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BUREAU OF RECLAMATION EXPERIENCE WITH DESTRATIFICATION OF RESERVOIRS

BY

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SESSION 13b BUREAU OF RECLAMATION EXPERIENCE WITH DESTRATIFICATION OF RESERVOIRS

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INTRODUCTION

Categories of Diffuser Equipment

There are various forms and modifications of diffused air equipment for destratification of reservoirs. In 1964, Bryan (3) introduced the hydraulic gun for destratification of small lakes in Ireland. This device is commercially known as the Aero-hydraulic Gun. A modification of the hydraulic gun is the Helixor, manufactured by Polcon Corporation. The primary use of this device has been to prevent winter kill of fish by maintaining ice free areas in small lakes (17). The Helixor presents an advantage of allowing a longer contact time between the bubbles and the water. Still another version of diffuser is the multileaf spring diffuser manufactured by Dravo Corporation. In this device, an opening leaf spring forms an orifice. Primary application is to waste treatment. Mention of these companies and their products does not imply endorsement or recommendation by the Bureau of Reclamation or the United States Government.

Various forms of porous diffusers have been used for introducing both atmospheric air and molecular oxygen to water. These diffusers include ceramic plates and disks and offer the advantage of producing small bubbles to enhance gas transfer.

A very common form of diffuser which is commercially available and widely used is perforated pipe. There is a need for design criteria for application of perforated pipe diffusers in large reservoirs; this is a main emphasis of this paper.

Categories of Impoundments

It is difficult to define ranges of size for small, medium and large impoundments. An example of a small impoundment is Ham's Lake in Oklahoma which has an average depth of 3 m, a surface area of 40 ha, and a volume of 1,150 ML. Lake of the Arbuckles in Oklahoma represents a medium size impoundment with an average depth of 9 m, a surface area of 950 ha, and a volume of 90,000 ML. Lake Casitas in California could be considered a large impoundment with an average depth of 60 m, a surface area of 1090 ha, and a volume of 300,000 ML.

Background

In 1919, Scott and Foley (21) applied the principle of destratification with diffused air to a small impoundment at Indiana University. They used perforated pipe with 3-mm holes spaced at 25 mm. They concluded that improved dissolved oxygen level was due more to convection currents than gas transfer from the bubbles.

A major contribution was made by Irwin, Symons, and Robeck in 1966 (9) when they applied mechanical pumping to several small impoundments. Symons and Robeck (22) also contributed a tabular method for calculating destratification efficiency. The work generally concluded that mechanical pumping was a more efficient method than diffused air.

In 1970, Ditmars (6) constructed a mathematical simulation of mechanical pumping for destratification. That simulation assumes that induced mixing takes place much faster than natural changes due to climate, etc. The model uses theories for jet diffusion and selective withdrawal. Ditmars raises the question of whether mechanical pumping is more efficient than diffused air and suggests that a modification of his model could be used to simulate diffused air destratification.

Application in Medium and Large Reservoirs

In 1962, Koberg and Ford (16) reported on work by the Geological Survey at Lake Wohlford in California. They diffused air through perforated polyvinyl chloride (PVC) pipe into the reservoir which has a depth of 15 m, a surface area of 90 ha, and a volume of 8,600 ML. Insufficient data were obtained to design for larger reservoirs.

In 1965, Fast (7) experimented at El Capitan Reservoir in California which has a depth of 35 m and a volume of 139,000 ML. Air was diffused through perforated PVC pipe. The work indicated the difficulty in determining destratification efficiency because of natural variations in the reservoir stability.

In 1970, the Geologic Survey (4) applied a diffused air system to Lake Cachuma, with a volume of 253,000 ML. The experiment was not successful because of inadequate sizing of the system.

Leach, in 1968 (18), used microporous porcelain diffusers in Lake Eufaula, Oklahoma. This large reservoir has a depth of 30 m, a surface area of 4370 ha, and a volume of 700,000 ML. The diffusers were located close to the dam and benefited water quality in that immediate vicinity and in the power releases.

