release temperatures dropped below optimum ranges, the trout growth rate decreased, and the quality of the tailwater fishery was materially reduced. A typical summer temperature profile is shown in figure 2.

Consequently, to secure higher release temperatures, consideration was given to using an air-diffusion system to mix the water near the dam. Use of the ice-prevention system on the penstock and outlet trashrack structures to secure indicative data which might be used in designing a subsequent system was discussed. Although it was anticipated that use of the existing systems would not greatly affect release temperatures because mixing would be restricted to elevations above the penstock entrances, it was believed that sufficient change in the temperature profile near the dam would be noted, which would be an aid in future design.

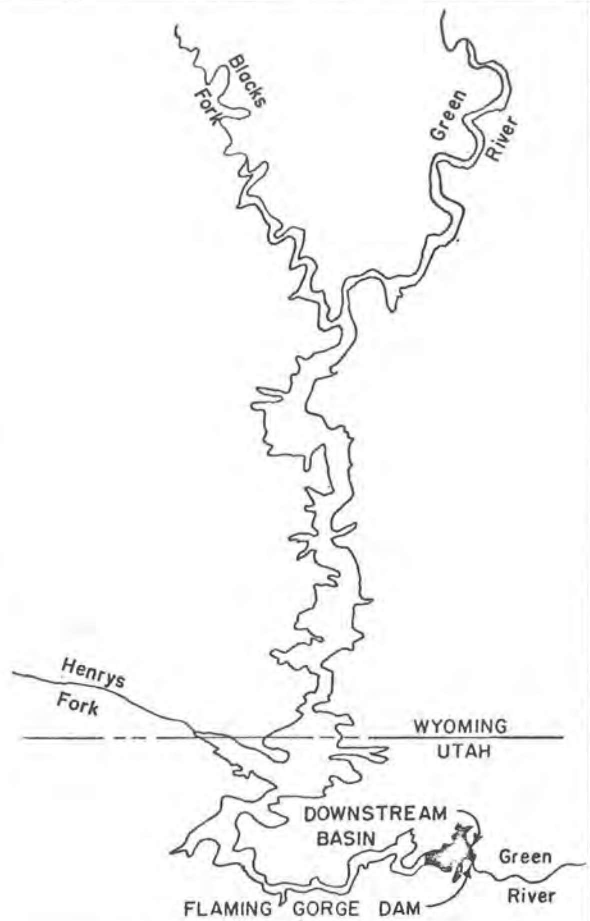


FIGURE 4 MAP OF FLAMING GORGE RESERVOIR

The pilot testing, as expected, produced no measurable effect on near the dam above the level of the intakes appeared to be affected. Data obtained were valuable in designing and estimating a conceptual prototype destratification system, and also aided in the design of alternative temperature control systems.

Some factors that made identification of effects of the diffuser pilot testing operation difficult were:

a. Lack of adequate background data prior to the start of the operation.

b. Natural, long-period perturbations in the temperature profile caused by variations in release, wind, and changes in storage.

c. An inadequate number of stations for measurment of temperature profiles in the immediate zone of testing because of limited manpower.

d. The very small energy input and low destratification efficiency of the air diffusers.

e. The proximity of the diffusers to the dam and the zone of influence of the penstock intake flow nets.

f. Poor timing of the tests; the pilot operation was not started until the reservoir had reached peak stratification.

It is believed that the efficiency of the pilot system, estimated at 0.02 percent, was severely limited by size and location. Results of a previous laboratory study suggested that below a certain critical limit of energy input, the destratification effect would be essentially negligible.

Prototype testing by the Corps of Engineers at Lake Allatoona in Georgia (a reservoir comparable in size to the downstream basin at Flaming Gorge and with similar power generation releases) increased water temperatures at a depth of

140 ft (43 m) by 10°F (5.6°C) under midsummer conditions. Efficiency of this system varied from 0.3 to 0.7 percent [1].