The Metropolitan Water District of Southern California has applied diffused air at several reservoirs such as Lake

Mathews, where a 15-m-diameter ring diffuser was used in the 224,000 ML reservoir. The ring diffuser concept was also applied at Lake Castaic (19) (volume unknown) and at 54,000 ML Skinner Lake in 1976.

Biederman and Fulton described 1967 experiments at Lake Waco in Texas (2). Their report did not include any discussion of cost or efficiency for the use of a perforated plastic pipe diffuser at the reservoir, which has an average depth of 26 m and a volume of 128,000 ML. A local water district used diffused air at Lake Thunderbird in Oklahoma in 1974 and 1975. The lake is 18 m deep with a volume of 130,000 ML. They successfully applied a 30-m-long line diffuser with 2.4-mm holes at 0.6-m spacing. They reported a daily cost of $6.58 (U.S.)

BUREAU OF RECLAMATION DESTRATIFICATION RESEARCH

Background

The Bureau of Reclamation became involved in the subject of reaeration in 1968 while considering a proposed high dam on the Snake River. The problem was to increase the DO level from zero to saturation in a flow of about 450 m^3/s in order to maintain adequate DO levels in the low level releases for spawning salmon. The dam has not been built, but the reaeration research program of the Bureau found its start in analysis of that problem. Late in 1969, a state-of-the-art review was conducted which consisted of a comprehensive review of reaeration methods and devices, with an annotated bibliography (12).

The Bureau of Reclamation operates 125 storage reservoirs in the U.S., with a total capacity of approximately 282,000,000 ML. Capacities range from 37,000,000 ML in Lake Mead behind Hoover Dam to less than 10,000 ML in several small reservoirs. A survey in 1971 (5) showed that water quality problems associated with low dissolved oxygen existed in at least 27 of these reservoirs. The problem of excessive dissolved gas (supersaturation) surfaced later in the research program.

Upon recognition of the importance of the environmental effects of artificial reaeration methods, a second state-of-the-art review, on biological aspects of destratification, was conducted by Oklahoma State University in 1972 (23). This report also includes a very comprehensive annotated bibliography.

The reaeration research program of the Bureau of Reclamation has produced a method for prediction of dissolved gases below operating structures. A predictive technique resulted from measurements performed at a variety of structures and is used today by the Bureau and the Corps of Engineers. Another aspect of the research involves diffusion of molecular oxygen into the hypolimnion of reservoirs. A microporous ceramic diffuser is being tested and developed for overcoming reduction conditions in an ice- and snow-covered mountain lake.

The primary emphasis of the Bureau has been on destratification of reservoirs. This research includes both engineering investigations and studies on physicochemical and biological aspects.

Other research studies associated with the subject of destratification include prediction of temperature in streams and reservoirs (14) and the mechanisms of selective withdrawal from stratified reservoirs (10). The former has value for use in predicting the stratification pattern of reservoirs without destratification in order to calculate destratification efficiency. The latter can be used in connection with destratification or other reservoir reaeration methods to control the quality of releases.

Various studies have been conducted to estimate the size and cost of destratification systems for large reservoirs. In 1972, small-scale pilot tests were conducted at Flaming Gorge Dam in Utah to determine the feasibility of using destratification as a method of controlling the temperature of releases through the powerplant (13). As the reservoir reached intermediate levels following the completion of construction, suspended material was retained in the reservoir and summer release temperatures were controlled to a range of 10 to 13°C, which created an ideal trout habitat in the river downstream. However, as the reservoir filled, the penstock entrances were at considerable depth and summer release temperatures dropped below optimum ranges, the trout growth rate decreased, and the quality of tailwater fisheries was materially reduced. To secure higher release temperatures, consideration was given to using an air diffusion system to raise the water temperature near the dam. An existing ice prevention system on the penstocks and outlet trashrack structures was operated to obtain data which might be used in designing a prototype system. The ice prevention system was too small to create any significant effect near the dam. Based on experiences of others at large reservoirs, a prototype system was designed using an assumed efficiency of 0.5 percent. The diffused air system would be placed at a depth of 60 m. A 240-kW compressor was calculated as the requirement to destratify only the downstream basin of the large reservoir. To destratify the entire reservoir would require a capacity of 4500 kW. Because of the high capital and operating costs of a diffused air system and uncertainties in its expected performance, it was decided to use selective withdrawal as the temperature control technique at Flaming Gorge.

An associated study involved predicting the destratification potential of the generating cycle for a pumped-storage project. A mathematical model was used to show that the jet from the generating flow was not sufficient to produce destratification of the reservoir (15).

Laboratory Studies

Studies in the hydraulics laboratory of the Bureau of Reclamation have included limited flume studies of air diffuser configurations. A hydraulic model study of the pumped-storage project mentioned above has also been conducted with the same conclusion that the operation would not cause general destratification of the reservoir. This question has been studied further through mathematical and hydraulic modelling by Schwartz, et al., at West Virginia University (20).

Other laboratory work by the Bureau of Reclamation has included development of an air driven propeller pump. The concept is that air released from nozzles which drive the propeller blades will provide additional lift to the jet issuing from the pump. This device requires further investigation but probably would not be advantageous except in relatively shallow reservoirs because of limited influence of the pumped jet.

Field Studies

At the same pumped-storage project mentioned above, tests are being conducted to develop a microporous diffuser system to inject molecular oxygen into the hypolimnion of a 30-m-deep lake during the winter. During severe winters, a very thick ice cover forms with a significant depth of snow above it. Photosynthesis ceases and the DO (dissolved oxygen) level in the lower layers of the lake drops to zero. A reduction state occurs and toxic metals come into solution. All aquatic life in the lake dies. The intent of the oxygen diffusion system is to maintain a level of dissolved oxygen high enough to prevent the reduction state. Recent winters have not been severe enough to obtain good data, but a pilot system is ready for installation when conditions warrant.

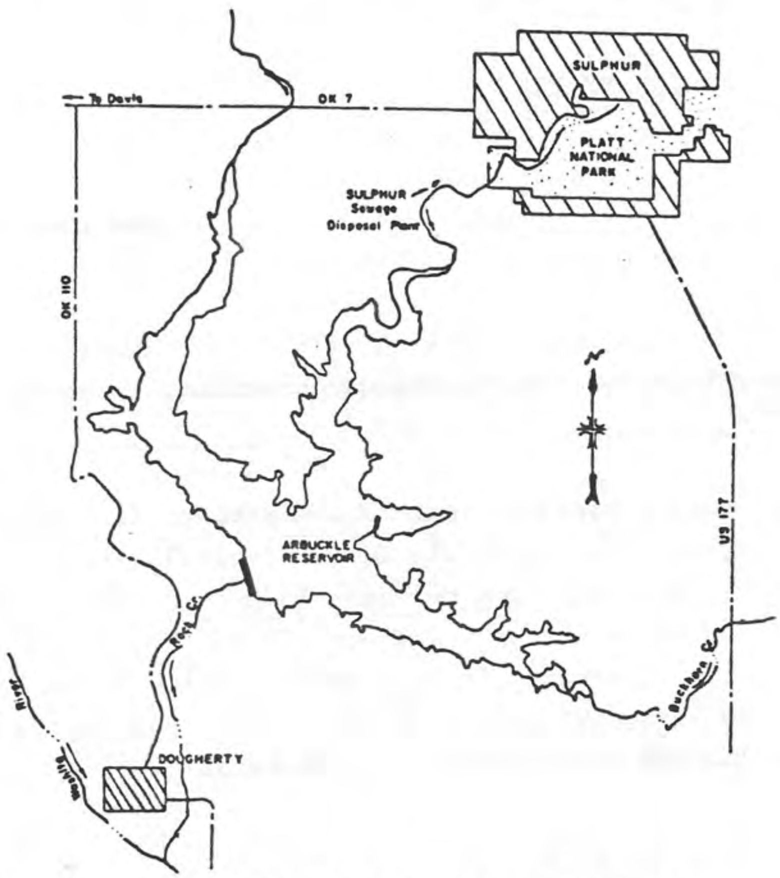

Fig. 1. Map of Lake of the Arbuckles, Oklahoma

A major field research activity has been at Lake of the Arbuckles in Oklahoma, (Fig. 1.). Lake of the Arbuckles has an average depth of 9 m, a surface area of 950 ha, and a volume of 90,000 ML . The reservoir was constructed in south-central Oklahoma in 1966 to provide municipal and industrial water supplies to several towns and a major oil refinery. Stream water quality data indicated that the reservoir would yield high quality water for municipal and industrial use. This has been true except that some form of chemical, algae, or microorganism in the reservoir causes a rapid depletion of chlorine in the water supply pipeline. Thus, additional chlorination is required at the point of water treatment.