Using the reasonable assumption that a diffuser system with an efficiency of 0.5 percent could be designed, power requirements for destratifying the downstream basin at Flaming Gorge (figure 5) to a depth of 200 ft (60 m) would be 325 horsepower (240 kW). The power requirement for the entire reservoir using 0.5 percent efficiency and under similar conditions would be 6120 horsepower (4565 kW), which is obviously impractical. It was estimated that the capital cost of an air-diffuser installation adequate for control of the downstream basin would be approximately $200,000. In addition, the annual operating costs for this installation, including power, would be $70,000 to $90,000. The annual cost of necessary monitoring would be $6,000. The cost of a one-season, full-scale prototype test was estimated at $283,000, which includes full capital cost plus 1 year's operation. Anything less than prototype scale testing would probably be inconclusive.

Previous experience with the use of diffused-air systems suggests rather conclusively that the destratification efficiency is on the order of 1 percent or less. Therefore, this technique would seem to be limited, for reasons of economics, to relatively small impoundments. However, an alternative approach would be to destratify only a portion of a reservoir, near the intake for example, or to partially destratify only to the degree necessary to control a specific water quality problem. The success of these latter two approaches depends greatly on the resulting reservoir hydrodynamics, which require further study.

Because of the uncertainties and high costs of destratification at Flaming Gorge Reservoir, selective withdrawal was chosen as the most economical and reliable method for controlling temperatures below Flaming Gorge Dam.