The development of thermal stratification resulted in depletion of DO in the hypolimnion and suggested that steps should be taken to prevent any further deterioration of water quality.

Destratification would 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 taste and odours, reduce the chlorine requirement, and reduce the cost of water treatment. An improved lake fishery would also be expected as well as improvement in the quality of downstream releases.

Dr. Garton and Dr. Summerfelt will describe Oklahoma State University activities at Lake of the Arbuckles using the Garton pump. Prior to application of that device, the Bureau of Reclamation Southwest Region in Amarillo, Texas, designed and constructed an air gun for application at Lake of the Arbuckles (11). The air gun has some similarity to Bryan's design and consists of a vertical tube with a chamber at the bottom which intermittently releases large air bubbles,(Fig. 2). The rising bubble fits snugly in the tube and acts as a piston which forces water out above the bubble and draws water from the lower part of the reservoir into the tube. The reservoir water is continuously circulated and the oxygen-depleted bottom waters are brought to the surface for reaeration from the atmosphere.

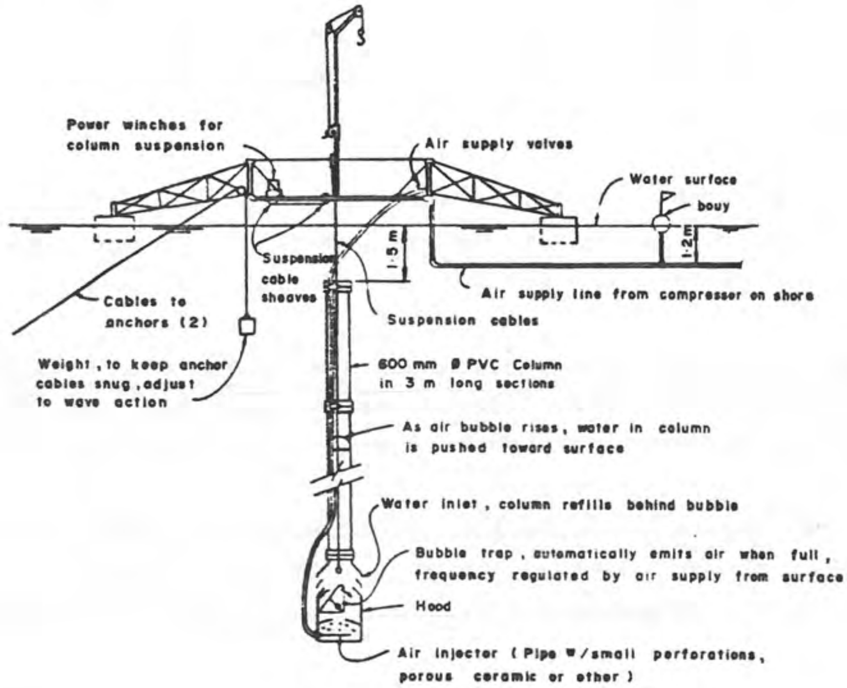

Fig. 2. Drawing of Lake of the Arbuckles air-gun

The air gun consists of a 0.6-m-diameter PVC pipe supported on a floating anchored barge. Air is supplied from a compressor on shore to a diffuser which produces small bubbles which rise about 1.5 m into a bubble trap. Accumulated bubbles periodically emerge as a single large bubble into the vertical tube. The device was operated during the summer of 1973 with an estimated pumping capacity of 0.8 m^3/s or 74 000 m^3/d. Water was withdrawn from a depth of about 17.5 m about 3 m above the bottom of the lake. Temperature, dissolved oxygen, conductivity, iron, phosphorus, ammonia nitrogen, phytoplankton, zooplankton, and the effect on fish growth were studied by Oklahoma State University (8).

The 1973 tests indicated an overall destratification efficiency of 0.3 percent using a gasoline-engine-driven compressor part of the time. An electric compressor was considerably more efficient and calculations suggested that it would result in an overall destratification efficiency of about 1.1 percent. This value compares 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 reoxygenation efficiency of the air gun primarily because the amount of oxygen utilized during the test period was not known. Other air gun devices have given an efficiency of about 0.5 to 1.0 kg O_2/kW h, and there is no reason to believe that the Lake of the Arbuckles 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 through the areal extent of the reservoir.

DESTRATIFICATION RESEARCH AT LAKE CASITAS

Background

At Lake Casitas, California, a study of compressed air diffusers is underway. Lake Casitas is a 300,000 ML reservoir, (Fig. 3.) 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 76 m and a surface area of about 1100 ha. The dam has a selective withdrawal outlet structure which contains nine gates located at 7.3 m vertical intervals.

Fig. 3. Map of Lake Casitas, California

The reservoir is monomictic. 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 6.1 m or less to avoid manganese and hydrogen sulfide problems. These problems occurred in deeper thermocline and hypolimnion waters when they became anaerobic. Waters in the upper 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 odour. 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 120 km north of Los Angeles and 11 km inland from the Pacific Ocean, Lake Casitas has heavy recreational use. Prior to the installation of a destratification system in 1968, only warmwater fish existed in significant numbers within the lake. Largemouth bass, red ear 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 sufficient dissolved oxygen to support coldwater fish were found in the epilimnion where temperatures often exceeded 25.5°C.

Operation with Point-source Diffusers

Barnett reported on the destratification of Lake Casitas for the years 1968 through 1975 (1). 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 21.4-m centers. During the first year of operation, the diffusers were located near the bottom of the reservoir. 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 a 43- to 49-m depth. The diffuser system was supplied with an airflow rate of from 17.0 to 17.8 m^3/min (standard conditions) 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 the 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 are eliminated. A successful coldwater fishery was also established and the number of algae blooms on the lake each year was reduced. Thus, the destratification effort was 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.

Research Program

Because of the existing compressed air diffuser facilities, the extensive existing lake water quality data, the desire of the Casitas Municipal 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 District agreed to cooperate in 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 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 Games of the State of California to assist in fisheries research studies.

Dr. Fast's monitoring began in June 1976, nearly one year before operation of the new diffuser, and continued through the 1977 season and part of the 1978 season. 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 California Department of Fish and Game has stocked identifiable fish and conducted creel censuses to assist in the evaluation of the fishery. Finally, the District has continued their monitoring of physical and chemical properties.

Operation with line diffuser

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 major value. Parameters considered that would affect pumping efficiency include orifice size, orifice spacing, discharge rate per unit length of diffuser, and diffuser depth. Initially, orifice spacing, orifice size, and diffuser depth would be held constant, and a relationship between unit air discharge rate and destratification and oxygenation efficiency would be developed. Due to the long time period required to evaluate individual operating conditions, development of the full relationship will take several years.

To prepare the field tests, cursory evaluations of line diffusers were made in a laboratory 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 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 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 210-m line diffuser was built and has operated through the 1977 and 1978 seasons. In 1977, the desired destratification levels were achieved using approximately half of the total air discharge rate previously used. As in the past, diffuser operation was continuous. The diffuser worked well and no difficulties were encountered. Physical, chemical, and biological properties of the lake appeared similar to those observed in previous years. The greatest variation from past data was noted in the thermocline and destratified hypolimnion. The new diffuser appeared 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 developed. Upper reaches of the destratified hypolimnion were cooler and had a lower DO than in past years while the lower reaches were warmer with higher DO. It appears that the circulation created by the new diffuser was weaker and, consequently, unable to disturb strong thermal and density gradients. The circulation would thus be limited to the homogeneous hypolimnion located between the thermocline and the diffusers themselves. This would maintain the observed homogeneous destratified hypolimnion and would account for the temperature and DO profiles observed. Figure 4 shows typical DO and temperature profiles for 1976 and 1977.