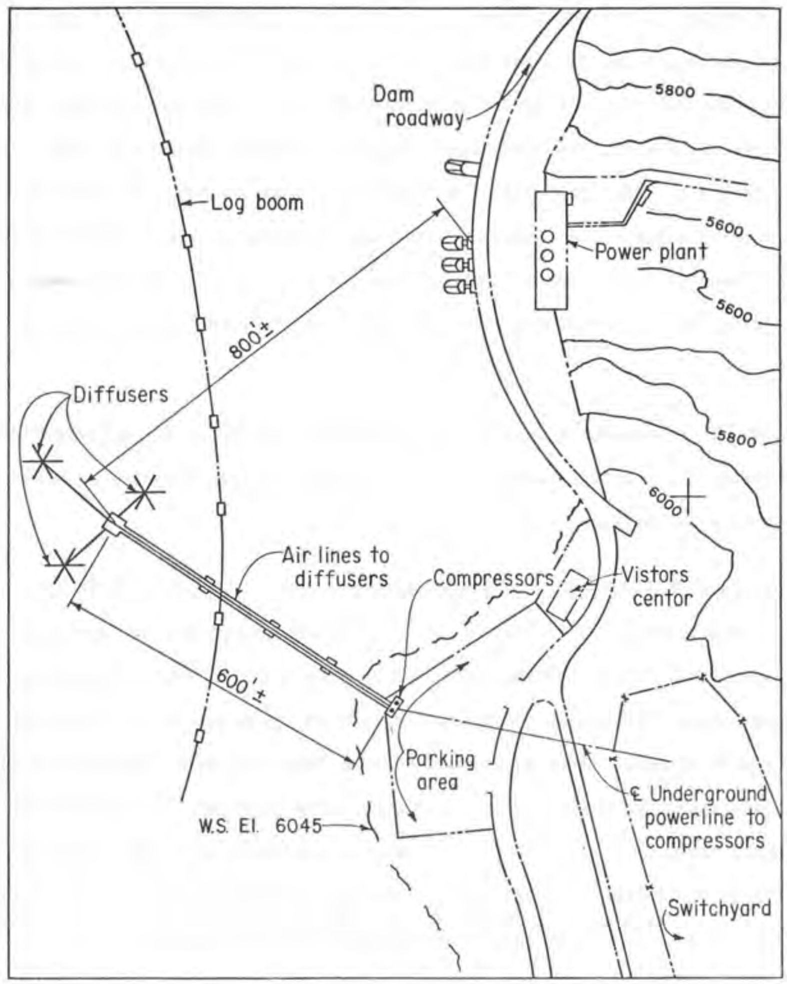


FIGURE 5 HYPOTHETICAL AIR-DIFFUSER SYSTEM FOR DOWNSTREAM BASIN OF FLAMING GORGE RESERVOIR

Lake Casitas

At Lake Casitas, California (figure 6), a study of compressed air diffusers is underway. Lake Casitas is a 254 000-acre-ft (3 x 10 m^3) reservoir. Casitas Dam, which was built by the Bureau of Reclamation, was completed in 1959. The dam, reservoir, and distribution system are now owned and operated by the Casitas Municipal Water District. The reservoir primarily supplies domestic and industrial water. The reservoir has a maximum depth of 250 feet (76 m) and a surface area of 2700 acres (1100 ha). The dam has a selective withdrawal outlet structure which contains nine gates located at 24 ft (7.3 m) vertical intervals.

The reservoir is monomictic (mixes once each year). Prior to any destratification efforts, the reservoir would begin to stratify in late February or March and turn over in December.

From July through November, waters were normally drawn into the distribution system from a depth of 20 ft (6.1 m) or less to avoid manganese and hydrogen sulfied problems. These problems occurred in deeper thermocline and hypolimnion waters when they became anaerobic. Waters in the upper 20 ft (6.1 m) of the lake were often of marginal quality because they were warm, exhibited a pH of 8.5 or higher, and contained objectionable taste and odor. In spite of all precautions, manganese was often drawn into the distribution system where it precipitated following chlorination. Extensive flushing through fire hydrants and blowoffs often failed to remove the manganese from the system.

Located 75 miles (120 km) north of Los Angeles and 7 miles (11 km) inland from the Pacific Ocean, Lake Casitas has heavy recreational use. Prior to the installation of a destratification system in 1968,only warm water fish existed in significant numbers within the lake. Largemouth bass, redear sunfish, and channel catfish were the major varieties present. Survival of rainbow trout within the lake was limited during summer months because the only waters with

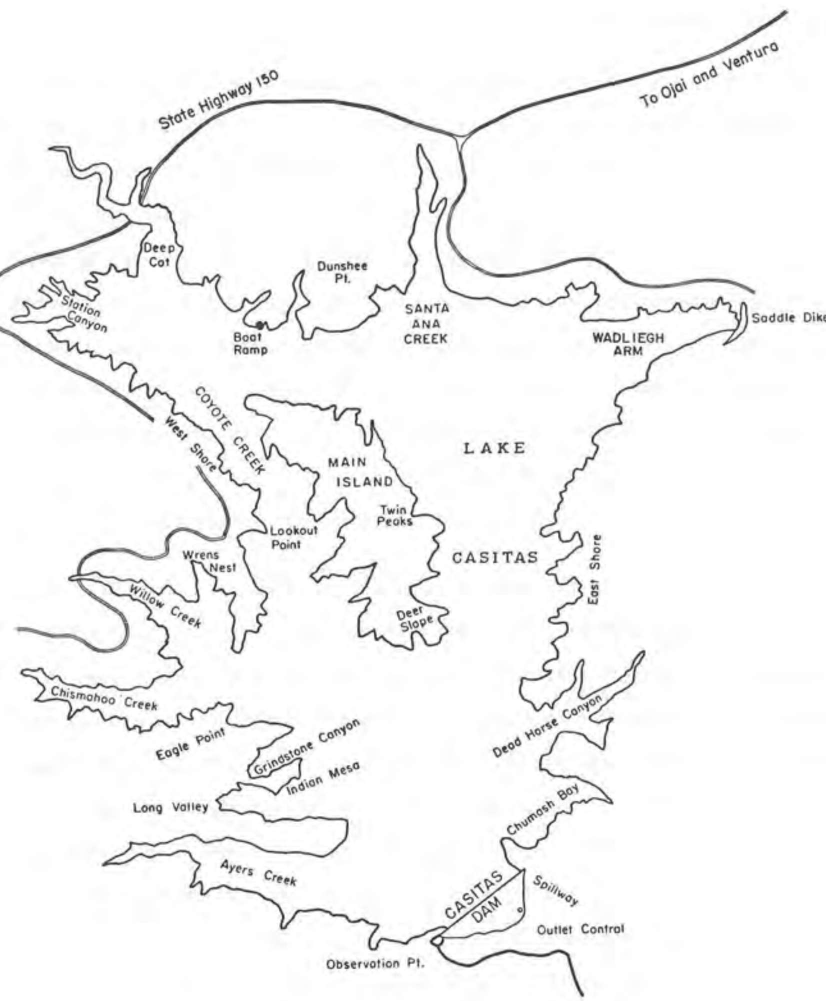


FIGURE 6 MAP OF LAKE CASITAS

sufficient dissolved oxygen to support cold water fish were found in the epilimnion where temperatures often exceeded 25.5°C.