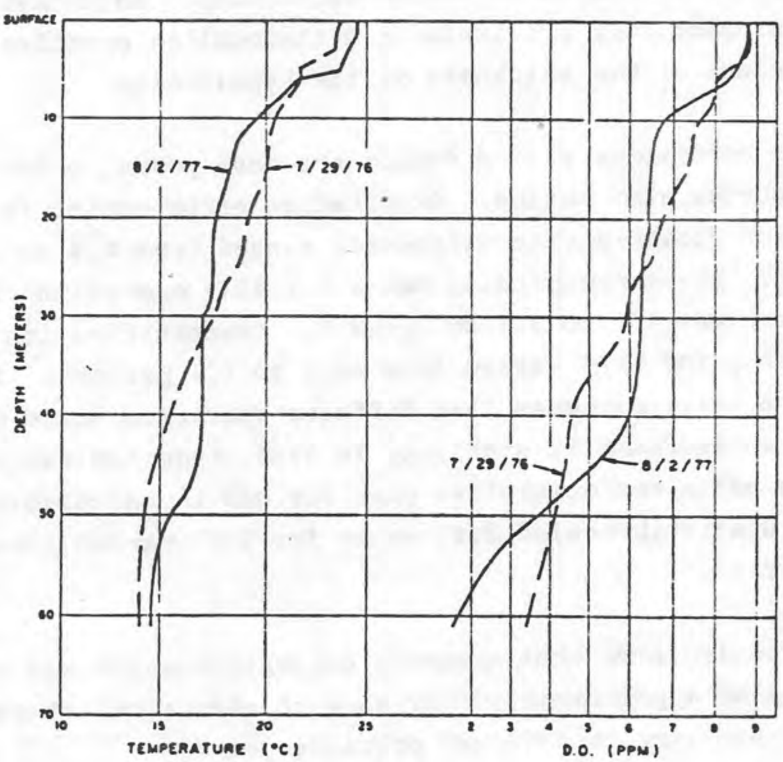

Fig. 4. Lake Casitas DO and temperature profiles for 1976 and 1977

A computer program was developed which computes total dissolved oxygen and stability of the reservoir using data on temperature, DO, and reservoir volume. The change with time is approximately linear through spring and early summer. By comparing total DO and stability for stratified and destratified years, the changes due to operation of the diffusers are determined. Dividing by the energy used by the air compressors yields oxygenation efficiency (kg O_2/kW h) and destratification efficiency (percent).

The stratified years of 1963, 1964 and 1966, representing high, medium and low DO and stability, were used as base years to calculate a range of efficiencies. Data were adjusted to eliminate the effects of volume variations. Adjustments were made assuming that epilimnion and thermocline profiles are independent of the thickness of the hypolimnion.

Because conditions varied during the base years, calculated efficiencies also varied. Oxygenation efficiencies for the 1976 operation (point-source diffusers) ranged from 0.8 to 1.8 kg O_2/kW h. The corresponding range for 1977 operation (line diffuser) was 2.6 to 3.8 kg O_2/kW h. Destratification efficiency for 1976 varied from -0.1 to 0.4 percent. The negative value suggests that diffuser operation would have caused an increase in stability in 1966, thus indicating that 1966 is not a representative year for use in calculations for 1976. Destratification efficiency for 1977 varied from 0.6 to 1.7 percent.

These results show that adequate destratification was possible with use of approximately half as much electrical energy in 1977 as was necessary in 1976 and previous years.

Future work will include application of a mathematical model for temperature prediction. This will increase the accuracy of the calculation of stability without destratification and help pin-point the diffuser destratification efficiency. A statistical analysis of dissolved oxygen trends and factors influencing those trends will hopefully develop a better model for calculating dissolved oxygen without destratification and thus yield more accurate oxygenation efficiency.

Analysis of data from the 1978 operation is not yet complete. The 1977 diffuser configuration was used but both compressors were operated (with twice the air discharge as in 1977) in a 12-hours-on, 12-hours-off pulsing mode. Temperature profiles were very similar to 1977 and DO profiles were approximately 0.5 to 1.0 mg/L lower than 1977. Oxygen data were masked by a sudden increase in oxygen demand, apparently caused by an algae bloom. On August 4, the pulsed operation was terminated and both compressors were used full time until the end of the season.