Barnett [2, 3] has previously reported on the destratification of Lake Casitas for the years 1968 through 1975. All destratification at Lake Casitas has been accomplished through the use of diffused air systems. The diffuser system used from 1968 through 1976 was comprised basically of four compressed air point sources located at 70-ft (21.4-m) centers. During the first year of operation, the diffusers were located near the botton. Their continuous use stirred bottom materials and resulted in unacceptable manganese levels throughout the vertical profile of the reservoir. After the first 2 years, the diffusers were located at 140- to 160-ft (43- to 49-m) depth. The diffuser system was supplied with an air flow rate of from 600 to 630 std ft^3/min (17.0 to 17.8 std m^3/min) and operated continuously from early-April to mid-October.

Operation of this system has had several positive effects on the lake. It has partially destratified the entire lake from its surface to the depth of the diffusers. The partial destratification is such that a cold water zone is maintained in the destratification region and yet aerobic conditions are also maintained throughout the region. Consequently, cold water may be withdrawn from the lake throughout the summer months. At the same time, the manganese, hydrogen sulfide, and pH problems were eliminated. A trophy cold water fishery was also established and the number of algae blooms on the lake each year was reduced. Thus, the destratification-reaeration effort was thought to be quite successful. In recent years, operation and maintenance costs have been over $20,000 per year. The largest portion of this sum is spent on electrical power to drive the compressors.

Because of the existing compressed air diffuser facilities, the extensive existing lake water quality data, the desire of the water district to reduce its operating costs, and the desire of the Bureau of Reclamation to expand knowledge about destratification and reaeration devices, the Bureau and the water district agreed to perform research at Lake Casitas. It was decided that any new device tested would be sized and operated in such a way that resulting destratification levels would be similar to those achieved in the past. Several years of chemical and physical property data were available for comparison. Biological monitoring of the lake would be started prior to testing to allow comparative evaluation in this area as well. Contracts were established with Dr. Arlo Fast to monitor the biological properties of the lake and with the Department of Fish and Game of the State of California to assist in fisheries research studies. Dr. Fast's monitoring began in June of 1976, nearly 1 year before operation of the new diffuser, and has been continuous since that time. He has monitored chlorophyll zooplankton, benthic fauna,and fish species and distribution and has also been monitoring caged fish which are held in and near the bubble plume, to evaluate the effects of the high dissolved gas levels in these areas. Beginning in 1976, the State Department of Fish and Game has stocked identifiable fish and conducted creel censuses to assist in the evaluation of the fishery. Finally, the water district has continued their monitoring of physical and chemical properties.

After considering various devices that might be tested, the line diffuser was selected. It was recognized that line diffusers are widely used, but a literature search indicated that little data exist which would assist in their design, especially when the diffuser is used in deep lakes. It was thought that because of the wide application of line diffusers the development of design guidelines would be of real value. Parameters considered that would affect pumping efficiency include orifice size, orifice spacing, discharge rate per unit length of diffuser, and diffuser depth. It was decided that initially orifice spacing, orifice size, and diffuser depth would be held constant and a relationship between unit air discharge rate and pumping efficiency would be developed. It was recognized that due to the long time period required to evaluate individual operating conditions, development of the full relationship will take several years.