SUMMARY AND CONCLUSIONS

Testing of an air gun at Lake of the Arbuckles (9-m depth, 90,000 ML volume) in Oklahoma was not completely conclusive but suggested a destratification efficiency on the order of 0.3 percent using a gasoline-engine driven compressor or 1.1 percent using an electric compressor. These values are comparable to results of previous work in smaller impoundments. Oxygenation efficiency of the air gun was not determined at Lake of the Arbuckles but has been reported at about 0.6 kg O_2/kW h by others.

At Lake Casitas (76-m depth, 300,000 ML volume) in California, a point-source diffuser system operated with a destratification efficiency of about 0.4 percent or less and an oxygenation efficiency of 0.8 to 1.8 kg O_2/kW h. A line diffuser operated with a destratification efficiency of 0.6 to 1.7 percent and an oxygenation efficiency of 2.6 to 3.8 kg O_2/kW h. For comparison, approximate oxygenation efficiency for mechanical pumping has been reported as 0.5 kg O_2/kW h.

Future work at Lake Casitas will include use of an existing temperature prediction model and a statistical analysis of dissolved oxygen data to refine efficiency calculations. An ultimate objective is to use information gained from this research to develop generalized diffused design criteria. These criteria will then be used to design and construct a destratification system for another large reservoir. Operation of that system will be monitored for design criteria verification.

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SESSION 13b DISCUSSION

BOWEN: Would it be possible to measure the amount of oxygen released into the reservoir, and compare this with the amount of oxygen delivered by the compressors as a measure of efficiency?

KING: To do that you would need to measure the air flow rate, which is easy enough to do, but somehow you would have to capture the bubbles leaving the reservoir, and analyse them for oxygen content, in order to know how much had gone into the water.

BOWEN: You could also measure how much oxygen was in the water after the bubbles had left. This would measure the amount of oxygen actually transferred to the reservoir in the whole process.

KING: That is essentially what we would be trying to do indirectly by capturing the bubbles leaving the reservoir.

BOWEN: But how about trying to measure it directly by analysing the water itself?

KING: We do analyse the water itself, but we need to know what the B.O.D. is, in order to accurately calculate the oxygen input. We do measure the oxygen, and determine the total mass of oxygen in the lake.

BOWEN: We have measured the depletion rate in Prospect Reservoir using the stratigraphy of the reservoir, and the dissolved oxygen at each of the levels, and have found it to be a fairly uniform decline. We have also found when we destratified that the increase was also fairly linear with time.

KING: Yes. I follow what you are doing, and that is essentially how we are getting the oxygenation efficiencies - by comparing the rate of natural oxygen depletion with the rate of oxygen increase when destratifying.

JUDELL: I would like to refer to the cost of destratifying. Could you give us this as horse power required and operating cost or some such measure? Could you tell me the energy input into Lake Casitas with your line diffuser?

KING: It was a 60 hp motor. There were two of them, but we only used one at a time during 1977. We also had Watt-hour meters on them, and this information will be reported.

JUDELL: Could you also tell me the time required for destratification?

KING: It was only partial destratification. I think Arlo could comment on how quickly it took place. It began while the reservoir was still uniform.

JUDELL: In other words the operation was to prevent stratification.

KING: Yes.

WALLIS: What was the diameter of the diffuser line?

KING: The line was 2 inches in diameter and made from plastic.

WALLIS: Also I think your conclusion that the line diffuser is more effective than the point source diffusers is valid. None the less, just looking at it, you probably could have put half as much air through those four point sources, and have had much the same result, doubling your efficiency. So the difference in efficiency might not be just the factor you suggested.

KING: That is an interesting possibility.