To prepare for the field tests, cursory evaluations of line diffusers were made in a labaoratory flume. Orifice size, orifice spacing, orifice orientation, and air discharge rates were varied and relative pumping efficiencies were evaluated. Based on these tests a line diffuser with 1.0-mm-diameter orifices spaced at 1-ft (0.3-m) centers and alternating from side to side on the diffuser line was selected. The 1.0-mm orifice diameter was selected because it was the smallest that could be easily drilled. Use of small orifices minimizes bubble size and individual orifice discharge rates. This allows the use of more orifices for a given total air discharge rate and, thus, allows for wider distribution of the bubble curtain. The flume tests indicated that linear spreading of the air plume results in more shear between the air plume and the water body, which in turn results in more efficient pumping action. Alternating the orifice placement from side to side on the diffuser line not only balanced the forces exerted by the released air but also slightly increased the pumping efficiency. The 1-ft (0.3-m) orifice spacing was controlled by the available total air discharge rate and by the feasible overall length of the prototype diffuser line.

A 700-ft (210-m) line diffuser was built and has operated through the 1977 season. The desired destratification levels have been achieved using approximately half of the total air discharge rate previously used. Pumping efficiency has consequently doubled. As in the past, diffuser operation has been continuous. The diffuser has worked well and no difficulties have been encountered. As of this writing, physical, chemical, and biological properties of the lake appear similar to those observed in previous years. The greatest variation from past data is noted in the thermocline and destratified hypolimnion. The new diffuser appears to have increased pumping action in these zones while having less influence on the rest of the reservoir. Consequently, a more clearly defined thermocline and hypolimnion are developed. Upper reaches of the destratified hypolimnion are cooler and have a lower DO than in past years while the lower reaches are warmer with higher DO's. It appears that the circulation created by the new diffuser is weaker and, consequently, unable to disturb strong thermo and density gradients. The circulation would thus be limited to the homogenous hypolimnion located between the thermocline and the diffusers themselves. This would maintain the observed homogenous destratified hypolimnion and would account for the temperature and DO profiles observed. Figure 7 shows typical DO and temperature profiles for 1976 and 1977.

Next season the diffuser will be tested at a higher air unit discharge rate and operated intermittently to achieve desired destratification levels. When the air discharge rate-destratification efficiency relationship is sufficiently developed, results of the, study will be reported.