FAST: Another unanswered problem involves the optimum air density along a diffuser line, in terms of Standard Cubic Litres per Second (SCLS) per linear metre of line. At Lake Casitas during 1977, we apparently had too low an air density during mid-summer. When the surface temperatures were at a maximum we observed an "uncoupling" of the air, and upwelled water below the thermal gradient near the surface. The upwelled water flowed out below this gradient, but the air rose to the surface. Surface water temperatures within the bubbles were about the same as outside the area. With higher air densities, the upwelled water surfaced, and was much cooler than the surrounding surface waters. This suggests that the mixing process is impeded by low air densities, and a large density difference between the surface and upwelled waters. There is probably an optimum bubble density (in terms of mixing efficiency) for each set of conditions.

WALLIS: Referring to the density of your plume, when it hits the point where it is in neutral equilibrium - at that stage it is all uphill - if it is going fast enough it will make it. If you have a long, fairly low momentum plume which is most efficient for oxygen transfer, it probably will not make the surface.

KING: Yes. It is what Speece called the uncoupling effect.

BURNS: Danny. Could you pass some comments on the effectiveness, or otherwise, of the 'Air Gun' system. When Joe Shapiro was referring to the horrible things we do to reservoirs the other day, I immediately thought of the 'Air Gun'. Surely one great bubble coming up from time to time is not a very efficient way of moving water.

KING: It seems to fall in the same order of efficiency of destratification as other diffuser devices. My state of the art report has some more information on that. I think it is less efficient, but it is of the same order.

BURNS: It seems to be used in just one area of the U.S.A. - around Philadelphia. May be there is a good salesman there, but it does not seem to be in general use.

McFIE: In the 'Air Gun' do you actually have a limit on the air bubble size?

KING: It is more of a pump. The air bubble completely fills the vertical tube and acts as a piston. This particular one was 0.6 m diameter.

McFIE: Then of course the size depends on pressure.

BURNS: They get away with very small compressors when using the 'Air Gun'.

KING: Yes. You only have to bubble the air into the bottom until it collects to form a single large bubble, which is then released.

SIMMONDS: In the 'Air Gun' - at least as far as the Aero Hydraulics design is concerned - the bubble discharged will always have the same volume, because the bubble is ejected by filling a siphon tank in the gun.

The water circulation is increased by increasing the rate at which the siphon tank fills and discharges the bubble.

KING: Yes. That is correct.

DORTCH: Danny. I notice your partially mixed profile. It looks real neat. Some people have mentioned the fact that if you don't totally mix - all the way up to the surface - then you may actually have a big problem with an algal bloom, and so on. How is it that in Lake Casitas you are able to partially mix and be so effective?

KING: I take note of those comments, but I am not sure I can answer them.

Let me add that Lake Casitas had a large algal bloom during this last year, late in the season. I wonder if something like you are suggesting might have been going on.

SHAPIRO: That is the thing. If you are not looking for it, or measuring it, you are not going to find it. If you are looking for iron and manganese, that is what you measure, and these other things somehow never get noticed.

DORTCH: Well some people have even mentioned that if you don't totally mix it, you might actually have less dissolved oxygen from top to bottom. He actually did improve the dissolved oxygen and he definitely did not totally mix it, because he has a double thermocline. I'm just curious.

FAST: The situation at Lake Casitas is complicated by many factors operating concurrently, but without any good way of separating their individual effects. Lake Casitas was created in 1959, but aeration did not begin until 1968. Before 1968 the lake was of relatively low volume. After 1968, it filled rapidly to near capacity, or a four-fold or more increase over pre-aeration conditions. During each water volume increase, new land was flooded, with releases of nutrients and other substances to the water.

Much of this flooded material has now decomposed, and the lake has aged. Its productivity has decreased greatly. At best, it is now mesotrophic. There is a tendency for some people to compare conditions now with the pre-aeration conditions, and attribute all the differences to the aeration. That is nonsense. Granted there are many confounding interactions, but for sure, the lake would not assume its pre-aeration condition, if the aerator was turned off. In fact, I believe it might even improve further if the aeration was discontinued. There is good evidence that the aerator is actually upwelling much phosphorus, and thus promoting algal growth. Algal growth may decrease further if aeration is discontinued at Lake Casitas.

TYLER: Arlo. Are they using much copper sulphate?

FAST: I think they would use even less if they would shut it off, but they are not using much.

END OF DISCUSSION