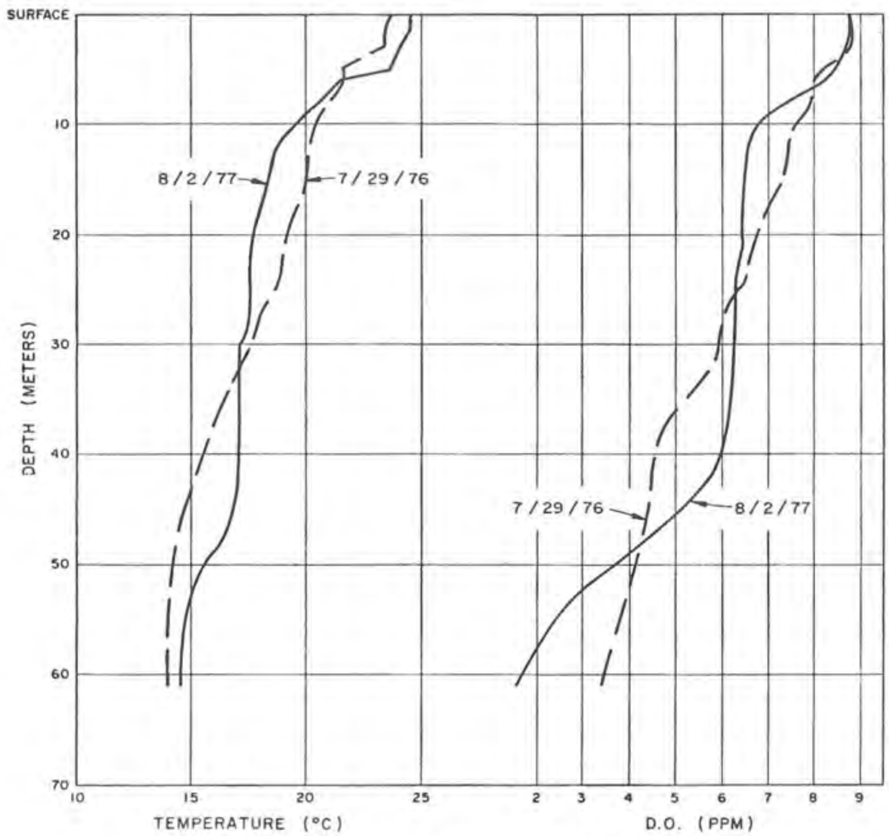


FIGURE 7 - LAKE CASITAS D.O. AND TEMPERATURE PROFILES FOR 1976 AND 1977

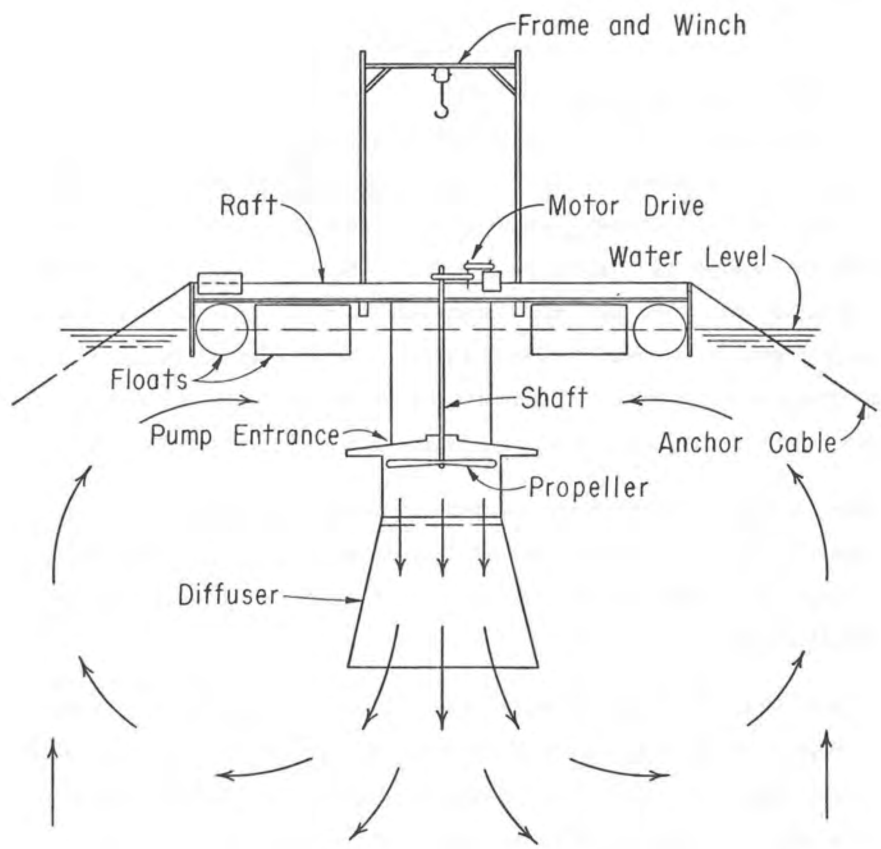


FIGURE 8 DRAWING OF GARTON PUMP

Surface Axial Flow Pump

Lake of the Arbuckles

At Lake of the Arbuckles, Oklahoma, a study of a surface-positioned axial flow pump destratifier is underway. The device was developed by Garton and Quintero of Oklahoma State University [8] and has been referred to as the Garton pump. Garton pumps have been built using a 3.5-ft (1067-mm) diameter cooling tower fan and a 16.5-ft (5030-mm) diameter aircraft propeller as impellers. In the pump, the impeller is suspended below a raft. The impeller is driven, through a reduction gear drive, by a motor located on the raft. When the pump is operating it draws in surface water and exhausts a low velocity jet that is directed vertically downward. A drawing of the pump is shown in figure 8. Current versions do not include the diffuser section below the propeller.

These pumps have high discharge-low head performance characteristics and are, therefore, ideally suited to a destratification application where efficient reservoir mixing requires the movement of large quantities of water with small velocities and pressure heads.

A 3.5-ft (1067-mm) diameter pump had been successfully operated at Ham's Lake in Oklahoma with a surface area of less than 100 acres (40 ha) prior to the Arbuckle tests [5]. Testing of the device at Lake of the Arbuckles hopefully would not only improve the water quality of the lake, but would also expand understanding of the capabilities of the Garton pump in larger reservoirs. The Bureau, therefore, has participated in financial support of the tests. Included in the tests are biological, chemical, and physical monitoring of the lake by Oklahoma State University staff, started a year before initiation of destratification activities.

Tests conducted in 1974 and 1975 used a 16.5-ft (5-m) diameter aircraft propeller as the pump impeller. The impeller has been driven by a 40-hp (30-kW) industrial motor. Power delivered to the impeller was measured using a torque indicator. Varying with operating condition and modifications to the device, delivered power ranged from 5 to 7.5 hp (3.7 to 5.6 kW). Minor modifications have been made from year to year. The impeller has been tested operating at rotational speeds of from 10 to 20 r/min. Pump discharges range from 300,000 gal/min (19 m^3/s) to 330,000 gal/min (21 m^3/s).

Tests to date have indicated that the device has good potential for destratification in reservoirs of this depth. Operation of the Garton pump near the water supply outlet has resulted in improved water quality for the delivered M&I water. No large changes in the biological or chemical properties of the lake have been noted. This season (1977) a matrix of 16 electric-motor driven Garton pumps are being used in an effort to destratify the reservoir in a shorten time.

CONCLUSIONS

Although the destratification research is in an active stage, several preliminary conclusions can be drawn:

1. Mechanical pumps and air diffusers used in large reservoirs have the same order of destratification efficiency as indicated by tests in very small impoundments; that is, less than 1 percent.

2. Design of air diffuser systems is very important; tests show a line diffuser to be more efficient than point source diffusers.

3. Local destratification near water intakes, and partial destratification (modification of temperature and DO profiles are possible.

4. Beginning desraficiation operations at the onset of stratification is more energy effective than beginning after stratification is well advanced. The latter may also circulate low DO waters and harmful substances, thus, creating adverse conditions in the reservoir.

5. Destratification equipment should be placed to avoid stirring up bottom materials.

APPENDIX I - REFERENCES

1. Anon, "Allatoona Lake Destratification Equipment Test Report," Corps of Engineers, Savannah, Georgia, June 1973

2. Barnett, R. H., "Reservoir Destratification Improves Water Quality," Public Works, Vol. 102, June 1971

3. Barnett, R. H., "Case Study of Reaeration of Casitas Reservoir," Presented at ASCE Symposium on Reaeration Research, Gatlinburg, Tennessee, October 1975

4. Busby, M. W., "Elimination of Stratification of Lake Cachuma," U.S. Geological Survey, 1970

5. Garton, J. E.; Summerfelt, R. C.; Toetz, Dale; Wilhm, Jerry; Jerrell, Howard, "Physicochemical and Biological Conditions in Two Oklahoma Reservoirs Undergoing Artificial Destratification," Oklahoma State University, Bureau of Reclamation Report REC-ERC-77-6, April 1977

6. King, Darrell L., "Evaluation of Water-Quality Data Collected During Aeration Studies at Table Rock Reservoir from September to November 1971," University of Missouri-Columbia for the Corps of Engineers

7. Koberg, G. E. and Ford, M. E., Jr., "Elimination of Thermal Stratification in Reservoirs and the Resulting Benefits," U.S. Geological Survey Water-Supply Paper 1809-M, 1965

8. Quintero, J. E. and Garton, J. E., "A Low Energy Lake Destratifier," Paper No. 72-599, presented at the 1972 Winter Meeting of the American Society of Agricultural Engineers, Chicago, Illinois, December 1972

9. Symons, J. M. and Robeck, G. G., "Calculation Technique for Destratification Efficiency," unpublished report, November 1966

10. Symons, J. M., "Quality Control in Reservoirs for Municipal Water Supplies," a report of the Quality Control in Reservoirs Committee, Water Quality Division, American Water Works Association, May 1971